Research on RMST Trade-off Optimization of Chemical Defense Smoke Vehicle Based on System Efficiency

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Abstract: For modern new-type chemical defense smoke equipment, quality has become a major difficulty in the formation of combat effectiveness. Therefore, on the basis of analyzing the related research, this paper put forward a design trade-off method which is applicable to the quality of the design development stage and the equipment development, that is RMST trade-off optimization method based on system efficiency. Firstly, based on the characteristics of smoke vehicle and the connotation of system efficiency, the paper analyzes the influence factors of the system efficiency and constructs the conceptual model of the system efficiency. Second, taking series complex structure as an example, it builds mission-reliability model and the model of readiness rate mode suitable for current system of supply guarantee, then obtains the system efficiency mathematical model under the structure; Finally, through the RMST general simulation process and the constraint value of the multi-objective decision variables, the system efficiency optimization simulation trade-off model is built to provide the basic algorithm for the next stage of the simulation design for real equipment.

At present, there is a great amount of studies of RMST trade-off optimization, which generally can be divided into RMST trade-off based on top-level design index [1-3], RMST trade-off based on cycle cost [4-6], and RMST trade-off based on system efficiency [7-9]. According to this paper, it is believed that the RMST of equipment system is decided by quality characteristics of various basic constitutional units and structural layout of equipment system, and the trade-off and optimization of RMST index is not only applied to demonstration stage, also promoted and used in the stage of development and design. Therefore, this paper, according to actual FLQM of chemical defense smoke vehicle in our army, based on previous studies, constructs RMST trade-off mode and simulation dynamics mode based on system efficiency suitable for the stage of development and design, and proposes RMST trade-off analysis process and bound variables of decision-making, providing research foundation for implementing the design of new-type equipment.

1. System Efficiency Model of Chemical Defense Smoke Vehicle

1.1 The influence factors of system efficiency

The anti-chemical smoke vehicle belongs to the intermittent equipment system, which is basically in alternative working and halt in life cycle [10]. The inherent ability of smoke vehicle mainly refers to the comprehensive performance of equipment smoke, protection, maneuvering, index control, etc. The impact of RMST design and equipment performance design is mainly reflected in the selection of basic components and infrastructure. Whereas, RMST trade-off optimization is aimed at optimizing the layout structure, and generally does not change its basic components and architecture, so the inherent ability can be set as constant when building a system efficiency model with the goal of RMST trade-off optimization.

Therefore, on the basis of analyzing influence factors of system efficiency of smoke vehicle, the model can be built as shown in Equation (1).

$$E = P \cdot D \cdot C \tag{1}$$

In Equation (1), E refers to system efficiency; P refers to the parameter of readiness rate, which indicates the integrity of the smoke vehicle in mission preparation; D refers to the parameter of mission credibility, which shows the probability of smoke vehicle to be successfully used to accomplish mission at any time on the basis of successful dispatch; C refers to the inherent ability parameters of smoke vehicle.

Based on the current supply guarantee system for spare parts of chemical defense equipment, this paper constructs a mathematical model of the system efficiency under the general series of complex structures, which provides a basis for the implementation of RMST trade-off of anti-chemical smoke vehicle. When constructing the model, name c as the identifier of the series structure, b as the identifier of the redundant voting structure, and y as the identifier of the preventive maintenance.

1.2 The model of mission reliability parameter

Mission reliability refers to the ability for equipment to complete the mission without failure or repair in time after failure, and the model is shown in Equation (2).

$$D(t) = R(t) + (1 - R(t)) \cdot \varphi_k \cdot M(t) \tag{2}$$

Wherein, $R(t)$ indicates the reliability of the equipment to perform mission at the time t; φ_k indicates the failure detection isolation rate; $M(t)$ indicates the maintenance function after the failure.

1.2.1 The calculation model of mission reliability

According to mission reliability model of simple series structure and redundant voting module, the mission reliability model of series complex structure can be deduced as shown in Equation (3).

$$R_S(t) = e^{-\sum_{i=1}^{n_c} \lambda_i t} \prod_{j=1}^{n_b} \sum_{g=1}^{o_j - k_j} C_{o_j}^g (1 - e^{-\lambda_j t})^g e^{-(o_j - g)\lambda_j t}) \tag{3}$$

Wherein, n_c is the number of modules in the series structure in the system; n_b is the number of redundant structures in the complex system; o_i is the number of units in the i-th redundant module; k_i is the number of voting units in the i-th redundant structure; λ_i is the failure rate in the i-th module.

1.2.2 The calculation model of maintenance

Because the calculation model of failure detection rate in [12] is scientific and correctly deduced, this paper uses the model (recorded as φ_{ks}) in this paper to construct the mission reliability model, which is shown in Equation (4), based on studies on mission reliability and maintenance parameter model.

$$D_s(t_s) = \left\{ \begin{array}{l} e^{-\sum_{i=1}^{n_c} \lambda_{ci} t_s} \prod_{j=1}^{n_b} \sum_{g=1}^{o_j - k_j} C_{o_j}^g \cdot (1 - e^{-\lambda_{bj} t_s})^g e^{-(o_j - g)\lambda_{bj} t_s}) \cdot \\ \left[1 - \prod_{i=1}^{n_c}(1 - e^{-\mu_{ci} t_s}) \cdot \prod_{j=1}^{n_b}(1 - e^{-\mu_{bj} t_s})^{o_j} \cdot \varphi_{ks} \right] \\ + \prod_{i=1}^{n_c}(1 - e^{-\mu_{ci} t_s}) \cdot \prod_{j=1}^{n_b}(1 - e^{-\mu_{bj} t_s})^{o_j} \cdot \varphi_{ks} \end{array} \right\} \tag{4}$$

Wherein, t_s is the average mission continuous working time of the system; other parameters are the same as above.

1.3 The model of readiness rate parameter

The readiness rate indicates that the conditions of equipment in mission preparation [13]. To achieve successful dispatch, the failure must be repaired before the next dispatch or the previous mission with no failure. Therefore, the readiness rate can be expressed not only by the ratio of the number of successful dispatches to the total number of dispatches, also for smoke vehicle, can be shown by the model in Equation (5).

$$P_{OR} = \frac{t_d}{t_d + E(\tilde{t}_m) + E(\tilde{t}_p) + E(\tilde{t}_f)} \tag{5}$$

Wherein, t_d is the specified or allowed maintenance downtime; $E(\tilde{t}_m)$ is the average maintenance delay time, indicating the average value of actual maintenance time exceeding the specified maintenance time or re-dispatch time; $E(\tilde{t}_p)$ is the average spare part delay time, indicating the average turnover time of waiting spare parts due to the lack of spare parts on site; is the average preventive maintenance delay time, indicating the average time value of equipment delay due to periodic maintenance.

1.3.1 The calculation model of delay time due to periodic maintenance

The failure probability of each module is only related to this module, independent of the integrated system. Therefore, when the average maintenance delay time of each module is integrated, the average maintenance delay time of each module cannot be simply added. It is necessary to clarify the relationship between the failure probability of the system and the failure probability of each module, and obtain average maintenance delay time of the entire series complex structure by replacing their own failure probability with the independent failure of each module in the system. Suppose whether it is series module or redundant module, once any failure occurs, it is recorded as a failure, that is, the redundant structure equivalence is taken as the series unit of the system, and the probability of failure of the integrated system is shown.

$$f_s(t) = 1 - \prod_{i=1}^{n_c+n_b} [1 - f_i(t)]$$

The relationship between the failure probability of the system and the failure probability of each module is shown in Equation (6).

$$h_i(t) = f_s(t) \cdot \frac{In\left(\frac{1}{1-f_i(t)}\right)}{\sum_{i=1}^{n_c+n_b} In\left(\frac{1}{1-f_i(t)}\right)} = \left[1 - \prod_{i=1}^{n_c+n_b}[1-f_i(t)]\right] \frac{In\left(\frac{1}{1-f_i(t)}\right)}{\sum_{i=1}^{n_c+n_b} In\left(\frac{1}{1-f_i(t)}\right)} \tag{6}$$

Thus, the model of average maintenance delay time in series complex structure is shown in Equation (7).

$$E_s(\tilde{t}_m) = \frac{1 - \prod_{i=1}^{n_c+n_b}[1-f_i(t)]}{\sum_{i=1}^{n_c+n_b} In\left(\frac{1}{1-f_i(t)}\right)} \cdot \left\{ \sum_{i=1}^{n_c} \frac{In\left(\frac{1}{1-f_i(t)}\right) \cdot e^{-\mu_{ci}t_d}}{\mu_{ci}} + \sum_{i=1}^{n_b}\sum_{j=1}^{o_i} \frac{In\left(\frac{1}{1-f_i(t)}\right)(-1)^{j+1} C_{o_i}^j e^{-j\mu_{bi}t_d}}{j\mu_{bi}} \right\} \tag{7}$$

1.3.2 The calculation model of average spare part delay time

The premise that the average spare part delay time is not 0 is that failure occurs in the system and the spare parts required for maintenance are lack on site. Under the three-level supply system of on-site, battle-level equipment warehouse and strategic-level equipment warehouse, the calculation model of the average spare part delay time of module *I* is shown in Equation (8).

$$E_i(\tilde{t}_p) = f_i(t) \cdot \left[t_{p1i}(t) \cdot \overline{P}_{1i}(t_0) \cdot P_{2i}(t_x) + t_{p2i}(t) \cdot \overline{P}_{1i}(t_0) \cdot \overline{P}_{2i}(t_0) \right] \tag{8}$$

Wherein, t_{p1i} is the turnover time for battle-level equipment warehouse to temporarily acquire

the spare parts of the module i; t_{p2i} is the turnover time for the strategic-level equipment warehouse to temporarily acquire the spare parts of the module i; $P_{1i}(t)$ is the probability of spare parts guarantee on site for the module i in the time t; $P_{2i}(t)$ is the probability of spare parts guarantee for battle-level equipment warehouse for the module i in the time t; t_0 is the accumulated working time of equipment in the period of supply guarantee of spare parts; t_x is the average working time of the equipment in the period of supply guarantee minus the average time of the exhaustion of the equipment spare parts on site. In addition to the effects of uncontrolled factors such as transportation and natural disasters, t_{p1i} and t_{p2i} can basically maintain a constant value, so the two can be assumed to be constant in the design.

Since the spare parts supply only considers the number of spare parts instead of the series or redundant structure, the series structure and the redundant voting structure can share a spare part guarantee probability model shown.

$$P_i(t) = \frac{1}{t}\int_0^t e^{-\lambda_i t}\sum_{j=0}^m \frac{(\lambda_i t)^j}{j!}dt$$

Thus, the calculation model of spare part delay time in series structure can be obtained from Equation (6) and (8), shown in Equation (9).

$$E_s(\tilde{t}_p) = \sum_{i=1}^{n_c+n_b} h_i(t)\cdot\left\{\begin{array}{l} t_{p1}[1-\frac{1}{t_0}\int_0^{t_0} e^{-\lambda_i t}\sum_{j=0}^{m_{1i}}\frac{(\lambda_i t)^j}{j!}dt][\frac{1}{t_x}\int_0^{t_x} e^{-\lambda_i t}\sum_{j=0}^{m_{2i}}\frac{(\lambda_i t)^j}{j!}dt] \\ +t_{p2}[1-\frac{1}{t_0}\int_0^{t_0} e^{-\lambda_i t}\sum_{j=0}^{m_{1i}+m_{2i}}\frac{(\lambda_i t)^j}{j!}dt]\end{array}\right\} \tag{9}$$

Wherein, m_{1i} is the storage capacity of the i-th module equipment regularly distributed spare parts of the repair organization of this level; m_{2i} is the number of equipment regularly distributed spare parts for the i-th module of the battle-level equipment warehouse; m_{3i} is the quantity of equipment regularly distributed spare parts for the i-th module of the strategic-level equipment warehouse; t_0 is the accumulated working time of the equipment system during the regular distribution period of the spare parts of the equipment; t_x is the average time of accumulated working time in the supplementary supply guarantee period minus the average time of the exhaustion of the spare parts of the equipment on site. The mode is presented.

$$t_x = t_0\left(1-\frac{1}{t_0}\int_0^{t_0} e^{-\lambda_i t}\sum_{j=0}^{m_{1i}}\frac{(\lambda_i t)^j}{j!}dt\right)$$

1.3.3 The calculation model of average delay time due to preventative maintenance

The average preventive maintenance delay is different from the maintenance delay and spare parts delay. The preventive maintenance interval is fixed. The interval between the maintenance of the smoke vehicle is set as T_F, the maintenance time parameter of each medium repair or overhaul as t_f, and the calculation model of average preventive maintenance delay time as Equation (10).

$$E(\tilde{t}_f) = \sum_{i=1}^{n_y} E_i(\tilde{t}_f), \text{ wherein, } E_i(\tilde{t}_f) = \begin{cases} \dfrac{t_s(t_{fi}-t_d)}{T_{Fi}} & t_{fi} > t_d \\ 0 & t_{fi} \le t_d \end{cases} \tag{10}$$

Thus, the calculation mode of readiness rate in series complex structure is shown in Equation (11).

$$P_{ORS} = \cfrac{t_d}{t_d + \cfrac{1 - \prod\limits_{i=1}^{n_c+n_b}[1-f_i(t_s)]}{\sum\limits_{i=1}^{n_c+n_b} \boldsymbol{ln}\left(\cfrac{1}{1-f_i(t_s)}\right)} \cdot \sum\limits_{i=1}^{n_c+n_b} \boldsymbol{ln}\left(\cfrac{1}{1-f_i(t_s)}\right) \left\{ \begin{array}{l} \cfrac{e^{-\mu_{ci}t_d}}{\mu_{ci}} + t_{p1}[1 - \cfrac{1}{t_0}\int\limits_0^{t_0} e^{-\lambda_i t}\sum\limits_{j=0}^{m_{1i}}\cfrac{(\lambda_i t)^j}{j!}dt] \cdot [\cfrac{1}{t_x} \\ \int\limits_0^{t_x} e^{-\lambda_i t}\sum\limits_{j=0}^{m_{2i}}\cfrac{(\lambda_i t)^j}{j!}dt] + \sum\limits_{j=1}^{o_i}\cfrac{(-1)^{j+1}C_{o_i}^j e^{-j\mu_{bi}t_d}}{j\mu_{bi}} \\ + t_{p2}[1 - \cfrac{1}{t_0}\int\limits_0^{t_0} e^{-\lambda_i t}\sum\limits_{j=0}^{m_{1i}+m_{2i}}\cfrac{(\lambda_i t)^j}{j!}dt] \end{array} \right\} + E(\tilde{\tau}_f)} \quad (11)$$

2. RMST Trade-off Optimization

According to the system efficiency model, there are 19 basic indicator data that need to be obtained, which are mainly determined by the component types and system structure layout selected by the equipment. The final object of the RMT trade-off optimization analysis is these 19 indicators. In engineering practice, if RMST trade-off of anti-chemical smoke vehicle is conducted with the goal of system efficiency, the three methods are generally used, including comparative trade-off analysis method, sensitivity trade-off analysis method and simulation trade-off optimization method. The first two are simple and there are many studies, referred in [14-16]. Thus, simulation trade-off optimization is demonstrated and verified in this paper.

Table 1 Definitions of basic parameters in simulation model of system efficiency

No.	Name of parameters	Symbol	No.	Name of parameters	Symbol
1	The number of modules in series structure	nc	11	The quantity of equipment regularly distributed spare parts for the i-th module of the strategic-level equipment warehouse	m3i
2	The number of modules in redundant voting structure	nb	12	The turnover time of spare parts from warehouse of this level to maintenance site	tp1
3	The number of units in the i-th redundant module	oi	13	The turnover time of supply module from strategic-level equipment warehouse to maintenance site	tp2
4	The number of voting units in the i-th redundant module	ki	14	The accumulated working time of equipment system in regularly distributed cycle of spare parts	t0
5	The failure rate of unit in the i-th module	ai	15	The number of projects with preventative maintenance of complex system	ny
6	The repair rate of unit disassembly and assembly in the i-th module	ui	16	The preventative maintenance cycle of the i-th sub-module	TFi
7	The average mission continuous working time of the system	ts	17	The average preventative maintenance time of the i-th sub-module	tfi
8	Specified or allowed maintenance and downtime	td	18	The frequency ratio of site replace module of the i-th sub-module and i-th failure mode	Aij
9	The storage capacity of the i-th module equipment regularly distributed spare	m1i	19	The number of modules replaced due to BITE isolated failure	Nk

	parts of the repair organization of this level				
10	The number of equipment regularly distributed spare parts for the i-th module of the battle-level equipment warehouse	m2i			

2.1 The simulation process of trade-off analysis

The simulation-based trade-off analysis method [17], according to the system efficiency mathematical model, is to adopt the system dynamics simulation principle, analyze the relationship between system efficiency and RMST indicators, and weighs the RMST indicator scheme under the optimal system efficiency, also can comparatively analyze the current scheme and optimal scheme to provide decision-making basis for the design of RMST indicators. The advantage of the simulation trade-off optimization method is that the optimal configuration can be obtained in as many schemes as possible, but it is necessary to provide as many boundary conditions as possible by simulation trade-off optimization to ensure the technical feasibility of the scheme as much as possible. In this paper, Matlab software is used to construct the optimization simulation algorithm of system efficiency, and the trade-off analysis is carried out through the process of "experiment design—simulation operation-efficiency optimization-result analysis".

2.2 The constraint of multi-objective decision variables

The selection of decision variables and the definition of constraint values are especially important for the final structure of simulation optimization. This paper design the requirements of the standard specification according to the anti-chemical smoke vehicle RMST [18], combined with the actual development requirements of the current equipment, set the eight variables as decision variables of the simulation trade-off, and set the threshold and constraint values, shown in Table 2.

Table 2 The setting of decision variables, the threshold and constraint values of simulation optimization of system efficiency

No.	Name of variable	Symbol	Threshold value	Constraint value
1	System efficiency	E	0~1	≥0.75 (optimal)
2	Readiness rate	POR	0~1	≥0.85
3	The average failure repair time	MTTR	≥0h	≤10h
4	The average failure interval	MTBCF	≥0h	≥500h
5	The average maintenance delay time	MLDT	≥0h	≤50h
6	The average spare part delay time	Tp	≥0h	≤100h
7	The isolation rate of system failure detection	XS	0~1	≥0.85
8	The guarantee rate of system spare parts	PS	0~1	≥0.70

3. Conclusion

According to the actual demand of insufficient methods and technologies for the quality of anti-chemical smoke vehicle, this paper, analyzes the main methods of RMST trade-off at home and abroad, proposes RMST trade-off of anti-chemical smoke vehicle suitable for development and design, and constructs the parameter model of RMST system efficiency and simulation model of

system dynamics in series complex structure, aiming to promote the implementation of RMST trade-off and realizing the optimal configuration of performance of anti-chemical smoke vehicle and RMST performance.

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