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Optimal Design of Command and Control System Based on Entropy Theory and Effectiveness Simulation

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Abstract: On the basis of entropy theory, the quality of information transmission is described with the introduction of time – effect and accuracy concepts, and then the evaluation model is established to analyze the information transmission quality; meanwhile, the simulation model based on the Monte – Carlo method is built to analyze its SE. After the SE & value evaluation by using value engineering theory, comprehensive comparison and optimization of several system designs is thus realized. The results can provide a theoretical basis of the innovating of C^2 system design and the optimizing of information flow, so as to enhance system value (effectiveness).

Key words: C^2 system; information transmission; transmission quality; effectiveness evaluation; entropy; Monte – Carlo method
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基于熵理论和效能仿真的指挥控制系统优化设计

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摘要: 以熵理论为基础,引入时效和准确度的概念描述系统信息传输质量,通过建立基于熵理论的评价模型来分析指挥控制系统信息传输质量.同时,建立基于蒙特卡罗方法的仿真模型进行系统效能分析;并运用价值工程理论对指挥控制系统进行了效能价值评价,实现了对多种系统设计使用方案的综合比较和优选.其结果可以为创新指挥控制系统方案设计、优化信息流程,提高系统价值(效能)提供一定的理论依据.

关键词: 指挥控制系统;信息传输;传输质量;效能评价;熵;蒙特卡罗方法

0 Introduction

Modern Command & Control system (C^2 system) is a complex system; its value is synthetically affected by system effectiveness (SE) and its cost. And the SE is also affected by various factors, which include not only the hardware performance, but also the own organizational structure and operational mode. Value Engineering(VE) is a modern techno – economic analysis theory, it provides effective methods to the optimization and innovation of products. Therefore, the evaluation of C^2 system's effectiveness and value analysis by using the system perspective and the value engineering theory, is an effective approach to improve system value.

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1 C^2 system's organizational structure and information transmission quality

Modern C^2 system is a "Man – Machine" system, which is made up by commanders, command structures, command means, and fulfils command & control functions to affiliated action units. We can regard the system's organizational structure as vertical and horizontal structure. The orders from the top down and the reports from the bottom up constitute the command system information vertical flow; and each command layer is linking main functional information subsystems according to horizontal direction, called the horizontal flow of information. The crisscross information network is a good foundation to fulfill command & control functions.

Information transmission quality mostly describes the quality of time – effect, accuracy and integrity[1]. Because of the C^2 system's work features, we can consider that the system can remain the same amount of information (System information integrity is the same); we can assume that information transmits from the top layers to down layers one by one within the system. Therefore, if we respectively define the order degree of system's organization structure from the point of time – effect and accuracy, the evaluating standard of C^2 system's information transmission quality is the weighted average of them[2]. The time – effect and accuracy of C^2 system's information transmission are mutually contradictory: with the increasing of command layers, information transmission paths have increased, thus it delays time – effect of information transmission but increases its accuracy. Conversely, reducing layers of command, it will definitely increase the scope of each command layer, although it can enhance time – effect, but information bifurcation points and mistaken probability will increase, thus the accuracy of information transmission will be reduced.

2 Evaluation model of system information transmission quality based on entropy theory

Nowadays, entropy theory has been widely applied in information system; entropy is not only a physics concept, but also a mathematical function. In statistical physics, system's entropy is the measurement of microscopic states' numbers; in information theory, it is the measurement of random incident's uncertainty. For a generalized system, entropy is the measurement of a state's confusion or disorder[2,3].

Reference to the use of structure entropy in biological systems, we can describe system organizational degree by the concept of system structure's order degree: $R = 1 - H / H_{max}$. Here, R represents the order degree of system structure, H represents the system structure entropy, and H_{max} represents system structure maximal entropy. The larger of the numerical value of R, the organizational structure is more efficient.

2.1 Mathematical description of system organizational structure

The system structure is shown as Figure 1, it has n factors and m command layers. Here: "②" represents the second factors; the string of two nodes represents the link numbers between two factors (the length of the links, L_{ij}), that is the shortest path of two factors in the organizational chart. We consider that the length of directly linked is 1, and add 1 to the length with per transfer (i, j respectively represents the serial number of factors, $i = 1, 2, \cdots, n, j = 1, 2, \cdots, m$).

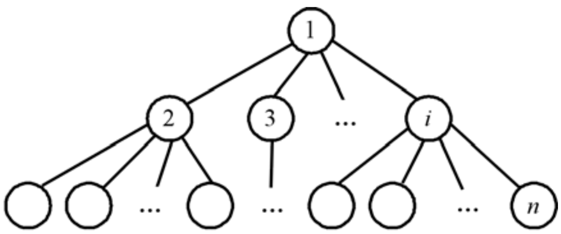

Fig.1 System organizational structure

Here, we define System Microscopic States (SMSS) as the possible microscopic state in a system from a certain point of view[2]. The possible paths quantity of which system evolves to a certain state is the total of SMSS. The larger of the total of SMSS, the possibility of system at this state is greater[2].

2.2 C^2 system time – effect and time – effect entropy

C^2 system time – effect reflects timely degree among factors in the information transmission process; and time – effect entropy reflects its uncertain degree. The calculating approach is as follows:

(1) $H_1(i,j)$ represents the time – effect entropy of two factors between two vertical layers in C^2 system, $H_1(i,j) = -p_1(i,j)\log p_1(i,j)$ (In this paper, the base of all logarithms is 2). Here, $p_1(i,j)$ represents the realization probability of system microscopic states' time – effect, $p_1(i,j) = L_{ij}/A_1$; and A_1 represents the total of system' time – effect microscopic states:

$$A_1 = \sum_i^n \sum_j^m L_{ij} \tag{1}$$

(2) H_1 represents the total of system time – effect entropy:

$$H_1 = \sum_i^n \sum_j^m H_1(i,j) \tag{2}$$

(3) $H_{1\max}$ represents system maximal time – effect entropy:

$$H_{1\max} = \log A_1 \tag{3}$$

(4) R_1 represents system time – effect:

$$R_1 = 1 - H_1/H_{1\max} \tag{4}$$

2.3 C^2 system accuracy and accuracy entropy

C^2 system accuracy reflects accurate degree among factors in information transmission process; and accuracy entropy reflects its uncertain degree. The calculating approach is as follows:

(1) $H_2(i)$ represents the accuracy entropy of each factor in C^2 system, $H_2(i) = -p_2(i)\log p_2(i)$. Here, $p_2(i)$ represents the realization probability of system microscopic states' accuracy, $p_2(i) = k_i/A_2$; k_i represents the contact scope of each factor (the number of other factors which contacted with a certain factor) in C^2 system; and A_2 represents the total of system accuracy microscopic states:

$$A_2 = \sum_i^n k_i \tag{5}$$

(2) H_2 represents the total of system accuracy entropy:

$$H_2 = \sum_i^n H_2(i) \tag{6}$$

(3) $H_{2\max}$ represents system maximal accuracy entropy:

$$H_{2\max} = \log A_2 \tag{7}$$

(4) R_2 represents system accuracy:

$$R_2 = 1 - H_2/H_{2\max} \tag{8}$$

2.4 Information transmission quality of C^2 system

R represents the information transmission quality of C^2 system, $R = \alpha R_1 + \beta R_2$. Here: α, β respectively represents the evaluation weight of information time – effect and accuracy ($\alpha = 0.6, \beta = 0.4$). The larger of the numerical value of R, the organizational structure is more efficient.

3 Simulation model of SE analysis based on Monte – Carlo method

System work process itself contains lots of random factors of uncertainty; therefore, it is difficult for building a unified analytic model to describe it. Among the simulation and analysis methods of SE, Monte – Carlo is one of the most effective methods. Its principle is: When we want to solve a mathematic, physical, technical or managing problem, we must found a probability model to describe the problem firstly, and then make sample examination about the problem. From the end of the examination, we can get the approximate end of the practical problem.

In this paper, on the premise of synthetically analyzing C^2 system's features, we build simulation system based on Monte – Carlo method, and then compile the action scenario. All action units and the corresponding state of both sides also have been simulated. After the obligatory times tests have been completed, we can obtain the statistical value of SE.

3.1 Simulation of C^2 system itself

In the simulation of C^2 system, corresponding to different system design projects, for the hardware installations of one – level command vehicle and two – level command vehicle, their work time is along with the simulation clock forward, and the increasing number is accordance with the time of enforcing command assignment.

In this paper, we suppose the life of C^2 system adapts to exponential distribution. Respectively, according to Mean Time Between Failure (MTBF) and Mission Time Between Critical Failure (MTBCF), Monte – Carlo method is used to generate life – distributed random number on every subsystem of C^2 system. Thus we can judge whether they are in generic failure and fatal fault or not.

We suppose the time of C^2 system's repairing adapts to exponential distribution. According to this regulation, we can use the distribution's inverse function to sample the time of failure and the time of repairing. Thus we can judge whether they have been repaired or not. According to the corresponding C^2 system's design projects, the work flow chart within a single simulation process is shown in figure 2.

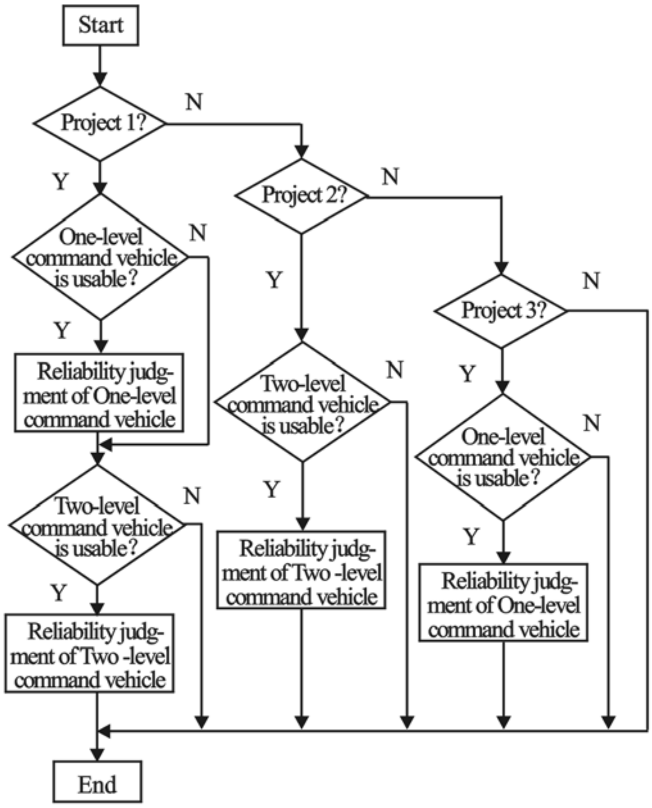

Fig.2　Flow chart of C^2 system within a single simulation process

3.2 Simulation of action units

Antagonizing sides will come through several events such as action, movement, maintenance and support, etc. In this paper, using Monte – Carlo method, we pushes the simulation clock forward by consistent steps, decides the event by simulation clock, and system´s reliability, maintainability and action effect have been simulated.

4 Case Study

4.1 Evaluation of system information transmission

According to three kinds of C^2 systems design project, we can draw the corresponding chart of system organizational structure, and they are shown in Figure 3, Figure 4, Figure 5.

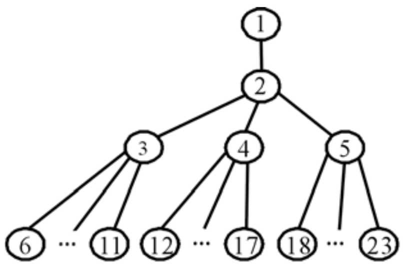

Fig.3　1st design project

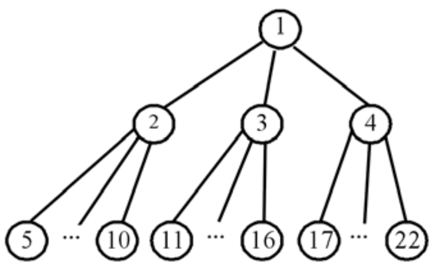

Fig.4　2nd design project

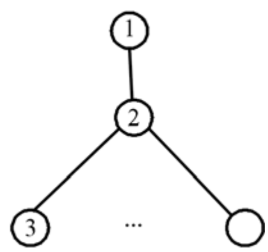

Fig.5　3rd design project

We can use time – effect and accuracy entropy evaluation models to calculate information transmission quality of three kinds of C^2 systems design project. The result is shown in Table 1.

Tab. 1 C^2 system's information transmission quality

project	total of system time – effect entropy (H_1)	total of system accuracy entropy (H_2)	system time – effect (R_1)	system accuracy (R_2)	information transmission quality (R)	system effecti – veness (SE)	units put into action (N)
1	5.801	3.938	0.157	0.279	0.206	0.393	23
2	5.201	3.875	0.108	0.281	0.177	0.434	22
3	5.127	3.124	0.113	0.405	0.230	0.427	20

4.2 Calculation of SE

The action scenario should be compiled firstly, and then the reasonable effectiveness measurement parameters should be selected. Now we can use MATLAB language to program, after putting the parameters of three kinds of C^2 systems design project to simulation model's program, the result will be obtained. It is shown in Table 1 and Table 2.

Tab. 2 Contrast of C^2 system's SE and information transmission quality

	Project 2 : Project 1/%	Project 3 : Project 1/%
The added proportion of SE	10.4	8.7
The added proportion of units put into action	–4.3	–13
The added proportion of information transmission quality	–13.7	11.7

We could draw a conclusion from results: Compared on the point of SE, Project 2 is optimal; but compared on the point of system value and information transmission quality, Project 3 is optimal.

5 Conclusions

In this paper, the evaluation model based on the information entropy theory has been established to analyze the quality of information transmission. And the practice shows that it is easy to count, and has the advantage of avoiding the subjective factors.

Monte – Carlo method is one of the uncertain simulation methods. The simulation model based on Monte – Carlo method has been built to analyze its SE, with the application of this model, C^2 system effectiveness assessment has been carried out. After the SE & value evaluation, we can comparatively analyze and optimize to several system design projects. And the practice shows that this model is particularly suitable for use in comparison and optimization of C^2 system's design.

C^2 system effectiveness (value) is also affected by information transmission security and its reliability; therefore, it needs more study and research.

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