System Structure Risk Metric Method Based on Information Flow

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Abstract. The measurement of structure risk aims to analysis and evaluate the not occurred, potential, and the objectively exist risk in system structure. It is an essential way to validate system function and system quality. This paper proposes the risk metric model and algorithm based on information flow and analysis risk trend between traditional tree structure and network-centric structure.

Keywords: System Structure, Risk, Information Flow, GIG

1 Introduction

With the development of information and network technology, the environment's uncertainty, the mission's complexity and the system functions' diversity have made the traditional platform-centric, tree structure information systems become network-centric information systems. System structure is the sum of the various relationships between the various components in information system. System functions are the characteristics and capabilities represented by system unit and relationship. System structure reflects the functions of the system through connection and topology. The optimalization of system structure can improve the ability of information system.

Structure risk is an important limiting factor in structure optimalization. The basic meaning of risk is uncertainty of loss. However, there isn't common concept applied to all areas . This paper argues that the risk of system structure refers to the risk probability and consequences of the risk event due to system specifications immaturity. System structure risk metric utilizes a certain method to calculate risk value by quantifying and integrated process .

The generating of information superiority in information systems rely on the producing, processing and utilizing of all kinds of information. When optimizing system structure, it should analysis the information flow in-depth. The system function can be abstracted as an orderly flow of intelligence, command and control and state information, including structure risk.

2 Background

Generally speaking, risk is the possibility of loss, injury, disadvantage or destruction, which is usually calculated through matrix or multiplication. While system structure risk consists of two levels of meaning: the first is the system performance risk; the second is the risk in the process of system structure migration.

Performance risk is the possibility that missions couldn't be completed because the stoppage of system units or relationships. System structure migration risk is mainly used to measure the influence of system migration failure or cost and schedule impacted than expected because of technological immaturity and uncertainty when system structure program development or system migration. The system structure migration risk includes technical risk, schedule risk and cost risk. Because this paper mainly considers the design phase of system structure, the system structure migration risk is not the main content of the study.

Complex network [1] is a complex structure consisting of huge number of nodes and relationships, which is a new and important method to represent system structure. However, complex network mainly considers the structure ability represented by topology while ignoring role of nodes. OPDAR model is an extended model of complex network through the classification of nodes which express the system structure better.

3 Risk Metric Method Based on Information Flow

System structure risk metric utilizes a certain method to calculate risk value that form quantified and integrated process of system structure risk. Usually the system structure risk can be used as one of the necessary constraints to optimize a system structure, of course, also used as a separate target to evaluate system structure.

3.1 System structure information flow model

This paper adopts OPDAR information flow model in references [2] to describe the information system structure, in which exists four basic units, namely Observer, Processor, Decision and Actor, also the relationships between the system units.

There are three kinds of information flow through the combination of system units and relationships: Intelligence information flow, Command and Control information flow, Cooperation information flow. Each kind of information flow refers to a functional link that information generating, and utilizing.

Analyzing the information flow of Intelligence support and share reflect the system's ability to safeguard intelligence, analyzing the information flow of command and control reflect the system's ability of decision making, analyzing the information flow of feedback and cooperation reflect the system's ability of synchronization . And then the overall performance of the system structure can be obtained through information flow.

3.2 Information Flow Risk Model

In OPDAR model, the information flow is a link combined by relationships end to end in structure. From a risk perspective, the relationships and units in system structure in the information flow are all risk factors. Each node or arc in information flow corresponds a risk event, contains a certain probability of occurrence and consequence.

Supposing information flow $f = v_0 e_1 v_1 e_2 v_2 \cdots e_n v_n$ is a simple path from system unit v_0 to system unit v_n. The occurrence probability of risk event A_i of unit v_i is p_i, and risk consequence is $c_i, 0 \le i \le n$; the occurrence probability of risk event B_i of arc e_i is q_i, and risk consequence is $d_i, 0 \le i \le n$. Thus the risk of $f = v_0 e_1 v_1 e_2 v_2 \cdots e_n v_n$ can be represented as follows.

$$\begin{aligned}
R(f) &= P(\mathrm{A}_0)c_0 \\
&+ P(\overline{\mathrm{A}}_0)\left(P(\mathrm{B}_1)d_1 + P(\overline{\mathrm{B}}_1, A_1)c_1\right) \\
&+ \cdots \\
&+ P(\overline{\mathrm{A}}_0 \cdots \overline{\mathrm{A}}_{i-1}, \overline{\mathrm{B}}_1 \cdots \overline{\mathrm{B}}_{i-1})\left(P(\mathrm{B}_i)d_i + P(\overline{\mathrm{B}}_i, A_i)c_i\right) \\
&+ \cdots \\
&+ P(\overline{\mathrm{A}}_0 \cdots \overline{\mathrm{A}}_{n-1}, \overline{\mathrm{B}}_1 \cdots \overline{\mathrm{B}}_{n-1})\left(P(\mathrm{B}_n)d_n + P(\overline{\mathrm{B}}_n, A_n)c_n\right)
\end{aligned}$$

Assuming the risk events corresponded to nodes and arcs in information flow occur or not are independent to each other, so

$$R(f) = p_0 c_0 + \sum_{i=1}^{n} (q_i d_i + (1-q_i) p_i c_i) \prod_{j=0}^{i-1} (1-p_j) \prod_{j=1}^{i-1} (1-q_j) \qquad (3.1)$$

Obviously, the key factor of the system structure risk is how to calculate the risk of each information flow, which have to rely on the system unit as well as the relationship in information flow.

In system design phase, it is difficult to calculate the failure rate of the system unit because the actual system units have not been finished. Therefore, when calculating the probability of system structure performance risk, we can assume system units themselves run without a fault and only consider fault caused by the accessing and supporting the structure.

Under the above assumption, regardless of the kind of system unit, the failure rate is identical, denoted p , $0 \le p \le 1$; system relationship is denoted as q, $0 \le q \le 1$.That in (3.1), $p_0 = p_1 = \cdots = p_n = p$, $q_1 = q_2 = \cdots = q_n = q$,so

$$R(f) = pc_0 + \sum_{i=1}^{n} (qd_i + (1-q) pc_i) \prod_{j=0}^{i-1} (1-p) \prod_{j=1}^{i-1} (1-q) \qquad (3.2)$$

Which is

$$R(f) = pc_0 + \sum_{i=1}^{n} (qd_i + (1-q) pc_i)(1-p)^i (1-q)^{i-1} \qquad (3.3)$$

(3.3) illustrates the key of information flow risk calculation is to determine the consequences of risk events occur, such as system units or relationships failure or interruption. In this paper, we use the “contribution” of unit(relationship) to repress the consequence of the unit’s(relationship’s) risk event occur, which consists the ratio between the number of information flows contained the unit(relationship) and all the information flows in structure and the rank in each information flow.

System Unit Risk Model

Assuming the set of intelligence information flow in system structure is $S_f^{IS} = \{ f_i^{IS} \mid i = 1,2,\cdots,N_f^{IS} \}$, the set of command and control information flow is $S_f^{CC} = \{ f_i^{CC} \mid i = 1,2,\cdots,N_f^{CC} \}$, the set of cooperation information flow is $S_f^{CO} = \{ f_i^{CO} \mid i = 1,2,\cdots,N_f^{CO} \}$. The weight of each kind of information flow is β^{IS}, β^{CC} and β^{CO}.

For each system unit $node_i$ $(1 \le i \le N_n)$, denoting the number of information flow which contain this unit is v_i^{CC}, v_i^{IS} and v_i^{CO}, denoting the system unit weight of each kind of information flow is α^{CC}, α^{IS} and α^{CO} .Assuming $node_i$ as v_i, according to (3.3) , the "contribution" the system unit to the risk of the information flow is

$$p\left(\frac{\alpha^{CC} v_i^{CC}}{N_f^{CC}} + \frac{\alpha^{IS} v_i^{IS}}{N_f^{IS}} + \frac{\alpha^{CO} v_i^{CO}}{N_f^{CO}} \right)(1-p)^i (1-q)^i \qquad (3.4)$$

Supposing v_i^{CC}, v_i^{IS} ,v_i^{CO} is denoted as v_i, given that $0 \le 1-p \le 1$ and $0 \le 1-q \le 1$, so the more forward position v_i in the flow $f = v_0 e_1 v_1 e_2 v_2 \cdots e_n v_n$ (i smaller), the more contribution to flow risk; the more rearward position in the flow(i bigger), the little contribution to flow risk.

If the rank of $node_i$ in intelligence information flow is $\sigma^{IS}(i,j), 1 \le j \le v_i^{IS}$, the system unit’s "contribution" for the system structure intelligence risk is

$$Risk^{IS}(node_i) = \frac{p\beta^{IS}}{N_f^{IS}} \left(\frac{\alpha^{CC} v_i^{CC}}{N_f^{CC}} + \frac{\alpha^{IS} v_i^{IS}}{N_f^{IS}} + \frac{\alpha^{CO} v_i^{CO}}{N_f^{CO}} \right) \sum_{j=1}^{v_i^{IS}} \left((1-p)(1-q)\right)^{\sigma^{IS}(i,j)}$$

(3.5)

If the rank of $node_i$ in command and control information flow is $\sigma^{CC}(i,j), 1 \le j \le v_i^{CC}$, the system unit’s "contribution" for the system structure command and control risk is

$$Risk^{CC}(node_i)=\frac{p\beta^{CC}}{N_f^{CC}}\left(\frac{\alpha^{CC}v_i^{CC}}{N_f^{CC}}+\frac{\alpha^{IS}v_i^{IS}}{N_f^{IS}}+\frac{\alpha^{CO}v_i^{CO}}{N_f^{CO}}\right)\sum_{j=1}^{v_i^{CC}}\left((1-p)(1-q)\right)^{\sigma^{CC}(i,j)}$$

(3.6)

If the rank of $node_i$ in cooperation information flow is $\sigma^{CO}(i,j)$,$1\le j\le v_i^{CO}$, the system unit's "contribution" for the system structure cooperation risk is

$$Risk^{CO}(node_i)=\frac{p\beta^{CO}}{N_f^{CO}}\left(\frac{\alpha^{CC}v_i^{CC}}{N_f^{CC}}+\frac{\alpha^{IS}v_i^{IS}}{N_f^{IS}}+\frac{\alpha^{CO}v_i^{CO}}{N_f^{CO}}\right)\sum_{j=1}^{v_i^{CO}}\left((1-p)(1-q)\right)^{\sigma^{CO}(i,j)}$$

(3.7)

Therefore, the system unit's total risk for system structure is

$$\begin{aligned}Risk(node_i)&=Risk^{IS}(node_i)+Risk^{CC}(node_i)+Risk^{CO}(node_i)\\&=\frac{p\beta^{IS}}{N_f^{IS}}\left(\frac{\alpha^{CC}v_i^{CC}}{N_f^{CC}}+\frac{\alpha^{IS}v_i^{IS}}{N_f^{IS}}+\frac{\alpha^{CO}v_i^{CO}}{N_f^{CO}}\right)\sum_{j=1}^{v_i^{IS}}\left((1-p)(1-q)\right)^{\sigma^{IS}(i,j)}\\&+\frac{p\beta^{CC}}{N_f^{CC}}\left(\frac{\alpha^{CC}v_i^{CC}}{N_f^{CC}}+\frac{\alpha^{IS}v_i^{IS}}{N_f^{IS}}+\frac{\alpha^{CO}v_i^{CO}}{N_f^{CO}}\right)\sum_{j=1}^{v_i^{CC}}\left((1-p)(1-q)\right)^{\sigma^{CC}(i,j)}\\&+\frac{p\beta^{CO}}{N_f^{CO}}\left(\frac{\alpha^{CC}v_i^{CC}}{N_f^{CC}}+\frac{\alpha^{IS}v_i^{IS}}{N_f^{IS}}+\frac{\alpha^{CO}v_i^{CO}}{N_f^{CO}}\right)\sum_{j=1}^{v_i^{CO}}\left((1-p)(1-q)\right)^{\sigma^{CO}(i,j)}\end{aligned}$$

(3.8)

System Relationship Risk Model

For each system relationship e_i, denoting the number of information flow which contain this relationship is ε_i^{CC}, ε_i^{IS} and ε_i^{CO}, denoting the system relationship weight of each kind of information flow is λ^{CC}, λ^{IS} and λ^{CO}.According to (3.3) , the "contribution" the system relationship for the risk of the information flow is

$$q\left(\frac{\lambda^{CC}\varepsilon_i^{CC}}{N_f^{CC}}+\frac{\lambda^{IS}\varepsilon_i^{IS}}{N_f^{IS}}+\frac{\lambda^{CO}\varepsilon_i^{CO}}{N_f^{CO}}\right)(1-p)^i(1-q)^{i-1} \quad (3.9)$$

Similar to system unit, the more forward position e_i in the flow $f=v_0e_1v_1e_2v_2\cdots e_nv_n$, the more contribution to flow risk, conversely smaller.

Denoting the set of system relationship in system structure is $S_r=\{r_i=(node_i^s,node_i^e)\mid node_i^s,node_i^e\in S_{node},i=1,2,\cdots,N_r\}$。

For each system relationship r_i $(1 \le i \le N_r)$, if the rank of r_i in intelligence information flow is $\delta^{IS}(i,j), 1 \le j \le \varepsilon_i^{IS}$, the system relationship's "contribution" for the system structure intelligence risk is

$$Risk^{IS}(r_i) = \frac{q\beta^{IS}}{N_f^{IS}}\left(\frac{\lambda^{CC}\varepsilon_i^{CC}}{N_f^{CC}} + \frac{\lambda^{IS}\varepsilon_i^{IS}}{N_f^{IS}} + \frac{\lambda^{CO}\varepsilon_i^{CO}}{N_f^{CO}}\right)\sum_{j=1}^{\varepsilon_i^{IS}}\left((1-p)(1-q)\right)^{\delta^{IS}(i,j)} \tag{3.10}$$

If the rank of r_i in command and control information flow is $\delta^{CC}(i,j), 1 \le j \le \varepsilon_i^{CC}$, the system relationship's "contribution" for the system structure command and control risk is

$$Risk^{CC}(r_i) = \frac{q\beta^{CC}}{N_f^{CC}}\left(\frac{\lambda^{CC}\varepsilon_i^{CC}}{N_f^{CC}} + \frac{\lambda^{IS}\varepsilon_i^{IS}}{N_f^{IS}} + \frac{\lambda^{CO}\varepsilon_i^{CO}}{N_f^{CO}}\right)\sum_{j=1}^{\varepsilon_i^{CC}}\left((1-p)(1-q)\right)^{\delta^{CC}(i,j)} \tag{3.11}$$

If the rank of r_i in cooperation information flow is $\delta^{CO}(i,j), 1 \le j \le \varepsilon_i^{CO}$, the system relationship's "contribution" for the system structure cooperation risk is

$$Risk^{CO}(r_i) = \frac{q\beta^{CO}}{N_f^{CO}}\left(\frac{\lambda^{CC}\varepsilon_i^{CC}}{N_f^{CC}} + \frac{\lambda^{IS}\varepsilon_i^{IS}}{N_f^{IS}} + \frac{\lambda^{CO}\varepsilon_i^{CO}}{N_f^{CO}}\right)\sum_{j=1}^{\varepsilon_i^{CO}}\left((1-p)(1-q)\right)^{\delta^{CO}(i,j)} \tag{3.12}$$

Therefore, the system relationship's total risk (r_i) for system structure is

$$\begin{aligned}
Risk(r_i) &= Risk^{IS}(r_i) + Risk^{CC}(r_i) + Risk^{CO}(r_i)\\
&= \frac{q\beta^{IS}}{N_f^{IS}}\left(\frac{\lambda^{CC}\varepsilon_i^{CC}}{N_f^{CC}} + \frac{\lambda^{IS}\varepsilon_i^{IS}}{N_f^{IS}} + \frac{\lambda^{CO}\varepsilon_i^{CO}}{N_f^{CO}}\right)\sum_{j=1}^{\varepsilon_i^{IS}}\left((1-p)(1-q)\right)^{\delta^{IS}(i,j)}\\
&+ \frac{q\beta^{CC}}{N_f^{CC}}\left(\frac{\lambda^{CC}\varepsilon_i^{CC}}{N_f^{CC}} + \frac{\lambda^{IS}\varepsilon_i^{IS}}{N_f^{IS}} + \frac{\lambda^{CO}\varepsilon_i^{CO}}{N_f^{CO}}\right)\sum_{j=1}^{\varepsilon_i^{CC}}\left((1-p)(1-q)\right)^{\delta^{CC}(i,j)}\\
&+ \frac{q\beta^{CO}}{N_f^{CO}}\left(\frac{\lambda^{CC}\varepsilon_i^{CC}}{N_f^{CC}} + \frac{\lambda^{IS}\varepsilon_i^{IS}}{N_f^{IS}} + \frac{\lambda^{CO}\varepsilon_i^{CO}}{N_f^{CO}}\right)\sum_{j=1}^{\varepsilon_i^{CO}}\left((1-p)(1-q)\right)^{\delta^{CO}(i,j)}
\end{aligned} \tag{3.13}$$

Therefore, the calculating process of system structure risk consists four steps: first, traversing all information flows in system structure; second, determining every system unit's rank in each information flow and computing the total contribution; third, determining every system relationship's rank in each information flow and computing the total contribution; forth, summing all system units' risk and system relationships' risk to obtain the system structure's risk.

4 Case Study

This paper compares traditional tree network structure with network-centric structure, which is good for comparative analyzing risk trend in network-centric structure and providing guidance for network development.

Network-centric structure dynamic organize and optimize the distribution of the loosely coupled system component in network, which can maximize system's function and capability and then realize the goal of dynamically adaptation to environmental changes. Reflected in the physical structure is that none of the system component is a must exist one, named "equality." Its manifestation includes circle, center or connection of tertiary-level in structure and so on.

The selected structure is Fig.1 and 2. Respectively, circle, triangle, square and diamond represent observer unit, process unit, decision unit and actor unit. Fig. 1 shows a traditional three-tree network which according to the triangular organization. Each decision unit has three child decision units and bottom decision unit controls two actor units. Each processor unit guarantees six decision units and has three father observer units. Fig. 2 adds some "horizontal" factor. (1) forms a p-circle by adding some cooperation relations among processor units. (2) forms a p-center by adding some intelligence relations among processor units and decision units. (3) joins some command and control relationships of tertiary-level. (4) joins intelligence relationships between processor units and actor units which forming safeguarding of tertiary-level.

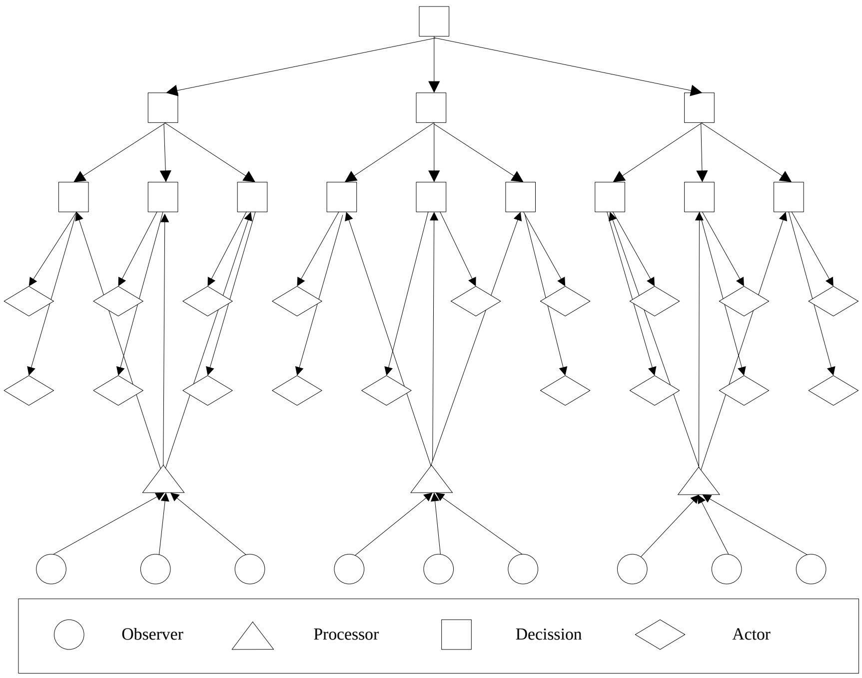

Fig. 1 structure 1

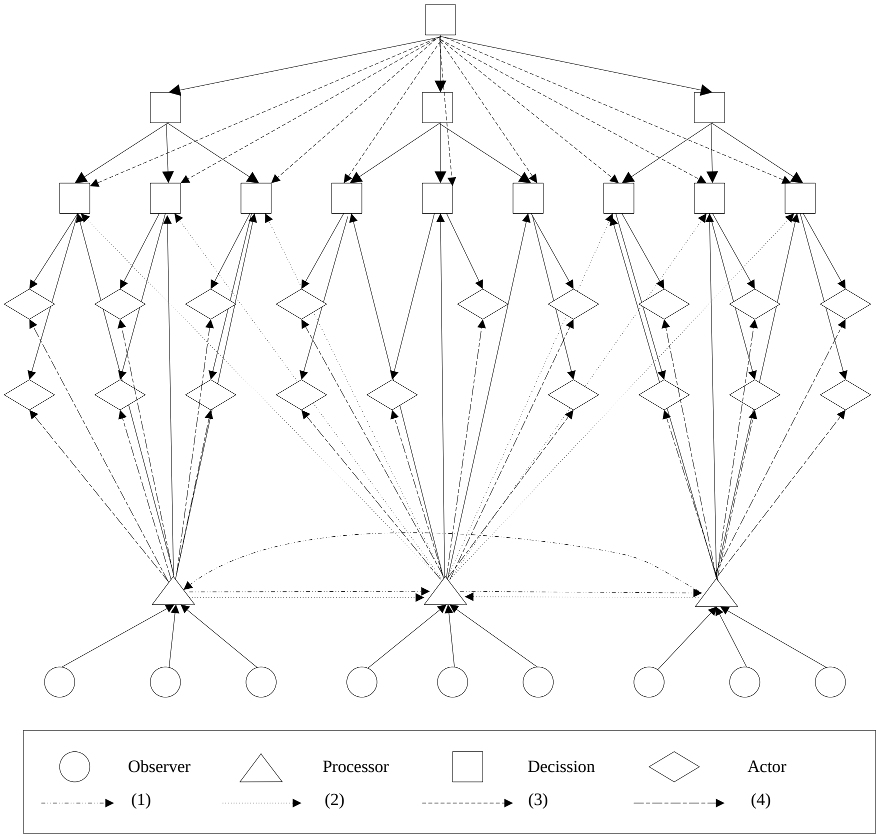

Fig. 2 structure 2

Assuming the probability of system unit's risk event occurrence is 0.1, the probability of system relationship's risk event occurrence is 0.1.Because the command and control relationship is more important in information transmission in information system, flow weight of command and control information flow is 0.5, the other two is 0.25. The same is with unit weight and relationship weight . To analysis the change of risk in-depth, extract the common law, we analysis the risk change process with the combination. The risk value of different combinations((1)(2)(3)(4)) is in Fig. 3 and Fig. 4. The intelflow represents intelligence information flow, c2flow represents command and control information flow, coflow represents cooperation information flow. Fig. 4 shows the average risk value of system structure.

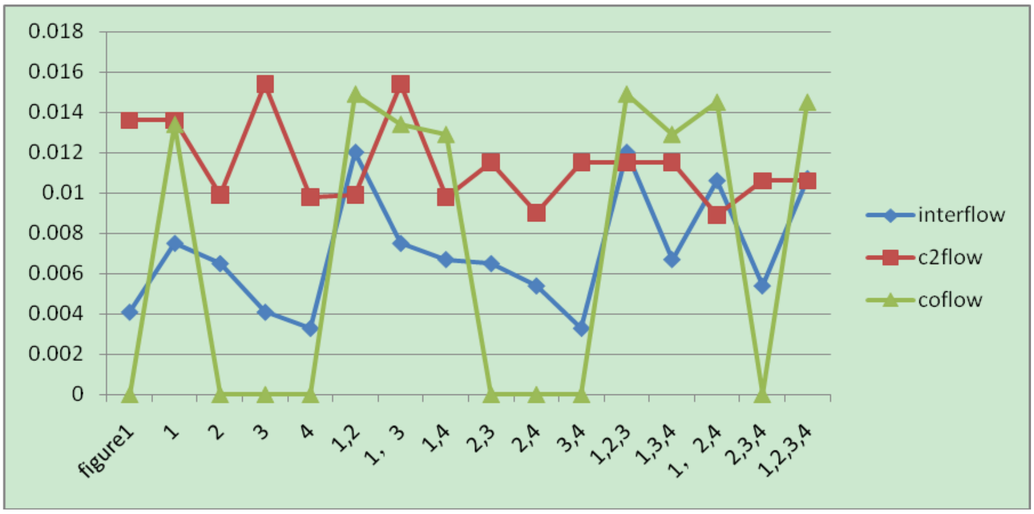

Fig. 3 risk value of each flow kind

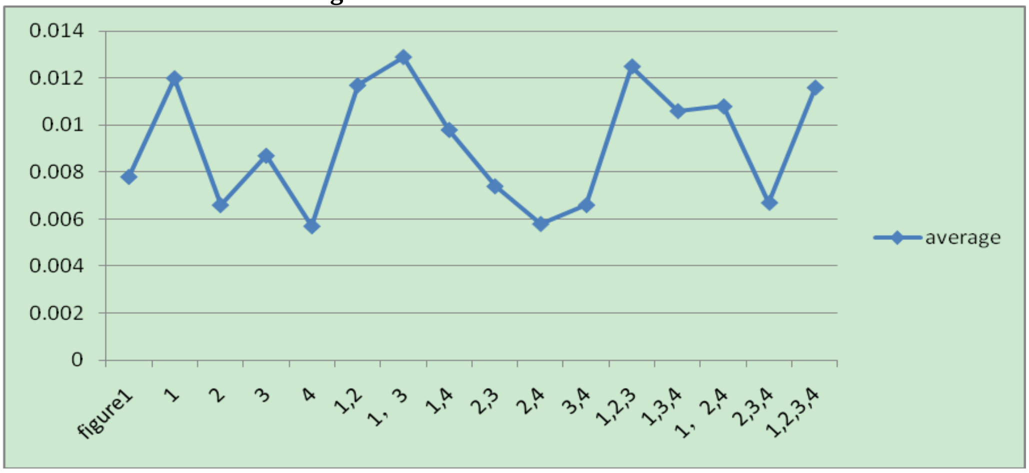

Fig. 4 average risk value

Fig. 4 shows the risk value in system structure in about 0.01, to the more realistic.

After analyzing the result, when adopting (1), the risk of cooperation flow appears. Because the number of cooperation flows is few, the risk value is relatively large. If we want to decrease the influence of cooperation flows, we can add the number of cooperation flows or decrease the ratio that flow through cooperation units. When adopting (2) and (4), the number of intelligence flows is increased, therefore risk of intelligence flow increases. However, the ratio that through decision units decreases, the risk of command and control information flows decreases. When adopting (3), the number of command and control flows is increased, therefore risk of command and control flow increases.

Overall, the total risk of system structure is increased relatively. But to some extent, we can adopt some measures to decrease risk. However, as the numbers of units or relationships getting larger, the cost increases relatively, which is an important factor in structure development we have to think.

5 Conclusion

This paper utilizes information flow in the risk metric of system structure, proposes risk metric model and algorithm based on information flow. In the basis of comparative analyzing different structures' risk trend, we conclude that:

- There are three reasons affecting the change of structure risk: the number of information flows; the proportion of the number of flows through units or relationships and system structure flows; the rank that the unit or relationship in each information flow;
- The general trend of structure risk is increased. Risk can used as a main consideration indicator of structural optimization, considering how to improve the system structure utility under the premise of meeting the constraint of the risk;
- The adding of "horizontal" factor in structure makes the risk value reduced possibly;
- When considering structural risk optimization, it may be appropriate to add some units or relationships that make certain types of information flow sudden increase except for the zero case, which reduces the risk. The physical meaning of such units' adding improves the probability of mission completing, which reduces risk of failure, but when the unit and the relationship continues to grow, the new unit and the relationship's risk becomes the dominant factor in the information flow risk, the risk becomes large.

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