Multi-Agent Analysis Model of Resource Allocation Variants to Ensure Fire Safety

Andrey Smirnov[1], Renat Khabibulin[1], Nikolay Topolski[1] and Denis Tarakanov[2]
[1]*The State Fire Academy of EMERCOM of Russia, 129366, B. Galushkina 4, Moscow, Russia*
[2]*The Ivanovo State Fire Academy of EMERCOM of Russia, 153040, Stroiteley 33, Ivanovo, Russia*

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Abstract: Algorithmization and program implementation of theoretical positions of multi-agent analysis of resource allocation variants to ensure fire safety were conducted. The informational decision support system was developed, within which variations of resource allocation in a multi-agent management system are offered. The feature of the developing informational system from similar is an ability of approximations of expert's opinion accounting multi-level procedure of variation's analysis in a multi-agent management system. The multi-level procedure of variation's analysis allows to approximate preference of the management centre more completely and, therefore, to reduce the subjectivity of the process of making decisions on resource allocation to ensure fire safety. The procedure includes two main stages: on the first stage component-goals are distributed by sets; on the second stage we get the ranking according to the preference of the management centre. Using quantitative measures of the Shannon entropy it is proved that the offered multi-level procedure of variations analysis in multi-agent management system allows to approximate the preference of the management centre more completely in comparison with known methods of variations of resource allocation analysis in long-term planning tasks.

1 INTRODUCTION

An emergency on industry facilities are character by human victims, high ecological and economic damage (Kwanghee Lee et al., 2016), (Hyuck-myun Kwon et al., 2016), (Nima Khakzad et al., 2016).

Using of multi-agent systems and technologies (MAS) is offered to manage the fire safety on such facilities because MAS are a perspective direction in a sphere of management on active systems (Yongcan Kao et al. 2013), (Dimos V. Dimarogonas et al. 2011), (Ferber et al., 2004). Using of MAS allows simulating interaction in the social system of subdivisions of organization (agents), that make an influence on the fire risk level and resource allocation in considering socio-economical system (SES) (Shaun Howelletal., 2017).

There are a lot of goals that need to be reached by SES while functioning, each of which is implemented by a particular agent – department, linear department or a specific agent. Agent management in SES is realized by the management center (figure 1). Every agent is endowed with several properties, which help to realize interaction with management center. Agents in the multi-agent system, possessing their own characteristics, are not interested in increasing the number of resources (rational conduct). One of the properties of rational conduct is the agent's possibility to refer to the management center for endowing it with number of resources that is necessary and is enough for the realization of the agent's charged purpose.

A total number of the system purposes can be divided into the purpose groups in accordance with their content. Besides the basic purposes, there are purposes, that are directed at the reaching the required fire safety level expressed in the probabilistic value, which should not exceed the specific values of fire risks (Desheng Dash Wu et al., 2017), (Gudin et al., 2017). In general, understanding purposes like these can be classified as the purposes, which are necessary for normal functioning of such objects. At the same time, each of these purposes for its realization, independently on the application, suggests the necessary quantity of resources, which is available or not available for the system.

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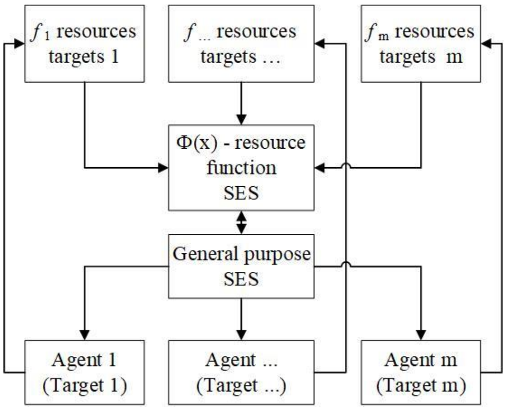

Figure 1: Structure of the multi-agent system.

MAS is applied in different spheres and subject areas: logistics, safety, informational search, risks management, healthcare, etc. However, despite the increasing MAS extension, the complexity of the process of their development remains to be extremely high, which causes a problem of the MAS universal design tool creation, which combines a theoretically proved design methodology and effective realization in the object-oriented sphere (Alexander, R. et al., 2013).

It is necessary to be noted, that the MAS use to ensure safety numerously was an object in the scientific researches (Zoumpoulaki A. et al., 2010), (Çetin Elmasa et al., 2011), (Mutovkina N. et al., 2014), but the task of resource allocation to ensure fire safety was not addressed within the context of these works.

2 MULTI-AGENT MANAGEMENT SYSTEM TO ENSURE FIRE SAFETY

In accordance with the general agent-modeling approaches, there is a conclusion, that there are a lot of purposes that need to be done by the system, each of which is implemented by a particular agent – department, linear department or a specific agent. Agent management is carried out by the management center. The agent in the multi-agent system is endowed with several properties, allowing to describe its interaction with the management center. Considering the agent in the resource allocation task for industry enterprise, besides the agent's general properties in the multi-agent system, it is necessary to add rational conduct in the resources allocation, which determines the situation, when the agent is not interested in the resource being increased. An additional property of a system agent's rational conduct is a possibility to refer to the management center for endowing it with number of resources that is necessary and is enough for the realization of the agent's charged purpose.

Multi-agent approach is the importance ranking of agent's purposes concerning the general purpose of the management center, that is assigning the important purpose parameters – w_i and excluding those purposes, that can't be realized because of the resources lack. In accordance with this approach, the excluded purposes of the system should have the worst estimation in compliance with ranking results, which is the purpose of which $w_i \to \min$. For the search of the minimum ranking coefficient purposes in the multi-agent system it is advisable to make the formal statement of the multi-criteria task, which includes:

– various options of the resource allocation in the system $x_i \in X$, $i = 1, 2, \ldots, n$, $n \geq 2$;

– various system purposes used for the variant estimation $f_i \in F$, $s = 1, 2, \ldots, m$, $m \geq 3$;

– various resource allocation estimations $F(X) = f_1(X) \times f_2(X) \times \ldots \times f_m(X)$, (1)

where: X - various resource allocation;

$f_i(X)$ – are various values of the system components with the number i on the various options $x_i \in X$;

$F(x_i)=(f_1(x_i), f_2(x_i), \ldots, f_m(x_i))$ – variant estimation x_i, and then $f_i(x_i)$ – x_i variant estimation according the f_i system purpose. Provided that, the management center by its choice longs to maximize the value of each purpose component that is $f(x) \to max$.

The general structure of the resource management system is shown in figure 1 in accordance to its formation results.

The provided structure of the agent system is hierarchical, that is why to determine the resources needed for the general purpose of the agent system, which is connected with the implementation of fire safety tasks, it is necessary to use the generalized target function that is expressed in the additive or multiplied form. It is known, that the model weight coefficients characterize the level of f_i influence of purpose components on the resulting function Φ, in the following way:

$$\Phi = \sum_{k=1}^{m} \omega_k f_k, \sum_{k=1}^{m} \omega_k = 1 . \qquad (2)$$

In other words, the solution of the resource allocation task is reduced to the determination of their quantitative shares – coefficients w_i.

There are two main approaches for the calculation of the weight coefficients in the multi-agent system:

- the first approach is the comparison of two variants of the resource allocation preference. This approach is formalized by the relative importance theory (Noghin V., 2014);

- the second approach supposes the component-purposes "weighting" by the experts within the matter of the general theory of multi-criteria usefulness (Lootsma F., 1993).

It should be noted, that these approaches are different on the methodological level, and in general case, the creation of the general decision-making system that based on these approaches consists in the creation of two different systems.

That is why from the theoretical point of view the actual task consists of the development of the unified theoretical provisions for the method realization that is based on two structurally different approaches.

The solution on this task was carried out in the way like this: at the first stage the relative importance theory was implemented for the comparison of the variants at the identical preference, and then the comparison of the component-purpose according to their importance method was implemented for the received results.

In accordance with the decision-making general task within the limits of the relative importance theory, each couple of solution variants $X_1$and X_2 induces the vector estimations $F(X_i)=\{f_1\ (X_i);\ f...\ (X_i);\ f_m\ (X_i)\}$ *and* $F(X_2)=\{f_i\ (X_2);\ f...\ (X_2);\ f_m\ (X_2)\}$. Applying the method of the relative importance of quantitative functions in the multi-criteria optimization process, let's suppose (Noghin V., 2014), that $X_i > X_2$, then let's separate the component-purposes of the multi-agent system by the importance groups, taking into conditions:

$$S_i = f_i\left(X_1\right) - f_i\left(X_2\right) > 0, then\, i \in A \qquad (3)$$

$$S_j = f_i\left(X_1\right) - f_i\left(X_2\right) < 0, then\, i \in B \qquad (4)$$

$$S_s = f_i\left(X_1\right) - f_i\left(X_2\right) = 0, then\, i \in C \qquad (5)$$

Where S – is the difference in accordance of the i – criterion between the variant X_1 estimation and the variant X_2 estimation; A, B, C are the importance groups of SES component-purpose. For all combinations i and j from the A and B groups we determine the relevant importance indexes θ_{ij} :

$$\theta_{ij} = \frac{\left|S_j\right|}{\left|S_i\right| + \left|S_j\right|} \qquad (6)$$

θ_{ij} –is the direct index of the relevant importance purpose component from group A with the number i, above the component-purpose from group B with the number j. Now, let's consider the reverse situation to $X_i > X_2$, then $X_i < X_2$, in this situation the component purposes will be distributed the way, when the component-purposes from the group B is more important for the component-purposes then from the group A, and the relevant importance index will be determined according to the formula:

$$\theta_{ji} = \frac{\left|S_i\right|}{\left|S_i\right| + \left|S_j\right|} \qquad (7)$$

Direct and reverse indexes of the relevant importance are connected with the expression:

$$\theta_{ji} = 1 - \theta_{ji} \qquad (8)$$

Which results from their formal determination:

$$\theta_{ji} = 1 - \theta_{ji} = 1 - \frac{\left|S_i\right|}{\left|S_i\right| + \left|S_j\right|} = \frac{\left|S_j\right|}{\left|S_i\right| + \left|S_j\right|} \qquad (9)$$

Then we will consider, that the simultaneous implementation of the condition $X_i > X_2$, then $X_i < X_2$ within the relevant importance theory (Noghin V., 2014) results in $X_i \sim X_2$.

For comparison by the preference "≈" of two options in a multi-agent system on the basis of the conditions (3)...(5) the preference matrix is formed, the elements of which are the relative importance direct indexes of the SES component-purposes. The preference matrix for clarity is convenient to be presented in tabular form in the table – table 1.

Table 1: The preference matrix of the relevant importance indexes.

$i \backslash j$	1	…	b	*Sum*
1	θ_{11}	$\theta_{1\ldots}$	θ_{1b}	$\sum_{j=1}^{b}\theta_{1j}$
…	$\theta_{\ldots 1}$	$\theta_{\ldots\ldots}$	$\theta_{\ldots b}$	$\sum_{j=1}^{b}\theta_{\ldots j}$
a	θ_{a1}	$\theta_{a\ldots}$	θ_{ab}	$\sum_{j=1}^{b}\theta_{aj}$
Sum	$\sum_{i=1}^{a}\theta_{i1}$	$\sum_{i=1}^{a}\theta_{i\ldots}$	$\sum_{i=1}^{a}\theta_{ib}$	$\sum_{j=1}^{b}\sum_{i=1}^{a}\theta_{ij}$

In Table 1, *a* is determined as the component-purposes quantity in group *A* and *B*, as the component-purposes quantity in group *B* respectively.

Then, the importance parameters calculation in the function (1) based on preferences expressed in the relevant importance indexes set can be realized through the Kramer's formulas (Vol'skii V. I., 1982):

$$w_i = \frac{\triangle_i}{\triangle} \tag{10}$$

for all component-purposes from group *B*:

$$w_j = \frac{\triangle_j}{\triangle} \tag{11}$$

where $\triangle_i = \sum_{j=1}^{b} \theta_{ij}$; $\triangle_i = a - \sum_{j=1}^{a} \theta_{ij}$ and $\triangle = b\sum_{j=1}^{b}\sum_{i=1}^{a}\theta_{ij} + b(a - \sum_{i=1}^{a}\sum_{j=1}^{b})\theta_{ij}$, so as $\sum_{j=1}^{b}\sum_{i=1}^{a}\theta_{ij} = \sum_{i=1}^{a}\sum_{j=1}^{b}\theta_{ij}$, the $\triangle = ab$.

Then we finally receive the formulas for the calculation of the function importance indexes (1) based on the relevant importance indexes:

for all component-purposes from group *A*:

$$w_i = \frac{\sum_{j=1}^{b}\theta_{ij}}{ab} \tag{12}$$

for all component-purposes from group *B*:

$$w_j = \frac{a - \sum_{i=1}^{a}\theta_{ij}}{ab} \tag{13}$$

A unified decision-making system for resource allocation variants to ensure fire safety is based on the method that includes the following stages:

Stage 1. The distribution of component-purposes of a formal model for resource allocation into two contradictory groups *A* and *B*.

As a result, the multi-agent system component-purposes are divided into importance groups. In the context of this method, only groups *A* and *B* are considered, the component-purposes that are not included in these groups, the component-purpose group *C* are excluded from further analysis. As a result of this stage, two non-empty component-purpose groups of components should be formed, provided that we will consider the component-purposes of the group *A* is equal to *a*, numbers of these component-purposes are designated as *i*, then the number of component-purposes from the group *B* is equal to *b* with the numbers *j*. The conditions (3) and (4) should be used in the components distribution into groups while the variants couple comparison within the relative importance theory. Within the relevant importance theory, a person, who makes a decision by itself, distributes the component-purposes into the groups based on his own understanding of their importance for decision making.

Stage 2. The determination of the relevant importance index set θ_{ij} for each combination of component-purposes by numbers *i* and *j*.

When calculating the importance relevant θ_{ij} based on the relative importance theory, it is necessary to use the formula (6) considering *S* parameters, calculated by formulas (3) and (4).

Within the usefulness of theory, the relevant importance theory coefficient should be determined with the formula:

$$\theta_{ij} = \frac{1}{1 + K_{ij}} \tag{14}$$

Where $K_{ij} = \exp(-pZ)$ and Z takes its indexes from the round number quantity in accordance with the described in the approach (Lootsma F., 1993).

Stage 3. The determination of the weight importance coefficient function of the variant ranking – resource allocation portions.

At this stage of the method, additive function coefficients for each component – purpose with the number *i* from group *A* and the component-purpose with the number *j* from group *B* are determined through the formula (14).

An important practical aspect of the developed method of resource allocation is the possibility of decision-making expert to get results with the formalization of the previous experience. In this connection it is worth mentioning, that the developed agent component functions relevant importance indexes account is varied from the existing higher level of expert estimations approximations, which are determined by a large quantity of agent component-purposes allocation variants into the importance groups *A* and *B*. The existing method of the component-purposes allocation into the importance groups, based on the preference $X_i > X_2$ determines the situation when *A* group includes the component-purposes with the coefficients $W_i > W_j$ for all $i \in A$ and $j \in B$. The proposed method is based on the preference $X_i \approx X_2$ and is free from this restriction.

Let's look at the application of the developed procedure on illustrated example.

If fire safety was consumed *R1* amount of resource and it was distributed between training of personnel $0{,}3R_1$ and automated informational system of fire and explosion safety (further – AISFES) 0,7*R1*.

Next year the budget increased 1.7 times, but the development of a safety system provides for the need to develop automated system of management primary rescue operations that costs *R1*.

Based on the specifics of object's fire safety measures realization of total conditions can be assigned *R2*=1,7*R1*, at the same time, the resources for the training system cannot be reduced, that is 0,3*R1*.

1,7*R1*-0,3*R1*=1,4*R1* is necessary to distribute between AISFES and automated system of primary rescue operations management.

Phase 1. The distribution of component objectives by importance.

Determine the importance coefficient between AISFES and training of personnel system.

If component objectives connected with implementation costs of AISFES with number 1, that is *f1*, then *a*=1. The remaining target component that determines the cost of personnel's training *f2* will be assigned to the *B* group, that is *b*=1. The new automated system of primary rescue operations management will be assigned to *A* group, that is *f3* belongs to *A* and (*a*=2)

Phase 2. Calculation of relative importance.

Source share of resources will be $\omega_1 = \frac{0,7R_1}{R_1} = 0,7$, likewise $\omega_2 = 0,3$.

By formula (11) we determine the value of last year relative importance index and it is $\theta_{12} = \omega_1 \times a \times b = 0,7$.

As the cost of personnel's training should be 0,3R1 then this year it will be spent 0,176*R2*. the value is obtained by the formula:

$$\omega_1 = \frac{0,3R_1}{R_2} = \omega_1 = \frac{0,3R_1}{1,7R_1} = 0,176.$$

Let's determine the value of the relative importance sum in this year based on the condition obtained using the formula (12):

$$\omega_2 = \frac{a-(\theta_{12}+\theta_{32})}{ab} = 2-(2\cdot 1\cdot 0,176) = 1,69.$$

Considering than last year $\theta_{12} = 0,7$, than relative importance index for the new system will be $\theta_{32} = 1,69 - 0,7 = 0,94$.

So, the result of this phase realization are two relative importance index $\theta_{12} = 0,7$ and $\theta_{32} = 0,94$.

Phase 3. Determining a share of resources.

Determine the importance coefficients.

So, target components with numbers 1 and 3 are in the A group, then by formula (11):

$$\omega_1 = \frac{0,7}{2\cdot 1} = \frac{\theta_{12}}{ab} = 0,35 \to 0,35R_2;$$

$$\omega_2 = \frac{\theta_{32}}{ab} = \frac{0,94}{2\cdot 1} = 0,47 \to 0,47R_2$$

For target component with number 2 from *B* group by formula (12):

$$\omega_2 = \frac{a-(\theta_{12}+\theta_{32})}{ab} = \frac{2-(0,7+0,94)}{2\cdot 1} = 0,18R_2.$$

Answer: optimal resource allocation in this task will be fire and explosion safety automated system – 0,35*R2*; training of personnel system – 0,18*R2*; automated system of primary rescue operations management – 0,47*R2*.

Thus, the way of optimal resource allocation variants to ensure fire safety based on the developed method is presented.

The application of the theory of relative importance in a formalized description of the resource allocation experience and it's applications in making a decision in the current period of.

Let's use the concept and quantitative criterion of Shannon entropy (Shannon C. E., 1948) for the quantified estimation of the approximation of expert opinion degree with the use of these two methods. We designate the existing expert opinion approximation method on the preference based on $X_i > X_2$ in *Q*, then the proposed method based on the preference of relation $X_i \approx X_2$. Shannon entropy for a deterministic case depends on the quantity of state allocation of component-purposes groups, which is *N* and is determined by the formula *S=logN*. *N* state quantity depends on the agent quantity in the system *m* for the existing method *Q*, the allocations quantity linearly depends on *m* and is equal to $N_Q=m-1$.

For the developed method *P*, the allocation quantity is determined by the complex combinatorial dependencies that are obtained by the numerical analysis of distribution component-purposes for agent quantity, which are measured in the first-order decimal system. For the convenience of perception of numerical analysis of results it's advisable to consider the combinatorial dependencies * and * * (even and odd):

if *n* is odd, then:

$$N = \sum_{j=1}^{k}\left(\frac{m!}{(m-j)!\cdot j!}\right) \quad (15)$$

if *n* is even, then:

$$N = \frac{m!}{2\cdot(m-K)!\cdot K!} + \sum_{j=1}^{k-1}\left(\frac{m!}{(m-j)!\cdot j!}\right) \quad (16)$$

where

$$K = \left\lfloor \binom{n}{2} \right\rfloor \tag{17}$$

The component-purposes allocation by variant evaluation results into the groups *A* and *B* in the binary system with *m*=2, ..., 9 are shown in Figure 2.

The corresponding Shannon entropy indexes are shown in Figure 3.

Analyzing the obtained data, we can draw the following conclusions:

- for the known method *Q*, the Shannon entropy linearly increases while the increase of agents in the MAS.
- for the proposed method *P*, this dependence is not linear and in all cases except (*m*=2), it exceeds the indexes of *Q* method.

Therefore, method *P* is more beneficial in comparison with method *Q* in all cases.

Thus, based on the developed method, the optimal resources allocation for the safety tasks was suggested. The relative importance application in formal description of the resources allocation experience and its application in decision-making in the current period of the safety system development and operation are shown.

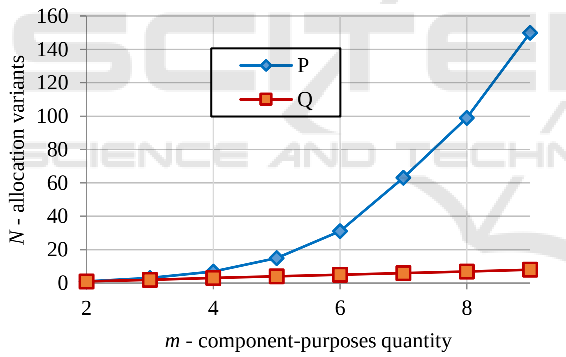

Figure 2: Component-purposes variants allocation quantity depending on their quantity in MAS.

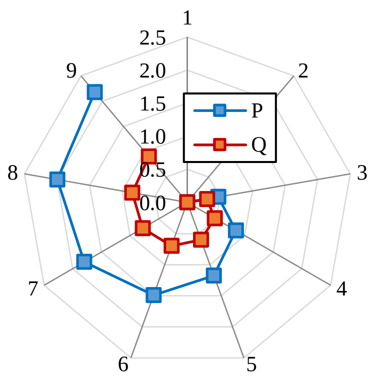

Figure 3: Shannon entropy estimation for the component-purposes allocation in the MAS.

3 DECISION-MAKING SUPPORT SYSTEM DEVELOPMENT

The decision-making support system (DSS) for resources allocation variants for ensuring the fire safety tasks of protection objects was suggested on the basis of developed method. The general structure of the system is shown as the scheme at the picture 4. The DSS allows carrying out ranking of resource allocation variant in the multi-agent system, as well as realization of the algorithms of multi-criteria analysis based on the optimal management concept in the agent system.

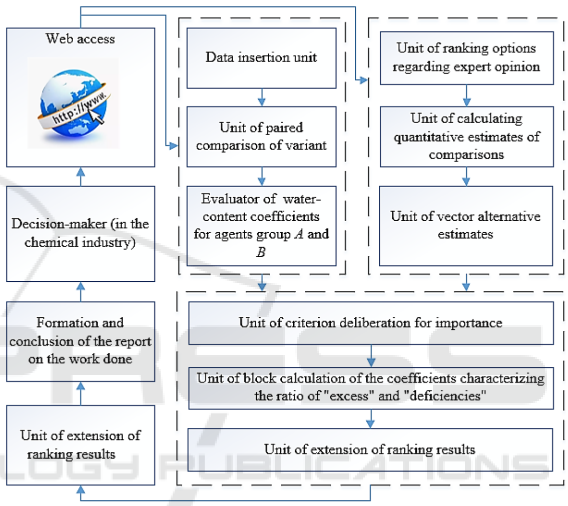

Figure 4: Decision support system functional scheme.

The following blocks can be specified in this scheme:

- Data entry block (researched object data entry);
- Double variants comparison block. Double variants comparison and results are drawn in this block.
- Importance coefficients determination for the agent groups *A* and *B*. According to double comparison results, the alternatives allocation into groups *A* and *B* is carried out. Relative's indexes of importance are determined for these groups.
- Variants ranking relatively of the expert's opinion block. Parallel with the previous actions in the system, the variants ranking relatively of the expert's opinion is carried out. The quantitative estimations variants of resources allocation are calculated. The received moisture indexes for groups *A* and *B* are used in the vector estimation calculation.

- Importance criteria weighing block. The importance criteria weighting coefficient (*Kij*) calculations are carried out.
- Importance coefficients array formation block. The importance indexes array is based on the conducted calculations. The received results are shown in the diagram. Allocation variants are ranked from more preferable to less preferable.

4 CONCLUSIONS AND FUTURE WORK

With the help of MAS, the task of resources allocation variants to ensure fare safety on industry enterprises was solved.

The distinctive feature of the developing model from similar is an ability of creation of multi-level procedure of options analysis in MAS, which is determined by the possibility of the importance indexes calculation for the agents and the relevant coefficient-purposes. The DSS, where the algorithms are formed in the way, that the MAS resources allocation variants on the first stage are distributed by multiplicities and then ranked in accordance with the management system preference, was developed. Multi-level procedure of variants' analysis in MAS allows approximating the preferences of management center more complete.

Further research is focused on the development of the evaluation of MAS application's efficiency criteria.

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