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ANALYSIS OF HUMAN-OPERATOR'S DECISION-MAKING IN AIR NAVIGATION SYSTEM

On the basis of the reflexive theory of bipolar choice the expected risks of decision-making by the Air Navigation System's operator influence of external environment, previous experience and intention were identified. The methods for analysis of decision-making by the human-operator in Air Navigation System using stochastic networks have been developed.

Keywords: *sociotechnical system, individual-psychological factors, socio-psychological factors, reflexive model, stochastic networks.*

Introduction

Currently, one of the main strategic problems of mankind on the path to sustainable development is the safety and stability of technogeneous production. Technogeneous production is a complex system that contains interrelated technical, economic and social objects. It has a multilevel hierarchical structure and a high level of risk [1]. Recent results show that there are frequent and common emergency such as disaster, accidents, crashes in hydraulic engineering, chemical and military industries, gas and oil pipelines, nuclear power plants and transport [2 - 4].

Aviation systems with its complex interrelation between a man and technologies have been evolved towards complex socio-technical systems. The interfaces between people and the technologies that comprise these systems are highly interactive, interdependent and affected by similar environmental events. The sociotechnical systems also tend to have two common features: high technologies and high risk activities. As such, they require much less direct operation due to the fact the technology replaces the human operator. On the other hand require much more remote operator's supervision due to the modern tendency to supervise the technology by distance. The systems' work is not transparent due to increased difficulty to know exactly what the technology is being used. The systems are also highly hazardous and of high-risk, and have greater potential for catastrophic consequences (i.e. accidents) [5].

The circular of ICAO presents the safety case for cultural interfaces in aviation safety with reference to three established main conceptual safety models: the SHEL model, Reason's model of latent conditions, and the Threat and Error Management (TEM) model and other models (Table 1).

Statistical data show that human errors account for up to 80% of all causes of aviation accidents [6]. Traditional methods like improving professional training, keeping work discipline and other may not be effective. Normally aviation personnel are trained professionally in a proper manner [7]. The causes of most aviation accidents are often connected with the psychology of the crew members which require appropriate consideration.

Modern approaches to control some factors (psycho-physiological, behavioural, ergonomic, professional, etc.) do not take into account the functional state of a human-operator (H-O) under conditions of dynamic changes of external and internal factors [6]. The ambient conditions determine the reaction of H-O, and this reaction changes the environmental conditions accordingly. One of possible approaches to solve these problems may be through formalization and mathematical description based on a system analysis of Air Navigation System (ANS) H-O's actions as a complex socio-technical system.

Review of research results

Ensuring safety in complex socio-technical systems like the aviation system is a key task to prevent threats at the operational level such as breakage of technical equipment or operating personnel's error [4].

Taking into account the influence of individual-psychological, physiological and socio-psychological factors of the environment on human-operator of ANS [8] allows us to predict his actions in specific flight situations. Using the theory of reflection the "large-scale" results which follow individual actions of man may be assumed [9].

For the formalization of the behaviour of ANS H-O in flight situations the graphic models relationships between a cause and an impact – graphs, trees, events and functional networks of stochastic structures – might be useful [10]. To study the impact of decision making by H-O during the flight situations development we had applied the stochastic network type GERT (Graphical Evaluation and Review Technique). GERT allows to model increase of flight situations complication as well as its decrease and/or simplification. GERT is an alternative probabilistic method of network planning, applicable in the case when these actions can only start after completion of a prior action including cycles and loops [10].

Table 1

Evolution of human factor's models

Years	Models	Content of model
1972	SHEL	Software (procedures), Hardware (machines) Environment Liveware
1990	Reason's "Swiss Cheese Model"	Active errors Latent errors Windows of opportunity Causation chain
1993	SHELL	Software (procedures) Hardware (machines) Environment Liveware Liveware (humans)
1999	CRM	Crew Resource Management
2000	TEM	Threat and Error Management
2000	MRM	Maintenance Resource Management
2004	SHELL-T SHELL-Team	Software (procedures) Hardware (machines) Environment Liveware Liveware (humans) Team
2004	SCHELL model and CRM	Software (procedures) Culture Hardware (machines) Environment Liveware Liveware (humans)
2004	LOSA	Line Operation Safety Audit
2009	HEAD	Human Environment Analysis and Design
2010	HFACS	Human Factors Accident Classification System

Purpose of work

The purposes of the article are:

– to develop the reflexive model of bipolar choice of H-O ANS in flight situations;

– to create stochastic network analysis of flight situations.

1. Reflexive model of bipolar choice of human operator of the Air Navigation System in flight situations

With bipolar reflexive behavioural model of H-O in extreme situations [9] we have received W-functions of a positive and a negative choice. The model represents the subject (H-O) located before the bipolar choice of one of the alternatives: A (positive pole) and B (negative pole).

The choice of H-O ANS is described by the function (1):

$$X = f(x_1, x_2, x_3), \tag{1}$$

where X – is probability, that H-O is ready to choose a positive pole A in the reality;

x_1 – is a pressure of the environment on H-O toward positive alternative at the moment of the choice, $x_1 \in [0, 1]$;

x_2 – is a pressure of the previous experience of H-O toward positive alternative at the moment of the choice, $x_2 \in [0, 1]$;

x_3 – is a pressure of the intention of H-O toward positive alternative in moment of the choice, $x_3 \in [0, 1]$.

The alternative solution B - is the choice of H-O, which is determined by H-O preferences system under which any form of arrangement of F-set is understood, i.e., removing the uncertainty of choice of some element $f^* \in F$ on the basis of selection rule K. A selection of a rule K shows the concept of a rational behaviour of individual γ and his preferences system ρ in a particular situation of choice: $\{\gamma, \rho\} \to K$.

The H-O ANS preferences system is influenced by professional $\overline{F}_p$ and non-professional $\overline{F}_{np}$ factors:

$$\overline{F}_p = \{\overline{F}_{ed}, \overline{F}_{exp}\}; \tag{2}$$

$$\overline{F}_{np} = \{\overline{F}_{ip}, \overline{F}_{pf}, \overline{F}_{sp}\}, \tag{3}$$

where $\overline{F}_{ed}$ – is knowledge, skills and abilities, acquired H-O during training;

$\overline{F}_{exp}$ – are knowledge, skills and abilities, acquired H-O during professional activity;

$\overline{F}_{ip} = \{f_{ipt}, f_{ipa}, f_{ipp}, f_{ipth}, f_{ipi}, f_{ipn}, f_{ipw}, f_{iph}, f_{exp}\}$ – is set of H-O individual-psychological factors (temperament, attention, perception, thinking, imagination, nature, intention, health, experience);

$\overline{F}_{pf}$ – is set of H-O psycho-physiological factors (features of the nervous system, emotional type, socio-type);

$\overline{F}_{sp} = \{f_{spm}, f_{spe}, f_{sps}, f_{spp}, f_{spl}\}$ – is set of H-O socio-psychological factors (moral, economic, social, political, legal factors).

For example, the preferences system of the pilot on the set of individual-psychological factors $\overline{F}_{ip}$, which reflect the objective characteristic of decision-making and thinking psychology of H-O: he is guided by a rational action, in cases of normal (4) and catastrophic situations (5):

$$(f_{iph}, f_{exp}) \succ f_{ipa} \succ f_{ipw} \succ f_{ipt} \succ \succ f_{ipi} \succ f_{ipp} \succ f_{ipth} \succ f_{ipn}, \tag{4}$$

$$(f_{iph}, f_{exp}) \succ (f_{ipt}, f_{ipp}) \succ f_{ipa} \succ \succ f_{ipw} \succ f_{ipth} \succ f_{ipi} \succ f_{ipn}, \tag{5}$$

where f_{iph} – is health;
f_{ipexp} – is experience;
f_{ipa} – is attention;
f_{ipw} – is intention;
f_{ipt} – is temperament;
f_{ipi} – is imagination;
f_{ipp} – is perception;
f_{ipth} – is thinking;
f_{ipn} – is nature.

In both cases, the most significant factors are the health and experience. During a flight situation development towards catastrophy such factors such as temperament and ability to perceive information are getting much more significant role. Other individual-psychological factors remain unchanged.

The obtained preferences models for military pilots and navigators determine the priorities of socio-psychological factors $\overline{F}_{sp}$ (6):

$$f_{sps} \succ f_{spe} \succ f_{spl} \succ f_{spp} \succ f_{spm}, \tag{6}$$

where f_{sps} – social factors;
f_{spe} – economic factors;
f_{spl} – legal factors;
f_{spp} – political factors;
f_{spm} – moral factors.

Similarly to civil aviation controllers and pilots [8], military pilots and navigators are under influence of socio-economic factors. Detailed analysis of the influence 13 socio-psychological factors (religious views, philosophical views, career, reputation, corporate interests, economic interests of enterprise, private economic interests, family interests, interests of colleagues, interests of the company's management, image, political interests, legal rules) demonstrated that for pilots their own image, corporation's image and family interests are on the first place. At the same time, for respondents-controllers main focus is on the family interests, their private economic situation and career development [8].

2. Stochastic networks analysis of flight situation development

In stochastic networks of the flight situation development of GERT type the tops are represented by stages of the situation (normal, complicated, difficult, emergency or catastrophic), and the arcs are represented by a process of transition between stages of the situation.

Let's consider the stochastic network model of the flight situation development GERT G = (N;A) with set of tops N and set of arcs A. The time t_{ij} of transition from i-flight situation to j-flight situation is a random variable. Transition (i;j) can be executed only if i-top has been done. For calculation of transition time t_{ij} from i-flight situation to j-flight situation, it is necessary to know conditional probability (in discrete case) or the density of distribution (in continuous case) of random variable Y_{ij}. This allows to research the performance of the whole network G = (N;A) and to identify the moments of time distribution t_{ij} of network G, calculate mathematical expectation μ_{jE} and variance of execution time δ^2 of network G in case of complicated, complex, catastrophic or emergency situation.

Let f_{ij} be conditional probability (density of distribution) of time to make the transition from flight situation Gi to flight situation Gj. Conditional producing function of moments of random variable Y_{ij} is defined by formula (7):

$$M_{ij}(s) = E\left[e^{Y_{ij}}\right]. \tag{7}$$

In continuous and discrete cases the random variables formula (7) is being transformed to formulas (8) and (9) accordingly:

$$M_{ij}(s) = \int e^{sy_{ij}} f(y_{ij}) dy_{ij}; \tag{8}$$

$$M_{ij}(s) = \sum e^{sy_{ij}} f(y_{ij}). \tag{9}$$

If y_{ij}=a=const, then $M_{ij}(s) = E\left[e^{sa}\right] = e^{sa}$.

W-function for random variable Y_{ij} as transmission coefficient of GERT-network is introduced (10):

$$W_{ij}(s) = p_{ij} M_{ij}(s), \tag{10}$$

where p_{ij} – probability, that j-flight situation will come and transition (i;j) has been made;

$M_{ij}(s)$ – conditional producing function of moments of random variable Y_{ij}.

The algorithm of stochastic network analysis is presented here on an example of GERT-network:

1. For obtaining close stochastic network G enter in the open stochastic network $W_E(s)$ additional dummy arc with W-function $W_A(s)$, which connects the drainage of open network t with a source s.

2. For modified network G to determine all k-loops, $k=\overline{1,n}$.

3. The equivalent transmission coefficient for all k-loops of G-network, $k=\overline{1,n}$ is being calculated (11):

$$T(L_n)=\prod_{k=1}^{n}T_k=\prod_{k=1}^{n}\left[\prod_{(i,j)\in L_{k_1}}t_{ij}\right], \qquad (11)$$

where $T_k=\prod_{(i,j)\in L_{k_1}}t_{ij}$ – is equivalent transmission coefficient of 1-loop L_{k1};

t_{ij} – is time of transition from i-flight situation to j-flight situation.

4. To apply Mason's rule for topological equation close stochastic network G (12):

$$\begin{aligned}H=1-\sum T(L_1)+\sum T(L_2)-\\-\sum T(L_3)+...+(-1)^k\sum T(L_k)+...=0,\end{aligned} \qquad (12)$$

where $\sum T(L_k)$ – is sum of equivalent transmission coefficients for all possible k-loops.

5. From topological equation of close stochastic network G transmission coefficient of open network $W_E(s)$ is determined.

6. To determine the first and the second moments of random variable Y_{ij} (13):

$$\mu_{jE}=\frac{\partial^j}{\partial s^j}\left[M_E(s)\right], \qquad (13)$$

where μ_{1E} – is mathematical expectation of execution time of network G;

μ_{2E} – is standard deviation of execution time of network G.

Thus according to results of stochastic network analysis of the flight situation development from normal to catastrophic the following values have been obtained:

– mathematical expectation of flight situation's development time t_{ij};

– variance of flight situation's development time t_{ij};

– probability of flight situation's development p_{ij}.

For example, let's analyze catastrophic situation development under hazardous weather conditions using the decision tree and stochastic network GERT (fig. 1). According to data of the National Transportation Safety Board (NTSB) [11], during the last 10 years 21,3% aviation accidents happened due to weather conditions, of which 39,1% - in bad weather conditions. The major cause of aviation accidents in bad weather conditions (68%) considered improper and untimely decision-making by crew of the aircraft.

Based on the W-functions of positive and negative of H-O choice the Markov's network of flight situations' development from normal to catastrophic was constructed (Fig. 1). Markov's process with discrete states W_{ij} is called process of death and life [12].

Expected risks R_A, R_B of H-O obtained in decision-making during the approach perfomed in bad weather conditions under the influence of external environment x_1, previous experience of H-O x_2 and intention of H-O x_3. Expected risk of H-O decision-making is (14):

$$R_{DM}=\begin{cases}R_A=\min\{R_{ij}\};\\R_B=\{\gamma,\rho\};\\R_{AB}=\{X(x_1,x_2,x_3),\gamma,\rho\},\end{cases} \qquad (14)$$

where R_A – is expected risk of H-O in decision-making taking into account the criterion of minimizing of expected value;

R_B – is expected risk of H-O decision-making taking into account his preferences model;

R_{ij} – is expected risk of A_{ij}-decision;

γ – is concept of rational behavior of individual;

ρ – is preferences system of individual in a particular situation of choice;

R_{AB} – is mixed choice of H-O.

Conclusion

On the basis of the reflexive theory of bipolar choice the expected risks of decision-making of the Air Navigation System's operator have been studied and the influence of external environment, previous experience and intention of the human-operator has been identified.

The methods for analysis of decision-making by the human-operator in Air Navigation System using stochastic networks have been developed.

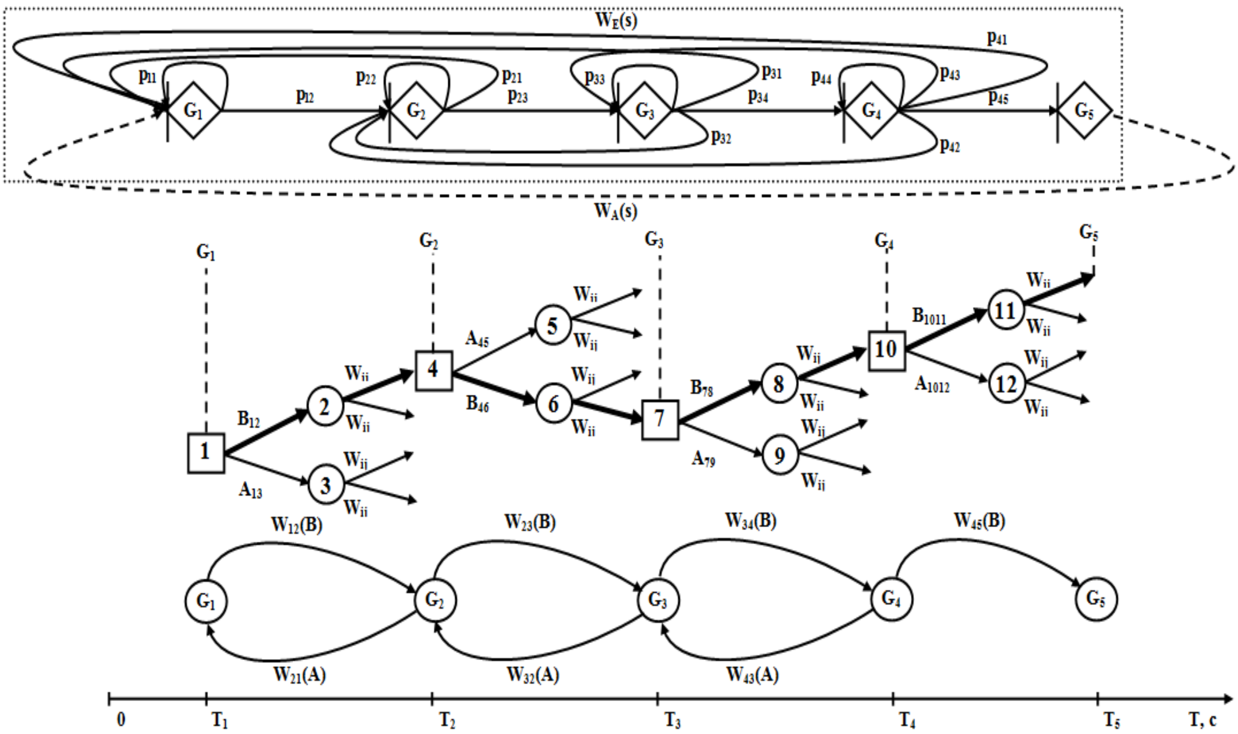

Fig. 1. Stochastic models: GERT network, decision tree and Markov's network

Figure 1 includes the next designations:

W_{ij}, $W_E(s)$, $W_A(s)$ – transmission coefficients of (i,j)-arc, of open network and of dummy arc;

G_1, G_2, G_3, G_4, G_5 – normal, complicated, difficult, emergency, catastrophic situations;

A, B – positive or negative choice;

p_{ii} (p_{11}, p_{22}, p_{33}, p_{44}) – probability of stabilization of i-flight situation, $i = \overline{1; n-1}$;

$p_{i(i+1)}$ (p_{12}, p_{23}, p_{34}, p_{45}) – probability of development of i-flight situation toward complications, $i = \overline{1; n-1}$;

$p_{i(i-k)}$ (p_{21}, p_{32}, p_{43} – 1-loop; p_{31}, p_{42} – 2-loop; p_{41} – 3-loop) – probability of flight emergency situation parrying, $k = \overline{1;3}$

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АНАЛІЗ ПРИЙНЯТТЯ РІШЕНЬ ЛЮДИНОЮ-ОПЕРАТОРОМ В АЕРОНАВІГАЦІЙНІЙ СИСТЕМІ

Т.Ф. Шмельова, Ю.В. Сікірда

На основі рефлексивної теорії біполярного вибору отримані очікувані ризики прийняття рішень оператором аеронавігаційної системи при впливі зовнішнього середовища, попереднього досвіду і вольового вибору людини-оператора. Розроблена методика аналізу прийняття рішень людиною-оператором в аеронавігаційній системі за допомогою стохастичних мереж.

Ключові слова: соціотехнічна система, індивідуально-психологічні фактори, соціально-психологічні фактори, рефлексивна модель, стохастичні мережі.

АНАЛИЗ ПРИНЯТИЯ РЕШЕНИЙ ЧЕЛОВЕКОМ-ОПЕРАТОРОМ В АЭРОНАВИГАЦИОННОЙ СИСТЕМЕ

Т.Ф. Шмелева, Ю.В. Сикирда

На основе рефлексивной теории биполярного выбора получены ожидаемые риски принятия решений оператором аэронавигационной системы при воздействии внешней среды, предыдущего опыта и волевого выбора человека-оператора. Разработана методика анализа принятия решений человеком-оператором в аэронавигационной системе с помощью стохастических сетей.

Ключевые слова: социотехническая система, индивидуально-психологические факторы, социально-психологические факторы, рефлексивная модель, стохастические сети.

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