Mathematical Modeling of Information Management of Social Systems in Emergencies

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ABSTRACT

A primary responsibility of the state is ensuring the safety of its citizens while alerting and informing the public of an impending emergency, and the required actions are important measures taken to protect the population. Information management is becoming increasingly important in bringing systematic information to improve the safety of daily life to people's attention. A proper science-based approach to informing the population using modern communication technologies will achieve a totally new level of promptness, reliability and precision.

The article presents a mathematical model for exploring patterns in the process of propagating information within the social environment and conducting simulations to determine how the target audience is covered by various emergency warning methods. It also lays out a methodology for selecting and justifying the parameters of disseminated information blocks, their structure and content, with consideration of the socio-psychological characteristics of their perception.

Keywords: *social system, emergency, mathematical model, information propagation, information exchange, information message*

1. INTRODUCTION

The high level of industrial development in modern society, while providing comfortable daily living, also brings many negative consequences, such as the threat of industrial accidents, environmental problems, which in turn leads to an increase in the scale of natural disasters. Excessive concentration of industrial facilities in certain areas, increased complexity of production processes, the use of substances harmful to human health and obsolete equipment – all this significantly increases both the likelihood of an emergency and the social, economic and financial damage.

A primary responsibility of the state is to ensure the safety of its citizens, while alerting and informing the public about potential emergencies, and the actions required are important measures taken to protect the population.

Information management is becoming increasingly important in bringing systematic information to improve the safety of daily life to people's attention. The promptness of information dissemination largely determines the extent and probability of damage and often also the number of human casualties.

The following is required to properly alert and inform the public in emergency situations:

– depending on the purpose and content of the information message, a correct choice of the channels, form and means of informational influence;

– using the capabilities of information technologies, digital mass media to disseminate information to the public about potential or occurring emergencies and required actions [1–3];

– the development of mathematical and software support to organise information flows, allowing determining the optimal functioning of the emergency warning systems, the duration of the information block, the structure of its components etc.;

– consideration of the qualitative and quantitative composition of the audience (age, gender, social, economic, ethnic, educational, professional heterogeneity) and, accordingly, psychophysiological nature of perception and understanding of the messages by various population categories.

Therefore, a critical task is to develop algorithms and models for studying information propagation patterns and to conduct simulation experiments to determine the coverage of the target audience by various emergency warning methods as well as justify the parameters of the disseminated information blocks, their structure and content, while considering the socio-psychological characteristics of their perception.

2. THE APPROACH TO MODELING INFORMATION PROCESSES

Researches with an interest in systems analysis, mathematical modeling, information theory etc. have recently began paying close attention to processes occurring in social systems. The most comprehensive systemic approach to analysing information exchange is presented in the works by scientists of V. A. Trapeznikov Institute of Control Sciences of the Russian Academy of Sciences under the leadership of Academician D. A. Novikov [4–8].

However, the models developed by them did not reflect all the specific features of social systems that are of interest in applied research. In particular, they do not consider subjective personality characteristics of the communication process participants that influence the information exchange process, for example, different degrees of sociability, readiness to propagate information and susceptibility to external influence.

It should also be noted that researchers in many areas study the information propagation processes based on the general network theory and consider them 'epidemic', similar to biological systems (obtaining information is similar to the 'infection' of a network node) [9–11]. The attempts at analysis and formalisation of network information structures are largely based on analogue differential equations. However, in differential and integral equations, it is rather difficult to correlate the coefficients with the characteristics the studied system. In addition, the discreteness of states of infected network elements as well as certain other features of epidemic processes requires discrete models.

Thus, although a range of scientific papers deals with this issue, the modeling of the information exchange process remains relevant.

3. THE MATHEMATICAL MODEL OF INFORMATION PROPAGATION

The following mathematical model is proposed to study the processes of informing the public.

The target audience (population living in the area of the emergency) is defined as a social system (SS) characterised by connectivity, sociability and susceptibility of its elements to informational influence. Social systems are characterised by inherent subjective uncertainty, thus the modeling of the processes occurring within them can be only poorly formalised. The fuzzy set theory apparatus is useful as a tool to solve this problem.

To formalise subjective assessments, a 'Factor Level' linguistic variable could be introduced, and the term-set of its values established with three or five elements:

$$\{low; medium; high\} \quad (1)$$

$$\{strongly\ negative; negative; neutral; positive; strongly\ positive\} \quad (2)$$

Information propagation (or information exchange) occurs as follows. Information is entered into the social system (announced using a particular communication channel) at an initial time point $t = 0$. The participants who received information from the primary source will be called the initiating set. Thereafter, the information is propagated by interpersonal information exchange. The purpose of the simulation is to determine the proportion of informed members of the social system as well as the distribution of their opinions in terms of set (2) at each step $t = t + 1$.

One step in modeling is the time interval necessary for a single activation of all communication ties among the exchange participants.

The number K of informed members of the social system at step $t = t + 1$ is a dependence:

$$K_{(t+1)} = K_{(t+1)}\left(L, \bar{b}, q_t, K_{(t)}\right) \quad (3)$$

where L is the size of the initiating set, $\bar{b}$ is the social system connectivity coefficient (the average number of ties between the interacting system participants), q_t is the proportion of participants at step t who are ready to share the received data and propagate information.

The value of the q_t coefficient depends on two factors: the share of participants with high sociability and relevance of the propagated information at time step t. The level of sociability is a permanent characteristic of the social system members. Information relevance usually decreases over time, but for emergencies endangering human life or health the value of this coefficient is predicted to be relatively high.

A sample-based representative sociological survey is proposed to obtain the initial data. The representative sampling parameters are determined based on statistical data about the general population of the information exchange participants as well as the recommendations of the Federal State Statistics Service for sample surveys. This makes it possible to extrapolate the findings to the entire social system.

The characteristics of large social systems are defined as statistical distributions.

Model parameters include:

– distribution of the number of ties between the participants allowing determining the average number of contacts per person;

– proportion of participants willing to propagate the received information;

– susceptibility indicators of the social system members estimated using values from the linguistic variable term-set (as shares of the total);

– initial distribution of opinions about the propagated information (also estimated as shares of the total using fuzzy values of the linguistic variable).

The 'level of susceptibility' refers to a person's susceptibility to changing their point of view under external influence. 'Low susceptibility' means the ability to retain one's opinion under the influence of the information environment, and 'high', on the contrary, means a significant degree of conformity.

Let us formulate the following rules of information exchange in a social system that allow for formalisation and automation of mathematical calculations:

1. Information is propagated by participants with high sociability and a strong opinion on this information.
2. The opinion of the participants with low susceptibility does not change, while participants with medium to high susceptibility change their mind after receiving emotionally charged reports.

3. Participants with moderate susceptibility are moderately susceptible to external pressure, those with high susceptibility are highly susceptible to external influence and can change their minds drastically.

Let us introduce the following designations:

– $\omega^L, \omega^M, \omega^H$ are the proportion of social system participants with low, medium and high susceptibility;

– K_t^{++} and v_t^{++} are the number and proportion of participants with a strongly positive attitude to the propagated information at time *t*;

– K_t^{+} and v_t^{+} are the number and proportion of participants with a positive attitude;

– K_t^{Neutr} and v_t^{Neutr} are participants with a neutral attitude;

– K_t^{-} and v_t^{-} are participants with a negative attitude;

– K_t^{--} and v_t^{--} are participants who at time *t* have developed a strongly negative attitude.

The number of informed social system members is determined using the following formula:

$$K_{t+1} = K_t + q_t \cdot \left(\frac{N - K_t}{N}\right) \cdot (K_t^{++} + K_t^{--}) \cdot \bar{b}, \qquad (4)$$

where N is the total size of the target audience, and coefficient $\frac{N-K_t}{N}$ reflects the share of participants uninformed at the previous step.

The number of social system members with a strongly negative attitude toward information is calculated as follows:

$$\begin{aligned} K_{t+1}^{--} = K_t^{--} + (K_{t+1} - K_t) \cdot [v_0^{--} - \\ -v_0^{--} \cdot (\omega^M + \omega^H) \cdot \left(\frac{K_t^{++}}{K_t^{++} + K_t^{--}}\right) + \\ +v_0^{-} \cdot (\omega^M + \omega^H) \cdot \left(\frac{K_t^{--}}{K_t^{++} + K_t^{--}}\right) + \\ +v_0^{Neutr} \cdot \omega^H \cdot \left(\frac{K_t^{--}}{K_t^{++} + K_t^{--}}\right)] \end{aligned} \qquad (5)$$

Factors $\frac{K_t^{++}}{K_t^{++}+K_t^{--}}$ and $\frac{K_t^{--}}{K_t^{++}+K_t^{--}}$ reflect the proportion of the information exchange participants sharing strong positive and negative opinions, respectively. The formula shows how they influence the participants with medium and high susceptibility and make them change their opinion in one or the other direction (increase or decrease their share).

The formula for the calculation of the number of participants with a strongly positive attitude is similarly determined:

$$\begin{aligned} K_{t+1}^{++} = K_t^{++} + (K_{t+1} - K_t) \cdot [v_0^{++} - \\ -v_0^{++} \cdot (\omega^M + \omega^H) \cdot \left(\frac{K_t^{--}}{K_t^{++} + K_t^{--}}\right) + \\ +v_0^{+} \cdot (\omega^M + \omega^H) \cdot \left(\frac{K_t^{++}}{K_t^{++} + K_t^{--}}\right) + \\ +v_0^{Neutr} \cdot \omega^H \cdot \left(\frac{K_t^{++}}{K_t^{++} + K_t^{--}}\right)] \end{aligned} \qquad (6)$$

Figure 1 illustrates the typical simulation modeling data. The application of the proposed model will allow assessing the information exchange dynamics and analysing the dependences between various social system characteristics and the degree to which the information is disseminated to the public [12].

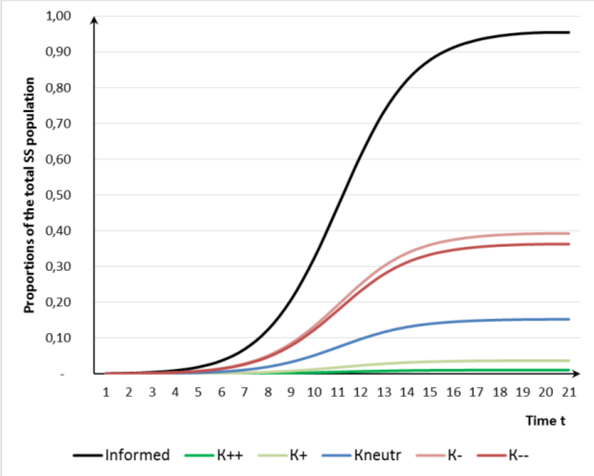

Figure 1 Graphs of the increase in the number of informed social system members and distribution of their opinions

The resulting graphs are in the shape of a sigmoid curve. The process of information propagation is characterised by a sharp increase in the number of informed participants after a certain time; thereafter, further propagation of information is virtually terminated.

The developed mathematical model based on the use of the fuzzy set theory apparatus is quite flexible and can be adapted to different situations and uses. In particular, the emotional component of the opinion forming in society about past or predicted events is fairly evident when the public is informed about emergencies, and understanding the usefulness and necessity of such information gains a key role its propagation.

Therefore, the following linguistic variable term-set is suitable for modeling the information exchange process in emergencies:

$$\begin{gathered} \{extremely\ harmful\ (EHarm); harmful\ (Harm); \\ neutral\ (Neutr); \\ useful\ (Usefl); extremely\ useful\ (EUsefl)\} \end{gathered} \qquad (7)$$

The graphs in figure 1 will then have the following substantive interpretation: when receiving information, the information exchange participants assess its usefulness differently, focusing on the authoritativeness of the information sources to a different degree depending on their susceptibility. Thus, the information is propagated by the participants who find it extremely useful.

The formulas for calculating the number of participants in each category (7) in comparison with the 'classical' model change as follows. The formula to calculate the number of participants who believe that the propagated information is extremely harmful:

$$K_{t+1}^{EHarm} = K_t^{EHarm} + (K_{t+1} - K_t) \cdot [v_0^{EHarm} -$$

$$-\nu_0^{EHarm} \cdot (\omega^M + \omega^H)] \quad (8)$$

The information is considered extremely useful and necessary to learn at step $t = t + 1$ by:

$$K_{t+1}^{EUsefl} = K_t^{EUsefl} + (K_{t+1} - K_t) \cdot [\nu_0^{EUsefl} +$$

$$+\nu_0^{Usefl} \cdot (\omega^M + \omega^H) + \nu_0^{Neutr} \cdot \omega^H] \quad (9)$$

The formulas for calculating the number of participants who consider the received information useful/neutral:

$$K_{t+1}^{Usefl} = K_t^{Usefl} + (K_{t+1} - K_t) \cdot [\nu_0^{Usefl} -$$

$$-\nu_0^{Usefl} \cdot (\omega^M + \omega^H) + \nu_0^{Harm} \cdot \omega^H + \nu_0^{Neutr} \cdot \omega^M] \quad (10)$$

$$K_{t+1}^{Neutr} = K_t^{Neutr} + (K_{t+1} - K_t) \cdot [\nu_0^{Neutr} -$$

$$-\nu_0^{Neutr} \cdot (\omega^M + \omega^H) + \nu_0^{Harm} \cdot \omega^M + \nu_0^{EHarm} \cdot \omega^H] \quad (11)$$

4. THE METHODOLOGY TO SELECT AND JUSTIFY THE OPTIMAL COMPOSITION OF INFORMATION MESSAGES TO ALERT THE PUBLIC IN THE CASE OF AN EMERGENCY

Reducing the risk of harm to the population and the inflicted damage in an emergency requires, first, comprehensive and timely dissemination of important information to all social system members, and, second, its correct understanding and perception. This creates a need to consider the social and psychological characteristics of the target audience, select and justify the optimal composition and structure of the information blocks.

The following basic requirements for the propagated messages can be described: consideration of the differences in perception and assimilation of the information by various population groups; correspondence of the message to the specifics of the current situation in the emergency area; consistency and specificity of its content; use of clear and concise wording with a simple grammatical structure; avoidance of alarming elements that can provoke panic [13].

The messages for different types of information should have different content, structure and presentation to be developed in advance. People's actions in case of a potential or occurring emergency can be made more effective by selecting the information block parameters such as volume, meaning and strength of impact [14].

Information management in an emergency should be performed at the following main stages: 'before', 'during' and shortly 'after' an emergency (figure 2).

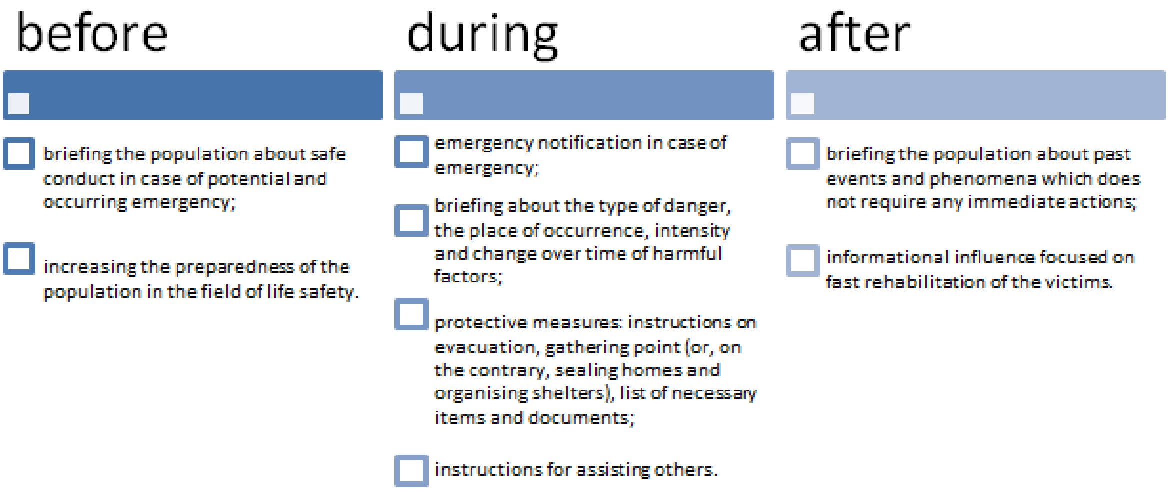

Figure 2 Message types at different information management stages in an emergency

The propagation of information at each of these stages has its own features that need to be considered for more effective informational influence [15].

Errors and omissions in information management have different effects at each stage. Defects at the 'before' and 'during' stages cause more damage which could have been reduced. Poor information management 'after' leads to loss of confidence, social tension, acts of civil disobedience, propagation of false information from alternative sources.

The first step is to disseminate information about the nature of possible emergencies in the area of their residence, about precautions and actions, if the emergencies occur to as many people as possible. This stage is characterised by low susceptibility of social system members and low willingness to propagate information because people tend to underestimate the risk of emergency and do not consider preliminary information significant and important. To increase the level of public preparedness in the field of life safety, information messages perform an instructional and educational function. Information should have a strong emotional content, be vivid and memorable for a high chance of propagation.

At the second stage, the emergency message should be simple, clear and concise as well as reliable and objective. Information should be provided promptly, frequently, in the shortest possible time. At the same time, the delivered message should not be highly alarming not to create panic, nor can it be trivial, so that the danger is not underestimated. The most essential information should be highlighted. Depending on the situation, the message can be expanded with additional information to attract attention and improve perception.

The classical information management function aimed at stabilising the information environment in the society, relieving psychological stress, establishing trust in the state services responsible for the elimination of consequences, rehabilitation of victims and compensation for damage is performed 'after' the emergency response.

To solve the problem of creating information blocks that provide optimal impact on the target audience, it is necessary to investigate the general information propagation patterns in the social system and determine the effect of properties and forms of presenting information on the social system characteristics.

It seems obvious that the content and form of the message primarily affect the willingness of people to propagate the information received and can also increase or decrease the degree of their susceptibility as part of this topic.

The objective is to choose effective information message parameters to maximise the number of people informed and approximate the distribution of their opinions to the required values. The developed mathematical model of the information exchange enables a series of simulation experiments to solve the problem according to the following scheme (figure 3):

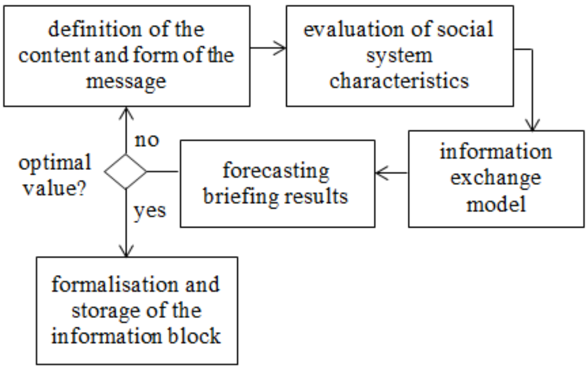

Figure 3 The scheme for the selection of the information message parameters

The sociological survey method based on a quota representative sample is used to assess the social system characteristics. This sample is based on defining quota groups – that is, categories of people characterised by different values of significant characteristics impacting the result of information exchange (age, social status, education level, physical abilities etc). Quota groups are determined based on linked characteristics while maintaining the proportions that exist in the general population.

The message parameters (its volume, presentation, quantity and structure of content blocks) that result in an optimal model output for achieving the informing and alerting goals are considered the most effective. Thus, the information block parameters can be defined for each type of danger and possible emergency.

5. AN EXAMPLE OF DETERMINING AND JUSTIFYING THE EMERGENCY INFORMATION MESSAGE PARAMETERS

To check the adequacy of the model and the proposed methodology, a social system was studied using the example of the population of the Chechen Republic. The population according to Rosstat was 1,456,951 in 2019. The size of the representative sample for a sociological survey was calculated as 384 people.

The respondents were asked to answer several questions about their social activity, social circle, sources they use for important information as well as their attitude to the possibility and probability of emergencies in their area of residence. The respondents were shown two prepared alternative messages with instructions on the plan of actions in case of an impending earthquake. The messages were expected to be propagated via social networks.

The following general characteristics of the studied social system were determined:

1. Distribution of the number of ties: 80% of participants had 1 to 5 communication ties; 20%, 6 to 15 stable ties with others.
2. The initial attitude of the social system members to the emergency-related information:
$v_0^{EHarm} = 0,\ v_0^{Harm} = 0{,}01$,
$v_0^{Neutr} = 0{,}48,\ v_0^{Usefl} = 0{,}29$, $v_0^{EUsefl} = 0{,}22$.
3. The size of the initiating set (residents receiving information about the topic from social networks) is 20%.
4. Coefficient of susceptibility to external opinion: 51% of participants – 'Low', 32% – 'Medium' and 17% – 'High'.

The first standard message version in text format (let us call it Inf1) is shown in figure 4.

Attention! To all residents, due to a **possible earthquake**, please take precautions:
turn off gas, water, electricity, put out the fire in stoves in private residences.
Notify your neighbours about this information.
Take your clothes, documents, food, water and go outside.
Help the elderly, sick and the children.
Stand away from buildings and power lines.
Stay tuned for our future messages.

Figure 4 Text message with instructions to the population in case of an impending earthquake

25% of respondents (q_0 = 0.25) confirmed their willingness to propagate such message among their contacts on social networks.

Figure 5 shows the predicted results of informing the population when initiating information block Inf1.

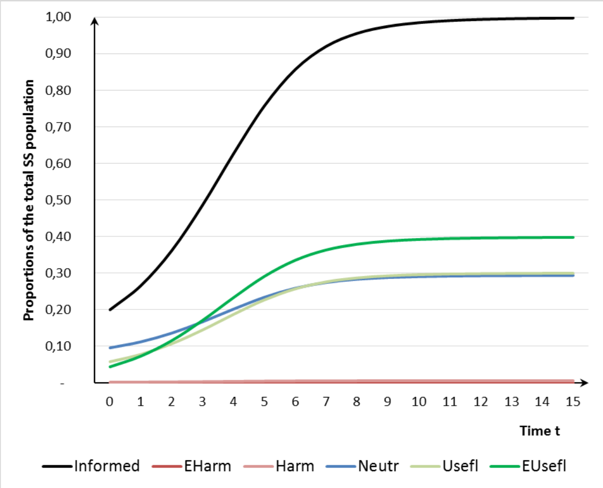

Figure 5 The information exchange dynamics during the propagation of information message Inf1

The second message (Inf2) with the same content had a different presentation – it included graphic elements along with text (figure 6).

According to the survey results, the indicator of the willingness to repost the information received in this case was $q_0 = 0.4$, which is already much higher than in the first experiment. Figure 7 shows a faster increase in the number of the information exchange participants who have received and viewed the instructions about actions during an earthquake.

Text information is well absorbed; however, when it is comprehended and analysed, the human brain breaks down the received information into a series of images convenient for perception and memorisation, which consumes additional time and mental effort. The information provided as images is perceived by the brain all at once and is logically integrated into the thought process, promoting easy memorisation.

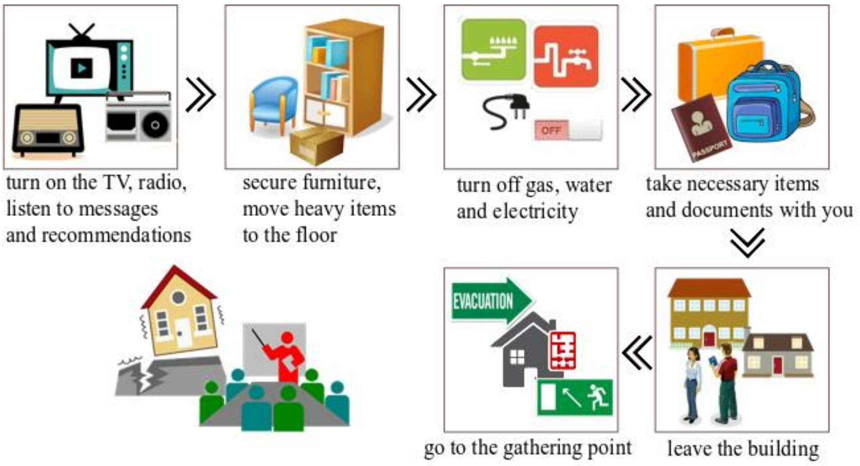

Figure 6 Graphic instruction message

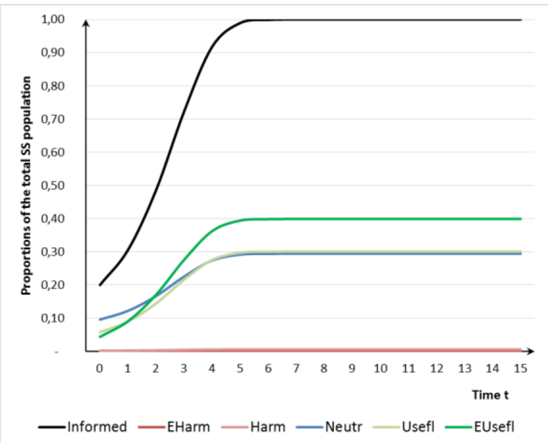

Figure 7 The information exchange dynamics during the propagation of message Inf2

Modern psychology of perception uses many different approaches, methods and specific concepts. The evaluation of information content uses both traditional sociological research approaches (respondent surveys, expert interviews, content analysis) and the latest methods and means of instrumental psychodiagnostics of a person's involuntary reactions to visual stimuli presented to them (eg, eye tracking, a technology that allows observing and registering eye movements).

Thus, the solution to the problem of selecting and justifying the optimal information message content can be built on an extensive scientific empirical base and has great potential for research and practical application of results.

6. CONCLUSION

An analysis of the risks of natural and industrial disasters at the start of the third millennium shows an increase in the likelihood of their occurrence and inflicted damage. On the other hand, the emergence of new information

technologies, development of the technical base and capabilities of modern communication methods allow adequately responding to these threats in terms of informing the population.
Competent management of information flows in these conditions becomes a key factor in ensuring the safety of life and property as part of emergency prevention and response measures. A science-based, practice-oriented approach to informing of the population using modern information and communication technologies allows reaching a totally new level of efficiency, reliability and precision.
Further consideration of the information exchange dynamics in social systems under different parameters of information blocks is a highly relevant and promising area of research.

ACKNOWLEDGMENT

The reported study was funded by RFBR according to the research project №18-47-200002.

REFERENCES

[1] D.S. Gluharev, The information and communication space in the theories of information society, Vestnik YUUrGU. Seriya: Social'no-gumanitarnye nauki, 2 (2013) 133-135

[2] A.V. Potemkin, Recognition information operations in internet mass media, Internet-zhurnal «Naukovedenie», 3(28) (2015).

[3] M.A. Sazonov, A.V. Potemkin, Research of mechanisms of information influence on media systems, Voprosy kiberbezopasnosti, 3(16) (2016) 55-59.

[4] A.V. Batov, V.V. Breer, D.A. Novikov and A.D. Rogatkin, Micro- and macromodels of social networks. II. Identification and simulation experiments, Automation and Remote Control, 77(2) (2016) 321-331.

[5] D.A. Gubanov, A.G. Chkhartishvili, A conceptual approach to online social networks analysis, Automation and Remote Control, 76(8) (2015) 1455-1462.

[6] D.A. Gubanov, D.A. Novikov, A.G. CHkhartishvili, Modeli informacionnogo vliyaniya i informacionnogo upravleniya v social'nyh setyah, Problemy upravleniya. Upravlenie v social'no-ekonomicheskih sistemah, 5 (2009) 28-35

[7] D.A. Gubanov, D.A. Novikov, A.G. CHkhartishvili, Models of reputation and information control in social networks, Matematicheskaya teoriya igr i ee prilozheniya, 1 (2009) 14-37

[8] V.V. Breer, D.A. Novikov, Modeli upravleniya tolpoj, Problemy upravleniya, 2 (2012) 38-44

[9] V.V. Islamgulova, A.G. Ostapenko, N.M. Radko, R.K. Babadzhanov and O.A. Ostapenko, Discreet risk-models of the process of the development of virus epidemics in non-uniform networks, J. of Theoretical and Applied Information Technology, 2 (2016) 306-315

[10] R. Pastor-Satorras, A. Vespignani, Epidemic spreading in scale-free networks, Phys. Rev. Lett. 86 (2001) 3200-3203.

[11] A.V. Parinov, E.A. Shvartskopf, L.G. Popova, I.L. Bataronov and N.N. Tolstykh, Risk models of destructive content diffusion between social network communities, AP – Int. J. of Pure and Applied Mathematics, 119(15) (2018) 2605-2609.

[12] I.M. Azhmuhamedov, D.A. Machueva, E.D. Alisultanova and N.A. Moiseenko, Simulation modeling of information dissemination process during public notification of emergency situations, Advances in Engineering Research, 182 (2019) 191-196.

[13] R.A. Durnev, A.V. Luk'yanovich, A.S. Kotosonova, Informing the population in emergency situations using text messages of cellular communication, Tekhnologii grazhdanskoj bezopasnosti, 2(36) (2013) 4-8.

[14] R.A. Durnev, A.V. Luk'yanovich, A.S. Kotosonova, Formulation of the scientific task of justification of rational parameters of text messages of cellular communication for the population notification at emergency situations, Tekhnologii grazhdanskoj bezopasnosti, 1(39) (2014) 12-17.

[15] A.A. Ryzhenko, N.Yu. Ryzhenko, O.V. Eltemerova, Problems of informing and notifying the population about emergencies, Tekhnologii tekhnosfernoj bezopasnosti, 2(54) (2014).