Entropy and information analysis of the interoperability of the emergency early warning system

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*Abstract***— One of the most effective ways to alert the public about an emergency (natural or man-made disaster) is through early warning systems, including those based on messaging. It is known from the literature that the problem of interoperability (interaction) is relevant in the interaction of heterogeneous forces and means operating in an emergency situation. In this paper, we will propose an entropy-information analysis of the system for communicating information about an emergency situation to citizens, taking into account the impact of interoperability on citizens' awareness of an emergency situation.**

I. Introduction

One of the ways to notify the population about an emergency situation (for example, a natural or man-made disaster) is an early warning system (EWS) [1], usually based on the transmission of messages to citizens. The message-based approach is also used in the interaction of disparate forces and means among themselves [2]. In such messaging systems, the problem of interoperability is mainly semantic in nature [3]. The problem of interoperability in message exchange systems is solved, as a rule, by an ontological approach [4] and the use of standardized message formats, including EXDL [5, 6]. In emergency early warning systems, the problem of interoperability is also semantic [7].

Entropy can also be considered as a necessary variety of, for example, information systems. The work of W.R. Ashby is also devoted to this area [8].

Since interoperability indicators have a physical limitation in implementation (all systems cannot be the same), in fact, one of the consequences of W.R. Ashby's law of necessary diversity is the presence "by default" of a certain number of interoperability barriers that must be overcome in order to bring information to the end user.

One of the ways to ensure interoperability in system modeling is to reduce entropy, including at the semantic level of interoperability through the use of standards (file formats, communication protocol, etc.) [9]. In this paper, unlike other papers, an entropy-information analysis of emergency early warning systems using message exchange is proposed in terms of obtaining a numerical value of entropy and reducing it during the application of mechanisms to overcome barriers to interoperability.

Thus, by ensuring interoperability at the semantic (as well as organizational and technical levels), entropy will decrease during the exchange of messages and, as a result, threats to the life and health of citizens in an emergency situation will decrease due to more accurate and perceived information to the public.

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II. Probabilities of interoperability barriers

According to the ISO 11354-1:2011 standard [10], interoperability barriers are located on three levels: conceptual (syntactic, semantic), technological (technical, architectural, and others), and organizational (see Fig. 1). The ISO 11354-2:2015 standard [11] proposes a maturity model for assessing enterprise interoperability.

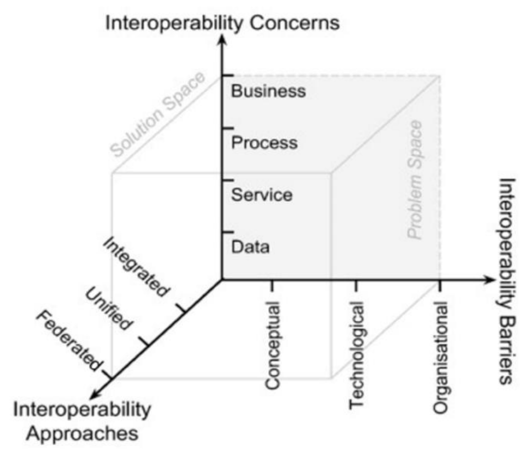

Figure 1. Conceptual area of interoperability according to ISO 11354-1:2011

An example of using the above standards when creating an interoperability lifecycle for networking between various organizations (forces and means) in an emergency situation is presented in [12].

To determine the probability of interoperability barriers, it is advisable to use the apparatus of stochastic Petri nets. For example, [13] shows the calculation of the probability of finding a token in a position. By developing this method in relation to interoperability barriers, it is possible to calculate the probability of barriers appearing at the borders of heterogeneous forces and means. Another way to identify barriers to interoperability may be an expert method based on the practical experience of specialists in compatibility and integration of information systems in the field of security in an emergency situation.

III. The Entropy Criterion for Evaluating the Interoperability of Messaging Systems in Early Warning of an Emergency

Using Hartley's formula, we write down the information entropy L (the amount of information in a message in bits):

$$L = M \log N \qquad (1)$$

where N is the dimension of the alphabet, M is the number of characters in the alphabet or characters in the message (log is the base 2 logarithm in this formula and further).

In the case of independent random events $x_i (i = 1...n)$ with probabilities of possible states p_i, the Hartley formula can be written using the Shannon formula, which makes it possible to calculate the average entropy of a message:

$$H(x) = -\sum_{i=1}^{n} p_i \log_2 p_i \qquad (2)$$

The following formula can be used to calculate the partial entropy characterizing the specific i-state:

$$H(x_i) = -p_i \log_2 p_i \qquad (3)$$

Here and further, interactions on three levels of interoperability (organizational, semantic, and technical) are presented to simplify calculations. As an example, we take a simplified message transmission cyclogram, where there are two systems (an early warning information system and a citizen's personal information system (smartphone, web browser, etc.). The option of integrating a citizen's personal information system into an early warning information system to minimize barriers to interoperability is not considered in this work.

For example, during the information analysis of the cyclogram of the transmission of an emergency message using a stochastic Petri net, a probability p=0.003 of the presence of a barrier at the semantic level of interoperability was found. This means that the message is technically transmitted, but the information, or rather it is washed away due to the semantic barrier of interoperability, is inaccurately perceived by the citizen, which in an emergency situation increases the risk of harm to health.

Calculate the initial entropy of the interaction according to formula (2).

$$H(initial) = -(0,003 \log_2 0,003 + 0,997 \log_2 0,997) \approx 0,029 \qquad (4)$$

Using a mechanism for overcoming barriers to semantic interoperability (standard EXDL protocols, mediators, web-service mediators, global ontology, etc.), the probability of a barrier at the semantic level reaches the value of p=0.0003.

In this case, the entropy after the activation of the mechanism for overcoming the barrier of semantic interoperability will be as follows:

$$H(bar\_sem) = -(0,0003 \log_2 0,0003 + 0,9997 \log_2 0,9997) \approx 0,004 \qquad (5)$$

The change in entropy can be written as:

$$\Delta H(bar\_sem) = H(initial) - H(bar\_sem) = 0,025 \qquad (6)$$

Thus, the use of a semantic mediator at the semantic level made it possible to significantly reduce the entropy of interaction during the exchange of messages, which means to increase the awareness of citizens in the context of early notification of an emergency situation.

IV. The Method of Entropy and Information Analysis of the Interoperability of Early Warning Systems

Developing an entropic approach in the field of emergency security [14] to interoperability barriers, let us consider the case of barriers appearing at all three levels.

1) barriers to interoperability in the exchange of messages:

R1 – barriers to the organizational level of interoperability;

R2 – barriers to the semantic level of interoperability;

R3 – barriers to the technical level of interoperability.

2) Probabilistic characteristics

P(R1) is the probability of organizational barriers when exchanging messages in the emergency early warning system;

P(R2) is the probability of semantic barriers when exchanging messages in the emergency early warning system;

P(R3) is the probability of technical barriers when exchanging messages in the emergency early warning system.

Upon the occurrence of the above events, the messaging system turns out to be partially or completely inoperable, since it does not perform the function of communicating information to citizens.

Then the probability of failure can be written using the probability of an accident from [14]:

$$P(fail) = 1 - \prod_{i=1}^{n} (1 - P(R_i)) \qquad (7)$$

where n=3 is the number of barriers by levels (to simplify the example, one interoperability barrier is given for each level of interoperability).

Based on the practical experience of the author and theoretical model studies (using the apparatus of stochastic Petri nets), we will identify the probabilities of the appearance of interoperability barriers at each of the three levels.

Based on practical experience, as a rule, the probability of barriers concerns the semantic level, because even with full interaction at the organizational and technical levels, the meaning of the result of the interaction may be perceived differently by the sender and recipient of the message in the emergency early warning system.

The probability of barriers at the organizational level:

P(R1) = 0,3.

The probability of barriers at the semantic level is lower, but exists because it is caused by different data formats and ontologies:

P(R2) = 0,6.

The probability of barriers at the technical level is minimal, but exists:

P(R3) = 0,1.

Then the probability of a failure in the messaging system will be calculated as follows:

$$P(fail) = 1- (1-0,3)(1-0.6)(1-0,1)=0,748 \qquad (8)$$

Under these conditions, there is a high risk of non-fulfillment of the objective function of informing citizens about an emergency situation.

As measures to counteract possible disruptions and reduce the risks of not accurately informing citizens, we will introduce additional mechanisms to overcome barriers to interoperability.

A method for determining the indicator of reducing barriers to interoperability using measures in EWS

Using graph theory and developing an approach based on numerical evaluation of the interoperability indicator [15], we propose the following methodology for calculating the indicator of reducing barriers to interoperability by levels (organizational, semantic, technical). Fig. 2 shows a simplified cyclogram (in the form of a graph) of the exchange of messages in an early warning system about an emergency (for example, of a natural nature – flood, earthquake, etc.), taking into account the architecture presented in [16].

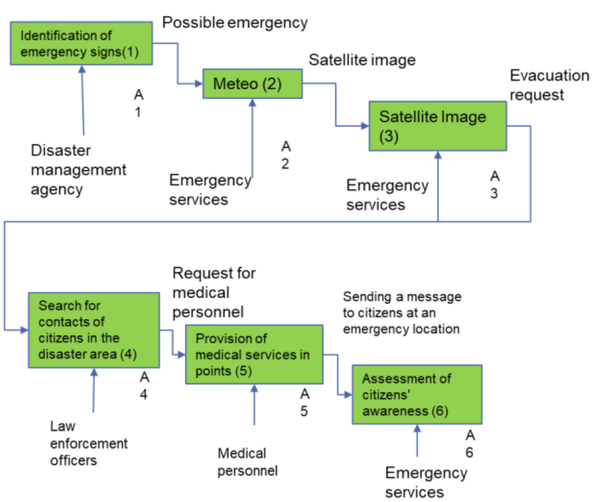

Figure 2. Simplified message exchange cyclogram in EMS

Let's formulate the cyclogram T and define the elements of heterogeneous systems (disaster agency, emergency services (rescuers, firefighters), law enforcement officers, medics) involved in preparing an emergency message.

Table I presents generalized names of information systems of various forces and means.

TABLE I. – INFORMATION SYSTEMS OF FORCES AND FACILITIES INVOLVED IN GENERATING EMERGENCY MESSAGES

Information system affiliation	**The sequence number in the cyclogram T for preparing and sending a message**
Disaster agency	1
Emergency services	2
Law enforcement officers	3
Medics	4
Emergency services	2

The order of operation of information systems in cyclogram T can be written as follows

$$T = (1,2,2,3,4,2) \qquad (9)$$

Creation of a matrix of the frequency of interaction of information systems C and a spin matrix of interoperability measures S.

For the procedure of actions when forming messages T = {1, 2, 2, 3, 4, 2} As part of the early warning, there are 15 pairs of forward-facing information systems., {(1-2), (1-2), (1-3), (1-4), (1-2), (2-2), (2-3), (2-4), (2-2), (2-3), (2-4), (2-2), (3-4), (3-2), (4-2)}.

To prepare matrix C, calculate the number of repetitions of pairs and write them into the corresponding cell of matrix C.

For example, the number of repetitions of pairs of systems 1 and 2 is 3. Thus, $C_{1,2}= 3$.

Then the matrix C will have the form:

$$C = \begin{bmatrix} 0 & 3 & 1 & 2 \\ 0 & 2 & 3 & 2 \\ 0 & 1 & 0 & 1 \\ 0 & 1 & 0 & 0 \end{bmatrix} \qquad (10)$$

For the S matrix, we will establish, according to Table II, the quality of information system interaction depending on the levels of interoperability and mechanisms, technologies and measures to ensure interoperability.

TABLE II. – INDICATORS FOR THE SPIN MATRIX S, DEPENDING ON THE LEVELS AND MECHANISMS, MEASURES TO ENSURE INTEROPERABILITY

The mechanism of ensuring/ the level of interoperability	**Indicators for the spin matrix S**
Technical level	
Gateway	-1
A single protocol	0
Standard protocol	1
Semantic level	
Converter for different formats and descriptions of data	-1
Mediator, composite web service	0
Global ontology, standard data formats	1
Organizational level	
Constant coordination and joint actions	-1
Temporary regulatory documents	0
General regulatory documents	1

The calculation of the matrices C and S will be carried out to evaluate the indicator of semantic-level activities (for organizational and technical calculations, the calculation is carried out similarly).

$$S = \begin{bmatrix} 1 & 1 & -1 & -1 \\ 1 & -1 & 0 & -1 \\ -1 & 1 & 1 & 0 \\ -1 & -1 & 0 & 0 \end{bmatrix} \quad (11)$$

Then the interoperability matrix M will be a multiplication of the elements of the matrices C and S.

$$M = \begin{bmatrix} 0 & 3 & -1 & -2 \\ 0 & -2 & 0 & -2 \\ 0 & 1 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{bmatrix} \quad (12)$$

The calculation of the indicator of interoperability measures by levels is carried out according to the formula:

$$O = \sum_{i=1}^{n} \sum_{j=1}^{n} m_{ij} \quad (13)$$

The metric for the semantic level will be O(R2) = -4

Then the data is normalized based on the range of each indicator [0...1] and eventually takes on a vector value for all three levels O=[0.4;0.5;0.1].

O(R1) = 0.4 – reducing the risk of barriers at the organizational level due to the appearance of requirements and their implementation in the early warning system (additional joint agreements, instructions, etc.);

O(R2) = 0.5 – reduction of the risk of barriers at the semantic level due to the appearance of requirements and their implementation in the early warning system (semantic mediators, global ontologies, thesauri, composite dynamic web services, etc.);

O(R3) =0.1 - reduction of the risk of barriers at the technical level due to the appearance of requirements and their implementation in the early warning system (gateways, unified technical protocols, etc.);

Then the calculation of the probabilities of barriers should be updated, taking into account the implemented mechanisms for ensuring interoperability by levels (see Table III).

TABLE III. – PROBABILITIES OF BARRIERS APPEARING BY LEVELS BEFORE AND AFTER THE USE OF INTEROPERABILITY TECHNOLOGIES

Probabilities of barriers to the implementation of interoperability mechanisms	**Probabilities of barriers following the implementation of mechanisms, technologies, and measures to ensure interoperability**
P(R1) = 0,3	P(R1)=0,3(1-0,4)=0,18
P(R2) = 0,6	P(R2)=0,6(1-0,5)=0,3
P(R3)= 0,1	P(R3)=0,1(1-0,1)=0,09

Thus, the entropy after the implementation of mechanisms, technologies and measures to ensure interoperability will look like:

$H(R1) = -(0,18\log_2 0,18 + 0,82\log_2 0,82) \approx 0,68$

$H(R2) = -(0,3\log_2 0,3 + 0,7\log_2 0,7) \approx 0,881$

$H(R3) = -(0,09\log_2 0,09 + 0,91\log_2 0,91) \approx 0,436$

Total (maximum) entropy:

$\sum_{j=1}^{3} H(R_j) = 0,68 + 0,881 + 0,436 = 1,997$

The relative increase in information, depending on the implemented measures to ensure interoperability by levels, can be written in the following form:

$$I(R_j) = H(R_j) / H_{\max} \quad (14)$$

Let's calculate the information significance (the contribution of each of the implemented mechanisms to overcome the barriers of interoperability for each of the levels) according to the formula 14:

I(R1) = 0,68/1,997=0,34
I(R2) = 0,881/1,997=0,441
I(R3) = 0,436/1,997=0,218

Thus, after the implementation of mechanisms, technologies and measures to ensure the probability of failure will be as follows:

P(fail) = 1-(1-0,18)(1-0,3)(1-0,09)=0,478 (15)

V. DISCUSSION

The use of mechanisms, technologies and measures has reduced the probability of a failure in the messaging system from 75% to 48%.

When ranking the implementation of measures to ensure interoperability (from an organizational and financial point of view), it is advisable to take into account the information significance for each of the barriers at the appropriate level of interoperability. In this example, measures to increase interoperability at the semantic level have a maximum value of 0.441.

Information significance allows us to direct financial resources to those activities, the implementation of which makes it possible to overcome significant barriers to interoperability, increasing the awareness of citizens in the emergency messaging system.

VI. Conclusion

The proposed combined entropy-information analysis applied to messaging systems for early notification of an emergency situation allows:

According to certain (for example, using Petri nets or based on expert, practical experience in the field of information system integration) probabilities of interoperability barriers by levels for a specific early warning system or for a prospective one, calculate the entropy and probability of failure during message exchange due to non-overcoming of interoperability barriers.

According to the indicators of measures calculated using graph theory aimed at overcoming barriers at certain levels of interoperability, the information significance for each pair is "the barrier of interoperability – an event to increase interoperability".

With a financial and time-based action plan, it is advisable to focus on more significant information-related measures to overcome barriers, since after their implementation, the likelihood of disruptions in the delivery and perception of emergency messages by citizens is sharply reduced.

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