Technical and economic assessment of design efficiency of information and measuring systems

V M Yurov¹, E N Eremin², Ya Zh Baisagov¹ and V V Arkhipov¹

¹Karaganda state industrial university, 30, Republic str., Temirtau 101400, Republic of Kazakhstan
²Omsk State Technical University, 11, Mira Ave., Omsk 644050, Russia

e-mail: weld_techn@mail.ru

Abstract. A thermodynamic approach to the analysis of information-measuring systems (IMS) is developed in the work. Expressions for efficiency of IMS are obtained. The connection between the amount of processor memory and the amount of incoming information and the accuracy of the IMS is obtained. It is shown that the probability of information loss in IMS decreases with the increase in the amount of information from the object. Using the analogy method, economic aspects of IMS design are considered. The innate ability of IMS and Moore's law are considered. The proposed approach and the resulting formulas will be useful in the design of new IMS.

1. Introduction
Information and measuring systems (IMS) have become an indispensable attribute of modern technological processes and industries, modern communication systems, transport and various communications, navigation systems and space stations and many other [1–3]. The rapid development of microelectronics, nanoelectronics and devices based on them has given rise to the urgent need to constantly update the IMS on a new element base and new physical principles that meet modern requirements of accuracy of measurement processes [4–6]. In this connection, problems arose in the design of complex IMS, requiring the use of modern mathematical methods, computer modeling and non-trivial circuitry solutions [7–9]. To the purely academic aspect of the above-mentioned problems, economic requirements are also being added: not too much cost of the design work of the IMS; Not too high cost of technology for their manufacture. In this connection, there arises the need to evaluate the efficiency of the design of IMS both in terms of the technical and economic feasibility [10]. The fundamentals of the thermodynamics of information processes were laid by L. Brillouin [11] and continued by P.P. Poplavsky [12]. In our paper [13], on which we shall rely on in the further presentation, IMS are considered from the point of view of nonequilibrium statistical thermodynamics. For small systems, nonequilibrium thermodynamics in the context of information theory was applied in [14].

2. Response function of IMS
The table 1 presents an analogy between thermodynamics and IMS parameters [13].
Every measurement process is connected with the interaction of certain objects (or field and objects) and every process of interaction is accompanied by dissipative processes leading to the loss of some information during the measurement.

### Table 1. Thermodynamics and IMS

| Thermodynamics | IMS | Thermodynamics | IMS |
|----------------|-----|----------------|-----|
| Free energy, work $A$ | Memory capacity $W$ | Production of entropy $\sigma$ | Production of information $\sigma$ |
| Amount of substance $\nu$ | Number of sensors (communication channels) $n$ | Coefficient of efficiency $\eta$ | Efficiency $\eta$ |
| Entropy $S$ | Amount of information $I$ | | |
| Temperature $T(t)$ | Precision $\Delta$ | Internal energy $U$ | Energy intensity $E$ |

The most important parameter of IMS (and for any system) is its efficiency $\eta$. In thermodynamics, it corresponds to the efficiency of a thermal machine:

$$\eta = 1 - \frac{T_h}{T_c},$$

(1)

where $T_h$ and $T_c$ are the temperatures of the hot and cold sources respectively. For IMS, equation (1) will look like this:

$$\eta = 1 - \frac{\Delta_{\text{in}}}{\Delta_{\text{out}}},$$

(2)

where, according to the Table 1, $\Delta_{\text{in}}$ and $\Delta_{\text{out}}$ are input and output accuracies of IMS respectively. The first is determined by the sensitivity of the sensor, and the second is determined by the sensitivity of the sensor and the parameters of the unifying converter. It follows from the formula (2) that the efficiency of IMS is largely determined by its structure.

If, as the response function $\Phi$ [13], to take the efficiency of the IMS $\eta$, then we get:

$$\eta = \frac{cT}{G^0} \frac{A}{m},$$

(3)

where $A$ is work (energy); $T$ is the temperature; $G^0$ is the Gibbs potential; $\nu$ is the amount of the substance; $k$ is the Boltzmann constant; $C$ is a constant.

Using Table 1, we obtain the following expression for the efficiency of IMS:

$$\eta = \frac{C_1 m W \Delta}{W - \Delta I},$$

(4)

Here $C_1$ is a constant. The limit value $\eta$ is 1 and from formula (4) it follows:

$$W = \frac{I \Delta}{1 - C_1 \mu \Delta}.$$

(5)

The formula (5) defines a rule of a choice of the processor at designing IMS. It follows that the amount of processor memory is determined, basically, by the product of the amount of information coming from the object under investigation, and the accuracy of the IMS. The latter, as a rule, is inversely proportional to the signal-to-noise ratio and tends to the optimum value when the noise level decreases. Note that the correct choice of the processor determines to a greater extent the cost of the IMS being developed. The choice of a processor with a large memory is not always justified.

Let's consider one more example. The probability of dissipative processes in a thermodynamic system is in most cases determined by the Arrhenius law:

$$p = \nu \exp(-Q/kT),$$

(6)
where $\tau$ is the relaxation time; $Q$ is the activation energy.

For IMS, $\tau$ is the response time of the system (IMS speed), and $Q=A-W$. Taking (5) into account, we get:

$$p = \frac{1}{\tau} \exp \left( - \frac{a}{1-C_1 n \Delta} \right),$$

where $\alpha$ is the coefficient of the dimension.

It follows from formula (7) that the loss of information in the IMS is less, the larger the measurement time $\tau$ and the greater the amount of information $I$ from the object. It is necessary to make the following remark. As follows from (7), the deceleration of the transient process (i.e., with increasing $\tau$), the probability of dissipative processes decreases. However, in practice, such a path is unacceptable and, conversely, modern and future IMS should have a high speed to transmit a large amount of information. This is achieved by moving from a scalar representation to a vector representation (digital IMS).

Asymptotically the best (in the sense of the product $\Delta S \cdot \tau$) is Shannon redundant coding, using a bit representation with additional (check) bits. Here, increasing the dimensionality of the vector space allows to detect and correct errors of some multiplicity, which reduces the requirements for the probability of distortion (and the signal-to-noise ratio) in single bit. At the same time, $\Delta S \sim \ln(1/\Delta)$ is attained with a simultaneous increase in time only by a factor of $\ln(1/\Delta)$ [12].

The probability of loss of information in the IMS decreases with increasing amount of information from the object (the formula (7)). Such increasing is possible due to the increase in the sensitivity of the sensor, the creation of a new type of sensors, new methods of measurement, the improvement of the systems for receiving and processing information. The key importance is the development of new types of sensors and receiving and processing systems based on nanotechnology information [4–6].

3. Economic aspects of IMS designing

Table 2 presents an analogy between IMS and economic indicators [13].

| IMS                  | Microeconomics          | IMS                  | Microeconomics          |
|----------------------|-------------------------|----------------------|-------------------------|
| Memory capacity $W$  | Basic resource $M$      | Production of        | Dissipation of          |
| Number of sensors    | Stock of resource $N$   | information $\sigma$ | capital $\sigma$       |
| The amount of        | Related capital $F$     | Efficiency of IMS $\eta$ | Profitability of the system |
| information $I$      |                         | Energy intensity of  | $P$, Total capital $U=M+F$ |
| Accuracy of IMS $\Delta$ | Price $c(t)$       | IMS $E$              |                         |

According to the formula (4) and table 2, for the economic efficiency of designing and manufacturing of IMS, we have the following expression:

$$\eta = C_1 N \cdot M \cdot c(t) \over M - F c(t).$$

Formula (8) shows that the efficiency of design and manufacturing of IMS is determined, basically, by the underlying resource $M$ and its stock $N$, as well as its price with $c(t)$. This practically corresponds to the standard approach in the economics of enterprises of the electronic industry.

With the maximum efficiency $\eta=1$, the value (cost) of the design and manufacture of IMS will be determined by the ratio:

$$c(t) = \beta \frac{M}{F + C_1 N M}.$$  


Here β is the coefficient of dimension. The associated capital F is defined as all the money invested by the firm or investor in the production of the products they are going to sell. However, in modern pricing, there is a process of reducing the share of "simple", material resources with a parallel increase in the share of various compensation - for software, project development, financial markets, trademarks, etc. There are changes in the content and arrangement of accents in the components of the price. So, the main purpose of advertising is not to inform about the properties of the goods, but to ensure attention (distribution of image advertising, elements of provocation, shocking). All this has a significant impact on the change in the nature of competitive relations.

We now introduce into the formula (9) the main parameter of the IMS-the amount of memory W, which is an analog of the basic resource M:

\[ c(t) = \gamma \frac{W}{F + C_tNM}. \]  

(10)

Here γ is the coefficient of dimension. The formula (10) shows the increase in the cost of IMS with an increase in its memory capacity and a decrease in the cost of IMS with an increase in investment volume F.

4. «Innate» abilities IMS and moore's law

Expanding the exponent in the denominator Φ [13] in a series and neglecting small terms, it is not difficult to obtain in the linear approximation, setting Φ equal to the IMS efficiency η:

\[ \eta_0 = \varepsilon \ln W, \]  

(11)

where \( \varepsilon \) is the parameter of the model; W characterizes the amount of IMS resources, which is proportional to the amount of IMS memory, sensitivity of sensors and a number of other parameters, which will be discussed below. At the initial moment of the formation of the system \( W = \varepsilon \) so that

\[ \eta_0 = \varepsilon \ln \varepsilon. \]  

(12)

The resulting expression is an innate ability of IMS. Now let’s turn to expression (11) and make a few remarks. If the innate ability of IMS (~\( \varepsilon \)) is small, then the increase in W resources due to the modernization of IMS will slightly change its efficiency. This is due to the logarithmic dependence of η on W. For example, an increase in IMS resources by a factor of 100 leads to a change in η only by a factor of ~ 5. Such IMS should be either substantially reconstructed or eliminated. The obtained equation allows to determine experimentally the innate ability of IMS. If the ratio of the output signal / input signal is taken as the efficiency of the IMS, then it is possible to determine \( \eta_1, \eta_2, \ldots \) from the given \( W_1, W_2, \ldots \) and, thus, the inherent ability of the IMS. Thus, it is possible to conduct an analysis of IMS from the point of their technical solvency and economic prospects.

Efficiency of IMS is defined as the ratio of the time of its development t to the period of its existence T, then from (11) for the time dependence of W we get:

\[ W = W_0 \exp\left( \frac{t}{\varepsilon T} \right), \]  

(13)

where \( W_0 = \varepsilon \ln \varepsilon. \)

In the 1960s, at the very beginning of the information revolution, Gordon Moore, later one of the founders of Intel Corporation, drew attention to an interesting pattern in the development of computers. He noticed that the amount of computer memory is doubling about every two years. This pattern became a kind of empirical rule in the computer industry, and soon it turned out that not only memory, but every indicator of computer performance - chip size, processor speed, etc. - obeys this rule [15]. Moore's law is an empirical observation originally made by Gordon Moore, according to which (in the
modern formulation) the number of transistors placed on an integrated circuit chip doubles every 24 months.

In addition to predicting the exponential growth of the density of the transistors, Moore made another important and seemingly paradoxical conclusion. Reducing the size of transistors should inevitably lead to the fact that integrated circuits based on them will be cheaper, more powerful and more affordable. From this it followed that the electronic industry as a whole would change.

The main characteristic of IMS is the amount of processor memory that is proportional to its resources, so equation (13) is a mathematical expression of Moore's law. However, unlike the usual interpretations of Moore's law, our equation contains an innate ability, which is an essential fact. The fact is that an exponential dependence of the type (13) is characteristic for many processes in nature and society, far from microelectronics, but the innate ability of the system is always present.

In 2007, Moore stated that the law would obviously soon cease to operate because of the atomic nature of the substance and the speed limit of light. One of the physical limitations on the miniaturization of electronic circuits is also the Landauer principle, according to which logic circuits that are not reversible must produce heat in an amount proportional to the amount of erasable (irretrievably lost) data. The possibilities for removing heat are physically limited [16].

The boundedness of Moore's law follows naturally from (13). At \( t = T \), the exponential dependence becomes \( W = \text{const} \). Graphically it looks like it is shown in Fig. 1.

![Figure 1. The time dependence of the memory capacity of the IMS processor](image)

It should be noted that Moore's law (in the interpretation of Gordon Moore) is not being fulfilled with such precision to call it a law or even an empirical regularity. It is possible that the hype surrounding Moore's Law is Intel's clever marketing move. Nevertheless, Moore's law, like the similar "exponential laws", reflects some general trends in the development of science, technology, human society, etc.

5. Forecast resources of IMS

Now it is generally accepted that information and information-measuring systems belong to the class of communication systems.

The generalized concept of the "resource" of the communication system was first introduced by L.I. Rozonoer [17]. In this work, the exchange and distribution of the resource in the system were considered as occurring according to laws analogous to the law of energy distribution in a closed system of mechanical particles. Later, the notion of the "resource" of the communication system began to be associated with the presence of some set of communications connecting the elements of the system, and with the characteristics of these communications.

After the linearization of the expression obtained by us, the response function \( \Phi \) of the system has the form:
\[ \Phi = \beta \frac{E}{\Delta G^0} \cdot \bar{N}, \]  
(14)

where \( E \) is the "capacity" of the communication channel in the system; \( \bar{N} \) is the average number of channels in the system; \( \Delta G^0 \) is the Gibbs energy of a thermostat (external environment); \( \beta \) is some constant of the theory, the magnitude of which is calculated for each particular system according to the procedure set forth in [13].

For ideal processes \( \Delta G^0 = \Delta F \) and, taking (14) into account, we obtain:

\[ W_i = \frac{\beta E \bar{N}}{\Phi}. \]  
(15)

If the "volume" of IMS is denoted by \( V \), then the total resources of the system will be equal to

\[ W = \frac{\beta E \bar{N}}{\Phi} \cdot V. \]  
(16)

It was intuitively expected that IMS resources would increase with the increase in the number of communication channels and the channel capacity of the system.

For the IMS response function from (16) we have:

\[ \Phi = \beta \varepsilon \ln \varepsilon \cdot E \cdot \bar{N} \cdot V \cdot \exp \left( - \frac{t}{\varepsilon T} \right). \]  
(17)

Thus, the IMS response function contains its main parameters (here the "volume" of the system can be taken to be equal to the amount of processor memory) and the inherent ability of IMS.

In the simplest case, as a response function, we can take the ratio of the output signal to the input signal and use the autocorrelation functions of the processes at the input and output of the system.

We note that most of the parameters in (17) can be determined experimentally, which has an important applied value.

6. Conclusions

Currently, in many countries, particularly in the United States, the cost of works on the automation of IMS design is more than 1/3 of the cost of developing large projects, which indicates the complexity, cost and urgency of automated design of IMS.

The thermodynamic approach and formulas obtained in the present paper can significantly reduce the cost of automation design work for IMS.

References

[1] Badiru A 2005 Handbook of Industrial and Systems Engineering (CRC Press, New York)
[2] Morris A S and Langari R 2012 Measurement and Instrumentation: Theory and Application (Elsevier/AP)
[3] Webster J G 2014 Measurement, Instrumentation, and Sensors Handbook (CRC Press, Taylor & Francis Group)
[4] Kaul A B et al. 2012 Microelectronics to Nanoelectronics: Materials, Devices & Manufacturability (CRC Press)
[5] Ismail R, Ahmadi M T and Anwar S 2012 Advanced Nanoelectronics (CRC Press)
[6] Khanna V K 2016 Integrated Nanoelectronics. Nanoscale CMOS, Post-CMOS and Allied Nanotechnologies (Springer India)
[7] Meyers R A et al. 2009 Encyclopedia of Complexity and Systems Science (Springer Science + Business Media)
[8] Duffy V G et al. 2008 Handbook of Digital Human Modeling. Research for Applied Ergonomics and Human Factors Engineering (CRC Press)
[9] Demin A and Dmitrieva S 2016 Applying math modelling methods for forecasting the engineering system states (ITMO University, St-Pb.)
[10] Kanaracus C 2008 *Gartner: global IT spending growth stable* (InfoWorld)
[11] Brillouin L 1959 *La science et la theorie de information* (Masson)
[12] Poplavskiy R P 1981 *Thermodynamics of information processes* (Science, Moscow)
[13] Yurov V M, Kolesnikov V A, Ismailov Zh T and Baisagov Ya Zh 2013 *Thermodynamics of information-measuring systems* (Karaganda)
[14] Sagawa T 2013 *Thermodynamics of Information Processing in Small Systems* (Springer, Kyoto, Japan)
[15] Pakhomov S A 2003 *Computer press* no 1 pp 16–22
[16] Dmitriyev A S 2012 *Thermal processes in nanostructures* (Fizmatlit, Moscow)
[17] Rozonoer L I 1973 *Automation and telemechanics* no 5 pp 115–133; no 6 pp 65–80; no 8 pp 82–104