Evaluation of the effectiveness of geographic information systems adaptation to destabilizing factors

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Abstract. Formulation of the problem. Geographic information systems are becoming an integral part of many automated control systems. The quality of the made management decision depends on their ability to work. At the same time, geoinformation systems operate in conditions of destabilizing factors reducing the quality of services provided. The existing indicators of the efficiency of the functioning of geoinformation systems do not allow to quickly and comprehensively assess the ability of geoinformation systems to adapt to the action of destabilizing factors, and therefore, to understand how the system is able to satisfy the requirements of its users. Purpose. To propose performance indicators that allow assessing the "usefulness" of geoinformation systems for the consumer in conditions of destabilizing factors. Results. Non-stochastic indicators of efficiency have been developed: integral and differential, a theorem has been formulated and proved about the independence of events in solving tasks for any directed graph, examples are given and conditions for the expediency of using the proposed indicators for the evaluating of the effectiveness of geographic information systems adaptation are given to the destabilizing factors action. Practical significance. The proposed indicators can be used to synthesize the structure and functions of geographic information systems in real time.

1. Introduction
Geographic information systems (GIS) are used in almost all existing automated control systems: from production management [1] and environmental situation [2] to determining the trajectories of air objects [3] and investigating crimes [4]. Therefore, the effectiveness of GIS should be assessed, among other things, when choosing the best option for the functioning and development of the system [5].

On the other hand, GIS is an information system that operates with spatial data [6].

All GIS in the course of their functioning are subject to the influence of destabilizing factors (DF). Such factors can be hardware and software failures, disconnections of communication channels, actions of intruders, etc. However, despite the presence of DFs, some GIS, especially those listed above, must fulfill the tasks assigned to them, even during their degradation. One of the options for giving GIS the ability to perform the assigned tasks in the process of GIS degradation is to endow the GIS with a mechanism of adaptation to destabilizing factors.
2. **Existing performance indicators**

The effectiveness of adaptation is usually assessed by how close the current value of the optimized performance indicator is to the required value, and by the speed of adaptation.

Various values can be used as optimized quality indicators, for example, indicators of structure survivability [8], vectors of average recovery time, etc. [9]. But such indicators have two significant disadvantages:

1. They indicate little to the consumer about the suitability of GIS for solving his problems;
2. To calculate many of them, a large number of calculations are required, and this requires additional time and computational resources from the system, which significantly affects the speed of adaptation.

There are given possible indicators of quality and methods of their calculation in [10], coefficients of potential survivability, coefficients of employment, etc in work [9]. The source [11] provides a comprehensive indicator of the effectiveness of information security management. Such indicators allow, to some extent, to take into account the usefulness of GIS for the user of GIS services and the GIS degradation effect, but the probabilistic description of the DF is used to calculate the indicators. It is extremely problematic to obtain such a description of the DF, mainly for two reasons: 1) it is difficult to get the necessary statistics, 2) in general form, the DF is not a stochastic environment for GIS, because has an aggressive purposeful environment [12].

The time for solving the target tasks \( tT \) and the GIS performance \( \Omega \) are free from the above disadvantages. Of the two named quality indicators for assessing the effectiveness of adaptation, the most preferable is performance \( \Omega \) for the following reasons:

1. The solving time the target tasks \( tr \), in general, may depend on quantities not controlled by the GIS control system, for example, on the user’s reaction speed, on the volume of incoming data, etc. The above is true primarily for interactive systems. The GIS performance mainly depends on the controlled quantities: on the performance of the GIS elements, the scheme of their connection, the temperature regimes of the GIS operation, etc.

2. The tasks performed in GIS, in addition to the reserve of execution time \( \Delta t^k \), in general, have a reserve in terms of the calculation accuracy \( \Delta \delta^k \). By reducing the accuracy of the calculation, we reduce the requirements for the GIS performance [13].

3. As a rule, the time of solving the target problem \( tr \) is not separated into the times of computation, data transfer, recording to a medium, display, etc. a is calculated for the problem as a whole. For performance, decomposition is a common practice.

Accounting for the influence of DF on the operation of GIS is based on the DF model described in [12]. One of the main ideas of the model is that for the end user of GIS services, the availability and performance of the service is important. The consumer does not care why the service has lost the expected performance, and how exactly the service was disabled. That is why there is accounted the consequences of DF, that is, deformation / degradation of the GIS structure \( \Psi_S \) and / or GIS functions \( \Psi_F \) leading to a loss of performance \( \Delta \Omega \) in the model.

\[
\Psi = \Psi_S \cup \Psi_F \rightarrow \Delta \Omega
\]

Ensuring integrity and confidentiality can be reduced to the required performance of the corresponding GIS components.

3. **Tasks representation in a geographic information system**

All consumer tasks in the model are represented in the form of various performance types \( \Omega \) required to solve the problems. So in any GIS there must be \( C, L, Sp, Tr \) - sets of computers, communication channels, memory, input / output devices. These elements have corresponding time-varying performances \( \Omega_C(t), \Omega_L(t), \Omega_{Tr}(t), \Omega_{Sp}(t) \). Tasks in GIS are represented as follows:
Information-control dependences of tasks from each other, as a rule, are represented in the form of a directed graph \( G \), the nodes of which denote tasks, and the arcs denote the directions of information transfer and control actions. However, the events that the \( k \)-th problem will be solved are independent for any directed graph. The assertion formed and proved as a theorem about the independence of the named events, it is possible to significantly simplify the formation of GIS performance. Let's introduce some definitions.

Event is the solution of the \( k \)-th task in the GIS.

Theorem. Let a directed graph \( G \) be given, reflecting the dependencies between tasks. Then the events involved in solving problems are independent for any directed graph.

Supposition. The considered technical systems are dynamic [14], therefore, the situation at the current time does not affect the situation at previous times (the situation at subsequent times does not affect the situation at the current times).

Corroboration. Let's take an arbitrary graph segment from two nodes. The following options are possible (figure 1):

![Diagram](image)  
**Figure 1.** Possible options for task interconnections.

1. The segment is not interconnected. In this case, the independence of events from each other is obvious.
2. Task \( A \) precedes task \( B \).

   In general, the probability of solving tasks \( A \) and \( B \) is
   \[
P(AB) = P(A)P(B/A) = P(B)P(A/B)
   \]
   Because of the supposition, the solution of task \( A \) does not depend in any way on the solution of task \( B \), therefore, \( P(A/B) = P(A) \), which means
   \[
P(A)P(B/A) = P(B)P(A).
   \]
   Assuming that \( P(A) \neq 0 \), we divide both sides of the equality by \( P(A) \), we get
   \[
P(B/A) = P(B),
   \]
   that is, the occurrence of the event "solving task \( B \)" does not depend on the occurrence of the event "solving task \( A \)", which was required to prove.

3. Task \( B \) precedes task \( A \). The case is similar to case 2.
4. Task \( B \) is interconnected with task \( A \). Since the tasks are separated on the graph into two interrelated ones, it can be argued that the tasks are performed in turn. Therefore, case 4 can be considered as cases 2 and 3, alternating each other.

   The case with two nodes in a segment can be extended quite simply to an arbitrary number of nodes. Since the segment was taken arbitrary, the theorem can be considered proven.

We will take into account the independence of events in the formation of indicators of GIS efficiency.
3.1 Integral and differential performance indicators

Each set of tasks of the same type has its own performance requirements. This leads to the fact that many tasks give rise to many adaptation goals, consisting in achieving and maintaining different performance values. This is inconvenient when implementing controls. We transform the performance so that the adaptation goal is the same for all the tasks performed, for this we introduce the efficiency indicator \( P \) showing which part of the tasks is solved in a given time \( T \).

\[
P = \frac{K}{K^*}
\]

where \( K \) is the number of tasks solved in the GIS, \( K^* \) is the number of tasks assigned to.

Let us take into account that performance \( \Omega \) is the number of problems \( K \) solved per unit time \( t \), i.e.

\[
K = \Omega(t) t,
\]

and write down the indicator general form

\[
P(t) = \frac{\int_{0}^{t} \Omega(z) dz}{\int_{0}^{t} \Omega^*(z) dz}
\]

where \( \Omega \) – performance used by the solved tasks (current performance), \( \Omega^* \) is the performance required to solve the tasks (required performance), \( t \) is the current time, \( T \) is the specified time for solving the tasks assigned to the GIS.

The introduced indicator has the following main properties:
1. \( P(t) \) – monotone non-decreasing function;
2. \( P(t) \in [0; 1] \), because of \( 0 \leq K \leq K^* \);
3. \( P(t) = 0 \).

The current performance in a real system is usually estimated through the system load, and is measured over fixed time intervals \( \Delta t \). This makes it possible to go from integrals to sums. Note that although the size of the interval is related to the number of intervals, it is the size of the interval that is more important.

\[
P(\Delta t) = \frac{\sum \Omega(\Delta t) \Delta t}{\sum \Omega^*(\Delta t) \Delta t} = \frac{\Delta t \sum \Omega(\Delta t)}{\Delta t \sum \Omega^*(\Delta t)}
\]

Reducing by \( \Delta t \), we get a new indicator characterizing the "performance reserve” available in the GIS.

\[
\mu = \frac{\sum \Omega(\Delta t)}{\sum \Omega^*(\Delta t)}
\]

If \( \mu < 1 \), there is a performance deficit, and as a result, the risk of not completing the tasks of the entire GIS in a given time. If \( \mu = 1 \), the process of functioning is proceeding normally. If \( \mu > 1 \), GIS has a performance reserve.

Let’s give examples of the application of the proposed indicators

3.2 Application of the proposed performance indicators

Suppose, with the help of GIS, the task of automated protection of the perimeter controlled by eight cameras is solving, with the following initial data:

- the period of the system’s existence is \( T = 24 \) hours;
- camera requesting period \( \Delta t = 0.02 \) hours, therefore, GIS for the period of its existence (24 hours) must complete \( 24 / 0.02 = 1200 \) requests;
- 1.6 MB is transferred from each camera for each request;
- to process each camera image, you need to perform 164 operations.

Accordingly, the required performance will be as follows:

\[
\Omega_C^* = 8 \frac{164}{0.02} = 65600 \text{ operations/hour}, \quad \Omega_L^* = 8 \frac{1.6}{0.02} = 640 \text{ Mb/hour}.
\]

Similarly \( \Omega_{SP}^*, \Omega_{TR}^* \).
The schedule for the regular operation of the GIS looks as shown in figure 2 (P1). When conducting DF, as a result of which it will be impossible to receive signals from one of the cameras, P2 will take the form shown in figure 2. Please note that for the calculation it does not matter how exactly during the DF process the camera was disabled (the camera destroyed, damaged communication channels, damaged port to which the camera is connected, etc.).

If during operation, on average, 30% of information from cameras is lost, for example, as a result of electromagnetic interference, then P3 will look like this (figure 2).

![Figure 2. GIS functioning efficiency.](image)

If $\Omega_\mathcal{C} = 135600$ operations/hour, $\Omega_\mathcal{L} = 530$ Mb/hour, then $\mu_\mathcal{C} = 2.06$, $\mu_\mathcal{L} = 0.83$, that means there is a reserve in the performance of calculators and a deficit in the performance of communication channels, therefore, additional computational tasks can be assigned to the resource, initiating small traffic.

Let us demonstrate how the proposed indicators can be used to assess the GIS adaptation effectiveness to DF.

Consider, for example, the adaptation of calculators and / or GIS communication channels. In this case, the required performance $\Omega^*(t)$ can be set simply by specifying the value $\Omega^*$ at each time $t$. The current performance $\Omega$ depends on the value of many quantities. For example, from the GIS structure. If calculators or communication channels are connected in parallel, then the overall performance of the connection $\Omega_i$ does not exceed the sum of the performance of individual elements of the connection $\omega_j$. If the elements are connected in series (multistage task solving), then the overall performance of the connection $\Omega_i$ does not exceed the minimum performance of the element $\omega_j$.

In general, the performance of an individual element depends on the current load of the element, its temperature regime, etc. changes in time $\omega_j(t)$. Further, for brevity, we will write $\omega_j$, assuming that it changes in time.

$$
\begin{cases}
\Omega_i \leq \sum_{j=1}^{M} \omega_j & \text{– parallel connection} \\
\Omega_i \leq \min(\omega_j) & \text{– serial connection (multistage processing)}
\end{cases}
$$

(1)

In the process of adaptation, GIS can change its structure (serial / parallel connections) and / or functions (summation and / or selection of minimum performance). The adaptation consists in the selection of such a GIS $S$ structure, which will have the required current performance $\Omega$. Based on the formulated laws (1), the most effective way is the parallel union of elements. However, each element has its own capabilities for the formation of links $\nu_j$: for servers, these are, in general, from two to four directly formed links. In this case, the structure, as a rule, has accompanying requirements, for
example, to maximize survivability $D_{ev}$ [15]. Additionally, some other limits may be imposed \{\nu_{limit}\}. Let's write what was said in the form of a functional.

\[
\Omega = f(S, \omega, \Omega, D_{ev}, \nu, \{\nu_{limit}\})
\]

(2)

The search for extremals and adaptation algorithms is beyond the scope of this article, so we will focus only on the features of using the indicators proposed in the article.

If the differential observation algorithm [14] of the measured values is implemented, then to assess the effectiveness of the GIS adaptation it is necessary to use $\mu$.

\[
\frac{\int_0^T f(S, \omega, \Omega, D_{ev}, \nu, \{\nu_{limit}\}) dt}{\int_0^T \Omega dt} = \mu
\]

In this case, it is possible to quickly correct the "gaps" in performance, but it is impossible to consider the operation of the system "as a whole", the ability of the system to switch the resources available to it from one task to another. If there is some reserve in time for solving the problem, then when applied $\mu$, this reserve cannot be used. Obviously, this indicator makes sense to use in real-time systems.

If an integral algorithm for observing the behavior of the system is implemented, then to assess the effectiveness of adaptation, it is advisable to use $P$.

\[
\frac{\int_0^T f(S, \omega, \Omega, D_{ev}, \nu, \{\nu_{limit}\}) dt}{\int_0^T \Omega dt} = P
\]

The advantages and disadvantages of using $P$ as an optimized indicator are completely opposite $\mu$. In this case, the main advantage is the ability to use reserves in terms of task execution time. The disadvantage is that when the system is actively influenced by destabilizing factors (a large number of impacts per $\Delta \Omega$), the system will not have time to "collect" information about the current available capacities and, therefore, will not be able to adequately respond to the impact of DF.

From the standpoint of efficiency theory, the introduced indicators have the following features:

– the main purpose of the proposed indicators is to display how the system is suitable for solving consumer problems. If the performance is not less than the required one $\Omega \geq \Omega^*$, then the system is suitable for use;

– the proposed indicators make requirements for the required performance to be provided in the required time frame, therefore, through the proposed indicators, the speed of adaptation can also be assessed;

– the resources necessary for the GIS to create the required performance are the quantities on which the performance depends (2), which means that the proposed indicators $P$ and $\mu$ also estimate the resources necessary for adapting the GIS.

4. Conclusion

Thus, the article presents indicators for evaluating the efficiency of GIS adaptation to DFs $P$ and $\mu$, the main features of which are as follows:

1. Customer focus. The proposed indicators allow us to assess to what extent the adaptation process will satisfy the consumer;

2. The indicators are not stochastic, and can be used to evaluate systems operating in non-deterministic non-stochastic environments;

3. The indicators are used to implement differential and integral algorithms for monitoring GIS, which makes it possible to evaluate the effectiveness of GIS adaptation, both in real time and at specified intervals of operation;

4. The entered indicators are integral, allowing to evaluate the efficiency of GIS from the standpoint of suitability, efficiency and resource intensity.
The above indicators can be used in the technical implementation of systems built on the principles pointed in [16-18].

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