Vulnerability of multilayer network systems to system-wide disruptions*

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Abstract

Based on structural and flow models of multilayer network systems (MLNSs), we determine the main structural and functional importance indicators of separate layers in intersystem interactions. These indicators are used to develop an effective strategy for system-wide targeted attacks on an MLNS. We analyze the effects of targeted attacks of different scales, the consequences of nontargeted disruptions for network systems (NSs), and their protection against and sensitivity to various negative influences. The advantages of the flow-based approach over the structural approach for assessing the vulnerability of NSs and MLNSs to heterogeneous internal and external negative impacts are demonstrated through an analysis of Ukraine's general transport system operation during the COVID-19 pandemic and the russian-ukrainian war.

Keywords

complex network, intersystem interactions, multilayer network system, flow model, system-wide attack, nontargeted disruption, critical infrastructure

1. Introduction

Any real system can be subject to various negative influences. In [1], the main types of such influences on complex network systems and processes of intersystem interactions were analyzed. First, targeted attacks and nontargeted disruptions of complex systems were distinguished, which can be internal or external to the NS; have a local, group or system-wide nature; and be aimed at damaging both the structure and the operation process of the NS and MLNS. In article [2], strategies for protecting multilayer systems from sequential attacks on their most important elements in terms of certain indicators were proposed, which were determined on the basis of structural and flow models of these systems, and in article [3], scenarios of simultaneous group attacks on the most important structural and functional components of such formations were proposed. Histories include many examples in which local disruptions of real NS and MLNS developed into group ones and group damage into systemic ones (e.g., the transition of epidemics into pandemics [4], local military conflicts into world wars [5], the development of marginal extremist views into nationwide ideologies [6], and the spread of agricultural pests and invasion processes [7, 8]). System-wide negative impacts are actions that affect a system in which all its elements are directly damaged or indirectly injured to one degree or another. Since the number of such elements can be quite large, attempts to carry out system-wide disruption are often made through successive group attacks [3], such as missile strikes on Ukrainian oil depots in the spring and summer of 2022, which led to a fuel shortage in the country, or attacks on energy infrastructure facilities in 2022–2026, which resulted in the introduction of electricity outage schedules for almost all its consumers. In the theory of complex networks, strategies for protecting against system-wide attacks and nontargeted damage to NS and MLNS have received relatively little attention until recently, and only the COVID-19 pandemic and the impact of the russian-

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ukrainian war on the world community have shown that such damage is quite real and that humanity as a whole is unprepared to counteract its spread and overcome its consequences [9, 10].

Currently, the main focus is on the development of strategies for protecting the structure of complex network and multilayer network systems from targeted attacks of various types [11, 12]. Of course, damage to the structure negatively affects the functioning of the NS and MLNS, but this process can be destabilized and even stopped even with an unaffected structure [13]. In [1-3], a flow-based approach was proposed to analyze the vulnerability of such formations, which is based on the study of the movement of flows through the network during the action of negative influences of various origins. The purpose of this article is to perform a comparative analysis of structural and flow-based approaches to study the consequences of targeted attacks and nontargeted disruption of MLNS using the example of the general transport system (GTS) of Ukraine during the spread of the COVID-19 pandemic and the russian-ukrainian war.

2. Models of multilayer network systems

In articles [2, 3], it was shown how, on the basis of the structural and flow models of a multilayer network system, it is possible to determine the indicators of the importance of its elements and subsystems, elaborate effective scenarios of targeted attacks on the structure and operation process of a multilayer system using these indicators, and assess the consequences of such attacks. We apply these models to determine the importance indicators of separate layers of the MLNS and elaborate effective scenarios of targeted attacks on the process of intersystem interactions in general.

The structural model of intersystem interactions is described by multilayer networks (MLNs) and represented in the form [14]

$$G^M = \left(\bigcup_{m=1}^{M} G_m, \bigcup_{\substack{m,k=1 \\ m \neq k}}^{M} E_{mk} \right)$$

where $G_m = (V_m, E_m)$ determines the structure of the m^{th} network layer of the MLN; V_m and E_m are the sets of nodes and edges of network G_m, respectively; E_{mk} is the set of connections between the nodes of V_m and V_k; $m \neq k$; $m,k = \overline{1,M}$; and M is the number of MLN layers. The set

$$V^M = \bigcup_{m=1}^{M} V_m$$

is called the total set of MLN nodes, where N^M is the quantity of V^M elements. In this work, we consider partially overlapped MLNs [15], in which connections are possible only between nodes with the same numbers from the total set of nodes V^M (Fig. 1a). This means that node sets of different layers may not coincide and that each node can be an element of several systems and perform one function but in different ways. The set

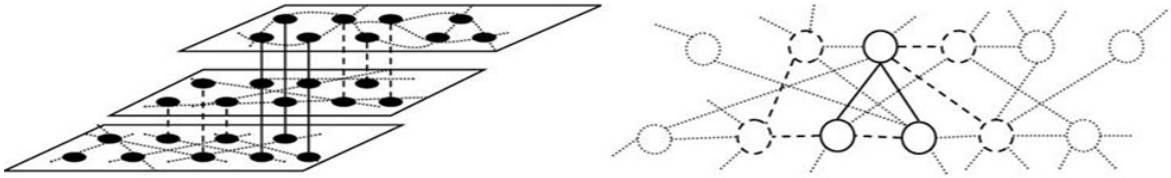
$$E^M = \bigcup_{m=1}^{M} E_m$$

is then called the total set of MLN edges, where L^M is the quantity of elements of the E^M.

The nodes through which interlayer interactions are carried out are called MLN transition points. The number of K^M connections that are carried out through the transition points from layer to layer in this case is calculated by the formula

$$K^M = \sum_{i=1}^{N^M} (k_i - 1)$$

in which the value k_i is equal to the number of layers that include node n_i, $i = \overline{1, N^M}$, of the total set of nodes V^M.



a) b)

Figure 1: Example of the structure of a partially overlapped three-layer network (a) and its aggregate network (b: ..... — element belongs to one layer, - - - - — element belongs to two layers, _____ — element belongs to three layers).

The multilayer network G^M is fully described by an adjacency matrix [16]

$$\mathbf{A}^M = \{\mathbf{A}^{km}\}_{m,k=1}^{M},$$

in which the blocks $\mathbf{A}^{mm}$ determine the structure of the intralayer and blocks $\mathbf{A}^{km}$, $m \neq k$, – interlayer interactions. Values a_{ij}^{km} =1 if the edge connecting nodes n_i^k and n_j^m exists, and a_{ij}^{km} =0, $i, j = \overline{1, N^M}$, if such an edge does not exist. Blocks $\mathbf{A}^{km} = \{a_{ij}^{km}\}_{i,j=1}^{N^M}$, $m, k = \overline{1, M}$, of matrix $\mathbf{A}^M$ are determined for the total set of MLN nodes; i.e., the problem of coordination of node numbers is removed in the case of their independent numbering for each layer.

To simplify the study and reduce the dimensionality of the problem of analysing the vulnerability of the structure of a multilayer system, in [3], the concept of an aggregate network of the MLN (Fig. 1b) was proposed, the structure of which

$$G_{ag}^M = \left(V^M, E^M = \bigcup_{m=1}^{M} E_m \right)$$

is completely described by the adjacency matrix

$$\mathbf{\Lambda} = \{\lambda_{ij}\}_{i,j=1}^{N^M}, \quad \lambda_{ij} = \sum_{m,k=1}^{M} a_{ij}^{mk}, \quad i, j = \overline{1, N^M}.$$

The elements of the adjacency matrix Λ of the aggregate network determine the integral structural characteristics of the elements of the total sets of nodes and edges of the MLN, namely, how many network layers these elements are included in. Notably, multilayer networks generally play a positive role in the organization of intersystem interactions since they provide duplication of the most important flow paths, increasing the reliability of the system and creating the possibility of access to nodes inaccessible in other network layers. However, from the point of view of the problem of vulnerability, such structures can contribute to the acceleration of the spread of negative impacts (epidemics of dangerous infectious diseases, computer viruses, cascading phenomena) [17, 18].

We distinguish between the concepts of MLNs as structures and MLNSs as systems. The railway, as a network of nodes (stations) connected by edges (tracks), ensures the functioning of two systems — fright and passenger transportation. These systems are interactive and

interconnected since they jointly use the railway network, locomotives, communication facilities, and workers and coordinate the schedules of passenger and freight trains but have different control systems and principles of work organization. The most general case of MLNSs is multidimensional (multiflow) multilayer systems [19]. In [1], a method for decomposing such MLNSs into monoflow multilayer systems was proposed, and a flow model of such systems was considered, which allows the main local and global functional characteristics of the elements of these formations to be calculated. To determine the indicators of the functional importance of the components of a monoflow MLNS, we use the flow model [2], which is described by the adjacency matrix $\boldsymbol{F}^{M}(t)$, the elements of which are determined by the volumes of flows that passed through the edges of the MLNS during the period $[t\text{-}T, t]$ to the current time $t \geq T > 0$:

$$\mathbf{F}^{M}(t) = \{\mathbf{F}^{km}(t)\}_{k,m=1}^{M}$$

in which the blocks $\mathbf{F}^{mm}(t)$ describe the movement of intralayer flows, and the blocks $\mathbf{F}^{km}(t)$, $m \neq k$, describe the movement of interlayer flows. The values of the elements of the blocks $\mathbf{F}^{km}(t)$ are calculated according to the ratio

$$f_{ij}^{km}(t) = \tilde{f}_{ij}^{km}(t) \Big/ \max_{n,l=\overline{1,M}} \max_{s,p=\overline{1,N^M}} \tilde{f}_{sp}^{nl}(t), \quad f_{ij}^{km}(t) \in [0,1], i, j = \overline{1, N^M}, k, m = \overline{1, M}$$

in which the value of $\tilde{f}_{ij}^{km}(t)$ is equal to the real volume of flows of a certain type, calculated in the corresponding units of measurement, and $f_{ij}^{km}(t) \in [0,1]$ is their normalized (dimensionless) value, which passed through the edge (n_i, n_j), $i, j = \overline{1, N^M}$, of the network during the time interval $[t\text{-}T, t]$ to the current moment $t \geq T \geq 0$. The structure of the matrix $\mathbf{F}^{M}(t)$ is clearly identical to the structure of the matrix $\mathbf{A}^{M}$. The elements of the flow adjacency matrix of the MLNS are determined on the basis of empirical data on the movement of flows along its edges. Currently, when modern means of information selection are used, such data are quite easy to obtain for many natural and the vast majority of man-made systems (transport, energy, financial, information, etc.) [20].

To simplify the study and reduce the dimensionality of the problem of vulnerability analysis of a multilayer system, in [3], the concept of a flow aggregate network of the MLNS, whose structure is identical to that of the G^{M}_{ag} aggregate network, was proposed, and the operation process is completely described by the flow adjacency matrix

$$\boldsymbol{\Phi}(t) = \{\varphi_{ij}(t)\}_{i,j=1}^{N^M}, \quad \varphi_{ij}(t) = \sum_{m,k=1}^{M} f_{ij}^{mk}(t), \quad 0 < T \leq t, \quad i, j = \overline{1, N^M}.$$

The elements of the adjacency matrix $\boldsymbol{\Phi}(t)$ of the flow aggregate network determine the integral functional characteristics of the elements of the total sets of nodes and edges of the multilayer system, namely, the total volume of flows, the movement of which they provide in all layers of the MLNS. On the basis of the structural and flow models of the multilayer system and its aggregate networks, the indicators of the importance of the components of such formations are calculated, which are used when elaborating scenarios of the spread of negative impact through the network. The usefulness of such indicators lies in the fact that they determine the objects of the system that require priority protection.

3. Importance indicators of the layers of multilayer network systems

Let us define the most important characteristics of the layers of a partially overlapped MLNS for the analysis of the vulnerability of the structure of intersystem interactions, the values of which

should be considered when elaborating scenarios of system-wide targeted attacks. The list of such characteristics includes the following [13]:

1. The specific weight θ_m of the set of nodes of the m^{th} layer in the total set of nodes V^M is calculated by the ratio $\theta_m = N_m / N^M$.
2. The specific weight ϑ_m of the set of connections of the m^{th} layer in the total set of edges E^M is calculated by the ratio $\vartheta_m = L_m / L^M$.
3. The input degree of the m^{th} layer is equal to the total number of input interlayer connections.
4. The output degree of the m^{th} layer is equal to the total number of output interlayer connections.
5. The specific weight ψ_m of the transition points of the m^{th} layer in the set of all the transition points of the MLN is calculated by the relation $\psi_m = K_m / K^M$, in which the value of K_m is calculated as the sum of the elements of the off-diagonal blocks to the $\mathbf{A}^{mm}$ blocks of the matrix $\mathbf{A}^M$, $m = \overline{1, M}$.

The integral indicator of the MLNS operation process $s(\mathbf{F}^M(t))$, which is equal to the total volume of flows in the monoflow multilayer system during the time period $[t-T, t]$, $t \geq T > 0$, is determined by the relation

$$s(\mathbf{F}^M(t)) = \sum_{m,k=1}^{M} s(\mathbf{F}^{mk}(t)),$$

in which the parameters

$$s(\mathbf{F}^{mk}(t)) = \sum_{i,j=1}^{N^M} f_{ij}^{mk}(t)$$

determine the total volume of the intralayer flow of the m^{th} layer; if $k=m$, and the volume of the intersystem flow between the m^{th} and k^{th} layers; if $k \neq m$, $m, k = \overline{1, M}$. It is obvious that

$$s(\mathbf{F}^M(t)) = s(\mathbf{\Phi}(t)) = \sum_{i,j=1}^{N^M} \varphi_{ij}(t), \quad 0 < t \leq T.$$

Let us define the most important flow characteristics of system layers in a monoflow multilayer network system, the values of which should be considered when elaborating scenarios for system-wide targeted attacks [13]:

1. Specific volumes $\varphi_m^{int}(t)$ of intralayer flows in the m^{th} layer of the MLNS, which are calculated by the formula

$$\varphi_m^{int}(t) = s(\mathbf{F}^{mm}(t)) / s(\mathbf{F}^M(t))$$

2. Specific volumes $\varphi_m^{ext,out}(t)$ of the output flows of the m^{th} layer in the MLNS, which reflect its role as a flow generator in a multilayer system and are calculated by the formula

$$\varphi_m^{ext,out}(t) = \sum_{k=1,\, k\neq m}^{M} s(\mathbf{F}^{mk}(t)) / s(\mathbf{F}^M(t))$$

3. Specific volumes $\varphi_m^{ext,in}(t)$ of the input flows of the m^{th} layer in the MLNS, which reflect its role as the final receiver of flows in a multilayer system and are calculated by the formula

$$\varphi_m^{ext,in}(t) = \sum_{k=1,\, k\neq m}^{M} s(\mathbf{F}^{km}(t)) / s(\mathbf{F}^M(t))$$

4. Specific volumes $\varphi^m(t)$ of the transit flows of the m^{th} layer, which are calculated as the ratio of the total volume of transit flows passing through the transition points of the m^{th} layer to the total volume of all interlayer transit flows in the MLNS for the time interval $[t\text{-}T, t]$, $t \ge T > 0$, $m = \overline{1, M}$.

Note that the layers with the highest values of the above structural and functional importance indicators or their aggregated values are potentially the primary targets of successive system-wide attacks on the MLNS layer systems. A typical scenario of such an attack consists of sequentially performing the following steps:

1. A list of MLNS layers is compiled in descending order of the values of the selected indicators of their importance in the multilayer system.
2. Remove the first layer from the created list.
3. If the attack success criterion is achieved, complete the execution of the scenario; otherwise, proceed to point 4.
4. Since the structure and operation process of the multilayer system due to the defeat of a certain layer (and its interlayer connections) changes, a new list of layers is compiled in descending order of the values of the selected indicators of their importance in the MLNS, and the process continues to point 2.

In this case, it is advisable to choose the criterion for the success of the attack as a reduction in the volume of flows in the multilayer system $s(\mathbf{F}^M(t))$, $t \ge T > 0$, by a certain predetermined value. The next most difficult problems in ensuring protection and overcoming the consequences are simultaneous attacks on several or all layers of the MLNS, which include hybrid wars and sanctions against countries that pose a threat to global security [21]. Scenarios of such attacks are built on the same principles as simultaneous group attacks [3], with the difference being that the attack targets are not the most important groups of nodes according to certain characteristics but the MLNS system layers. To develop scenarios of sequential or simultaneous targeted attacks on a multilayer system, it is generally advisable to use the concept of its structural and/or flow aggregate networks, the adjacency matrices of which allow the determination of integral structural and functional indicators of the importance of MLNS elements and subsystems. For a deeper analysis of the vulnerability of a multilayer system to the action of negative impact, it is also advisable to use the parameters of input and output influence, as well as the betweenness and interaction of the layer–system with the MLNS as important indicators [3]. These parameters are similar to those for a group of nodes if all nodes of the layer are selected as a group.

It is clear that damage to the structure of the network system leads to the limitation or even termination of its function. During the russian-ukrainian war, 80–90% of thermal plants and 40–50% of all hydroelectric power plants were destroyed or damaged, the Zaporizhzhia NPP was blocked, and approximately 90% of the wind and a significant part of the solar generation were lost. This led to a decrease in the total capacity of the Ukrainian power system from 55 to less than 15 GW, i.e., by more than 73%. Moreover, it is possible to destabilize or even stop the functioning of the NS even when it has an unstruck structure. Thus, starting on February 24, 2022, the aviation transport system of Ukraine actually stopped its operation only because of the threat of aircraft being shot down. Notably, the structure of this system remained practically intact. It follows that the objective level of protection of the NS or MLNS can be determined only on the basis of an analysis of the consequences of the action of a negative impact, such as the ratio of the number of directly damaged elements of the system to the number of targets at which this impact was directed (the effectiveness of vaccination on the spread of an epidemic of a dangerous infectious disease, the results of the operation of the air defense system on massive missile and drone strikes, etc.). No less important is the sensitivity of the system to the action of a negative impact, which is determined by the ratio of the number of directly damaged elements of the system to the number of all its indirectly injured nodes. It is obvious that the closer this value is to zero, the more

sensitive the system is to the action of a negative impact, since even a small number of directly damaged elements generate a large number of indirectly injured ones.

A convenient tool for comparative analysis of the consequences of a negative influence is the so-called temporal network [22], with which we can track the impact of a change in the structure on the process of system operation or, if the structure is unaffected, the dynamics of this process change over certain time intervals. Temporal networks can be used to describe the behavior of the NS before the onset of the negative impact, during this action (especially if it is long-term) and after its completion. Such a reflection allows us to objectively assess the course and consequences of the damage, analyze the security and sensitivity of the system to the action of diverse negative impacts and develop strategies for the fastest possible restoration of the NS. Temporal networks are formed similarly for multilayer network systems. Let us consider a specific example of the vulnerability of real MLNS to targeted attacks and the action of nontargeted disruption.

4. Damage to the country's general transportation system

One of the illustrative examples of a multidimensional network is the general transport system of the country. The GTS is a two-dimensional NS that provides the movement of two main types of flows: freight and passenger [13]. For most multidimensional networks, the transition of flows between layers (the conversion of passengers into cargo and vice versa) is impossible. Each of the layers of the two-dimensional GTS can be represented as a four-layer monoflow network system, which provides the movement of passengers or cargo by rail, road, water (sea and river) and air transport. The layers of each of these single-stream MLNS have different structural and flow characteristics. Thus, the road transport system includes 29711 nodes, the railway includes 1447 nodes, the aviation includes 25 nodes, and the sea includes 18 nodes. The flow characteristics of each layer of the passenger and freight MLNS also differ significantly from each other (see Tables 1 and 2, data for 2018 [23]). This applies to an even greater extent to the structural and functional indicators of the importance of different layers of these multilayer systems. For example, the specific weight of the nodes of the automobile layer in the total set of nodes of the GTS is $\theta_{auto} = 1{,}0$, and the specific weight of the nodes of the marine layer is $\theta_{sea} = 0{,}00084$. Moreover, the specific volume of intralayer cargo flow in the marine layer for 2018 is $\varphi_{sea}^{int}(t) = 0{,}55$, and that in the automobile layer is $\varphi_{auto}^{int}(t) = 0{,}35$ (see Table 2).

Table 1

Passenger transportation by the GTS of Ukraine in 2018–2023 (millions of people)

Year	Road	Auto	Sea	Avia	Common
2018	158	1907	0	12	2077
2019	155	1805	0	14	1974
2020	68	1084	0	5	1157
2021	81	1089	0	9	1175
2022	53	663	0	0	717
2023	65	803	0	0	869

It also follows from Tables 1 and 2 that Ukraine's sea transport is practically not used for passenger transportation, and air transport is not used for cargo transportation. Passenger air transport, although not as significant as it is in the road and rail layers, provides the movement of passengers to regions inaccessible to other modes of transport or with which there is no direct or convenient connection. However, much more interesting is the analysis of the consequences of the spread of the COVID-19 pandemic (nontargeted disruption) and russian aggression against Ukraine (targeted attack) on the structure and operation of the general transport system.

Notably, during the COVID-19 period (2020–2021), the structure of the Ukrainian transport system remained unaffected, but from the data presented in Tables 1 and 2, overall, the number of passengers decreased by 42% compared with that during the pre-COVID-19 period (2018–2019), while the amount of freight transportation decreased by only 6%. That is, the structural approach, which is generally implemented by the theory of complex networks, does not allow for adequate tracking of such processes.

During the war period (2022–2023), the structure of the GTS decreased by approximately 20% because of the occupation of parts of the territories of Ukraine (5 out of 25 airports and 5 out of 18 seaports were destroyed or blocked; it is quite difficult to calculate the exact number of railway and road network nodes removed from the structure). However, compared with that during the pre-COVID period, the volume of flows provided by transport structures decreased significantly more (by 61% for passengers and by 63% for freight). This also confirms the advantage of the flow-based approach for analyzing the consequences of the negative impact on the MLNS.

Table 2

Freight transportation by the GTS of Ukraine in 2018–2023 (million tons)

Year	Road	Auto	Sea	Avia	Common
2018	322	1206	1892	0,1	3420
2019	313	1147	2120	0,1	3580
2020	306	1232	1812	0,1	3350
2021	314	1121	1852	3	3287
2022	151	695	598	N/A	1444
2023	149	677	363	N/A	1189

Note that the data presented in columns 2–5 of Tables 1 and 2 actually reflect the integral indicators of the operation process of separate layers of the GTS in the corresponding temporal networks (rail, road, sea and aviation), which cover the time period from 2018 to 2023 with an interval of one year. The data presented in the “Common” column of Tables 1 and 2 also describe the integral indicators of the operation process of the GTS flow aggregate network and therefore of the general transport system of Ukraine as a whole in the corresponding temporal network.

An important problem is the possibility of redistributing the traffic of flows between the layers of the transport system because of the negative impact on one of them. In 2018–2019, products of the metallurgical and agricultural industries accounted for 77% of all cargo transportation by sea (Table 3) [23]. During the war, Ukraine practically stopped (reduced by 94%) the export of metals because of the destruction or blocking of most metallurgical plants. However, the export of agricultural products by sea, although significantly reduced (by 70% compared with that in the pre-COVID period), did not stop. In 2023, it amounted to almost 55 million tons. To transport such a volume of grain by sea, approximately 900 NOVA Star class bulk carriers are needed, by rail—18

thousand grain trains—and by road—more than 2.4 million grain trucks. Insufficient means of transport, limited road capacity, increased transportation distances, logistical difficulties, and the threat of blocking the western borders of Ukraine by neighboring countries are the main reasons for the impossibility of redirecting grain flows that were carried out by sea to the railway and automobile layers of the GTS.

Notably, on the basis of known statistical data [23], a comparative analysis of the processes that took place in the general transport system of Ukraine during the precrisis and crisis periods caused by various factors can be performed. In addition, on the basis of these data, we can identify nodes that are critical for ensuring reliable and uninterrupted flow motion in the GTS; determine the dependence of the normal function of the MLNS on the operation of nodes—generators and final receivers of flows, and ensure their replacement in advance; and create alternative (backup, duplicate) traffic routes with sufficient capacity to avoid destabilization of the operation of the multilayer system because of blocking of transit nodes.

Table 3

Freight transportation by sea in 2018–2023 (million tons)

Years / Type of flow	2018-2019		2020-2021		2022-2023	
	mil. tons	% of total	mil. tons	% from 2018-19	mil. tons	% from 2018-19
Total	4012	100	3664	91	961	24
Metals	2036	51	1774	87	130	6
Crops	1060	26	888	83	317	30
Others	916	23	1002	109	514	56

5. Conclusions

In recent decades, humanity has faced many global challenges and threats, such as climate change, the emergence of new strains of dangerous infectious diseases, the decline in biodiversity in nature, the increase in the number and intensity of natural disasters, the threat of famine and intercivilizational conflicts, and even World War III. Studying such threats and developing strategies for protection against them are important problems. This article presents structural and flow models of monoflow partially overlapped multilayer network systems that describe the structure and process of real-world intersystem interactions. On the basis of these models, the main structural and functional indicators of the importance of separate layers-systems of the MLNS are determined, and a scenario of an effective targeted attack on it is elaborated. The value of such scenarios lies in the fact that they determine the components of a multilayer system that require priority protection. It is shown that damage to the structure of a separate layer clearly affects the operation process of this layer and destabilizes the work of all the layers-systems of the MLNS associated with it. Using the example of the general transport system of Ukraine, it is confirmed that it is possible to stop or significantly destabilize the functioning of separate layers of the MLNS and the process of interaction between them even if the structure is not damaged. An analysis of the spread of the COVID-19 pandemic in Ukraine and the russian-ukrainian war shows that the flow-based approach makes it possible to study the course much more objectively and accurately and assess the consequences of damage to separate layers and the multilayer system as a whole to develop effective strategies for their recovery and the earliest possible return to normal life.

Declaration on Generative AI

During the preparation of this work, the authors used Google Translate to check the grammar and spelling. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the publication's content.

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