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IDENTIFICATION OF INFLUENTIAL RAILWAY STATIONS USING LOCAL SYNCHRONIZATION IN COMPLEX NETWORKS OF TRAIN FORMATION PLANS

The object of research is the dynamic processes of coordination of interactions among railway stations within the train formation plan (TFP) network. The problem addressed lies in the insufficiency of traditional topological approaches for identifying influential stations in railway networks. An analysis based solely on degree centrality indicators does not allow the detection of hidden sources of dynamic vulnerability.

An approach is proposed for identifying critical stations and links that reduce the coherence of the TFP network, based on the investigation of local synchronization characteristics. A procedure for analyzing station influence is developed through the integration of centrality measures with a local order parameter calculated using the Kuramoto model. The application of the proposed procedure to real TFP networks representing different structural states revealed changes in local synchronization characteristics. The average value of the local order parameter within the largest strongly connected component decreased from 0.6664 to 0.4976. It was established that topologically significant marshalling stations may exhibit low values of the local order parameter, that is, they may remain locally desynchronized from their immediate neighborhood. It is substantiated that the key factor reducing local synchronization of stations is the phase heterogeneity of their nearest neighborhood, in particular the presence of adjacent stations belonging to other phase clusters.

The practical application of the results is possible provided that the TFP is formalized as a network model and data on the structure of train assignments are available. The proposed approach can be used to support managerial decision-making regarding adjustments to the TFP, improvement of station coordination, and enhancement of the resilience of the railway system under structural changes.

Keywords: railway, wagon flow, railway stations, train formation plan, Kuramoto model, local synchronization.

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1. Introduction

The efficiency of the freight railway system depends on the coordinated operation of a large number of interconnected railway stations. One of the key regulatory documents that ensures the coordination of the operation of stations in a railway system with centralized management is the train formation plan (TFP) [1]. TFP determines for each freight year the technological logic of the system for organizing wagon flows into trains of different categories and the direction of their movement within the railway network [2]. The study [3] shows that technological solutions in transport and technological complexes directly affect the level of energy costs and the efficiency of the system. The work [4] substantiates the need for integrated planning that combines the timetable, transportation plan and rolling stock turnover, taking into account variable traffic parameters. Therefore, the train formation plan is a comprehensive tool for managing the transport process, which determines the nature of interaction between stations and significantly affects the operational efficiency, reliability and stability of the railway system.

Traditionally, the analysis of train formation plans is based on the assessment of its topological and static characteristics, such as the degree of vertices, centrality indicators or transportation volumes [5, 6]. In the study [5], the structural evolution of the freight railway system of

Ukraine under conditions of partial loss of the network was analyzed, which allowed to assess changes in topological connectivity and the role of key stations. In the work [6], the evolution of the railway network of China was studied from the standpoint of regional connectivity and urbanization impact, which confirms the importance of analyzing the structural characteristics of transport networks. Such approaches are useful for identifying the main hubs and structurally important stations. However, real processes of transportation organization are dynamic in nature, which is associated with failures of technological processes and delays, fluctuations in the intensity of wagon flows and adaptive responses of the system to disturbances. In the study [7], a model for predicting the time of departure of goods from a sorting station was developed, which demonstrates the significant influence of local technological factors on the formation of delays in the network. In [8], the logistical challenges of grain exports from Ukraine in wartime were analyzed, which showed the dependence of transportation efficiency on the network adaptability to external disturbances and capacity constraints. Therefore, taking into account the dynamic characteristics of the transport system is a necessary condition for an adequate analysis of the efficiency of train formation plans. Under such conditions, railway stations with similar topological characteristics can affect the operation of the railway network in different ways, and influential sorting stations

can be sources of a decrease in the speed of transmission of wagon flows in the network. This reveals a fundamental limitation of purely topological approaches, which do not allow for an adequate description of the dynamic coordination processes underlying the formation of wagon flows into trains.

Modern advances in the theory of synchronization in complex networks open up new possibilities for the analysis of such processes [9]. Within this approach, network nodes are considered as interacting dynamic elements, the collective behavior of which is formed as a result of local interactions. One of the most common models for studying the coherence, stability and vulnerability of complex systems is the Kuramoto model [10], which proposes a mathematical description of the collective synchronization of an ensemble of phase oscillators. In a fundamental review [11], the Kuramoto model is presented as a basic paradigm for the analysis of synchronization phenomena in physical and biological systems. In the study [12], modern approaches to the analysis of synchronization in complex networks are summarized and directions for further development of the theory are determined. The practical significance of such a model has been confirmed in various fields. In [13], the emergence of spontaneous synchronization in power networks and its connection with the stability of power systems are shown. In [14], the effects of synchronization in complex social networks and their impact on collective behavior were demonstrated. In [15], the Kuramoto model was applied to distributed synchronization of vehicle speed trajectories in road networks. Thus, the Kuramoto model is a universal tool for analyzing synchronization processes in complex systems of various natures, including transport networks. However, the application of synchronization theory to train formation plan networks remains limited, and existing research focuses on global synchronization indicators [16], which masks local heterogeneities and the individual influence of individual stations. In order to overcome these limitations, this work proposes to shift the emphasis from global network coherence to local synchronization properties. In [17], an approach to detecting synchronization transitions in coupled oscillator networks based on the analysis of local structures is proposed. In [18] it is shown that adaptive local routing can cause explosive synchronization in complex networks, which emphasizes the importance of local interactions for shaping the global behavior of the system. In modern studies of synchronization in complex networks, more and more attention is paid to the local properties of nodes. In [19], the influence of topological heterogeneity on the level of local synchronization in complex networks is investigated and the role of the structural position of nodes in the formation of coherence is shown. In [20], approaches to the analysis of synchronization in complex networks are systematized and the use of local order parameters for assessing the state of nodes is justified. In [21], a generalized order parameter is proposed for the analysis of angular velocity synchronization, which expands the possibilities of quantitative assessment of local coherence of network elements. Thus, modern theoretical and applied studies confirm the feasibility of the transition from purely global synchronization indicators to the analysis of local order parameters. Early studies of coherence in complex oscillator networks showed that global synchronization is formed through local clusters of phase coherence, the structure of which is determined by the network topology [22]. However, the paper does not propose a formalized procedure for identifying dynamically critical nodes that reduce the coherence of real infrastructure networks. The paper [12] emphasizes the importance of selecting individual nodes to improve the efficiency of network synchronization management. This may be important in an applied aspect for improving the efficiency of the railway system based on the identification of critical nodes taking into account their local dynamic properties. The paper [23] confirms that the local structural properties of nodes determine the scenarios for coherence formation and can significantly affect the global stability

of the system. The research in the paper [18] proves that synchronization in complex networks can be formed under the influence of local flow transfer rules, and the decisions of individual nodes can change the global phase structure of the network. In particular, changes in the intensity of traffic flows in the network can cause sudden phase transitions of the explosive synchronization type. This is of particular importance for transport systems, in particular railway systems, where flows determine the level of coherence and stability of the network. However, a literature review shows that there is no formalized procedure for identifying critical stations in train formation plan networks based on their local dynamic properties. Existing approaches either focus on global metrics or do not take into account the specifics of flow processes in railway networks. This necessitates the development of tools that would allow combining topological characteristics with local synchronization indicators to identify nodes and links that reduce the coherence of the railway system.

The aim of this research is to identify influential railway stations in train formation plan networks based on local synchronization analysis.

To achieve this aim, the following research objectives were solved:

1) to conduct an analysis of local synchronization in train formation plan networks with different structural states based on the Kuramoto model by estimating local order parameters, which allows to determine the level of coherence of stations with their immediate environment and to investigate the impact of network structural changes on synchronization processes;

2) to identify critical stations and destinations in the train formation plan network based on the analysis of phase deviations in the local environment of hubs, which allows to identify stations with high topological centrality but low level of local synchronization, which are potential sources of network destabilization.

2. Materials and Methods

The object of research is the dynamic processes of coordination of interaction of railway stations in the train formation plan network. The hypothesis of research is the assumption that the influence of railway stations in the TFP network is determined not only by their topological centrality, but also by the level of local synchronization, therefore, the combination of these characteristics allows to identify critical nodes and hidden sources of dynamic vulnerability of the network.

This research proposes to assess the influence of stations within the TFP based on the analysis of the consistency of their functional state with the immediate environment. The TFP is presented in the form of a graph, where each vertex is a station, which is interpreted as an oscillator with a certain phase state, and the edges reflect the technological relationships of the formation and transmission of car flows between stations. The dynamics of the interaction of vertices is modeled using the Kuramoto model. The evolution of the phases of stations is described by a system of differential equations of the form

$$\frac{d\theta_i}{dt} = \omega_i + \frac{K}{N} \sum_{j=1}^N A_{ij} \sin(\theta_j - \theta_i), \quad (1)$$

where θ_i – the phase of the oscillator at vertex i ; θ_j – the phase of the oscillator of neighbor j ; ω_i – the natural frequency; K – the coupling strength; N – the set of neighbors of vertex i . The level of coherence of each station with its neighbors is estimated through the local order parameter; A_{ij} – the adjacency matrix of the TFP graph. The local order parameter for a station determines the coherence of its own phase with its immediate neighbors, thereby allowing to assess the influence of each station of the TFP network on the global coherence of the network. This is an indicator of local coherence, which is calculated by the formula [20]

$$r_i^{local} = \frac{1}{|N(i)|} \left| \sum_{j \in N(i)} e^{j(\theta_j - \theta_i)} \right|, \quad (2)$$

where $N(i)$ – the set of neighbors of vertex i ; $e^{j(\theta_j - \theta_i)}$ – a complex exponent reflecting the phase difference on the unit circle; $|\cdot|$ – the modulus of the complex number of the expression showing the degree of phase cohesion around vertex i . A high level of the local order parameter r_i^{local} indicates a positive contribution of the station to global coherence, while the low value signals problems with synchronization in its local environment. In this research, it is proposed to consider $r_i^{local} \approx 1$ as complete local synchronization, where all neighboring nodes have an almost similar phase with the center i . Partial coherence is achieved when the phases are close, but not perfectly coordinated at $r_i^{local} \in [0.7; 0.9]$. When $r_i^{local} < 0.5$, the phases of the neighbors are chaotic or very different, which characterizes the process as local disintegration. According to the above, it is possible to identify the neighboring stations that "unbalance" the network and have $r_i^{local} < 0.5$, which allows, in addition to topological properties, to establish the criticality of the station from the position of dynamic transportation processes. For the purpose of systematic analysis of influential nodes and connections in the TFP network, a special procedure was developed, which is presented in Fig. 1.

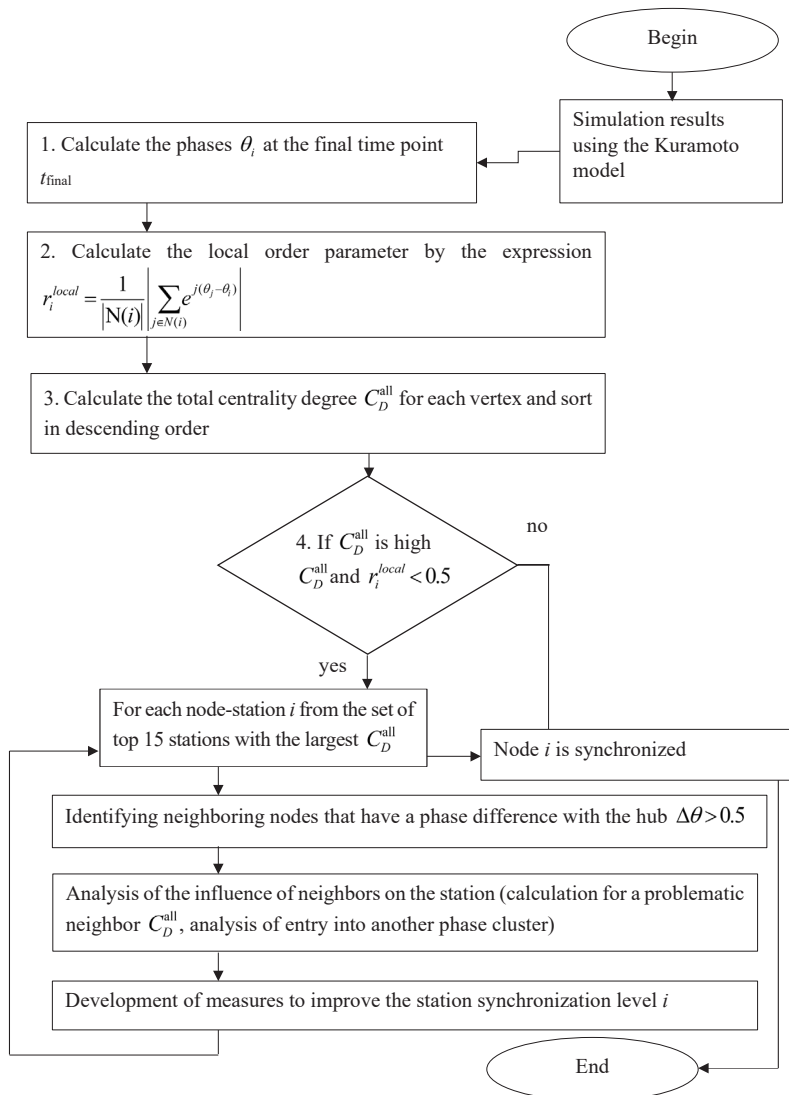


Fig. 1. Procedure for analyzing the influence of stations on synchronization in the Kuramoto model by the local order parameter to increase the coherence of the TFP network

The procedure includes the first stage, where the largest strongly connected component of the TFP network is identified, which serves as the basis for further calculations and analysis. At the second stage, synchronization modeling is performed for the obtained component using the Kuramoto model with equations of the form (1), which allows obtaining the phase distribution of nodes in the operating mode close to the critical coupling strength $K \approx KC$ for the corresponding subnet. Numerical integration is performed using the Euler method [24].

At the third stage, the local order parameter r_i^{local} is calculated for each station based on the obtained phases of the stations, which characterizes the consistency of its phase with the phases of its immediate neighbors. In parallel, the total degree of centrality indicator is calculated for each vertex C_D^{all} . After that, descending sorting is performed according to the centrality indicator, which allows forming a rating of the most influential stations according to topological characteristics.

At the fourth stage, the most problematic stations from the top 15 according to the total centrality indicator, which have a low local order parameter $r_i^{local} < 0.5$, are expected to be identified. From the first ranked hub stations, the neighbors of each i -th hub are sequentially separated in descending order from the top 15, a detailed analysis of

their indicators, their entry into phase clusters, etc. is performed. This allows to analyze all the problems that affect synchronization. It should be noted that the selection of the top 15 stations is not a fixed parameter of the procedure, but is due to the need to ensure a balance between the representativeness of the sample of key network nodes and the possibility of their detailed local analysis. In the studied TFP networks, it is the first 15 stations in terms of the overall centrality indicator that form the core of the network, where the largest number of interactions is concentrated. This allows to cover all significant topologically influential hubs – sorting stations, without overloading the procedure with excessive calculations and interpretations. The proposed approach is flexible and allows the use of a different number of stations depending on the characteristics of the network. In particular, it may be appropriate to select the top 10 or top 20 stations in cases of changes in network size, density of connections, and shape of centrality distribution.

According to the results of the procedure, a list of stations and links that are most critical from the point of view of synchronization is formed, which allows to determine the priority areas of structural and functional optimization of the TFP network to increase its coherence. Thus, the proposed procedure (Fig. 1) allows to clearly identify nodes and links that reduce the overall coherence of the network phases, and to develop targeted management solutions for their optimization, thereby ensuring the effective functioning of the TFP network as a whole.

Numerical calculations were performed in the Python environment (Python Software Foundation, USA) using the NetworkX libraries (developers Aric Hagberg, Dan Schult, Pieter Swart, USA), NumPy (NumPy Developers, USA), SciPy (SciPy Community, USA) and Matplotlib (John D. Hunter and the developer community, USA). The initial data were processed in Microsoft Excel format (Microsoft Corporation, USA) with subsequent import into the Python environment.

3. Results and Discussion

3.1. Analysis of local synchronization in train formation plan networks with different structural states

A preliminary analysis of the properties of the TFP network from the synchronization position allowed to establish the main patterns of the global behavior of the network system based on the Kuramoto model [16]. However, to develop effective strategies for improving the functioning of the railway system, it is necessary to move from the global synchronization characteristics to the local level, studying the properties of individual stations and their connections in the network. This will allow to identify the most critical stations and destinations, the impact of which on the coherence of the entire network is the most significant.

For comparative analysis, two TFP networks were used, corresponding to different structural states of the railway system, in particular, the TFP of JSC "Ukrzaliznytsia" for the period 2012–2013 and the TFP for the period 2018–2019. The calculations adopted the names of the graphs G2013 and G2019, respectively. According

to the procedure, the analysis was carried out for the largest strongly connected components (SCC) of each TFP graph, which ensures the correctness of the research of mutual synchronization processes. To ensure the adopted modeling condition in the regime close to the critical coupling strength, $K = 0.1$ for G2013 and $K = 4.0$ for G2019 were adopted [16].

According to the implementation of stage 2 of the proposed procedure (Fig. 1), the local order parameter indicator r_i^{local} was calculated. According to the calculation results, Fig. 2 shows color maps that visualize the level of local agreement within the largest strongly connected component of the graphs G2013 and G2019. In Fig. 2, the size of the node circle is proportional to the value of the local order parameter.

According to the results of the implementation of stage 3 (Fig. 1), Table 1 shows the rating of fifteen hub stations with the highest total degree of centrality and the calculated local order parameter.

Analysis of the top 15 nodes by total degree in the SCC graph G2013 shows that the highest degree is characteristic of the main sorting and hub stations, which form the backbone of the network and play a leading role in the transfer of wagon flows (Table 1).

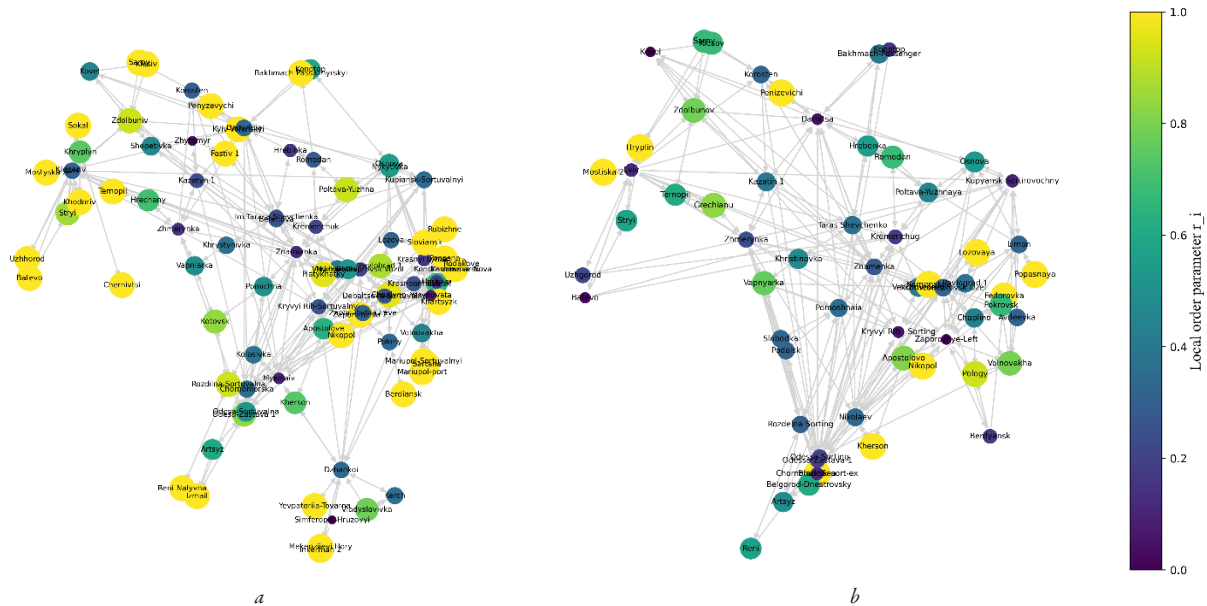


Fig. 2. Visualization of the level of local coordination of SCC nodes of the graph: *a* – G2013; *b* – G2019

Table 1

Comparative analysis of the values of the total degree of centrality of the top 15 stations in SCC G2013 with the local order parameter

Station name	Total degree of centrality C_D^{all}	Local order parameter r_i^{local}
Znamianka	37	0.072259269
Nyzhniodniprovs'k-Vuzol	37	0.17364395
Yasynuvata	28	0.132144011
Darnytsia	25	0.237587313
Debaltsevo-Sortuvalna	24	0.220497338
Dzhankoy	21	0.121751478
Chervonyi Lyman	21	0.082029278
Zaporizhzhia-Live	20	0.2979475
Osnova	17	0.652896343
Kryvyi Rih-Sortuvalnyi	17	0.063249119
Mykolaiv	17	0.28250035
Odesa-Sortuvalna	15	0.914978334
Kupiansk-Sortuvalnyi	15	0.101557309
Zhmerynka	15	0.201861377

However, according to the results of Table 1, there is a significant difference in the local order parameter r_i for different stations with almost the same total degree of vertex centrality (C_D^{all}). For example, in Znamianka the total degree is $C_D^{all} = 37$, and $r_i = 0.07$, while in Nyzhniodniprovsk-Vuzol with the same degree $r_i^{local} = 0.17$. The Osnova station with $C_D^{all} = 17$ stands out in particular, for which $r_i = 0.65$, as well as Odesa-Sortuvalna with $C_D^{all} = 15$, and the local order parameter is close to the coherent state $r_i^{local} = 0.91$. This means that the degree of the node itself does not guarantee high local coherence. Some nodes with an average degree of centrality have a high level of local synchronization, while network hubs may remain locally less coherent. This indicates that the efficiency of synchronization in the network is determined not only by the topological centrality of nodes, but also by the features of their local environment. Thus, to identify critically important elements of the railway network, it is necessary to take into account both global, in particular, the overall degree of centrality, and local indicators – the order parameter r_i . The combination of these approaches allows for a deeper assessment of the structural and functional features of the network and to optimize its modernization and management strategies. According to the results for SCC G2019, which are presented in Table 2, the key hub stations remain similar, but the structural restructuring of the network leads to a change in both the role of individual nodes and their local properties. In SCC G2013, the emergence of nodes with a rather high local order parameter was observed, for example, Odesa-Sortuvalna, which indicates the presence of cells of strong local coherence. The values of the local order parameter r_i for these stations demonstrate a low level of coherence, where r_i for no station exceeds 0.4 (Table 2). This indicates a decrease in local synchronization of the network. Under such conditions, phase clusters in the G2019 graph become important elements for improving the development of the railway network.

Table 2

Comparative analysis of the values of the total degree of centrality of the top 15 stations in the G2019 SCC with the local order parameter

Station name	Total degree of centrality C_D^{all}	Local order parameter r_i^{local}
Nyzhniodniprovsk-Vuzol	35	0.101667
Znamianka	34	0.0758
Darnytsia	30	0.096409
Zaporizhzhia-Live	28	0.188247
Zhmerynka	22	0.269546
Lviv	22	0.106415
Mykolaiv	21	0.33645
Kryvyi Rih-Sortuvalnyi	20	0.363889
Kupiansk-Sortuvalnyi	20	0.193943
Odesa-Sortuvalna	19	0.311559
Kremenchuk	19	0.201703
Odesa-Zastava 1	18	0.29132
Lyman	16	0.358918
Rozdilna-Sortuvalna	15	0.397761

Summarizing the results of Tables 1 and 2, in SCC G2013, 13 stations out of 15 have a low level of local coherence $r_i^{local} < 0.5$, which is 86.67% of the total, while in SCC G2019, all 100% of stations have an index less than 0.5. The situation is different with the set of all SCC stations. Fig. 3 shows pie charts of the distribution of local order parameters depending on the level of influence on coherence in SCC of the graphs being compared. For SCC G2013, the average order parameter for 15 stations is 0.257, while for SCC G2019 it is 0.235. However, for all stations in SCC, the average local order parameter for G2013 is 0.6664,

and for G2019 it is 0.4976. In addition, the set of stations with a high level of local parameter in G2013 is 39.3% of the total number of stations or 35 stations, while in G2019 there are only 13 stations, which is 21.7% of their total number (Fig. 3). A high level of local coordination in the network is characteristic of a centralized topology. This indicates a stronger concentration of G2013 on hubs. In contrast, in the SCC graph of G2019, a shift towards lower values is observed, which indicates a fragmented coherence inherent in a distributed routing structure.

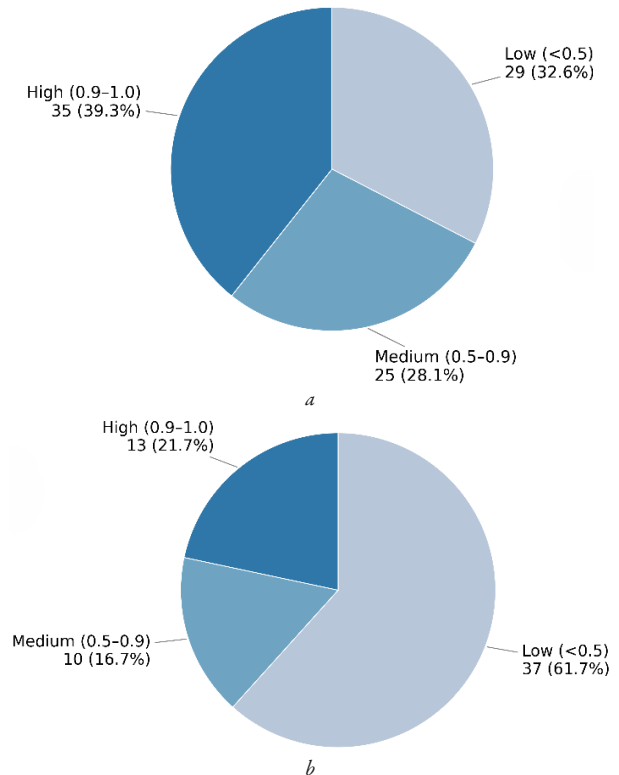


Fig. 3. Distribution diagrams of local order parameters r_i^{local} of stations in SCC graphs: a – G2013; b – G2019

3.2. Identification of critical stations and assignments based on the analysis of phase deviations in the local environment of hubs

From the above-identified dependencies, it can be concluded that to increase the efficiency of the TFP network, it is necessary to implement management solutions that are focused not only on the development and support of large hubs, which are characterized by high values of power centrality. No less important is ensuring a high level of local synchronization of stations within their immediate environment, which determines the real dynamic coherence of the network. When improving the technology of operation of influential topological hubs of the network, its local order parameter r_i should be taken into account. If the indicator is low in the station with the highest vertex degree, the work of its neighbors should be improved. This will turn the central hub into a truly effective "engine" of the network, reduce the number of congestions, and increase the stability and reliability of the transport system. Therefore, management decisions aimed only at "strengthening" or modernizing large hub stations will not necessarily lead to improved railway system performance if local communities around these hubs are not synchronized.

For example, in the work for the G2013 TFP graph, it is proposed to find all neighbors of the Znamianka station to identify connected TFP stations that reduce its local order. According to the program given in Appendix D, a procedure was developed that finds stations in the SCC of the TFP graph that have a destination at the Znamianka station. It is proposed to calculate the phase of each neighbor θ_i ,

the phase difference between Znamianka and the neighbor, and the local order parameter r_i . The calculation results for the first five detected neighbors that affect the coherence of the Znamianka station are given in Table 2.

According to Table 3, stations with significant phase deviations relative to the Znamianka phase are Verkhivtseve, Osnova and Chornomorsk. All stations in this group have a phase difference exceeding 2.9 rad, which corresponds to close to opposite phases.

Table 3

Top 5 problematic neighbors of the Znamianka station

Station	Phase difference, rad	Local coherence coefficient r_i^{local}	Phase θ_i
Verkhivtsevo	3.074405	0.554588	1.861165
Osnova	3.061498	0.652896	1.874072
Chornomorska	2.987345	0.695617	1.639730
Mykolaiv	2.771646	0.282500	1.424031
Zhmerynka	2.682360	0.201861	1.334745

The Mykolaiv and Zhmerynka stations have less influence due to lower coherence, but they also prevent the Znamianka station from agreeing with the majority. Some of these nodes, in particular the Osnova and Chornomorska stations, demonstrate high values of the local order parameter (respectively $r_i^{local} = 0.65$ and $r_i^{local} = 0.69$), which indicates their internal coherence within the corresponding phase cluster. However, it is the phase discrepancy between these nodes and Znamianka that leads to a decrease in the local synchronization index of the latter. The visualization of neighbors with TFP assignments to the Znamianka station from SCC G2013 is shown in Fig. 4. In Fig. 4, the size of the circle of a neighbor station is proportional to its local order parameter r_i^{local} .

Stations such as Osnova or Zhmerynka are "leader" stations of foreign clusters. Even if they are coherent themselves, their phases in the Kuramoto model reduce the coherence of the Znamianka topological hub due to the strong difference in the phase of their cluster from the Znamianka phase (Fig. 4). This phenomenon illustrates an important property of the dynamics of complex networks. Increasing the local coherence of a hub with a high vertex degree is possible

provided that not only its neighbors are highly synchronized, but also that their phases are consistent with the phase of the hub itself. In the TFP network, highly coherent neighbor nodes are in different phase clusters, and their influence, even despite the high eigenvalue r_i^{local} , becomes destabilizing for the hub. Thus, to increase the level of synchronization of key nodes of the network, it is advisable not only to ensure the general connectivity and coherence of the environment, but also to carry out targeted work on harmonizing the phase states of the most influential neighbors. This can be achieved both through structural changes in the TFP with a change in assignments, and through technological measures aimed at harmonizing the technologies of operation of adjacent stations.

The results obtained in developing a procedure for analyzing local synchronization in TFP networks made it possible to move from a purely topological interpretation of the influence of stations to a dynamic assessment of their contribution to network coherence. The application of the developed procedure scheme (Fig. 1) and modeling made it possible to compare the local coherence of key hub stations in the largest strongly connected components of TFP networks for two structural states of the system and to identify nodes and assignments that most significantly reduce network synchronization.

The modeling results show patterns indicating such a phenomenon. Topologically influential stations, in particular with a high overall degree of centrality, may be in a locally "conflicting" phase environment. In this case, their neighbors either have significantly different phases or form other phase clusters, which reduce the level of local coherence.

It is this heterogeneity of local interactions that explains why in the G2013 network there is a significant difference in the values of the local order parameter r_i^{local} for stations with a similar degree of centrality. For example, for Znamianka for $C_D^{all} = 37$, $r_i^{local} \approx 0.07$ was obtained, while for Nyzhniodnprovsk-Vuzol for the same $C_D^{all} = 37$ it has $r_i^{local} \approx 0.17$. Some nodes with an average degree demonstrate significantly higher local coherence. For example, Osnova $C_D^{all} = 17$ has $r_i^{local} \approx 0.65$, Odesa-Sortuvalna $C_D^{all} = 15$ has $r_i^{local} \approx 0.91$, which indicates the presence of local "islands" of coherence even outside the core of network hubs. This effect is consistent with the idea of synchronization clustering in complex networks, when global coherence is formed through local groups of mutually coordinated nodes [22].

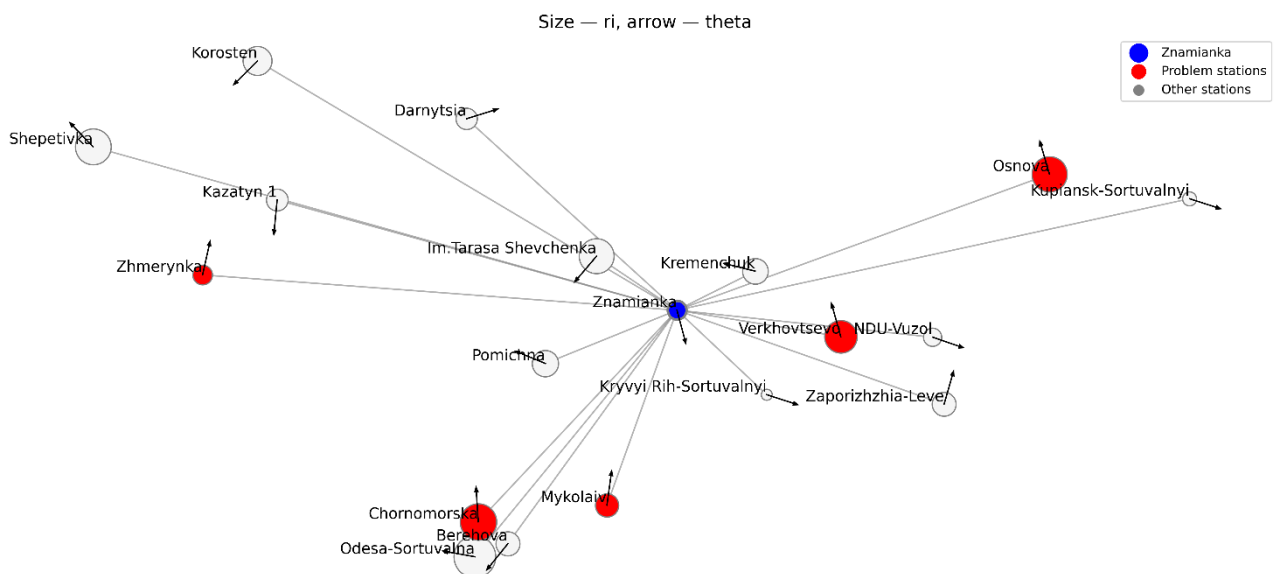


Fig. 4. Visualization of neighbors with TFP assignments to the Znamianka station from SCC G2013 (the arrow shows the phase of the node, the size of the circle corresponds to the value r_i^{local})

Comparison of networks of different years demonstrates systemic changes in local synchronization, which can be explained by the transformation of the TFP structure and the redistribution of streaming interactions. On the scale of the entire SCC, the average decreases from 0.6664 in G2013 to 0.4976 in G2019, when the share of stations with a high level of local coherence decreases from 39.3% (35 stations) to 21.7% (13 stations). Such dynamics are interpreted as a transition from a more centralized configuration with a pronounced "hub" framework to a more fragmented, route-oriented structure, in which local interactions are less coherent, and phase clusters become a key element in explaining the behavior of the system. This confirms the statement that the efficiency of the network is determined not only by the concentration of connections in hubs, but also by the coherence of their immediate environment. A detailed example for the Znamianka station demonstrates the mechanism of "local destabilization" of the hub. For a number of neighbors, significant phase deviations were found relative to the phase of Znamianka (over 2.9 rad), in particular for Verkhivtsevo (3.074 rad), Osnova (3.061 rad) and Chornomorska (2.987 rad). It is important that some of these neighbors have relatively high eigenvalues of the local order parameter, that is, they are coherent "within" their own phase clusters, but it is their phase mismatch with the hub that leads to a decrease in the local synchronization of Znamianka. Thus, the criticality of a node in the railway network is determined by the presence of a stable, but different phase regime that conflicts with the regime of the key hub. This result is important for practice. Since it allows to conclude that increasing the efficiency of sorting stations cannot be reduced only to increasing their processing capacity or increasing the number of assignments. It is also necessary to coordinate the technology of operation of neighboring stations and rationalize the structure of assignments in the TFP, taking into account their local dynamic interaction.

3.3. Discussion of the results and practical aspects of their application for railway network management

Most works on synchronization of complex networks focus on global coherence indices or structural metrics, which do not allow to unambiguously identify "problematic" elements in the local environment of hubs [9, 12, 20]. This often leads to the conclusion that strengthening key nodes automatically improves the system performance [11, 12, 24]. Instead, the results obtained show that a station with high topological importance can remain locally inconsistent and thus can be a source of slowing down the transmission of weight flows even with high structural importance. Similar studies for railway systems are absent. Therefore, the advantage of the conducted research compared to the work [16] is the development of an applied procedure for identifying critical stations and assignments for TFP networks. The proposed approach is based on a combination of topological centrality indices with a local order parameter and analysis of phase deviations of neighboring stations. Unlike works [9, 12, 16], where mainly global synchronization indicators were used, this research used local diagnostics of the coherence of stations with the immediate environment, which ensures the interpretability of the results at the level of specific management actions to improve the TFP.

The limitations of research are primarily model assumptions related to the description of interactions and oscillator parameters. In the basic formulation, the interactions between stations were determined only by the presence of a connection, without taking into account the weight of the arcs, which would reflect the actual volumes of car traffic at the destination. As a result, connections of different intensities affect the synchronization process to the same extent, which may change the quantitative estimates of local coherence when switching to a weighted formulation. To highlight the influence of the topology, it was also assumed that the natural frequencies of the oscillators are the same or specified according to a simplified scheme. Such an assumption limits the reproduction of individual technological features of the stations.

In particular, differences in work intensity, sorting operation duration, and traction and infrastructure constraints are not taken into account. In real conditions, these factors can form additional sources of phase heterogeneity and significantly affect the level of local synchronization.

The conditions for the practical application of the research results are the importance of taking into account that management decisions aimed only at the modernization of large marshalling yards will not necessarily produce the expected effect if local communities around these yards remain uncoordinated. Instead, targeted measures to harmonize phase states in the local environment, in particular through the adjustment of the TFP assignments, the coordination of technologies for the interaction of adjacent stations, are more justified by increasing the TFP stability.

The results obtained can be directly used in the practice of planning and managing development in railway transport. The proposed procedure can be integrated into analytical modules of digital decision support systems used at the level of central and regional railway management. It can be used for scenario analysis of structural changes in the network, assessing the consequences of adding or canceling assignments, as well as for prioritizing investments in infrastructure development.

The scope of application of the results covers infrastructure development planning, improving the train formation plan, increasing the stability of the transportation process in the conditions of structural changes in the network and developing measures to prevent the accumulation of delays in the railway system.

Further research should be directed at expanding the proposed mathematical model by taking into account the weight characteristics of the connections that reflect the intensity of car traffic by destination. A separate direction should be the calibration of oscillator parameters using operational data to reproduce individual technological features of stations.

4. Conclusions

1. An analysis of local synchronization in train formation plan networks with different structural states was carried out based on the Kuramoto model, which made it possible to assess the level of coherence of stations with their immediate surroundings and to establish the sensitivity of local order parameters to structural changes in the network. It was found that a change in the network structure leads to a deterioration in local synchronization. The share of stations with low local synchronization among the fifteen largest hub stations increases from 86.67% to 100%. The average value of the local order parameter in the largest strongly connected component decreased from 0.6664 to 0.4976. This indicates a decrease in the level of coherence at both the local and global levels of the network. It is proven that local synchronization indicators are sensitive indicators of structural changes in the TFP network and can be used to assess its functional state. In addition, it is proven that the efficiency of synchronization in the network is determined not only by the topological centrality of nodes, but also by the features of their local environment. Thus, to identify critically important elements of the railway network, it is necessary to take into account both global, in particular, the total degree of centrality, and local indicators – the order parameter.

2. Critical stations and destinations in the train formation plan network were identified based on the analysis of phase deviations in the local environment of hubs. This allowed to identify nodes with high topological centrality, but a low level of local synchronization as potential sources of network destabilization. It is proven that topological centrality in itself is not sufficient to identify influential railway stations in TFP networks, in particular, in Znamianka the total degree of centrality is 37, and the local order parameter is 0.07, while in Nyzhniodniprovsk-Vuzol with the same degree, also a low order parameter is 0.17. This indicates their low coherence with the environment. However, the stations Osnova and Odesa-Sortuvalna are more coherent and, having a general

degree equal to 17 and 15, respectively, demonstrate higher values of the local parameter of the order of 0.65 and 0.91, respectively. It is established that the key factor of destabilization is the phase heterogeneity of the local environment, in particular the presence of neighbors with significant phase deviations or belonging to other phase clusters. Thus, the criticality of stations in the TFP network is determined not only by their topological position, but also by the nature of local dynamic interaction, which justifies the feasibility of using phase characteristics to support decisions on adjusting assignments and increasing the stability of the network. The proposed procedure can be used as an analytical tool to support decisions on adjusting TFP assignments and prioritizing railway network development measures.

Conflict of interest

The authors declare that they have no conflict of interest regarding this research, including financial, personal, authorship or other, that could influence the research and its results presented in this article.

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Data availability

Data will be provided upon reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

Authors' contributions

Andrii Kyman: Conceptualization, Methodology, Validation, Investigation, Software, Writing – original draft; **Andrii Prokhorchenko:** Formal analysis, Investigation, Supervision, Writing – review and editing; **Mykhailo Kravchenko:** Data curation, Validation, Software, Investigation, Writing – reviewing and editing; **Mykhailo Muzykin:** Data curation, Visualization, Writing – review and editing.

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