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The effect of the structural composition on the resilience of pipeline systems to node damage

Igor A. Tararychkin, *V. Dal Lugansk National University, Ukraine, Lugansk*

Igor A. Tararychkin

Abstract. *The* **Aim** *of this paper is to study the effect of the structural features of pipeline systems on the development of emergency situations by the mechanism of progressive blocking of transportation nodes. The blocking of an individual point element of a system is considered as the result of simultaneous failure of all the pipelines converging into the node. The process of progressive blocking of a certain set of nodes of a pipeline system in random order is called a progressive blocking. The development of progressive blocking is associated with the disconnection of the consumers from the source of end product and is a dangerous scenario of emergency development. The system's resilience against progressive blocking is estimated by the resilience indicator* F_x*, the average share of the system's nodes whose blocking in a random order causes the disconnection of all consumers from the source of the end product.* **Methods of research.** *The values of* $0 \leq F_x \leq 1$ *were identified by means of computer simulation. After each fact of damage associated with a random blocking of an individual node, the connection between the source and consumers of the end product was established. The statistical characteristics of the process of progressive blocking were evaluated according to the results of repeated simulation of the procedure of damage of the analyzed network structure. In general, the structure of a pipeline system is characterized by a graph that describes the connections between point elements. The valence of an individual graph node is the number of edges that converge into it. Similarly, the valence of the respective network node is the number of converging linear elements (pipelines). Furthermore, an important characteristic of an individual node is the composition of the converging linear elements. Thus, the set of a system's linear elements includes the following varieties that ensure the connection between: the source and the consumer (subset G1), two consumers (subset G2), a consumer and a hub (subset G3), two hubs (subset G4), the source and a hub (subset G5).* **Results.** *The author analyzed and examined the effect of the structural characteristics on the ability of pipeline systems to resist the development of emergency situations through the mechanism of progressive blocking of nodes. It was established that with regard to structural optimization the most pronounces positive effect associated with the increase of the values* F_x *is observed as the valence of the source node grows and additional linear elements of subset G1 are included in the system.* **Conclusions.** *The process of progressive blocking of pipeline transportation system nodes is a hazardous development scenario of an emergency situation. The most efficient method of improving pipeline system resilience against progressive blocking consists in increasing the valence of the source node and inclusion of additional linear elements of subset G1 in the system. Structural optimization of pipeline systems should be achieved by defining the values* F_x *for each of the alternatives with subsequent adoption of a substantiated design solution.*

Keywords: *pipeline, system, resilience, damage, node, structure, blocking, optimization.*

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Introduction. Pipeline transportation systems are used in various industries for the purpose of delivering raw materials and end products to consumers [1-3]. The highest potential hazard is associated with the processing and delivery of toxic, flammable, explosive substances. Efficient operation, dependability and operational characteristics of such complex technical systems depend both on the properties of individual structural elements and the specificity of their interaction [4-7].

Transition into the state of non-operability of individual pipelines negatively affects the process capabilities of transportation systems and their operational efficiency [8]. The highest hazard to an operational system is associated with the process of node damage. That is due to the fact that normally several linear elements converge at a single node. In this context, damage (blocking) to a node means simultaneous failure of all the pipelines converging into it.

If in an emergency situation a system's nodes are progressively blocked in a random order, such scenario is called progressive blocking.

The development of emergency situations in the form of progressive blocking of nodes is associated with rapid degradation of the system's properties and can cause complete interruption of the end product's delivery to all consumers.

The ability of a system to resist the development of progressive blocking of nodes is characterized by the resilience indicator F_x [9]. Resilience indicator $0 \leq F_x \leq 1$ represents the average share of a transportation system's nodes whose blocking in a random order causes the complete disconnection of all consumers from the source of the end product. For the specified structure of a transportation system the value F_x is established by means of simulation [10]. The closer F_x is to one, the higher is the analyzed system's resilience against the development of progressive blocking.

The **Aim** of this paper is to study the effect of the structural features of pipeline systems on the development of emergency situations by the mechanism of progressive blocking of nodes.

Computer simulation of progressive damage to various network structures allows identifying the following specifics and patters of the process.

1. Any network structures of pipeline transportation systems with equal numbers of nodes and equal numbers of end product consumers are comparable regardless of the number of the linear elements they include.

2. The increasing number of linear elements in a system is associated with growing values of the resilience indicator F_x, however, this effect is manifested to different degrees and depends on the structural features of the analyzed object.

In the general case, the structure of a pipeline transportation system is described with a marked-out graph that clearly shows the existing connections between individual point elements. The number of edges that converge into a node is called valence that is a characteristic of each node [11]. Similarly, the number of pipelines converging into an individual transportation node is further considered to be its valence. Additionally, a system is characterized by the set of linear elements *G* that is divided into 5 subsets whose designations are shown in Table 1 [12].

As the blocking of an individual transportation node causes immediate transition into the state of non-operability of all connected pipelines, we should assume that the number of linear elements in the node is its characteristic that affects the development of the progressive damage process.

Table 1. Characteristic and designations of subsets of the transportation system's linear elements

Designation of subset of linear elements	Nodes of the transportation network connected by linear elements out of different subsets
*G*1	product source – consumer
*G*2	consumer – consumer
*G*3	consumer – hub
*G*4	hub – hub
*G*5	product source – hub

If, as part of solving the synthesis problem, an additional linear element is included in the system, such structural variation causes increased valence of two transportation nodes at once. Thus, a change in the valence of any node of the system in the process of structural synthesis should be

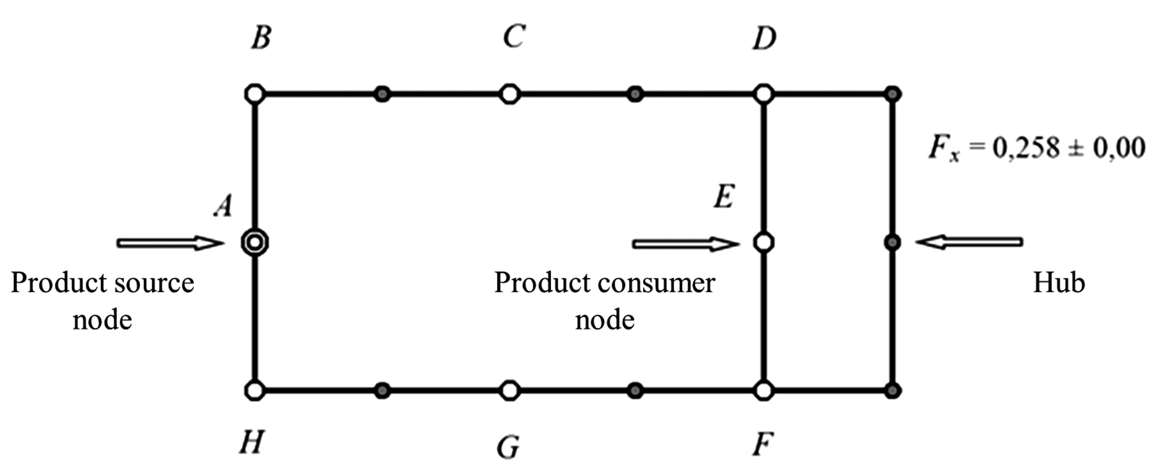

Figure 1. Structure diagram of a pipeline transportation system

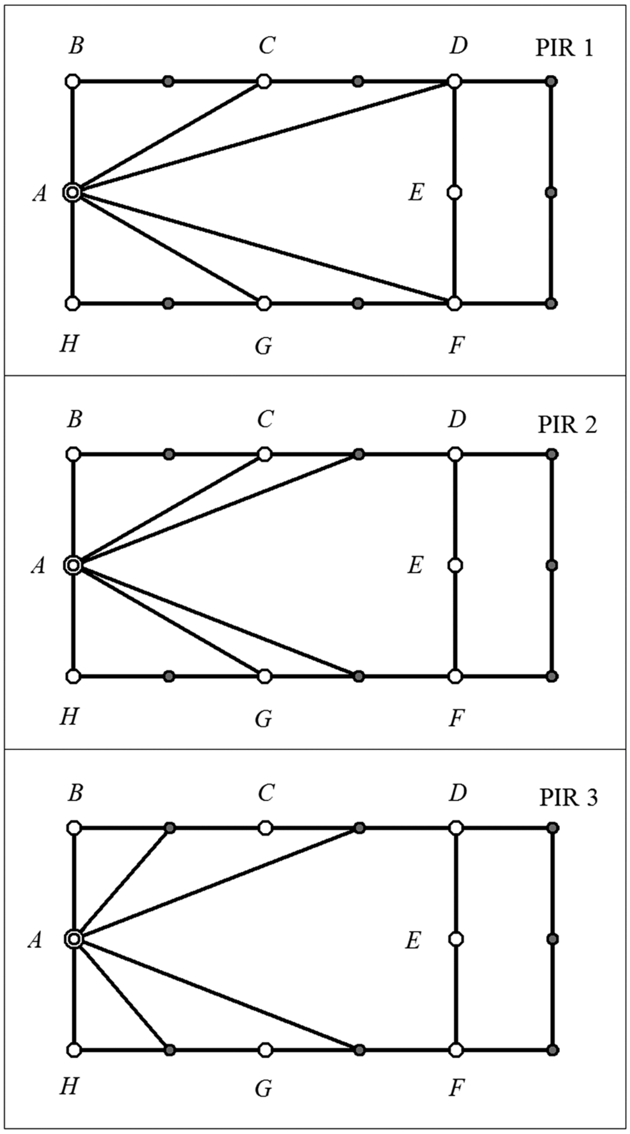

Figure 2. Derivative network structures with increased valence of the source node

examined subject to the observed changes in the valence of the other associated node.

The analysis of the effect of the valence of the transportation nodes on the resilience of network structures against the development of the progressive blocking process is of practical interest and requires additional research. Identifying such patterns involves selecting appropriate network structures and substantiating the associated computational schemes.

In this context, let us examine the basic structure diagram of a pipeline system shown in Figure 1. The analyzed facility includes the source of end product *A*, that is a point element with valence of 2, as well as 7 consumers of end product *B*, *C*, … *H*.

Let us increase the valence of the source node 3 times. For that purpose, let is include 4 additional linear elements into the basic object. The above elements may be part of subsets *G*1 and *G*5 and their inclusion in the system will increase the valence of not only the source node, but other nodes as well.

Structure diagram variants PIR1 to PIR3 with an increased valence of the source node *A* are shown in Figure 2. All the mentioned objects are comparable and their characteristic and results of calculation of the values of F_x are shown in Table 2. As we can see, the most pronounces positive effect associated with the increase of the valence of the source node is observed when linear elements of the subset G1 are added to the system. If the number of elements of subset *G*1 decreases at the expense of elements of subset *G*5, the value of the resilience indicator F_x decreases as well.

Thus, the valence of the source node should be increased primarily by including additional linear elements of the subset *G*1 into the system. In this case the achieved positive effect is most pronounced.

Now, using the base structure diagram, let us increase 3 time the valence of the consumer node *E* as it shown in Figure 3. The characteristics of derived structure diagrams designated PIR4 to PIR6, as well as the modeling results of progressive blocking of nodes are shown in Table 2. As we can see, the most pronounces positive effect associated with the increase of the valence of the source node is observed when linear elements of the subset *G*2 are added to the system. As they are gradually replaced with elements of subset *G*3 the system's resilience against progressive blocking of nodes decreases.

Table 2. Characteristics of derivative network structures

Network structure designation	Number of linear elements belonging to different subsets converging at the valence node 6, pcs					Resilience indicator, F_x	Correlation of values of F_x for the derivative and basic structures
	***G*1**	***G*2**	***G*3**	***G*4**	***G*5**		
PIR1	6	0	0	0	0	0.374±0.001	1.45
PIR2	4	0	0	0	2	0.348±0.001	1.35
PIR3	2	0	0	0	4	0.339±0.001	1.31
PIR4	0	6	0	0	0	0.320±0.001	1.24
PIR5	0	4	2	0	0	0.316±0.001	1.22
PIR6	0	2	4	0	0	0.302±0.001	1.17
PIR7	0	0	0	6	0	0.294±0.001	1.14
PIR8	0	0	2	4	0	0.304±0.001	1.18
PIR9	0	0	4	2	0	0.307±0.001	1.19

Let us now examine the effect of the hub's valence on the resistance of a network object to progressive damage. For that purpose, let us increase 3 time the hub's valence using elements of subsets *G*3 and *G*4 as it is shown in Figure 4. The characteristics of thus synthesized structures are also shown in Table. 2. As we can see, the minimal increase in the values of F_x is observed when only elements of subset *G*4 converge at the hub.

Thus, based on the results of performed analysis is was established that there are three types of point elements of systems whose growing valence to different degree affects the increase in the values F_x.

Thus, the most pronounces positive effect associated with the increase of the valence of the source node is observed when linear elements of the subset *G*1 are added to the system.

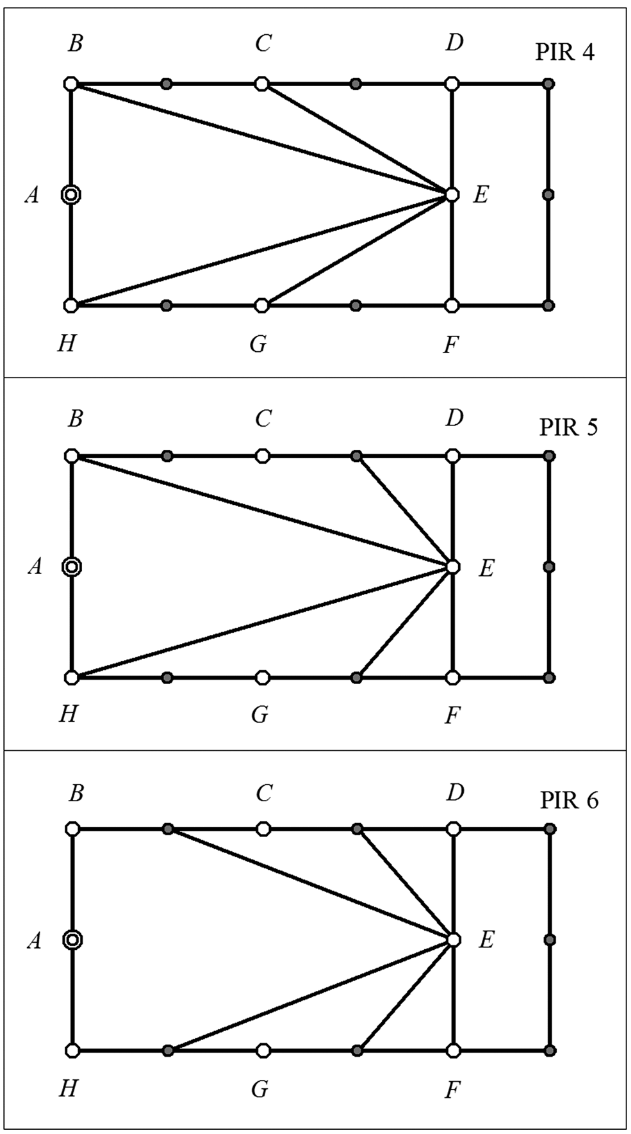

Figure 3. Derivative network structures with increased valence of the consumer node

The least increase of the values of F_x is observed as the valence of the hubs grows and additional linear elements of the subset *G*4 are included in the system.

The increasing valence of consumer nodes has an intermediate effect on the growth of the resilience indicators of network structures against the development of the progressive blocking process.

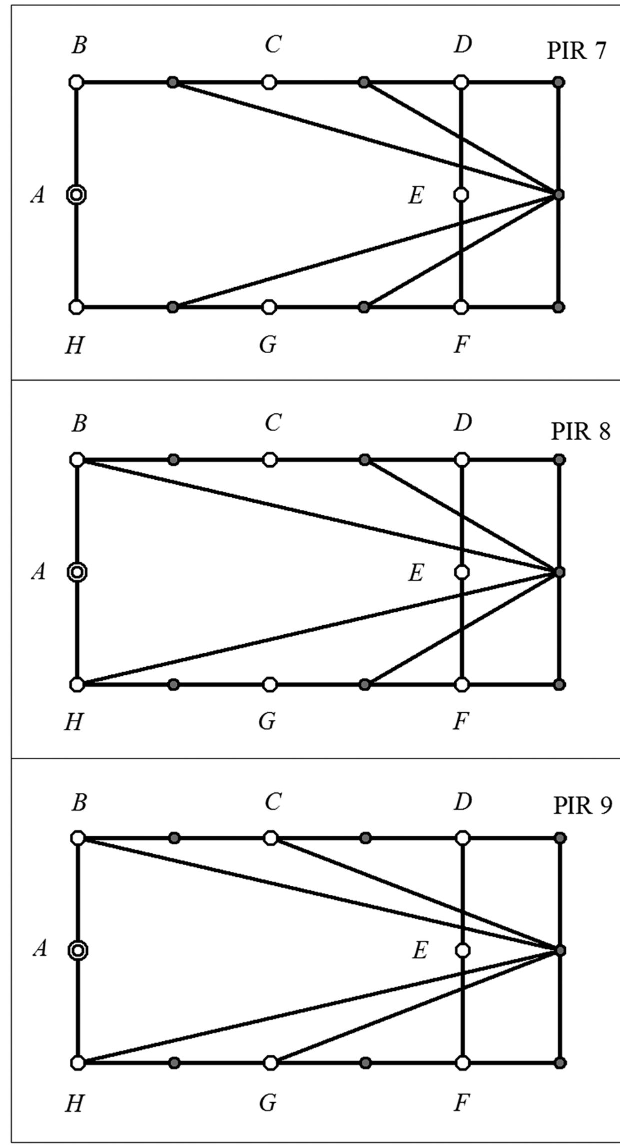

Figure 4. Derivative network structures with increased valence of the hub

Obviously, with regard to problems of structural synthesis the inclusion of additional pipelines into a system is always costly. Therefore, in practical terms, it is important to enable the required level of resilience of network structures to the development of the progressive blocking processes by adding the minimal possible number of linear elements into them.

Then, the most efficient method of improving pipeline transportation system resilience should consist in the inclusion of a small number of linear elements of the subset *G*1.

As an example, let us examine the structure diagram of a pipeline system designated TTR1 shown in Figure 5a.

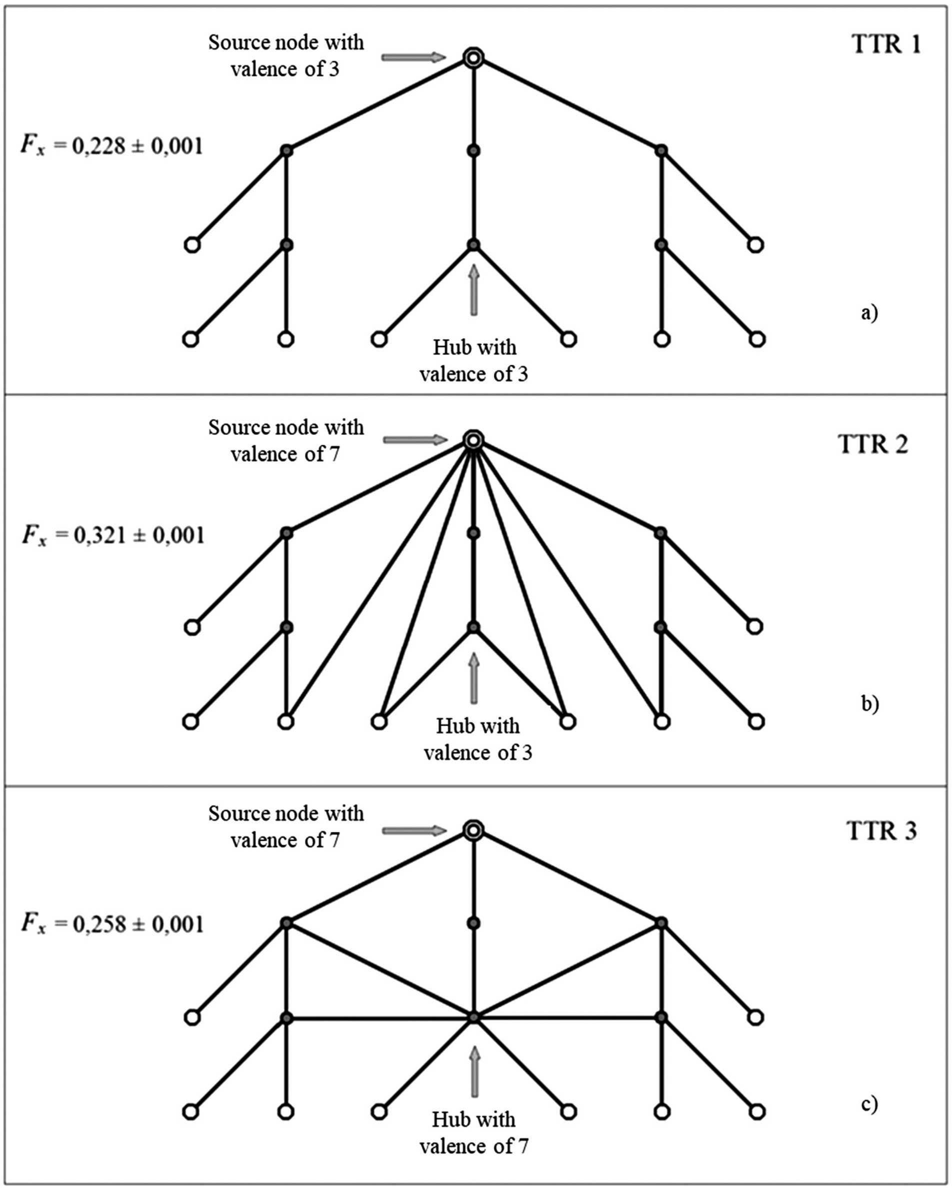

Figure 5. Structure diagram of a basic pipeline system (a) and derived structures with increased valence of the source node (b) and the hub (c)

Let us assume the solution of the synthesis problem is associated with planned inclusion of 4 linear elements into such base object. If the valence of the source node is increased by 4 out of elements of subset $G1$, thus synthesized structure diagram TTR2 will take the form shown in Figure 5b.

Now, let us increase the valence of the hub of TTR1 by adding 4 linear elements of subset $G4$. Thus, obtained derived structure TTR3 has the form shown in Figure 5c.

Taking into account the previously obtained results, it should be assumed that solution shown in Figure 5b will be close to the best, while the one shown in Figure 5c will prove to be one of the worst. The expected values of the resilience indicator for each of the above variants of derived network structures are shown in Figure 5.

As we can see, the value of F_x identified for the version shown in Figure 5b exceeds the value of the resilience indicator of the structure shown in Figure 5c approximately 1.24 times.

Thus, the results of the calculations confirm the earlier assumption regarding the expected properties of synthesized network structures.

Conclusions

1. The process of progressive blocking of pipeline transportation system nodes is a hazardous development of an emergency situation, as each fact of blocking is associated with the simultaneous transition to the state of non-operability of all the pipelines converging to the node.

2. The most efficient method of improving pipeline system resilience against progressive blocking of nodes consists in increasing the valence of the source node and inclusion of additional linear elements of the subset $G1$ in the system.

3. Structural optimization of pipeline systems should be achieved by defining the values of F_x for each of the alternatives with subsequent adoption of a solution that enables the highest level of resilience against the development of progressive damage processes.

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About the author

Igor A. Tararychkin, Doctor of Engineering, Professor, V. Dahl Lugansk National University, Ukraine, Lugansk, e-mail: donbass_8888@mail.ru

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