The Study of Resilience of Transport and Logistics Systems

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Abstract

Analysis of modern methods of evaluation of resilience of transport and logistics systems (TLS) in the management of their configuration and reconfiguration under conditions of destructive effects has shown that in the design and creation of TLS it is necessary to develop conceptually new methodological approach to the detection of disruption scenarios, recovery paths in TLS and carry out analysis of such important property of TLS as structural resilience of their configuration. The outcomes of this research constitute a useful decision-making support tool that allows detecting disruption scenarios at different risk-aversion levels based on the quantification of the structural robustness with the use of the genome method and observing the scope of disruption propagation. Our results can be of value for decision-makers to compare different TLS structural designs regarding the robustness and to identify disruption scenarios that interrupt the TLS operations to different extents.

1 Introduction

The structural TLS design may change due to disruptions, defined as "events that interrupt the regular flow of goods or services within a system" [Bla11]. Modern TLSs have grown in scale and complexity, increasingly exposing firms to various and scattered disruptive events [Hos16, Mis16, Iva18, Dub19]. The creation of effective TLS is possible by ensuring their reliability and resilience both in nominal conditions of operation and in the event of predictable and unpredictable disruptions. TLS resilience has become one of the main research categories over the past decade [Gun15]. Moreover, the resilience is understood as the property of the system to preserve and restore its characteristics (vector quality indicator of the functioning of the TLS) under the influence of a catastrophic environment on the production and logistics process. To assess the resilience of a TLS taking into account the risks of failures in the event of design abnormal situations or "normal" operating conditions, as a rule, a deterministic approach is used, methods of reliability theory and simulation modeling [Fox00, Rob02), Iva13, Mun15, Das15, Iva16, Kim15, Sim14, Xu14, Sny16]. The imitation of TLS production and logistics processes is performed. The imitation of TLS elements, key nodes and connections failures is also produced. The failure of every aforementioned part leads to loss of the TLS resilience, which depends on the modelled level of reliability. For each time point of imitation, a functional check of the TLS functional elements is performed. The random time of forced breaks in the work of one or another TLS node, the values of the target indicators are estimated in case of failure. The calculation is terminated in case of failure of the TLS elements, in which further operation is impossible (the occurrence of critical failures). Such calculations are performed for different levels of reliability of computational emergency situations. At each level, a predetermined number of statistical tests or an amount that provides the specified simulation accuracy is produced. The calculated data are displayed on the radar chart (Kiviat diagram). To determine the TLS resilience index, the area of the figure in the chart is compared with the areas of the figures reflecting the assumed and admissible limit values of the target indicators. If at least one of the targets is less than the admissible limit value, then it corresponds to the loss of the TLS resilience, which requires a decision on the nature of its further functioning.

But at present such dependencies are obtained only as a result of the exploitation of existing TLS. It's a problem with the mentioned approach. But for new TLS design the existing networks statistics is usually used. It is normal if the new network is similar in structure and composition with the previous TLS. But, if the developed TLS differs significantly from the previously created ones, this approach is not always acceptable.

In addition to the predictable disruptions, there are unpredictable, such that no one can foresee in advance, and therefore it is impossible to prepare for them in advance. And not least in real conditions of operation, these unpredictable disruptions occur, if not more often, then, at least, in frequency, they appear commensurate with the calculated ones. Under these conditions, models and

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methods used in the theory of reliability, simulation modelling are not applicable to ensure the TLS resilience, which requires the development of a conceptually new approach to ensuring the TLS resilience.

2 The Traditional Approach to the Assessment of the Structural TLS Resilience in the Conditions of Destructive Influences

Within the framework of studies devoted to the development of methodological foundations for ensuring the TLS resilience, it is necessary to analyze such an important feature as the TLS configuration structural resilience. In a broad sense, the structural TLS ***resilience*** is understood to be such an ability of the object in question, which allows it to maintain, within certain limits, the quality of its target functioning (or restore such ability) by changing (forming) the corresponding structures (configurations).

The change in the structural states of the TLS is associated both with the proliferation and restoration of malfunctions in the elements of the structure of the TLS, and in the process of fulfilling orders. We will consider the failure (inoperable) the TLS functional element, which is not able to perform all the production and technological operations assigned to it. A functional element will be considered partially efficient if it can perform at least one of the assigned production and technological operations. It is obvious that the values of the particular indicators of the quality of functioning of the TLS in each state depend on: many failed, workable or partially workable functional elements; distribution of production and technological operations; reallocation of these operations between workable or partially workable functional elements.

An important and indispensable condition for studying the capabilities of the TLS is the analysis and evaluation of the architecture of its structural states, reflecting both the functional and production-technological features of the TLS control.

Structural models of the functioning of most complex technical systems can be correctly described [Rya76, Kop10, Pav18] by block diagrams, fault and event trees, connectivity graphs, multi-terminal networks, etc. However, these structural models can describe the functioning of only monotonic systems. In monotonous models, it is impossible to take into account the logically complex and contradictory relationships and relationships between functional elements, for example, which in some structural states of the system increase, and in others, decrease the indicator of the effectiveness of its functioning. Also, monotonous models do not represent systems in which elements simultaneously operate, some of which provide an increase, for example, reliability or resilience, and another part causes failures or accidents, i.e. has the opposite, detrimental effect on the security of the system as a whole.

In the study of the TLS resilience, the structure of which is described by graphical models (monotone system [Pav18a], the TLS is considered "destroyed" if, in the case of deleting vertices or edges, the graph will satisfy one or several of the following conditions: the graph consists of at least two connected components; there are no directed paths for certain sets of vertices; the number of vertices in the largest component of the graph is less than some predetermined number; the shortest path exceeds a given value. Accordingly, the TLS is considered to be tenacious if these conditions are not met.

To analyze the properties of the structural resilience of the TLS under these conditions, as well as to synthesize a system with the required property of structural resilience, it is necessary to introduce a quantitative assessment that adequately depicts the property in question.

When studying the TLS structural resilience according to the approach proposed in that study [Pav18], introduces the notion of generalized failure of the i multiplicity, which considers the structural states of the TLS formed upon the sequential refusal of various combinations (C_n^i) of the entire set of functional elements structures for i different functional elements ($i \le n$ where n is the number of functional elements of the TLS structure considered). Among the set of structural states for a given generalized failure is determined by the set of working states, the power of which we denote R_i, or the set of unworkable states, the power of which we denote

$N_i (N_i + R_i = C_n^i)$.

For comparison of various structures, the ***relative function of*** the TLS ***structural resilience*** is determined $\Psi(i/n)$

$$(\Psi(i) = G_i = \frac{R_i}{C_n^i} = 1 - \frac{N_i}{C_n^i}),$$ its linear interpolation is performed by a piecewise linear function $\tilde{\Psi}(x),\ x \in [0,1]$ and the integral indicator of the structural resilience of the the TLS is introduced as the following functional $F_g = \int_0^1 \tilde{\Psi}(x)dx$.

We assume that the TLS is in an inoperable structural state if, in a generalized refusal, all elements that are included at least in at least one of the minimal failure sections of the TLS structure are removed.

In the most general case, the TLS structure is characterized by k minimal failure sections, each of which consists of m_j ($j = 1,...,k$) elements. Moreover, the failure sections have common elements.

In this situation, the number of inoperable structural states with a generalized failure of the i multiplicity takes the following form [Pav18a]:

$$N_i = \sum_{j=1}^{k} \delta(i-m_j) C_{n-m_j}^{i-m_j} -$$
$$-\sum_{j_1=1}^{k} \sum_{j_2>j_1}^{k} \delta(i-m_{j_1}-m_{j_2}+m_{j_1 j_2}) C_{n-m_{j_1}-m_{j_2}+m_{j_1 j_2}}^{i-m_{j_1}-m_{j_2}+m_{j_1 j_2}} +$$
$$+\sum_{j_1=1}^{k} \sum_{j_2>j_1}^{k} \sum_{j_3>j_2}^{k} \delta(i-m_{j_1}-m_{j_2}-m_{j_3}+m_{j_1 j_2 j_3}) \cdot \quad ,(1)$$
$$\cdot C_{n-m_{j_1}-m_{j_2}-m_{j_3}+m_{j_1 j_2 j_3}}^{i-m_{j_1}-m_{j_2}-m_{j_3}+m_{j_1 j_2 j_3}} - \ldots$$
$$\ldots(-1)^{k-1} \delta(i-m_{j_1}-m_{j_2}-\ldots-m_{j_k}+m_{j_1 j_2 \cdots j_k}) \cdot$$
$$\cdot C_{n-m_{j_1}-m_{j_2}-\ldots-m_{j_k}+m_{j_1 j_2 \cdots j_k}}^{i-m_{j_1}-m_{j_2}-\ldots-m_{j_k}+m_{j_1 j_2 \cdots j_k}}$$

where $\delta(x) = \begin{cases} 1, & x \ge 0 \\ 0, & x < 0 \end{cases}$ is a discrete form of the Heaviside step function.

In formula (1), the values $m_{j_1 j_2 \cdots j_k}$ represent the total number of common elements in the minimum sections of failures with numbers $j_1, j_2, \ldots, j_k$.

Using formulas (1), it is possible to calculate the relative function of the TLS structural resilience with a monotonic structure, and accordingly determine the integral index of the structural resilience of the system $F_g = \int_0^1 \tilde{\Psi}(x)dx$.

To calculate the structural vitality, a set of minimum failure sections is needed, as well as the definition of common functional elements in these sections. In general, finding the minimum failure rates is NP difficult. In this case, the calculation of the index of structural resilience using the generalized formula (1) is a super-complex combinatorial problem. At the same time, it should be noted that not all monotonic structures can be described using graphical models.

3 The Genome Concept to the Assessment of the TLS Structural and Functional Resilience in Conditions of Destructive Influences

To overcome the above features of estimating the TLS structural resilience, the following approach is proposed based on the concept of the genome structure [Kop10]. As a rule, the structural analysis of the functioning of a complex object begins with the construction of its functional integrity scheme (FIS) [Kop10], Pav18**.** The functional integrity scheme is a logically universal graphical tool for the structural representation of the studied properties of system objects. The functional integrity schemes allow to correctly represent both all traditional types of structural schemes (flowcharts, failure trees, event trees, graphs of connectedness with cycles) and a fundamentally new class of non-monotonic (non-coherent) structural models of various properties of the systems under study. The development of the TLS functional integrity schemes means, first of all, a graphical representation of the logical conditions for the implementation of its own functions by the elements and subsystems of the TLS. The second important aspect of building and further using the functional integrity scheme is an indication of the specific purpose of the simulation — the logical conditions for the realization of the system property being investigated, for example, reliability or failure of the TLS, etc.

It is known that the genome structure $\chi = (\chi_0, \chi_1, \chi_2, \ldots, \chi_n)$ [Pav18a], which is a concentrated representation of the structural state of the object, contains and allows to determine the following information in the process of structural study of complex objects: first, information about the topological properties of the structure of a monotone system; secondly, information on the belonging of the object under study to the class of monotone or non-monotonic systems; thirdly, to assess the indicators of the structural and functional resilience of the system.

For the formal description and analysis of the process of degradation (restoration) of the TLS, we will consider the operation of removing (restoring) critical elements $\{P_{j_1}, P_{j_2}, \ldots, P_{j_N}\} = \tilde{P}$ from the functional integrity scheme as factors for changing the structure. In the general case, all TLS functional elements can be considered as critical elements.

In the process of removing (restoring) elements, the TLS structure can be in one of its intermediate states S_α.

According to the concept of the genome structure, structural states S_α (initial, final, intermediate) are characterized by their genomes $\vec{\chi}_\alpha$ ($\vec{\chi}_\alpha$ by this material we mean the dual analogue of the genome), while the indicators of the TLS structural and functional resilience, consisting of homogeneous, non-uniform functional elements, depend on the reliability of their functions, can be calculated by the following formulas [Pav18a]:

$$F_{hom}(\vec{\chi}_\alpha) = \vec{\chi}_\alpha \cdot (1, \frac{1}{2}, \frac{1}{3}, \ldots, \frac{1}{n+1})^T \ ,$$
$$F_{het}\ (\vec{\chi}_\alpha) = \vec{\chi}_\alpha \cdot (1, \frac{1}{2}, \frac{1}{2^2}, \ldots, \frac{1}{2^n})^T , \quad (2)$$
$$F_{possib}\ (\vec{\chi}_\alpha) = \sup_{\mu\in[0,1]} \min\{\vec{\chi}_\alpha \cdot (1, \mu, \mu^2, \ldots, \mu^n)^T ,\ g(\mu)$$

We assume that the structural state S_α characterized by the genome $\vec{\chi}_\alpha$ is directly related to the structural state S described by the genome $\vec{\chi}$, if there is a functional element ($\exists P_j \in \tilde{P}$), the failure (restoration) of which ($P_j = 0$ or $P_j = 1$) takes the system from state S to state S_α (from state S_α to state S).

Let us designate this variation of the structural state of the PLS as follows: $\vec{\chi} \xleftrightarrow{P_j} \vec{\chi}_\alpha$. The set of all structural states directly associated with the state $\vec{\chi}$ is denoted by $X(\vec{\chi})$.

One of the possible trajectories of the reconfiguration of the TLS structure during the occurrence of failures (recovery) can be described by the following chain of transitions

$$\vec{\chi}_{\alpha_0} \xleftrightarrow{P_{j1}} \vec{\chi}_{\alpha_1} \xleftrightarrow{P_{j2}} \vec{\chi}_{\alpha_2} \xleftrightarrow{P_{j3}} \ldots$$

$$\ldots \xleftrightarrow{P_{jN-1}} \vec{\chi}_{\alpha_{N-1}} \xleftrightarrow{P_{jN}} \vec{\chi}_{\alpha_N},$$

Where $\vec{\chi}_{\alpha_0} = \vec{\chi}_0,\ \vec{\chi}_{\alpha_N} = \vec{\chi}_f$, the set $\{P_{j_1}, P_{j_2}, ..., P_{j_N}\} = \tilde{P}$, i.e. the set of failed (restored) element TLS in the transition chain is a permutation of the elements of the set $\tilde{P}$.

The structural changes occurring in the intermediate state $\vec{\chi}_\alpha$ on the reconfiguration trajectory will be evaluated by one of the indicators of the structural and functional resilience of the TLS (2) included in the considered set: $F_{failure}(\vec{\chi}_\alpha) \in \{F_{hot}(\vec{\chi}_\alpha), F_{het}(\vec{\chi}_\alpha), F_{possib}(\vec{\chi}_\alpha)\}$. In addition, in each intermediate structural state $\vec{\chi}_\alpha$, the TLS is characterized by a certain set of structural and topological constraints $\Psi_l(\vec{\chi}_\alpha) \le 0,\ l = 1,2,...,L,$ formally defined and quantified using (Pavlov et al. (2018)) relevant indicators of structural vitality, flexibility, reachability, structural complexity, etc. In other words, these restrictions define the range of allowable variations, which will be denoted in the following Ξ.

Then the task of building an optimistic (pessimistic) PLS reconfiguration scenario can be represented as the following optimization problems (3).

$$\sum_{j=0}^{N} F_{failure}(\vec{\chi}_{\alpha_j}) \to \max_{\substack{\vec{\chi}_{\alpha_j} \in X(\vec{\chi}_{\alpha_{j-1}}) \\ \vec{\chi}_{\alpha_0} = \vec{\chi}_0,\ \vec{\chi}_{\alpha_N} = \vec{\chi}_f, \\ \Psi_l(\vec{\chi}_{\alpha_j}) \le 0,\ l=1,2,...,L \\ \{P_{j_1}, P_{j_2}, ..., P_{j_N}\} = \tilde{P}}} (\min) \qquad (3)$$

In the work [Pav18a], a combined method of random directional search for solutions to the problem is substantiated and an algorithm is developed that implements the above method. The combined method and the corresponding algorithm allows you to search for both optimistic and pessimistic trajectories, as well as intermediate trajectories chosen randomly.

Then, as a generalized indicator of the TLS structural and functional resilience, in the process of its structural reconfiguration according to the scenario $\mu_\varsigma^{(k)}$, a relationship can be proposed $J^k = S_0^k / S^k$. Here $S_0^k = \sum_{j=0}^{N-1} \frac{F_{failure}(\vec{\chi}_{\alpha_j}^{(k)}) + F_{failure}(\vec{\chi}_{\alpha_{j+1}}^{(k)})}{2}$, it is equal to the TLS total structural and functional resilience functioning in the process of reconfiguration within the scenario $\mu_\varsigma^{(k)}$, and $S^k = \max_{j=0,1,...,N} \{F_{failure}(\vec{\chi}_{\alpha_j}^{(k)})\} \bullet N$ is proportional to the TLS total structural and functional resilience functioning along the trajectory if the possible maximum resilience of the function is maintained during the development of the considered scenario.

It should be noted that the maximum value of ***the generalized index of structural and functional resilience*** $J^{\max} = \max_k \{J^k\}$ will be achieved in the optimistic scenario of reconfiguration of the TLS, and the minimum value $J^{\min} = \min_k \{J^k\}$ - in the pessimistic one. We will conduct M simulation experiments. On each k experiment, a sequence is constructed $\mu_\varsigma^{(k)} = \left[\vec{\chi}_{\alpha_0}, \vec{\chi}_{\alpha_1}^{(k)}, \vec{\chi}_{\alpha_2}^{(k)}, ..., \vec{\chi}_{\alpha_{N-1}}^{(k)}, \vec{\chi}_{\alpha_N}\right]$ (where $\vec{\chi}_{\alpha_0} = \vec{\chi}_0, \vec{\chi}_{\alpha_N} = \vec{\chi}_f$) corresponding to the TLS reconfiguration trajectory. For the constructed trajectory, the value of the generalized index of structural and functional resilience $J^k = S_0^k / S^k$ is calculated. Next, we find the average value of the structural resilience of all tests $J^0 = \frac{1}{M} \sum_{k=1}^{M} J^k$. Then it can be argued that the real values of ***the generalized index of the*** TLS ***structural and functional resilience*** J_{SG} are in the interval [$J^{\min}, J^{\max}$] and the most expected value is J^0. In this case, the predicted values of the indicator J_{SG} can be set with a fuzzy triangular number (a, α, β), where $a = J^0$, $\alpha = J^0 - J^{\min}$, $\beta = J^{\max} - J^0$.

In addition, the calculation of the values of the structural and functional resilience index $F_{failure}(\vec{\chi}_\alpha) \in \{F_{hot}(\vec{\chi}_\alpha), F_{het}(\vec{\chi}_\alpha), F_{possib}(\vec{\chi}_\alpha)\}$ can be made on the assumption that the TLS structure consists only of elements that are homogeneous in the reliability of their functions, only elements that are not uniform in the reliability of their functions, and finally there are potential failures to perform their functions. For each of these three cases, by calculating the indicator values J_{SG}, we obtain, respectively, three fuzzy triangular results: (a^o, α^o, β^o),(a^n, α^n, β^n),(a^b, α^b, β^b). Then, as the value of ***the generalized indicator of*** the TLS ***structural and functional resilience*** J_{SG}, we will assume the average value of the results obtained $J_{SG} = \frac{(a^o, \alpha^o, \beta^o) + (a^n, \alpha^n, \beta^n) + (a^b, \alpha^b, \beta^b)}{3}$.

Thus, the task of calculating the value of ***the generalized indicator of the structural and functional resilience*** of the TLS has been reduced to the analysis of optimistic, pessimistic or random (arbitrary) trajectories of the structural and functional reconfiguration of the object, caused by failures (restoration) of the TLS functional elements.

It should be noted that the failure (recovery) of an element leads to the failure (recovery) of the remaining TLS functional elements logically associated with it. Therefore, in addition to the introduced generalized indicator of the TLS structural and functional resilience J_{SG}, it is possible to introduce an ***absolute index of the*** TLS ***structural and functional resilience***. Each trajectory of the reconfiguration of the TLS structure is characterized by the number of degradation levels J_D, the last of which corresponds to the transfer of the TLS to an inoperable state. So for a pessimistic trajectory the number of levels is minimal and equal $J_D^{\min}$, for an optimistic trajectory it is maximal - $J_D^{\max}$. The values of the absolute indicator of the TLS structural and functional resilience J_{AG} will lie in the interval [$J_D^{\min}, J_D^{\max}$], and you can also calculate the most expected value equal J_D^0. In this case, the values of the indicator J_{AG} are similar, as well as J_{SG}, can be set with a fuzzy triangular number (a_A, α_A, β_A), where $a_A = J_D^0$, $\alpha_A = J_D^0 - J_D^{\min}$, $\beta_A = J_D^{\max} - J_D^0$.

4 Numerical example

We explain the major determinants of the proposed method using an example. Consider an TLS given in Figure 1.

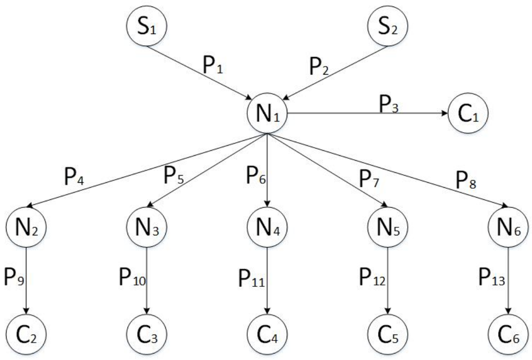
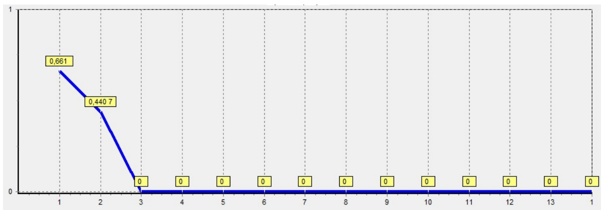


Figure 1: TLS structure

The simplified TLS in Figure 1 comprises fourteen nodes, i.e., the TLS elements (nodes S_1 and S_2 are sources, i.e., suppliers; node N_1 – Main Warehouse which receives the products from the suppliers; nodes N_2 – N_6 – Regional Warehouses who receives the products from the main Warehouses; node C_1 – Customers region which is served by the main warehouses; nodes C_2 – C_6 – Customers regions which are served by the regional warehouses) and thirteen arcs.

The computational example for the TLS design given in Figure 1 is considered. Based on the genome method, the edges 1, 2, and 3 have been shown to be critical in the TLS considered. In Figure 2, the corresponding robustness assessments and disruption scenarios are presented according to different structural degradation levels.

In Figure 2, the structure dynamics scenarios are depicted. $S_{i_1, i_2, \dots, i_k}$ denotes the structural states where disrupted operations (*edges*) in the TLS from Figure 1 are described by indexes $i_1, i_2, \dots, i_k$ on the abscissa scale. The state transitions are disruption-driven. In this context, a state represents the TLS (i.e., the graph G= (V, E)) as a network of non-disrupted and disrupted elements. Since the structural genome represents the TLS design, each structural state S_α can be described by a genome χ_α. Therefore, the total robustness or total failure of a path in the TLS structure dynamics can be computed using Eqs. (2).



a)

b)

c)

Figure 2: Structural robustness and disruption scenarios a) pessimistic scenario, b) optimistic scenario, c) arbitrary scenario

In the example in Figure 2, different degradation levels are shown. The degradation level 1 reflects the states with a failure in a single element that does not result in any other consequently disrupted TLS elements. The advantage of using the robustness computation by the genome method is that this allows both disruption scenario identification and the corresponding path of the ripple effect. As such, the results of this structural analysis can be used further to optimize the network reconfiguration paths with consideration of the operational TLS parameters such as capacities, processing intensities, and inventory storage. However, even in the structural analysis without a parametric optimization, the method proposed allows the critical TLS elements, the disruption of which would result in a non-fulfillment state, to be identified.

5 Conclusions

The aim of this research was to establish an explicit interrelation between the disruption scenario recognition and the optimization of the TLS reconfiguration paths – a distinctive and substantial contribution made by our study.

Our study explicitly includes the risk aversion of decision-makers both in the disruption scenario detection and reconfiguration path optimization. Such a combination is unique in the literature and mimics the complexity of business reality affording for more realistic applications to TLS design and sourcing planning. A distinctive feature and novelty of the proposed approach is that on a single methodological basis (the original concept of the genome of the structural construction of structurally complex objects) it is possible to carry out a study of structural and functional properties and carry out an operational calculation of interval, optimistic and pessimistic estimates of structural vitality indicators as monotonic, non-monotonic, and homogeneous, heterogeneous TLS structures. The proposed indicators of the functional structural resilience, in the case of predictable, and especially unpredictable disruptions, will allow to analyze and evaluate the resilience of a particular TLS configuration.

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