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CHAPTER 3

COORDINATION OF MATERIAL AND INFORMATION FLOWS IN INTERCITY LOGISTICS SYSTEMS

ABSTRACT

The problem of the effectiveness of the use of road transport in logistics systems is considered. Carriers attract additional motor vehicles according to increasing in freight turnover, namely in long-distance routes. The trend of growth in the volume of transportation and the distance of cargo transportation has been maintained in recent years, despite the crisis periods in the economies of the European Union countries. However, the increase in the number of vehicles of fleets is accompanied by an increase in their idle time and delays in the delivery of goods. This phenomenon is explained by the lack of necessary coordination of material flows on the transport network. We considered two types of material flows, namely cargo flows and automobile flows. Both types of flows are discrete in nature. In order to represent the interaction of material flows in the logistics system, the term elementary logistics operation is used, which is the smallest constant element of the logistics chain. Despite the wide variety of processes that occur in logistics systems, the number of typical elementary logistics operations is limited and quite small. For the numerical characterization of material flows, such parameters as a tact, a front, the size of a group of material elements, and the average intensity of the flow are used. Based on the known dependencies between these parameters and taking into account the connections of elementary logistics operations, a structural model of logistics chains is built. It is taken into account that information messages in the logistics system arise when material flows change. The impact of changes in the intensity of cargo flows in logistics chains has been studied and the majority of sources of information messages in space and time have been determined. It has been proven that the use of the objectively necessary amount of information with the necessary advance time makes it possible to reduce dynamic and static delays of cargo flows to a minimum. Due to the fact that changes in the intensity of material flows occur stochastically in logistics chains, the feasibility of assessing the resistance of a given logistics system to external disturbances was developed. The influence of information provision of truck crews performing transport tasks on highway connections is studied. An information support scheme has been developed on the terms of cargo delivery with the need for the truck to arrive at the unloading point on time.

KEYWORDS

Cargo delivery, material flows, intercity transportation, continuity principle, discrete flows, sources of messages, stabilization, logistics system, flows delay logistic chain.

3.1 INTERCITY AND INTERNATIONAL TRUCK DELIVERING OF GOODS. PROBLEMS AND SOLUTIONS

The freight turnover of road transport and the delivery distance of 1 ton of cargo in the logistics systems (LS) of Europe has a steady upward trend, despite the past crisis periods of 2014 and the coronavirus pandemic of 2019–2022. This trend has been observed in recent years. Thus, the average volume of cargo transportation by road transport in the European Union in 2008–2016 was 14.86 million tons. This volume was slightly higher in 2008–2012. The volume of cargo transportation began to grow again, starting from 2014. However, this value did not reach the average level established for the European Union for the period 2008–2016 until 2016. The results of the conducted research indicate that in the period 2014–2016, the mass of goods transported by motor vehicles grew [1]. The same trends were observed in Ukraine. The cargo turnover of road transport in Ukraine amounted to 311.0 billion t-km in January-November 2020 or 102.4 % of the volume of the same period in 2018. The data on the distance of transportation of 1 ton of cargo indicate that in the structure of road trunk transportation occupies a prominent place in Europe. However, the given data do not contain a forecast of the consequences of such a trend, nor have the reasons for the corresponding growth been identified. This was all because the obvious purpose of the research was only to provide conditions for the future planning of the transport business. Therefore, one of the distinctive features of the modern economy is the growth of the share of road transport in intercity and international trade [2, 3].

It was shown in the work [4] that the satisfaction of the growing demand for long-distance freight transportation occurred due to an increase in the number of small and medium-sized transport companies. The growth is even faster due to the renewal and increase in the number of trunk road trains. However, not all researchers note that an increase in the total number of rolling stock units does not lead to a proportional increase in their carrying capacity [5]. Such a fact was not recorded by them due to outdated approaches to evaluating the performance of trucks on long-distance routes. In addition, the increase in the number of small transport companies in Ukraine is a consequence of the artificial division of enterprises in order to minimize taxes [6]. The number of new registered motor vehicle enterprises in Ukraine is decreasing [7]. Both internal and external competition in the market of transport services is growing with the indicated trends. Also, the fleet of motor vehicles, although being updated, still remains with outdated vehicles, which reduce its competitiveness and reliability of use. However, the main cause for the low productivity of trucks and road trains on intercity routes is the lack of clear communication of their crews and coordination of the information available to them. Thus, starting from 2014 to 2021, the mileage of trucks in Ukraine with cargo increased from 4042.5 to 6031.3 million km and to 6332 million km in 2020. The mileage without cargo changed, respectively grew up from 1767.8 to 3460.3 million km by 2017 and to 3021.4 million km in 2020. That is, the mileage utilization ratio decreased from 0.56 to 0.42, and then increased to 0.67 [8].

The 2014–2017 period is characterized by the main signs of a negative management of transportation processes, such as low mileage and output ratios of trucks due to a rapid increase in the number of carriers. At the same time, connecting links, i.e., logistics companies that have the most information about freight transportation, began to develop only in 2015. Companies that provide 3PL logistics services and did not have 4PL or 5PL functions in 2019 have only established themselves in Ukraine, at a time when such companies are widespread in the world.

The peculiarities of the organization of intercity road freight transportation in modern conditions are sufficiently fully researched. However, there are quite a few works that note that time has also become a very important resource in modern transport processes of intercity large-scale cargo delivery. This is due to the growth of freight traffic, significant competition of motor transport companies, restrictions on the modes of operation of road trains and the work of their crews. So far, it is used irrationally (**Fig. 3.1**). The conducted studies show that the forced downtime of motor vehicles on long-distance and international routes largely depends on the properties of the routes [4, 9, 10]. In general, these downtimes reach 75 % of the duration of the transport cycle. However, on long international routes there is an increase in the share of inter-shift rest for drivers. However, there were no actual reasons for the increase in downtime in the specified publications. The main reason for this shortcoming is the lack of understanding of the transport process as a discrete sequence of relevant operations that differ in properties, so they may be uncoordinated in the process.

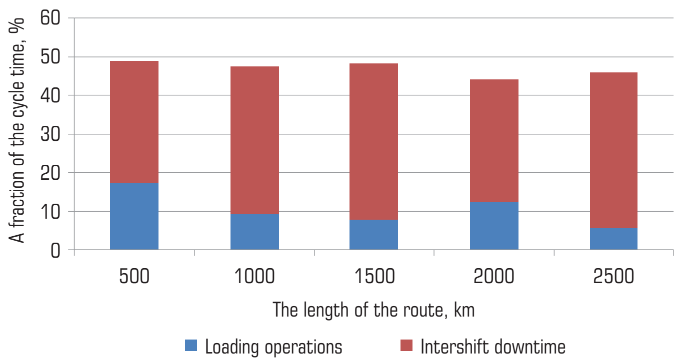

Fig. 3.1 Dependence of the structure of individual time losses for long-distance transportation of goods on the length of the route (author's research) [11]

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The approximate cycle time structure is as shown in **Fig. 3.2** on most long-distance routes (500–700 km).

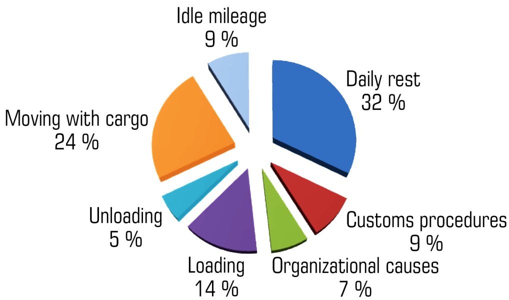

Fig. 3.2 Cycle time structure of long-distance and international freight transportation by road (author's research) [11]

The organization of intercity road transportation also has certain features that increase the problem of truck fleet productivity. Firstly, it is a considerable distance from the points of departure to the reception of goods, in which the duration of the entire process depends on the moment of departure and arrival of the road train at the place of delivery of the goods. Secondly, it is a useless mileage of motor vehicles (MV), which significantly increases the cost of transportation, so carriers cannot allow it. And thirdly, it is a wide geographical distribution of points of formation and absorption of cargo flows, due to which the development and observance of the schedule has significant limitations.

The problem of the productivity of the rolling stock has significantly worsened in connection with the significant competition of automobile carriers. Refusals occur in case of non-compliance with the terms of service provision, or non-compliance with the guaranteed parameters of the process. Across the country, they lead to inefficient use of rolling stock and delays of cargo delivery. The estimated average output ratio of the fleet of mainline MV in Ukraine is 0.45...0.66, and the average speed of cargo delivery in long-distance traffic, depending on the type of cargo, is 26...34 km/h. Therefore, on the one hand, refusals can be caused by a carrier that does not comply with delivery terms and quality of transportation. The carrier may refuse to fulfill the application due to the lack of practical benefit, on the other hand. Refusals are perceived by their customers as a reason for canceling further cooperation. In the conditions of fierce competition of carriers. As a result, the receipt of subsequent orders for transportation is reduced [11].

The work of long-distance and international carriers has recently become more difficult under the influence of a number of factors. The financial load on them has increased significantly during 2015–2021 due to a number of reasons: the prices of fuel and lubricants have risen sharply, tax rates on vehicle owners have increased, some foreign countries have introduced additional road fees and fuel import restrictions, there are additional costs and restrictions, related to the need to issue permits and other obstacles [12]. However, the statistical reports do not contain the true reasons for such financial aggravation. This leads to the need to conduct additional research to identify such causes.

Logistics and information technologies are the key to increasing competitiveness and sustainable growth of transport and industry as a whole. Today, the efforts of many enterprises are directed to the creation of their own logistics divisions or integration into regional logistics centers [13]. It starts from economic necessity. Brand logistics centers began to develop in Europe from the 1980s, which was associated with a wave of bankruptcies of wholesale trade enterprises. Mostly medium and small companies that had an outdated organizational structure and a large number of employees went bankrupt. Large firms that had sufficient financial resources to reorganize and create logistics centers, which increased the efficiency of their work, survived. Small firms that had a modern flexible production structure also survived. At the same time, new small and medium-sized companies with logistics centers and a simple and economical organizational structure were created. Ukrainian enterprises are trying to apply such positive experience, often without restrictions. As a rule, large firms that use modern management methods based on the latest information technologies (IT) achieve the greatest success. Positive results of small enterprises obviously depend on the content of integration processes. This means that there is a need to describe these processes using parametric models. However, since the approach of decomposition of a complex system is used, the essence of the effect of the centralization of transport and warehouse operations cannot yet be formalized [14].

Logistics operators of the 4th generation (providing 4PL services) have successfully coped with the functions of information provision and management of transport processes until now. The best 4 of them come from the EU and outside the global environment of the Top 10. Seven of them are in the EU [15]. However, there are forecasts that in the next 10–15 years, 90 % of the growth of the world economy will take place outside the EU [12–16]. EU countries therefore have an interest in ensuring that their companies remain competitive and can access new markets and benefit from these sources of growth. This requires the use of a wide range of information technologies and a new approach to the formation of logistics systems (LS).

A characteristic feature of international road transportation of goods is the high mileage of MV on routes [17]. To increase the efficiency of this type of transportation, it is necessary to pay special attention to the process of searching for and selecting return loaded rides. The task of cargo transportation in the accompanying/return directions is partially solved, which is connected with the development of transport and information portals on the Internet. However, the problem of choosing a rational transportation option from a set of alternatives remains relevant [16]. The decision to accept this or that cargo for transportation is currently made by managers of carriers based on intuitive decisions of personal practical experience. As a rule, such strategies for making a decision about choosing a rational return trip come down to the fact that the vehicle transports the cargo whose waiting time is minimal. The work [15] proposes new decision-making strategies based on the processing of statistical information on the choice of rational return transportation.

However, the authors of the study chose statistical modeling as a methodology, which made it possible to adopt only one of the alternative strategies for building a transport cycle for the entire MV fleet in general. This is a non-detailed technique and it does not allow to develop a flexible strategy in a case where there is an opportunity to use available information. The authors consider the organization of random one-off orders. One of the reasons for the wide popularity of the use by cargo owners of such a form of concluding contracts as "one-time order" is the powerful development of information technologies, which caused the emergence and successful functioning of specialized logistics sites.

The authors of the work [15] also apply the theory of mass service systems (MSS) to plan a set of such orders, and use simulation modeling for verification. However, it was not taken into account that the freight market may have a situational advantage of supply over demand, or vice versa.

The roadmap for the development of highway road transport indicates that the use of IT can solve the current problems of highway freight transportation [17]. However, this requires a more thorough approach to the analysis of operational information, decision-making and control over their implementation. In this regard, Ukraine should focus on advanced EU countries, its producers and transport and logistics firms. Although they represent considerable competition, there are no objective obstacles for them to integrate Ukrainian carriers into the European market [16]. The benefits that Ukraine can gain from transport integration will be both direct and indirect. Direct benefits are less obvious, but available: increased access to markets, increased volume of transportation and export of transport services, inflow of capital, modernization of infrastructure, direct supply of resources from the EU, budgetary support. Intermediate benefits are more accessible: improved distribution of productive factors, redistribution of cargo flows, improvement of the efficiency of economic processes of transport and service enterprises, improvement of transport service provision standards and the level of transport safety, reduction of barriers in relations between states of EU.

Large European heavy trucks carriers face the problem of underloading their fleets due to the uneven flow of orders, low capacity of cargo terminals, and due to non-systematic planning of transport processes in most cases. A similar situation is typical for Ukraine. In addition to the indicated shortcomings, it is also possible to note the low actual level of industrialization and standardization in the segment of transportation. Product supply processes are demand-driven with very short predictable schedules. A rather low level of planning certainty is also characteristic. The lack of information about the chronological and geographical appearance of subsequent orders makes it a problem to effectively use the MV fleet, and ensure the compliance of drivers' work and rest modes. Management of transport companies operating costs increase every year since the carrying capacity of MV fleets significantly exceeds the volume of orders for intercity road freight transportation, despite their efforts [12]. Ukrainian carriers, for example, are trying to reduce the useless mileage of trucks. Carriers use various information systems for forecasting demand, planning the schedule of individual crews [18–20]. However, the information service will not work if it does not have a functional connection with cargo flows. Examples of this are software and information tools used by carriers. The most popular of them can perform many functions, including: search and selection of customers, free vehicles, drawing up routes, processing documents, calculating the cost of trips and so on. These systems make it possible to reduce downtime and wasted mileage of individual trucks. However, most of the management decisions of carriers are unsystematic. In return, transportation companies receive underutilization, downtime, and even disruptions in order fulfillment. At the same time, fines for cargo owners are inevitable. After all, companies do not take into account the basic directives of medium and large vehicles, in which vehicles can be used as efficiently as possible [20]. Therefore, the tasks of their effective operation must be solved in new conditions. First, the individual vehicles of the fleet must be coordinated. Secondly, orders for cargo transportation should be systematic, preferably periodical. Third, information about the origin and properties of orders should be used as efficiently as possible.

Carriers, which use automated information systems, are able to forecast orders in advance and allocate available MV to them. Thus, they manage to partially avoid unproductive transportation costs. However, the dynamics of order fulfillment during the planned period is significant. They are interdependent often. This imposes additional restrictions on the timetable of road trains that serve customers. The essence of the problem of organizing transportation by modern MV fleets is that two conflicting requirements are put forward to them. On the one hand, the work of the aggregate of MV should correspond to the received information about potential cargo flows and ensure the fullest possible satisfaction of the known demand. Mileage without cargo is excluded. On the other hand, the complex structure of a single transportation process for a fleet of interacting trucks has a random and cyclical character [19]. This leads to forced stoppages of road trains due to the inconsistency of their work schedule. There is obviously such a schedule that is optimal according to the specified criteria and restrictions in this regard. However, there are no prerequisites and regularities for the functioning of such schedules in the publications. The reason for this is the lack of a suitable discrete-event approach to modeling cyclic transport systems. According to scientists' conclusions, problems of this kind are solved in the context of the implementation of IT, that is, a self-organizing system and automated logistics, which is provided by intermodal transportation and efficient use of infrastructure in all modes. Road maps of the European Road Transport Research Advisory Council (ERTRAC) emphasize that long-distance and regional freight transport must become even more sustainable, while maintaining transparency and accessibility for users and system participants [21]. However, the real patterns of the development of intercity road freight transportation have not been analyzed.

As trucks carry more than 71 % of all goods transported by land, the HGV sector is the backbone of efficient freight transport in Europe. At the same time, this sector contributes to the further integration of different parts of Europe. Today, annual scientific reports of researchers note the following trends:

– approximately 29 million road trains operate on the roads of Europe and are used for long-distance transportation;

– harmful emissions from heavy vehicles are increasing and account for almost a quarter of all ground transport emissions; by 2030, CO_2 emissions are expected to increase by up to 10 %;

– due to the increase in the number of MV on highways, traffic jams and delays at transport points are increasing [22]. In addition, the known studies do not indicate that there is a growing contradiction, the meaning of which is that when the transport capacity of the carrier's fleet of vehicles increases, the duration of downtime of the rolling stock often also increases.

So far, no significant attention has been paid to the loss of time of MV while driving on intercity roads. However, traffic congestion in the EU often occurs both in and around urban areas and is worth almost €100 billion in additional costs each year, i.e. roughly 1 % of EU GDP. There are limits to how much new road infrastructure can be built because there is a strong demand for longer road life. According to the founders of the program [23] the problem of delays and traffic jams will be further aggravated by improving the use of the existing capacity of the trunk transport network. However, the authors of the program did not specify the obvious reasons for this phenomenon. New ways of organizing freight transportation and logistics in order to overcome growing electronic commerce and new technologies can also contribute to the solution of these problems. Examples can be the automation of truck traffic and processes, as well as new trends in the organization of public transportation that affect the environment. "Seamless freight transport" is important to increase the efficiency of operation and avoid overloading of trunk transport networks [24]. Freight transportation should gradually develop as integrated packages of services for the delivery of goods and raw materials, increasing the load factor, avoiding idle runs and gradually turning into a single information space. Realization of the possibilities of using digital information in road transport is a key factor in the stable delivery of goods [25]. But this should be preceded by deeper studies of information and cargo flows.

Another key point of long-distance freight transportation is the creation of multimodal solutions that contribute to the standardization and automation of loading and unloading processes to minimize the time of overloading and complexity between different modes of transport. For example, communication between "smart" vehicles and infrastructure requires harmonized infrastructure development, as well as appropriate investments by national, regional and local authorities, and the private sector. Timely prediction and early initiation of these measures is extremely important. According to the forecasts of ERTRAC SRA 2050 and ALICE Integrated Transport System, the overall goal of road freight transport is to develop affordable and efficient freight delivery solutions for European citizens. This includes intelligent logistics solutions, smart modal infrastructures and robotic cargo delivery. According to this vision, the supply chain in the future should be continuous, coordinated and environmentally safe [26]. But the theoretical basis for streamlining and optimizing supply chains from well-known sources of research is still unknown.

An important component of efficiency is the avoidance of idle runs or unclaimed vehicles. According to the AEROFLEX-27 project report, the optimization of vehicle loading refers to the reduction of empty mileage, as at EU-28 level, a quarter of all trips were made by empty vehicles (25.4 % in 2016). The share of empty runs increased to 30.3 % in domestic transport, but in international transport in 2018, it was only 14.3 % [27]. As for the priorities for the introduction of automated management of highway transport by 2030, a higher level of automation is expected in limited areas and points where the transport environment is predictable, the average speed of traffic is relatively low, and traffic can be fully controlled [23]. The complexity of IT, their application, connection and implementation of automation for the management of MV and infrastructure is constantly increasing. This is a significant obstacle to the introduction of IT. It is also important to develop decision-making strategies regarding the operational control of the MV, in particular for heavy-duty trucks. Convergence of transport and information systems is a priority task of scientific research in Europe. It is important to develop and implement reliable, complementary and highly reliable control systems and vehicle positioning technologies [27].

Labor costs make up from 35 to 45 % of operating costs for long-distance freight transportation in Europe [5]. In addition, limits on the amount of time a driver can drive in a given day or week limit the speed and availability of a long-haul truck, where individual drivers are attached to each rolling stock unit. At the same time, truckers may struggle to attract drivers for such long-distance trips. Obviously, the opportunity opened by cargo delivery automation changes the initial labor costs, and relaxes travel time restrictions, increases the productivity of MV, would be of great interest [28]. Automated vehicles provide the opportunity to revolutionize the field of highway transportation. When used correctly, automated commercial truck can increase the efficiency, flexibility and overall profitability of fleet operations. It also has great potential to effectively reduce travel costs due to congested traffic, improve driver behavior, reduce driver labor costs, and increase fleet mobility and safety. According to the International Road and Transport Union's (IRU) 2017 report, Managing the Transition to Driverless Road Freight Transport, reductions in operating costs are likely to be much greater in long-haul haulage. The labor payment accounts for a larger share of the cost base than in urban freight transportation there. In work [22] it is indicated that, in general, up to 30 % reduction of operating costs for freight transportation over long distances is possible when operating without a driver. However, this does not stipulate what achievements the carrier receives. However, there are no detailed data on the coordination of information flows with the processes that occur during cargo delivery.

The expansion of traffic flow management systems, the interaction between traffic control centers, service providers and individual vehicles, should optimally combine the information coming from the point of departure, information about road traffic and the service provider for the planning and optimization of highway freight transportation [26].

To increase the efficiency of freight transportation, more volumes of data are available, some of them are collected in "smart" infrastructure, equipped with various sensors, connected to transmission networks [29]. This data may be combined with that coming from vehicles and other sources for various purposes:

1) to assess the interaction of vehicles and infrastructure;

2) to facilitate the operation of the vehicle, provide some services or improve its safety;

3) to assess the impact of vehicles on the infrastructure, possible damage to road clothing and its service life;

4) to ensure constant monitoring of traffic and infrastructure.

Therefore, monitoring, diagnosis and maintenance of the road infrastructure are crucial to strengthen the existing restrictions. For example, data collection based on weighing in motion (Weight Into Movement (WIM)) on highways and other roadways makes it possible to carry out prevention, save money, without disrupting the operation of MTM as a whole [29].

On-board monitoring of MV (for example, weighing in motion, measurement of friction force on the road/tire, evaluation of the rolling resistance coefficient) provides a data that can be used for sustainable assessment of the infrastructure and, thus, effective diagnostics of the LS during its execution is carried out. This requires a high the level of communication between stationary and mobile logistic facilities, and communication between the vehicle and the infrastructure as a whole. Such accurate and constant monitoring is necessary to ensure higher loads or traffic intensity, a longer service life, but to maintain the accepted safety factors for greater productivity of MV in general.

3.2 DYNAMICS OF CARGO FLOWS AND INFORMATION SOURCES IN CYCLICAL LOGISTICS SYSTEMS

Goods delivery of in LS, especially those where road transport is used, is their periodic adjustment to the conditions of material production and consumption, which design discrete material flows [30]. Adaptation takes place on the basis of changes in the structure of logistic chain (LC). Therefore, the execution of logistics operations is a source of informational messages in LS. As their intensity increases, the structure of the LC becomes more complex. The structure of such operations is mostly branched. The varying duration of operations, and their structure, and random nature lead to the presence of non-productive states of delivery processes, i.e. delays in material flows. We have formulated a hypothesis that there are such sequences of logistics operations in which the total number of undesirable states will be minimal.

We will determine the adaptability of the LS of cargo delivery to changes in the parameters of incoming material flows (MF) associated with fluctuations in demand for products delivered, taking into account the known forecast. We will MF henceforth the totality of goods, including transportation means and objects, which change their spatial location relative to any two phases in a time that does not exceed the duration of their physical wear. Consumer properties of goods of any two phases do not differ significantly. MF is the spatial movement of objects and means of transportation, which are unchanged [31]. The primer physical unit of the MF is the material element (ME), which is the smallest indivisible part of the MF. Moving ME in time and space does not affect its internal structure and properties. These properties are manifested only in interaction with other elements of MF. Let's call such events *Elementary Logistics Operations* (ELO). Thus, ELO is an action aimed at changing the direction, speed, duration of spatial movement of ME. A sequence of homogeneous events that occur one after the other at random moments of time is called a flow of orders for the transportation of goods. In order to reflect the essence of material flows on trunk transport network (TTN) we will apply the following principles of their objective consideration.

The principle of elementality of material flows comes down to the fact that the smallest indivisible material element of the material flow is singled out, as well as the smallest indivisible part of delivery process is an elementary operation. ME is a part of combined groups, which can be a container, a transport package, a shipment group, a production group, etc. There are a finite number of elementary logistic operations. Elementary operations are invariant in structure and properties. However, they are characterized by such interconnections that form larger structures. Thanks to the finite number of elementary operations, it is possible to synthesize an almost infinite number of operations and processes according to established criteria.

The principle of continuity of the material flow, which also applies to discrete flows. To formulate it, we mean that a discrete MF is characterized by a sequence of moments of the beginning (completion) of elementary operations / a group of elementary operations. A changes in the direction, speed of movement or the number of material elements in a single group occur during the period when a qualitative change in the flow is present. In this case, the principle of continuity is that in any *i*-th continuous time interval $\Delta t = t_i + 1 - t_i$ in any completed part of the MF, the number of material elements is a constant value. This can be interpreted as the number of ME entering a given phase of the MF per unit of time is equal to the number of ME leaving this phase.

The principle of rhythmicity consists in the fact that the duration of each ELO is directly proportional to the size of the group of material elements and inversely proportional to the intensity of the MF that passes through it. That is, the dependence is valid for each *i*-th division of the MF:

$$\mu_i = \frac{k_i}{\tau_i}, \qquad (3.1)$$

where k_i is the size of the ME group; τ_i is the *tact* of the discrete MF.

The model of typical LS of cargo delivery from the manufacturer M, by trunk transportation, to the distribution point Dp and to consumers C is shown in **Fig. 3.3**. Each ELO is evaluated by three parameters: duration t_i, tact τ_i, group size k_i, manufacturer f_i. The intensity of the MF on every *i*-th successive ELO is constant and is determined by expression (3.1), in connection with the principle of the indissolubility of the MF [32]. If the consumer's demand for products increases, then the intensity of material flows in LS should increase. However, this can happen successfully under two conditions. The first is: information must be provided to manufacturer M in a timely manner (in **Fig. 3.3**, the information flow is shown by a dashed line).

The advance time of information submission is comparable to the duration of the LC:

$$t_{adv} = \tau_4 \cdot f_2 + \tau_4 + \tau_3 + \tau_3 \cdot f_1 + \tau_3 + \tau_2, \qquad (3.2)$$

where the tact rate of each *i*+1 ELO acceleration/deceleration is determined by the expression:

$$\tau_{i+1} = \frac{k_{i+1}}{k_i}\tau_i, \qquad (3.3)$$

and the front of trucks on the routes will be determined by the expression:

$$f_i = \left[\frac{t_{m.i}}{\tau_i} \right], \qquad (3.4)$$

where $t_{m.i}$ is the mathematical expectation of the duration of movement on the i-th route; the expression enclosed in square brackets is rounded up to an integer.

Taking into account expressions (3.3) and (3.4), with constant values of the sizes of transport and consumer packages, the volume of vehicle loading, expression (3.2) will be rewritten in the form:

$$t_{adv} = \frac{1}{\mu}\left((f_1 + 1) k_4 + (f_2 + 1) k_3 + k_2 \right). \qquad (3.5)$$

The dependence of the time required to satisfy the demand on the intensity of the material flow of the given LS is shown in **Fig. 3.4**.

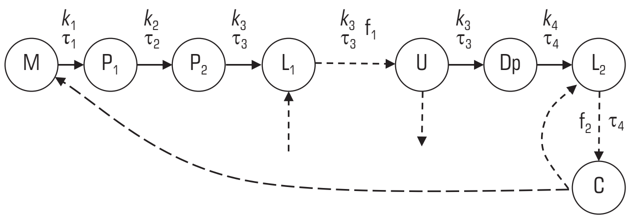

Fig. 3.3 LS of cargo delivery: M – manufactory; P_1 – packaging of goods into a consumer packages; P_2 – packaging of goods into a transport packages; L_1 – loading on a trunk road train; U – unloading; Dp – distribution of packages by consumers; L_2 – loading on a light-duty vehicle; C – consumer; $\tau_1 ... \tau_4$ – ELO tact; $k_1 ... k_4$ – size of cargo group; f_1, f_2 – fronts of motor vehicles on routes

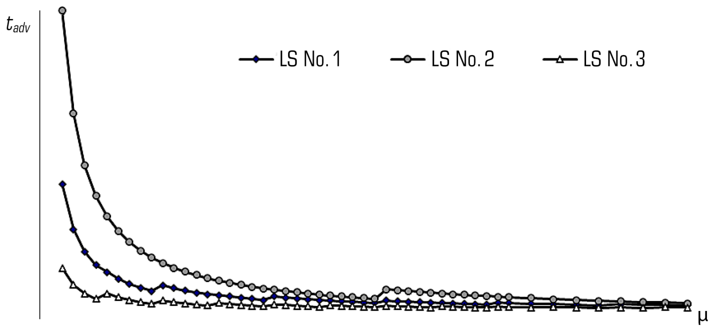

Fig. 3.4 Dependence of the necessary time advance for forecasting the demand for products on the intensity of the material flow, and the structure of the LS that provides it

Fig. 3.4 shows three dependencies for three LS models. The model of LS No. 1 is shown in **Fig. 3.3**. LS No. 2 corresponds to LS No. 1 functionally, but has a shortened structure. LS No. 2 does not have a Dn distribution center and the delivery of goods to consumers is carried out by a heavy duty trunk train. LS No. 3 is similar to LS No. 2, but transportation is carried out by a light trucks. As can be seen from the **Fig. 3.4**, the resulting dependencies are piecewise continuous. The longer the forecasting horizon (the time of the forecasted period), the more cost LS needs [33]. On the other hand, the forecasting horizon indirectly affects the amount of necessary information for managing the LS as a whole object. This time advance is too important for those LS that are characterized by high intensity of MF (small flow cycle). However, this importance is weakened if the LS becomes less dependent on product and cargo warehousing and more if its LC is shortened.

The second condition for the increase in the intensity of the MF with the growth of demand is the successful adaptation of the LS to new requirement, which is the suitability of its structure for operational restructuring. The suitability was investigated using the next example. Let's assume that at the *i*-th moment, manufacturer M (**Fig. 3.5**) received information about the demand to increase the intensity of MF μ by the amount $\Delta\mu$. Manufacturer can do it without disrupting the technology at the current production capacity by reducing the output cycle τ_1. However, the next phase of the LC is the ELO of the package P_1, which we denote by $i+1$. P_1 is not adapted to such a flow pulse like the subsequent phases of the LC. Therefore, part of the products will remain unpackaged in the manufacturer's warehouses. This is shown in **Fig. 3.5** by introducing additional ELO S_1 – first stage of storage.

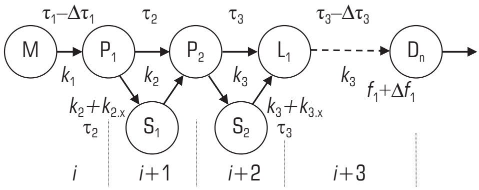

Fig. 3.5 Fragment of the LS when the material flow is increased by $\Delta\mu$

As it is possible to see, the introduction of S_1 is accompanied by additional delays of the MF part for one cycle τ_2. The next $i+2$ phase is characterized by the same impulse and, accordingly, the needs for a new stocking and a new delay τ_3. It is impossible to reserve cargo during the transportation operation, so the flow must be accelerated by the amount of $\tau_3-\Delta\tau_3$ using additionally involved MF. The front of MV will increase by Δf_1. Therefore, in such a LS, the pulsation of the MF is maintained by:

a) storage of products/cargo;

b) involvement of additional transport and technological means.

Case (a) is characterized by flow delays, (b) – by accelerations. The total delays at positive $\Delta\mu$ account for only part of the MF. Therefore, to assess the degree of adaptation of LS to new conditions, it is advisable to use specific delays in the products transportation per physical unit:

$$\Delta_k = \frac{\tau_2}{k_{2x}} + \frac{\tau_3}{k_{3x}} - \frac{\Delta\tau_3}{k_3} + \frac{\tau_3}{k_{3x}} + \frac{\tau_4}{k_{4x}}. \quad (3.6)$$

If $\Delta\mu$ is negative, that is, the intensity of the MF decreases. Then such a "wave" along the LC is balanced by a temporary decrease in the group of material elements: the sizes of transport and consumer packages, the degree of loading of the MV. This leads to the following consequences: on the one hand, MF is accelerated due to a decrease in the amount of stock of packages in warehouses. On the other hand, the MF slows down due to the reduction of the MV front during transportation. Reducing the size of packages also leads to a violation of the technology of transportation operations, as a result the cost of delivery increases. Using expressions (3.3)–(3.6), it can be shown that the ratio of the production cycle before and after the decrease in the intensity of MF in the LS is related to the ratio of the sizes of packages:

$$\frac{\tau_1}{\tau_{1.1}} = 1 - \frac{\Delta k}{k_2}. \quad (3.7)$$

As many times as the input tact increases, the size of the goods group in the consumer/transport package decreases by the same amount.

3.3 ANALYSIS AND ARRANGEMENT OF INFORMATION FLOWS

Information flows play a key role in modern goods delivery processes. This is confirmed by a number of publications, for example, [34–37]. It has been proven that the synergistic effect of a large LS, which is characteristic, for example, of logistics centers, is a consequence of the centralization and concentration of operations of an informational and analytical nature [18]. However, there are very few works where such an effect was reflected in models and was reproduced under different flow conditions and external disturbances.

The entire volume of telemetric signals that is received by the driver/crew of a cargo MV performing the transport task of goods delivering to the LS can be conventionally divided into four categories, in the form of discrete messages. These are such messages. The first type I_1 is a message about own current coordinates and speed received from Automatic Vehicle Location (AVL). The second type is the I_2 message about traffic conditions (phase density of traffic flow, intensity, and others), received, for example, from Automotive Short Range Radar (SRR) or from cellular communication dispatch centers. The third type is a I_3 message about probable delays at the destination point. The fourth type is the I_4 message about road conditions (coefficient of adhesion, micro- and macro irregularities, etc.) obtained, for example, by comparing messages of the I_1 type from the

Global Positioning System (GPS) and from on-board measurement systems. Messages I_1–I_4 can be received in discrete-quantized form, in independent streams. But these massages can influence decision-making in different ways. It is logical to formulate the following tasks:

1) investigate the influence of the parameters of message flows I_1, I_2, I_3 on the probability of making optimal decisions;

2) to establish the limit moments of the receipt of messages, taking into account the probability of making optimal decisions based on them regarding the execution of route tasks.

The following assumptions were made when solving these problems. First, the amount of information contained in messages was calculated using the expression:

$$I = 0.5\log_2\left(1+\frac{\sigma_\lambda^2}{\sigma_\varepsilon^2}\right), \tag{3.8}$$

where Σ_λ is variance of telemetrically measured parameter; Σ_ε is variance of its measurement error.

The expression (3.8) applies to messages of all 4 types of massages, since they are all built on continuous signals. Formula (3.8) is applied with the hypothesis that the a priori and a posteriori distribution of the transmitted signal obeys the same law (entropy coefficient is constant). According to formula (3.8), it turns out that there cannot be a complete lack of information about any telemetric parameter, since the maximum value of Σ_ε is finite. So, then we will use the term *minimum available information*. Similarly, complete available information also does not exist because $\Sigma_\varepsilon > 0$. Therefore, we will use the term maximum available information under the given conditions of its receipt.

Secondly, it was considered that I_4 messages were received in their entirety even before the start of MV traffic. Thus, the idealized LS for traffic conditions on a TTN is formed a priori.

Thirdly, it was assumed that the lack of maximum information contained in the received messages I_2, I_3 when choosing the LS parameters can be compensated by a directly proportional time reserve.

The fourth assumption was that messages I_2 and I_3 of any volume and category can be received at any time during the routing task. The interaction of information flows is shown on the example of a typical elementary transport task on a trunk network. Let the MV must be having loaded at point A at the moment t_0, deliver the cargo to point B and unload no later than the moment t_{11} (**Fig. 3.6**).

MV movement modelled in the presence of the maximum available information I_3 and various methods of obtaining information I_2: 0–4 – movement of the MV with a margin of time at the maximum speed under the condition of the minimum available information I_1, I_2, I_3. The speed V_{opt} deviation is maximum. 0–7 is MV trajectory with a time reserve for the maximum available information I_1, I_3, and minimum information of I_2. 0–3‴–7 is MV trajectory at a speed, which provided by the information I_2 arrived at the maximum permissible moment 3‴. Road conditions on the AB route are known. Knowing Road conditions, the driver/crew of the MV can perform the delivery with optimal parameters (for example, according to fuel consumption), which includes the selection of the average speed of movement V_{opt}. At the end point B, other MVs arrive for unloading. Since the moments of their arrival and the duration of service are random variables, a queue may form before unloading. It can be assumed that the unloading process at point B is a mass service system of the M/G/m type, using the results of earlier studies, without significant restrictions [15]. M is the input flow subject to the exponential law. G is the service process with a general duration distribution. A number of unloading devices is *m* (unloading front). If the intensity of the arrival of MV at point B and the intensity of their service are known, then it is possible to calculate the average expected duration of idle MV in the queue t_q. Taking this into account, the LS can be adjusted so that the moment of arrival t_{10} will take into account the average guaranteed delay time in the delivery of cargo $t_{10}-t_{11}$. The ideal image of the transportation of goods process of the LS is formulated in this way, subject to the maximum available information I_2 and I_3 (dash-dotted line).

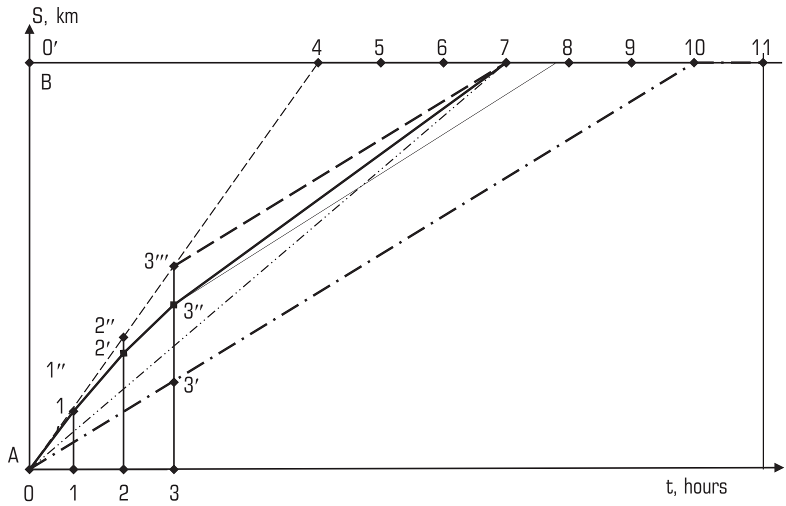

Fig. 3.6 Traffic charts of MV trajectory

It was assumed that messages I_1, I_2, I_3 periodically arrive to the MV crew. This periodicity, as well as the volume of messages, can be changed at an arbitrary, necessary interval. Accordingly, the volume of messages can be variable. If at the *i*-th moment of time, $t_0<t_i<t_{11}$, according to the next message I_1, the MV has the coordinate x_i, then, depending on the amount of information in the received messages I_1 and I_3, it should move with the time-averaged speed $V_e \geq V_{opt}$, which is determined by the formula:

$$V_e = (x_{11} - x_i)/(T_{opt} + \Delta t_i), \text{ km/hour}, \quad (3.9)$$

where $\Delta t_i = \Delta t_{i1} + \Delta t_{i2}$, hours; T_{opt} is the optimal duration of the delivery process at the speed of V_{opt} (in the absence of obstacles from the traffic flow and queues before unloading);

Δt_{i1}, Δt_{i2} are time reserves for, respectively, delays in movement and in the queue at the end point B; it is, according to the conditions, impractical to reduce the speed below V_{opt}.

To calculate the actual average speed of MV on the TTN, a macroscopic model of the traffic flow derived from a microscopic model with consideration of Paveri-Fontan corrections was used [22]:

$$V_e = V_d - V_f = V_d - (1-p)t_r\rho\Theta, \text{ m/sec}, \quad (3.10)$$

where V_d is the average desired speed; V_f is the forced change of the desired speed under the influence of the traffic; p is the probability of overtaking; t_r is the duration of motion relaxation as a result of random disturbances; θ – speed variation.

The values of p and t_r do not depend on the individual speeds of MV in the maneuver, but on the density ρ and the average speed V at the overtaking location, i.e. $p=F_1(v,\rho)$, $p=F_2(v,\rho)$. The information is accumulated about changes in the phase density of the traffic with each message of type I_2, that is, about the range of values of the function $f(x,v,t)$. At the same time the area of definition in terms of x and t is expanded. Information on the region is available as much as possible $x \in (x_A, x_B)$, where x_A, x_B are coordinates of the starting and ending points of the route. According to the data on the posterior phase density that could be determined at the moment t_i, the value of the a priori values for the given coordinate x at the moment of time $t_j > t_i$ was calculated:

– traffic flow density:

$$\rho(x,t) = \int_0^\infty f(x,v,t)\,dv; \quad (3.11)$$

– average speed of MV in the traffic flow:

$$V(x,t) = \frac{1}{\rho(x,t)}\int_0^\infty vf(x,v,t)\,dv; \quad (3.12)$$

– variations in vehicle speeds:

$$\Theta(x,t) = \frac{1}{\rho(x,t)}\int_0^\infty (v-V)^2 f(x,v,t)\,dv. \quad (3.13)$$

One should provide research in two stages. At the first, it can be assumed that the MV crew has the minimum available amount of information based on type I_3 messages (**Fig. 3.7**).

Messages I_1 and I_2 were submitted in three different ways:

1) at the beginning of the movement, once, in the full available volume;

2) during movement, at the extreme moment in terms of the effectiveness of the decision made, in full;

3) during movement, repeatedly, in equal amounts at equal time intervals.

CHAPTER 3

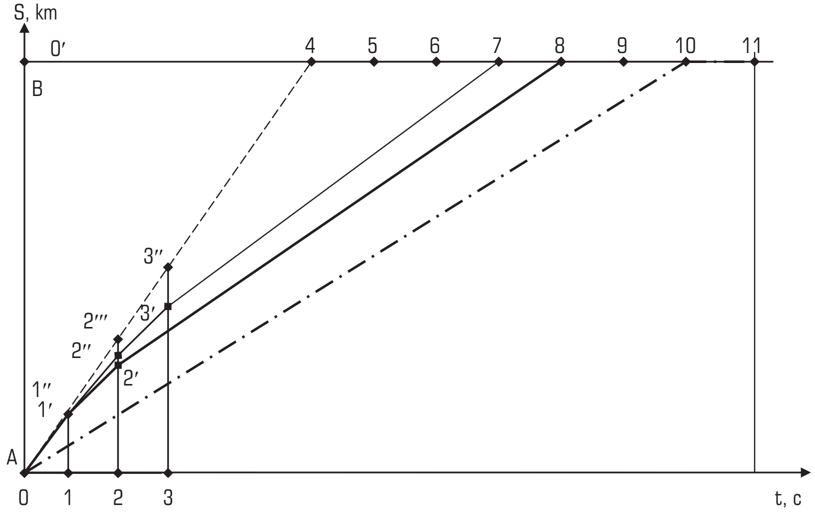

Fig. 3.7 Traffic charts of MV trajectory, if messages I_1, I_2, and I_3 are synchronous; 0-1′-2″-3′-7 – the movement of MV, provided that I_2, I_3 are received evenly, after the same intervals of time. The I_3 massage volume information is minimal. 0-1′-2′-8 – movement of the MV under the condition that I_1, I_2, and I_3 arrive uniformly, synchronously, at equal time intervals. The permissible moment of receipt of complete information is shifted to t_2

At the second stage, it was assumed that information I_1–I_3 arrives to the MV crew synchronously with the same amount at the same time intervals.

The time reserve Δt_{i2} is maximum if only one actual messages stream I_2 is available (**Fig. 3.6**) and therefore the MV crew is oriented to the moment t_7 of arrival at point B. The maximum total deviation from the optimal driving program will be achieved when the maximum available information I_2 is presented at the beginning of the movement t_0. This is due to the fact that the traffic, even in the first approximation, cannot be called stationary. Therefore, the value of the function $f(x,v,t)$ cannot be extrapolated to more than $t>t_0+\tau$, where τ is the period of discretization of I_2 messages. Therefore, decisions about the choice of V_d will not be adequate. So, there is a moment, after which the MV, moving, moreover with minimal information I_2, having received it cannot effectively use it (point 3″).This moment is called the limit for making a decision. Later, from the limiting moment, it is not advisable to also obtain information by I_2 quanta. Although this method of obtaining results has the smallest deviations from V_{opt}. If messages I_2 and I_3 are sent simultaneously, this affects not only the deviation from the optimal mode and the moment of arrival at the final destination, but also shifts the final decision-making moment to earlier times (**Fig. 3.7**).

3.4 INFORMATION SUPPORT FOR THE STABILITY OF TRANSPORT PROCESSES UNDER THE CONDITIONS OF VARIABLE MATERIAL FLOWS

The importance of the information support of LS grows especially when the LC is functioning for the supply of goods, namely as MF variable. It is then that the available messages are used to adopt LS to new conditions, that is, to stabilize business processes. In order for all intersecting LC of LS to function more efficiently, it is necessary to know the laws of their transformation in the external environment [37]. In addition, it is necessary to take into account the discrete nature of the LS, which consists of structural and parametric modules. A study of the transient processes that occur in the LS during changes in demand for goods delivered on the trunk transport network, as well as changes in supply conditions and other random external influences, was carried out. The principle of continuity of the flow was used for the maximum reduction of material flow delays in LC, which is subject to random external influences. So, if the initial ELO in the LS are characterized by the values of the input tact τ_{in}, then all subsequent ones are functionally dependent on them. The corresponding dependencies are preserved in the same way as in stationary material flows. The duration of the *j*-th ELO should be $t_j \le \tau_i$, where *i* is the number of the previous ELO. If this ratio is not preserved, then the value of the front of the *j*-th ELO should increase according to the expression:

$$f_i = \left\lceil \frac{t_i}{\tau_i} \right\rceil, \tag{3.14}$$

where f_i is the front of technical means for performing ELO. If two adjacent ELOs have mismatched modes, then at least one of them will experience a delay. The static delay of each ELO can be calculated using the formula:

$$Z_i = \left(f_i \cdot \tau_i - t_i\right) \cdot f_i. \tag{3.15}$$

A simple linear LC, which, for example, consists of ELO: 1 – manufacturing; 2 – packaging; 3 – loading and transportation; 4 – unloading and unpacking; 5 – consumption (**Fig. 3.8**), will have static delays if the modes of its operations are inconsistent (not multiples of the clock). Each ELO of this chain is characterized by four parameters τ_j, k_i, f_i, t_i.

Since the parameters of neighboring ELOs are dependent, the following expressions are valid:

$$\tau_4 = \frac{k_4}{k_3}\tau_3,\ \tau_2 = \tau_3;\ \tau_2 = \frac{k_2}{k_1}\tau_1;\ f_3 = \left\lceil \frac{t_3}{\tau_3} \right\rceil \ge 1;\ f_1 = f_2 = f_4 = 1. \tag{3.16}$$

Thanks to them, we can get $\tau_4 = \dfrac{k_4}{k_1}\tau_1$.

CHAPTER 3

Thus, the linear LC leads to a linear dependence of its parameters. The value of the criterion can be calculated using the formula:

$$Z_{\Sigma} = \sum_{i=1}^{4} \left(f_i \tau_i - t_i \right). \tag{3.17}$$

The total delays of the cargo delivery process are static, that is, they will repeat from cycle to cycle, if the intensity and modes of MF do not change. As expression (3.17) shows, these delays depend on the initial tact and on the values $k_1 \dots k_4$ (**Fig. 3.9**).

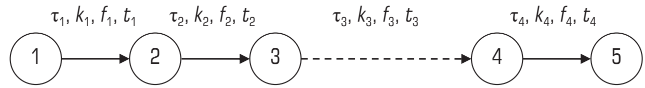

Fig. 3.8 Scheme of the model of the elementary logistics chain

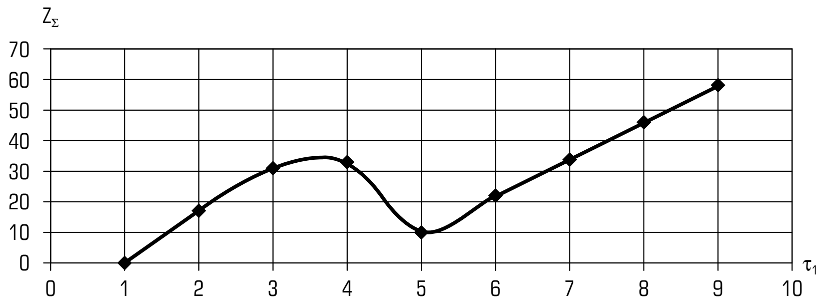

Fig. 3.9 Dependence of static delivery delays on the tact rate of the incoming MF

The quality of the built LC depends on the rational selection of parameters in expression (3.17). When the demand for the supply of goods changes, the input tact of this LC will change:

$$\tau_1^{j+1} = \tau_1^j \pm \Delta\tau_1, \tag{3.18}$$

where j is the index of the next phase of LC. The sign of the value $\Delta\tau_1$ depends on the type of MF change. If the volume of consumption increases, then the input tact of the LC decreases and vice versa. Depending on the value of $\Delta\tau_1$, certain changes may occur in the LC, which lead to the formation of dynamic process delays. These delays are also the reason for the mismatch of neighboring ELOs, but they have the ability to disappear if the MF in the LC stabilizes. This can be demonstrated with the help of a cyclogram of operations (**Fig. 3.10**, ***a***). Stationary flow is in two neighboring ELOs No. 1 and No. 2. Segments ABGDE are a sequence of incoming ELOs No. 1 with a constant cycle time $\tau_1=15$ hours. During ELO No. 2, the size of the group of material elements is doubled, i.e. $k_2=2k_1$. Therefore, the tact of the next ELO No. 2 also doubles and equals $\tau_2=30$ h. Such a change is shown with the help of two chains of operations: JZ and CU, according to the multiplicity of flow changes that occurred in ELO No. 2. Delays in such a LC are static. They arise due to the fact that the duration of the ELO is shorter than the duration of the tact during which it is performed. **Fig. 3.10**, ***b*** shows that the intensity of MF increases. The tact of the input operation of ELO No. 1 was initially equal to $\tau_1=15$ h. Then it decreased to $\tau_1=10$ h, which can be seen from the length of segment BG. TTS remains unchanged.

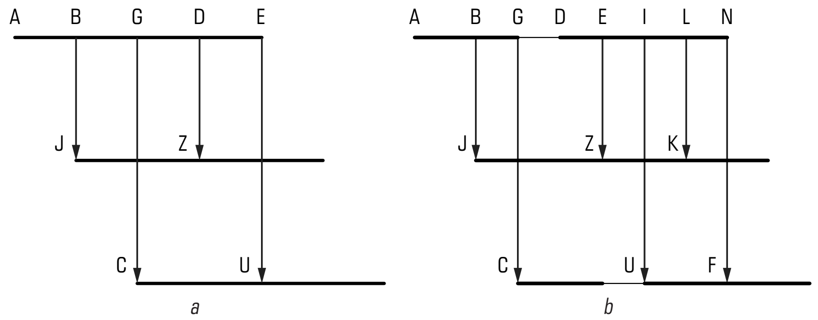

Fig. 3.10 Cyclograms of cargo delivery operations No. 1, No. 2:
a – at stationary flow; *b* – with an increase in the intensity of MF

Therefore, the ELO No. 2 tact also doubles. It acquires the value $\tau_2=20$ h, which is visible along the length of the segment CU. However, operations that have different tacts end up in the same LC after the changes occur. This leads to forced dynamic process delays, which in **Fig. 3.10**, ***b*** is shown by dashed lines GD and UF. It is clear that the value of these delays depends on the change in the intensity of the incoming MF. The execution of ELO No. 1, for example, is delayed by the amount ΔZ, which can be determined by the expression:

$$\Delta Z_1 = Z\left(\tau_1^{j+1}\right) - Z\left(\tau_1^{j}\right). \tag{3.19}$$

The value of the difference (3.19) is affected not only by the absolute change in the tact rate $\Delta\tau_1$, but also by the number of discrete periods during which this change occurs. The task is to determine such a sequence of values for which the value of the Z_Σ criterion is minimal. The method of finite difference equations was used to solve this problem. Thus, the total delay of the process when changing the input tact $\Delta\tau_1$ in two steps can be written as a second-order differential equation:

$$\Delta^2 Z = Z\left(\tau_1^{j+2}\right) - 2Z\left(\tau_1^{j+1}\right) + Z\left(\tau_1^{j}\right), \tag{3.20}$$

which can be written as:

$$Z\left(\tau_1\right) = \tau_1 \frac{k_4}{k_2} f_1 + 2\frac{k_2}{k_1} f_2 \cdot \tau_1 + \tau_1 f_1 - T, \tag{3.21}$$

where T is the total permissible duration of operations in LC, which does not depend on their execution sequence and other organizational parameters. By introducing notations, equation (3.21) can be simplified:

$$Z\left(\tau_1\right) = A \cdot \tau_1 - T, \tag{3.22}$$

where A is a constant. Similarly, it is possible to write differential equations of higher orders. In the case when the LC is branched, that is, it has an ELO of the distribution, or a connection of the MF, it is also necessary to find the function of the output tact of the longest linear LC and write down the differential equations for this function. Let's simplify the notation, bearing in mind that the state of MF delays depends on the selected constants A and on the input flow rate τ_1. The second-order differential equation can be reduced to the form:

$$a_1 z_{j-1} + a_2 z_{j-2} + a_0\left(j\right) = z_j,\ j = 0,1,\ldots n. \tag{3.23}$$

It is called a linear differential inhomogeneous equation. Solution of a homogeneous equation:

$$a_1 D_{j-1} + a_2 D_{j-2} = D_j, \tag{3.24}$$

can be found in the form $z_j=\lambda_j$. Substituting z_j, $z_j-1=\lambda_j-1$, $z_j-2=\lambda_j-2$, in equation (3.23), we get the characteristic equation for determining λ:

$$P\left(\lambda\right) = \lambda^2 - a_1\lambda - a_2 = 0. \tag{3.25}$$

Its roots λ_1, λ_2 can be calculated from the formula:

$$\lambda_{1,2} = \frac{a_1 \pm \sqrt{D}}{2}, \tag{3.26}$$

where $D = a_1^2 + 4a_2$. It is proved that, depending on the sign of the discriminant D, the following three cases are possible:

1) $D>0$. Then λ_1, λ_2 are real and different, and the general solution of equation (3.24) is found by the formula $\tau_j=A_1\lambda_1^t+A_2\lambda_2^t$, where A_1, A_2 are arbitrary constants, which are determined from the initial conditions: $\tau_{j=0}=A_1+A_2$, $\tau_{j=1}=A_1\lambda_1+A_2\lambda_2$;

2) $D=0$. Then the characteristic equation has roots $\lambda_1=\lambda_2$, and the general solution (3.16) is determined by the formula: $\tau_j=(A_1+A_2 j)\cdot\lambda_1^j$, and arbitrary constants are determined from the initial conditions, that is, for $\tau_{j=0}=A_1$, $\tau_{j=1}=\lambda(A_1+A_2)$;

3) $D<0$. Then λ_1, λ_2 are complex variables $\lambda_{1,2}=\alpha\pm i\beta$, where $\alpha=a_1/2$, $\beta=\sqrt{-D}$, $i_2=-1$, which are easier to use in trigonometric form:

$$\lambda_{1,2}=\rho(\cos\omega\pm i\sin\omega),\ \rho=\sqrt{\alpha^2+\beta^2}=\sqrt{-a_2},\ \mathrm{tg}\omega=\beta/\alpha. \tag{3.27}$$

The general solution (3.27) is given:

$$\tau_j=\rho^j\left(B_1\cos\omega j+B_2\sin\omega j\right), \tag{3.28}$$

where B_1, B_2 are arbitrary constants determined from the initial conditions.

Thus, for $D<0$, the solution of the difference equation (3.23) has the character of oscillations, the amplitude of which increases if $\rho>0$ and fades if $\rho<0$. Such models of LC dynamics make it possible to find out whether an external disturbance will lead to LS in the form of a change in the input flow rate until stabilization, or dynamic delays in this connection will continue to grow from cycle to cycle.

For example, if the general solution of the difference equation has the form:

$$z_j=2^{0.5j}\left(C_1\cos\alpha j+C_1\sin\beta j\right)+1. \tag{3.29}$$

Then its partial solution depends on the initial conditions, i.e., on the time τ_{11} and on its change $\Delta\tau_1^1$. It can be seen from **Fig. 3.11** that the process of changing the value of MF by $\Delta\tau_{11}$ leads to destabilization of the LS, which manifests itself on the 3rd cycle and continues to grow.

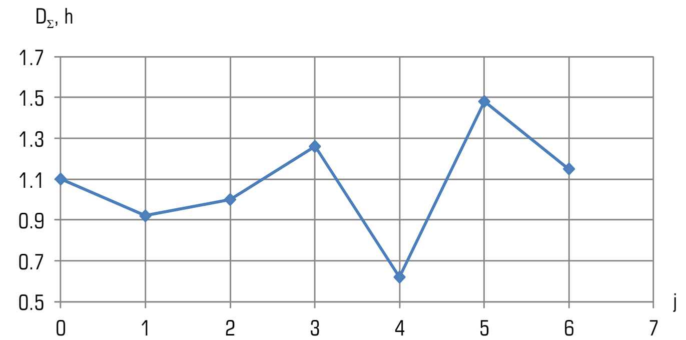

Fig. 3.11 An example of an unstable linear LC: j is the LC cycle number

Total delays in this LC arise for two reasons. Static delays are visible at stage $j=0$, and they appear as a result of the mismatch of the tacts of neighboring ELOs. Dynamic delays in LC fluctuate in time and, in general, increase. In order to reduce fluctuations, it is necessary to change the structure of the LC, or to apply the initial redundancy of the ME to smooth out the rapid pulses of the incoming flows.

It is expedient to evaluate the level of perfection of the LC of cargo delivery on the trunk transport network by the minimum total static and dynamic delays in the LC. If the total MF on the LS is constant, then only static delays will occur. They are due to the inappropriate multiplicity of the tact and duration of ELO. The total delays cannot be reduced if only the appropriate parameters of the group k and tact τ are selected. Dynamic delays occur in LC if the tact of the initial ELO changes. Therefore, additional regulation of incoming flows is necessary, which consists in their stabilization, for example, using warehouses, or long-term forecasting.

3.5 STABILIZATION OF MATERIAL FLOWS IN LOGISTICS CHAINS

As was discussed above, the fluctuation of the MF leads to the occurrence of additional delays in the movement of the ME. MF fluctuations can be smoothed out by stream stabilization, which can be demonstrated using the following example. A typical LS was considered, consisting of LC of long-distance delivery of goods from the manufacturer to the regional network of consumers according to the flow technology studied earlier: production – packaging in consumer containers – packaging in transport packages – formation of a shipment group – loading – distribution by directions – delivery to the distribution center point – distribution by consumers – delivery on circular routes. Peculiarities of the LS model in relation to the studied trunk network are:

1) several sources of cargo flows – several manufacturers;

2) the TTN subjects is not limited in their interconnections, in particular there are no restrictions on the supply of goods from any manufacturer or from any distribution point;

3) the number of final consumers in the distribution network is finite but not fixed, that is, the volume of goods supplied is a function that depends on the intensity of consumption of goods by each consumer μ_i and the total number of consumers taken into service $i=1...n$. In the model, the principle of inseparability of the cyclic MF is preserved: with the work front $f=1$, any i-th ELO cannot start, if the previous one is not completed. The mathematical expectation of its execution duration t_i is not greater than the rhythmicity index τ. This indicator is constant if the MF is not transformed in the size of discrete groups k, or if it does not change according to the average intensity, which is determined by expression (3.1). The total intensity of MF in the network is the sum of all flows coming from sources or the sum of all flows reaching consumers (total demand). The total intensity does not depend on how branched the network is and how many end points of material flows (consumers) S_i. The delays of ME movement at a constant total flow occur as a result of the mismatch of t_i and τ_i values. It is known that with a constant total MF there is such

a LC, in which the inconsistency of the majority of the ELO of the process, therefore, the delays will be minimal [38]. Qualitative transformations of LC occur when critical values of the tact rate of the input flow are reached. If the input flow in the LC is variable, then flow delays can occur. The reason is due to the multiplicity of ELO tacts and durations, but also due to the inconsistency of neighboring operations in the LC in terms of the absolute value of the tact. We will show in more detail the formation of a flow delay when its intensity changes on the example of one ELO No. 4 (**Fig. 3.12**).

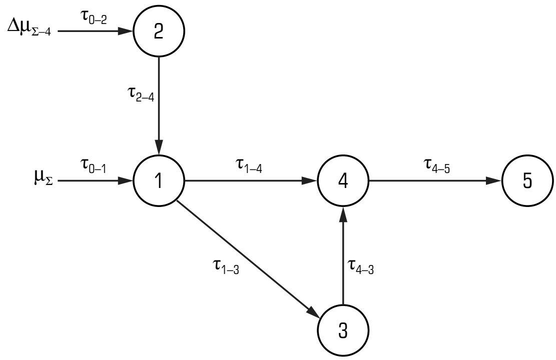

Fig. 3.12 An elementary example of changes in the structure and properties of ELO when changing the input flow: 1–5 ELO

The model shows the flows that undergo transformations in ELO No. 4, and those adjacent to ELO No. 1 and No. 5. The total flow is constant (μ_Σ=const). In this case, the ratio is preserved:

$$\mu_\Sigma = \frac{k_1}{\tau_{0-1}} = \frac{k_2}{\tau_{1-4}} = \frac{k_3}{\tau_{4-5}}, \tag{3.30}$$

where μ_Σ is constant average intensity of the incoming MF; k_1, k_2, k_3 are the sizes of ME groups, which, in general, can be different; τ_{0-1}, τ_{1-4}, τ_{4-5} are the tacts of the corresponding ELO. The zero operation is the arrival of the ME to the given LC.

Disturbances occur in the LC. These disturbances are transmitted in the form of an additional input flow with an intensity of $\Delta\mu_\Sigma$. The value $\Delta\mu_\Sigma$ can be positive or negative (a decrease in the total flow). It was shown in previous paragraph that additional flows necessitate the temporary reservation of part of the ME to equalize pulsations. In this case, such reservation is reflected in the form of ELO No. 2 – the reserve of the input flow, which occurs when $\Delta\mu_\Sigma$ has the sign "–", and ELO No. 3, which is characteristic of the case of the increase of the input flow. The stability of MF in the LC is violated at any value of $\Delta\mu_\Sigma$, this requires additional capacity reserves and, at the same time, leads to flow delays (**Fig. 3.13**).

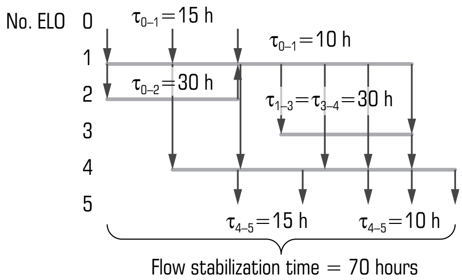

Fig. 3.13 Example of a LC cyclogram

The figure shows an example of the effect of an increase in the input MF on the stabilization of the LC. For this example, it is assumed that the sizes of groups of material elements do not change. The flow delay is a number of cycles τ_{1-3} and τ_{3-4}, which are transitions of the system from the initial (it is equal to the initial cycle τ_{4-5}) cycle $\tau_{0-1}=15$ h up to 10 h. Material flows do not carry out the necessary transformations during this delay, but accumulate in the LC. The general period of stabilization of the flow after its disturbance in this network consists of two half-periods: stabilization at the entrance and during execution, in fact, ELO No. 4. Such an example makes it possible to make an assumption that ways to stabilize flows should be sought in the structure of the LC itself.

Based on the previous considerations, let's name the possible ways of stabilization:

1) a branching of LC in directions, each of which has its own fluctuations in the intensity of flows;

2) a changing the length of the LC, using operations that are associated with the acceleration/deceleration of flows;

3) to change in the number of flow sources;

4) to change in the amount of waste.

It is also clear that the MF stabilization time will depend on the value of $\Delta\mu_{\Sigma}$, but in practice it cannot be controlled. The research was carried out with the isolation of each individual factor affecting MF delays. Thus, the branching of supply chains is also considered on an elementary example (**Fig. 3.14**). It specifies the point of reception and redistribution of flows ELO No. 1 and there are three finite numbers of directions in this case.

It was assumed that the sizes of ME groups did not change before and after redistribution. Prior to the change of MF was fulfilled in this LC the equality:

$$\frac{k}{\tau_{0-1}}=\frac{k}{\tau_{1-4}}+\frac{k}{\tau_{1-6}}+\frac{k}{\tau_{1-8}}=\mu_1+\mu_2+\mu_3.$$

The additional vertex 2 of the graph is formed after the increase/decrease in the intensity of MF. The vertex means a temporary delay in the flow due to the system's unwillingness to adjust to a new value of the input tact. As well as vertexes 3, 5, 7 symbolize the ELO of a temporary delay in the flow due to its inconsistency with the consumer's demand, respectively μ_1, μ_2, μ_3. A new equality is taking shape:

$$\frac{k}{\tau_{0-1} \pm \Delta\tau_{0-1}} = \frac{k}{\tau_{1-4} \pm \Delta\tau_{1-4}} + \frac{k}{\tau_{1-6} \pm \Delta\tau_{1-6}} + \frac{k}{\tau_{1-8} \pm \Delta\tau_{1-8}} =$$

$$= (\mu_1 \pm \Delta\mu_1) + (\mu_2 \pm \Delta\mu_2) + (\mu_3 \pm \Delta\mu_3), \quad (3.31)$$

where $\Delta\tau_i$ is the change in the supply cycle of MF as a result of its new redistribution; $\Delta\mu$ is a change in the average intensity of MF due to a change in the demand for goods.

The sign $\pm$ is indicated, taking into account the increase/decrease of the total MF. The right-hand side of equality (3.31) shows that the $\pm$ signs for $\Delta\mu$ values can be different. This means that the function of ELO No. 1 is not only distributive, but also stabilizing. So, if the change in flow intensity in the direction of μ_1 is positive, and μ_2 is negative, then the total intensity of the MF will change only by $\Delta\mu_\Sigma = \Delta\mu_1 - \Delta\mu_2 + \Delta\mu_3$, The value $\Delta\mu_\Sigma$ is less than with a total increase in demand in all directions.

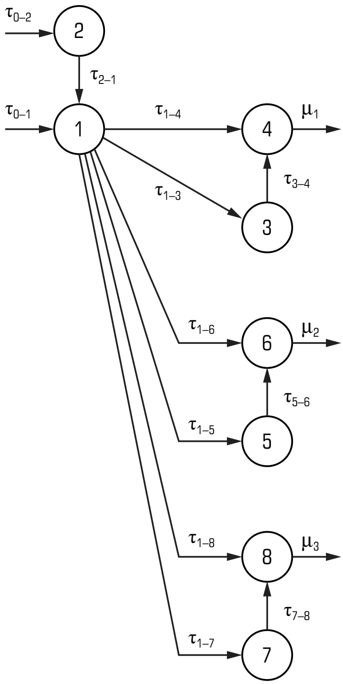

Fig. 3.14 To study the influence of branching of LC on cumulative time delays

CHAPTER 3

Let's also assume that the combination of such flows, which change in intensity collectively minimizes the overall growth of μ_Σ. That can be a way to stabilize fluctuations in the LC, as this reduces the need for significant redundancy on ELO No. 2. However, even in the presence of a slight fluctuation of inputs and flows between directions, there are delays in the time of movement of products. An example of such delays is shown in the cyclogram (**Fig. 3.15**).

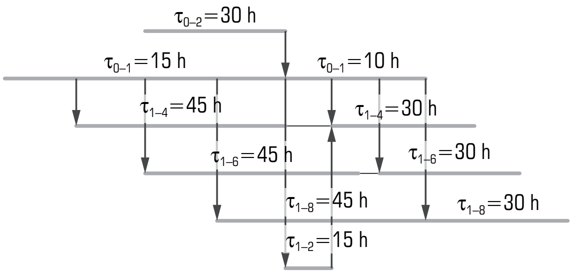

Fig. 3.15 The cyclogram of MF with their branching and change of average intensity

Flows are increasing in all three directions of intensity in this example. That means the additional flow with a cycle time of $\tau_{0-2}=30$ hours is necessary. As a result, the input tact τ_{0-2} is reduced to 10 hours and all three days off to 30 hours. Due to the fact that their previous value was 45 hours, there is a mismatch and flow breaks. There is also a need for additional stocks to stabilize the execution of cyclical LC. Modeling was carried out and the dependence of total delays on changes in flow intensity was plotted (**Fig. 3.16**). When constructing this dependence, the simplest case was considered, in which its size increases proportionally in all directions of the branched flow. Due to this, the obtained dependence is linear.

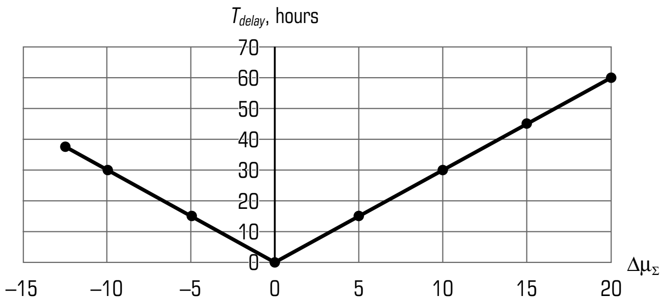

Fig. 3.16 Dependence of the total time delays of the MF on the change in its total intensity

It can be assumed that there is a suitable combination of distributed flows that leads to an optimal LC stabilization mode in which the total delays are minimal. It was also found that the increase/decrease in the branching level of the LC at a constant value of the total output flow does not affect the total duration of delays, if at the same time the different directions of the flows are not the same in response to the disturbance.

While studying the effect of the length of the LC on the stabilization period of the LC and the total delays, we took into account the known regularities of the influence of the sizes of groups of material elements on the intensity of the MF. So, if the intensity of MF in a linear LC (without branches) increases, then at each additional ELO time delays will be added to the total. However, if at the same time it is possible to increase the flow rate by reducing the size of the k_i at every i-th ELO, without disrupting the transport technology, then additional cargo storage will not be necessary. Consider the expression:

$$\mu_{\Sigma} + \Delta\mu = \frac{k_i}{\tau_i} + \frac{k_i}{\Delta\tau_i} = \frac{k_j}{\tau_i}, \tag{3.32}$$

the left part of which shows an increase in the intensity of MF as a whole, the middle one shows how it is possible to stabilize the LC, using additional ELO stacking with a duty cycle $\Delta\tau_i$ when increasing the flow. The right-hand side of (3.32) shows how to avoid delays without increasing inventory. The main variable here is the size of the k_j. However, the reduction in the size of the ME group has a negative effect on the cost of resources for their movement. Therefore, the value k_j/k_i should have limited use as a stabilizing factor. It is more appropriate to perform stabilization by changing the group of material elements with a larger number of consecutive ELOs in the LC.

CONCLUSIONS

1. Adaptation of the LS to the change in the intensity of the MF leads to delays in the LC. Increasing the intensity of MF on trunk network, where transportation operations are the longest, leads to a decrease in additional time spent.

2. When organizing the delivery of goods according to the principle of "no later than the specified period" with the observance of optimal traffic modes. It is necessary to reasonably choose the method, number of sources and moments of receiving information messages about road and transport traffic conditions and conditions for the sale of the goods. The use of several independent information flows reduces deviations from the optimal program, on the other hand, it reduces the time for making effective decisions.

3. When the intensity of the input cyclic LS changes (increases or decreases), the need for redundancy functionally arises on the LC. There are also MF delays associated with a mismatch of ELO parameters.

4. To stabilize LS with minimal loss of time and money, it is advisable to apply partial and full redistribution of MF between directions and sources, as well as variable groups of material elements.

5. The model describing the dynamics of the MF in the linear LC is adequately presented in the form of a linear difference homogeneous equation of the second order. Its solution shows the way to stabilization of organizational parameters of LS.

6. It became possible to reduce the number of refusals in the execution of orders in the operating LC on the basis of the developed MF models, by an average of 30...40 % for one motor vehicle enterprise, up to 35 % of the total flow of applications. The duration of orders on long-distance routes is reduced by 12...20 %. The method of optimizing the traffic schedules of road trains based on the stabilization of freight flows and the method of optimizing the mode of work and rest of drivers have been improved. This was done taking into account the parameters of the route, improvement of the system of dispatching management of the fleet of trunk trucks with the help of a developed computer program. Unproductive time spent by road trains on intercity routes is reduced, on average, by 20...25 % of the total duration of transport cycles. The duration of cargo delivery is reduced by 15...20 %. A positive technical and economic effect from the implementation of practical methods is achieved by reducing non-productive downtime of trucks by at least 20 %, reducing fines due to violations of delivery deadlines, as well as rational use of drivers' working time.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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