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Optimization of the Process of Unloading of Iron Ore Raw Materials: The Case of a Steel Plant



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ABSTRACT

The process of unloading iron ore raw materials of the metallurgical plant to the sinter plant has not been considered for a long time as a particular topic. Over the last years the conditions of metallurgical production have undergone certain changes: its intensification has occurred, which entails the need to re-evaluate parameters of stable operation of sinter production. The objective of the suggested study is to consider the issues of possible technical and technological improvement harmonizing transport flows with the requirements of the main production process. To achieve this goal, a technique of mathematical modelling is used, based on the mathematical apparatus of linear programming; graphic-analytical method; method of probability theory.

The issues of the process of unloading, storage of iron ore raw materials, of their preparation for sinter production are primarily considered.

The article presents the main positions of the process of optimizing unloading of sinter batch of a metallurgical plant. The general characteristics of the technology of metallurgical production and of each particular process are described. The agglomeration process is considered in more detail. The tables of initial iron ore raw materials for sintering production for certain reporting periods are given, for the sake of clarity, the data of one of the tables are summarized in a diagram. A diagram of a standard trestle-type ore warehouse is considered, which sequentially shows the main processes of sintering production from supply of raw materials to the car dumper to getting through a belt conveyor into a stack, and then into receiving bins. The article also provides an example of formation of piles of iron ore raw materials using manganese limestone.

The study is based on a dynamic transport problem with delays (DTPD), which considers time of transportation of goods, the dynamics of production volumes over time, the dynamics of consumption, the dynamics of stocks of suppliers and consumers, dynamics of cost of transportation and storage, dynamics of cost of consumption losses. The study contains several mono-problems with a mono load, which overlap each other, forming a multiplicative overlay of single-product problems.

<u>Keywords:</u> *industrial transport, steel plant, metallurgical plant, unloading, iron ore raw materials, mathematical model, optimization, agglomeration.*

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Background.

The process of unloading iron ore raw materials and the problem of optimizing this process have become of acute interest to researchers at the present time. This issue has not been addressed in detail for 20 years, at least in Russian scientific sources. The conditions of metallurgical production have changed over this period: the output of finished products has increased, and it is planned to further increase it at the existing production facilities; sintering speed of the agglomerate on the belt became higher, and so, intensification of production took place. Thus, the issues of the process of unloading raw materials, their storage, preparation for sinter production come to the fore [1]. And also the number of sinter charge (batch) components has increased significantly: if earlier their number did not exceed ten, now it reaches 23–29 items. In connection with the changes that have occurred, it becomes necessary to study the transport infrastructure and the operational structure of the technical process; its main objective is to find their inconsistencies in incoming and outgoing flows. It is advisable to explore the possibilities of harmonizing transport flows with the requirements of the main production process in order to consider the issues of possible technical and technological improvement, and that is the *objective* of the suggested study [1]. To achieve it, a *method* used is based on application of methods of mathematical modelling, in particular, on the mathematical apparatus of linear programming; graphic-analytical method; method of probability theory.

Theoretical foundations of the technological process

Rolled steel with and without coatings is the end product of metallurgical production. To obtain this metallurgical product, iron ore goes through a long chain of continuous technological processes. The work of an average metallurgical plant includes sintering, blast-furnace, coke-chemical, steel-making, rolling production.

The main components for blast-furnace shops, which are agglomerate, coke, are obtained at sinter and by-product coke plants, respectively. In turn, blast-furnace production produces pig iron, which can be a commercial product of the first processing, and not only a semi-finished product for steel production. The latter, by blowing liquid iron and scrap metal with oxygen, produces steel, poured into continuously cast billets (slabs), which serve as commercial products of the second processing, and are also used for production of rolled products [2; 3; 4]. The purpose of rolling production is to obtain metal of the required shape, with the required properties and structure [1]. The most productive and efficient way of metalworking is rolling. Rolling is the process of deformation of metal between rotating rolls, as a result of which the original workpiece is stretched, and its thickness decreases. This operation, in turn, is divided into hot and cold rolling. The initial temperature of steel during hot rolling reaches 1000–1200°C. Cold is used to obtain a product with better surface quality and mechanical properties and, as a result, a higher added value.

Analysis of practices of functioning of sinter production

The described metallurgical cycle is based on an agglomeration process. The primary goal of this operation is transformation of a small multicomponent charge into a lumpy product (agglomerate), which is the main iron ore raw material for a blast furnace [1]. If the issues of interaction between transport and incoming flows of raw materials of sinter production are not sufficiently resolved, then these failures following the principle of «dominoes» will spread to all the indicated stages of metallurgical processing. This will lead to a multiplicative increase in lost profits in production of metal products. At the moment, the question of solving these problems arises, which is what this study is aimed at [2–6].

The initial raw materials for the sintering process are sinter ores, fluxes (dolomite, limestone, lime), iron ore concentrates (products of enrichment of iron ores), metallurgical waste (blast furnace dust, scale, sludge), coke breeze, sinter and pellets screening from blast furnaces, screened-out small agglomerate, which is returned for re-sintering (return) (Tables 1, 2) [1]. The period for laying a zone (stack) depends on the required volume of feedstock, as well as on its availability and can vary from several days to several weeks.

Analyzing Table 1 and Table 2 we see that the most massive flow to sinter production consists of the concentrate of iron ores, the least powerful flows are scale of converter workshops, oxide of dynamo steel, cold rolling, screening. Fluctuations in flows arriving at different periods of time are absent or minimal and range from 0,002 % to 0,5 %, which indicates

Table 1

Initial iron ore raw materials for the agglomeration process (October 2019)

No.	Name	Number of cars, pcs	Weight, t	Percentage, %	In dry form
1	Concentrate of iron ore agglomerate	1387	95 704	79,75	86 133, 60
2	Scale of ferrous metals	6	417	0,35	396,15
3	Iron ore	146	10 214	8,51	9 314,15
4	Blast furnace dust	10	522	0,43	502,25
5	Aspiration dust	10	573	0,48	553,98
6	Scrap of convertor workshops (0–10 mm)	23	1 446	1,21	1 446,00
7	Scale of convertor workshops	1	65	0,05	63,57
8	Iron scale CC cr.	2	182	0,15	174,17
9	Scale (hot rolling)	11	1 003	0,84	975,02
10	Scale lime oiled	6	534	0,45	469,92
11	Fractional crushed stone	47	3 257	2,71	3 105,55
12	Oxide (cold rolling)	1	78	0,07	76,28
13	Oxide of dynamo steel	1	65	0,05	44,59
14	Screening out of metal dolomite	1	78	0,07	78,00
15	Lime	95	5 863	4,89	5 863,00
	TOTAL	1 747	120000	100,00	109 196,22

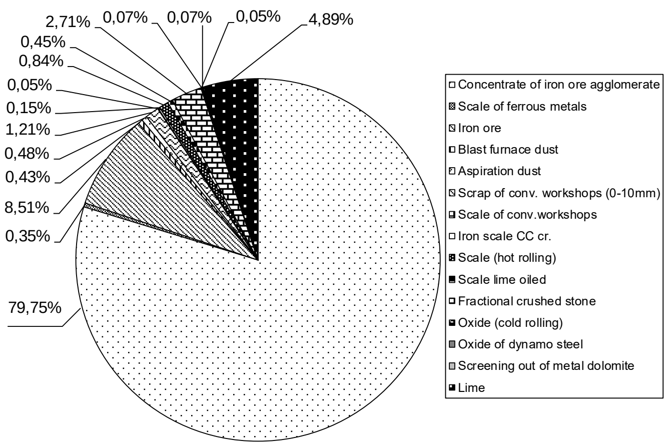
Table 2

Initial iron ore raw materials for the agglomeration process (November 2019)

No.	Name	Number of cars, pcs	Weight, t	Percentage, %	In dry form
1	Concentrate of iron ore agglomerate	1386	95 663	79,72	86 096,70
2	Scale of ferrous metals Ural	6	417	0,35	396,15
3	Iron ore	146	10 214	8,51	9 314,15
4	Blast furnace dust DC-1	6	261	0,22	251,87
5	Blast furnace dust DC-2	5	261	0,22	253,22
6	Aspiration dust DC-1	6	287	0,25	271,50
7	Aspiration dust DC-2	5	287	0,25	275,96
8	Scrap of conv. workshops (0–10 mm)	23	1 446	1,21	1 446, 00
9	Scale of conv. workshops	1	65	0,06	62,67
10	Iron scale CC cr.	2	182	0,15	174,94
11	Scale (hot rolling)	11	1 003	0,84	960,87
12	Scale lime oiled	6	534	0,45	469,92
13	Fractional crushed stone	38	3 257	2,71	3 128, 35
14	Oxide (cold rolling)	1	78	0,07	53,51
15	Oxide of dynamo steel	1	65	0,05	62,86
16	Screening out of metal dolomite	1	78	0,07	78,00
17	Lime	94	5 902	4,92	5 902,00
	TOTAL	1 738	120000	100,00	109 198,64

stabilization of the technology. That is, on the one hand, there is a stable core of stability, on the other, there are some changes, if there are changes, therefore, there is optimization, there is dynamics. Stack capacity is standard. Meeting these requirements, namely, formation of a multi-layer stack, is the main problem for the personnel of industrial railway transport. The main task of the non-public access road is a reliable, impeccable transport service.

Agglomeration includes the following operations: homogenization, storage, batch preparation and sintering, carried out on sintering machines, batch cooling on coolers, and sintered agglomerate processing [1]. Averaging occurs during development of the



Pic. 1. Average percentage of iron ore in a stack [1] (authors' drawing).

stack, when the material of the stack is fed by an excavator to the receiving hoppers (Pic. 2), from where the raw material enters the technological belt conveyor that feeds the sintering belt. The processes of storage and averaging of iron ore raw materials are carried out in warehouses of sintering factories in special stacks in layers, with the obligatory observance of the given proportions (Pic. 1). The number of layers and their volume are prescribed in the corresponding schemes, an example of such a scheme is given in Table 3. At the agglomeration production we are considering, the stack is formed from 29 layers of iron ore raw materials.

The process of preparing the charge includes the following operations: dosing (carried out to maintain the required amount and ratio between the components), followed by mixing, wetting, and pelletizing. The latter, in turn, is performed in order to obtain a homogeneous mixture of charge components, which have high gas permeability during the sintering process.

The sintering process takes place on sintering machines, which represent a closed conveyor, which, in turn, consists of pallets (baking trolleys) moving along guide rails. When the sintering trolley passes under the feeder, the prepared charge is loaded onto it. At the moment the loaded pallet passes under the gas burners of the incendiary furnace, solid fuel of the upper layer of the charge begins to burn, and the circle of combustion spreads from top to bottom. The trolleys are sequentially passed under vacuum chambers, in order to suck air through the sintered charge, which is required for combustion of solid fuel and removal of combustion products [1; 2; 4].

As soon as hot return is separated in the tail of the sinter machine, the sinter flows to the cooler. And then the screening stage is repeated again, during which a cold return is released [2; 4; 7; 8]. The sorted sinter is sent in cars to the blast furnace shop.

At the metallurgical plant we are considering, sintering production uses open ore storages (SR) of the trestle type (Pic. 2) [1].

The agglomeration plant under consideration includes three trestle (rack) type warehouses: SR (ore storage)-1, SR-2, SR-3. The SR-2 warehouse contains two stacks, the other warehouses have only one at a time [1]. In the process of unloading iron ore, two stacks are simultaneously formed, each of which is a multicomponent «pie», the number of layers, their sequence and the volume of each layer are strictly regulated. When laying a stack, it is necessary to be guided by the scheme of its formation, an example of which is given in Table 3.

Mathematical model

The task of the study is to build a mathematical model for optimizing unloading of iron ore raw materials, which is based on a dynamic transport problem with delays (DTPD) [1; 9; 10].

The production volumes are known, that is, the volume of raw materials coming from the adjoining stations to the metallurgical plant, A_i, $i=\overline{1,x}$; demand volumes – the amount of raw materials required to form a specific layer, B_j, $j=\overline{1,y}$. We have an optimization period in the

Table 3

**Formation of stacks of iron ore raw materials using manganese limestone.
Layout «section» of the stack [1]**

No.		Name of the layer	Volume of each layer, t	Volume of each layer, cars
1		Iron ore concentrate	6000	90
2		Manganese limestone	1080	16
3		Crushed stone	500	6
4		Iron ore concentrate	2000	30
5		Iron ore	2240	32
6		Iron ore concentrate	4500	128
7		Scrap	400	7
8		Iron ore concentrate	2000	30
9		Crushed stone	500	6
10		Iron ore concentrate	4500	128
11		Manganese limestone	1010	15
12		Iron ore concentrate	2000	30
13		Iron ore	2240	32
14		Iron ore concentrate	4500	64
15		Crushed stone	500	6
16		Iron ore concentrate	9000	128
17		Scrap	400	7
18		Manganese limestone	1010	15
19		Iron ore	2240	32
20		Crushed stone	500	6
21		Iron ore concentrate	12000	170
22		Crushed stone	500	6
23		Manganese limestone	1010	15
24		Iron ore concentrate	4500	64
25		Scrap + scale	400	7
26		Iron ore	1680	24
27		Iron ore concentrate	9000	128
28		Crushed stone	500	6
29		Iron ore concentrate	18000	256

form of discrete clock cycles $[0, T]$, $T\epsilon\{0,1,2...\}$. The specific cost of a unit of cargo $C_{ij}(t)$ at the t^{th} moment of time is known [1].

To solve the problem, it is necessary to minimize the functional [1; 9–13]:

$$F=\sum_{t=0}^{T}\sum_{i=1}^{m}\sum_{j=1}^{n}C_{ij}(t)\cdot U_{ij}(t)+\sum_{t=0}^{T}\sum_{i=1}^{m}C_{i}^{*}(t)\cdot X_{i}^{A}(t)+$$
$$+\sum_{t=0}^{T}\sum_{j=1}^{n}C_{j}^{*}(t)\cdot X_{i}^{B}(t), \qquad (1)$$

where $U_{ij}(t)$ is volume of delivery from the i-th supplier to the j-th consumer, that is, the number of cargo with cargo sent from A_i and arriving at B_j at time t;

$X_i^A(t)$ is volume of stock of iron ore raw materials at the i-th supplier at time t;

$X_i^B(t)$ is volume of stock of iron ore raw materials at the j-th consumer, at time t;

$C_j^*(t)$ are costs of storing a unit of stock at time t at the i-th supplier;

$C_j^*(t)$ are costs of storing a unit of cargo of the j-th consumer at time t [1].

The optimization of the functional (1) is subject to such restrictions as:

1. Equation of dynamics of communication between suppliers and consumers [1]:

$$U_{ij}^{+}(t)=U_{ij}^{-}(t-t_{ij})\,; \qquad (2)$$

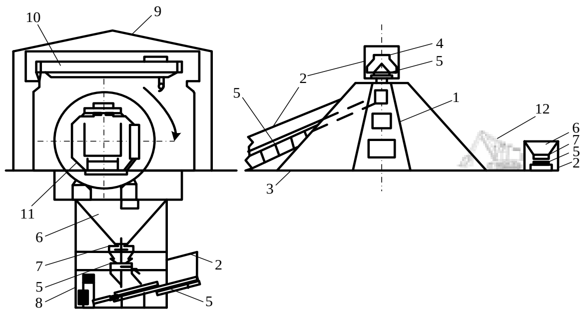
$$U_{ij}^{+}(t+t_{ij})=U_{ij}^{-}(t)\,, \qquad (3)$$

where $U_{ij}^{+}(t)$ is supply arriving at the consumer;

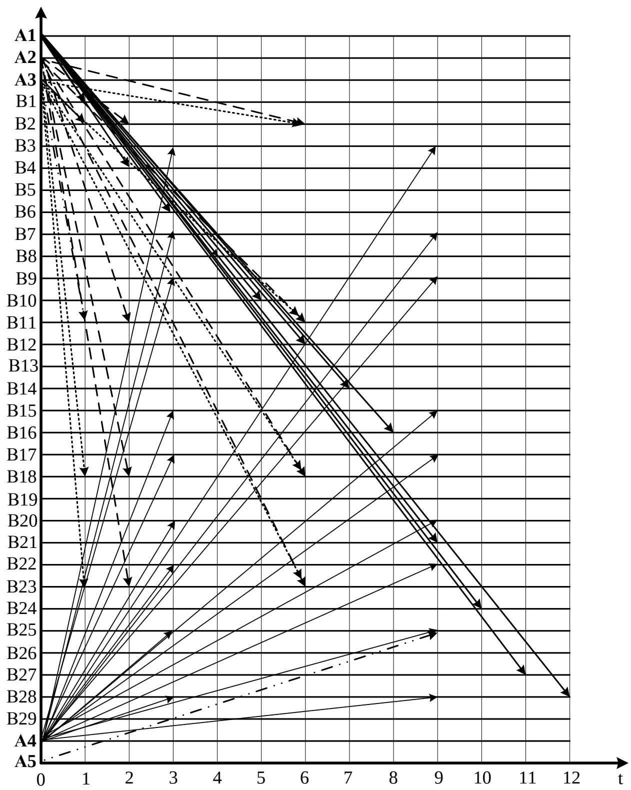
$U_{ij}^{-}(t)$ is delivery coming from the supplier;

t_{ij} is transport delay time, equal to duration of transportation from A_i to B_j [1].

2. Equation of dynamics of stocks at suppliers [1; 10]:



Pic. 2. Trestle type ore warehouse: 1 – overpass, 2 – galleries, 3 – under-stack cover, 4 – unloading trolley, 5 – belt conveyor, 6 – receiving bins, 7 – feeder, 8 – underground part of the receiving device, 9 – receiving device building, 10 – bridge crane, 11 – car dumper, 12 – excavator [3].



Pic. 3. Diagram of the relationship between the periods of optimization of suppliers and consumers (authors' drawing).

$$X_i^A(t+1) = X_i^A(t) - \sum_{j=1}^{n} U_{ij}^{-}(t) + a_i(t)\,, \quad (4)$$

where $a_i(t)$ is volume of supplies.

3. Equation of dynamics of consumer stocks [10]:

$$X_j^B(t+1) = X_j^B(t) - \sum_{i=1}^{m} U_{ij}^{+}(t) - b_j(t)\,. \quad (5)$$

4. Equation of balance of volumes of production, consumption, supplies [10]:

$$\sum_{t=0}^{T}\sum_{i=1}^{m} a_i(t) = \sum_{t=0}^{T}\sum_{i=1}^{m}\sum_{j=1}^{n} U_{ij}(t) = \sum_{t=0}^{T}\sum_{j=1}^{n} b_j(t)\,. \quad (6)$$

5. Limiting natural non-negativity of supplies and stocks [10]:

$$U_{ij}(t) \geq 0; \quad X_i^A(t) \geq 0; \quad X_j^B(t) \geq 0.$$

Obtaining DTPD solution is possible [1; 14; 15], if condition (7) is satisfied: there is a dynamic balance of volumes of suppliers and consumers, that is, if there is a relative consistency of their production programs:

$$\sum_{t=0}^{T}\sum_{i=1}^{m} a_i(t) \geq \sum_{t=0}^{t+t_{ij}}\sum_{j=1}^{n} b_j(t); \; t = 0, \ldots, T_0. \quad (7)$$

In formulation of this mathematical model, we will conventionally take the adjoining stations for the supplier, providing sinter production with agglomerated raw materials, as the consumer is the layer; thus, the number of consumers is equal to the number of layers in the stack being formed. In this case, the metallurgical plant is served by five adjoining stations. That is, in the task at hand, we have five suppliers (A1, A2, A3, A4, A5). As mentioned earlier, in the formed stack we have 29 layers, therefore, in the described problem there are 29 consumers (B1, ..., B29). The flow of raw materials must «get» into a certain layer, and each of these layers can be formed by several suppliers. This is how layering is formed, that is, several mono-tasks with a mono load are superimposed on each other; as a result, we get a multiplicative imposition of single-product tasks, on the basis of which a diagram of the relationship between optimization periods of suppliers and consumers is constructed (Pic. 3).

The number of mathematical models is equal to the number of layers in the stack being formed. But do not forget that we cannot form two or more layers at the same time, only single layer is formed at a certain time.

Brief conclusions. Having investigated the possibilities of harmonizing transport flows with the requirements of the main production process, the authors could present ways of possible technical and technological improvement.

Having solved the problem, we obtain scientifically, theoretically grounded standards for technological downtime of raw materials pending unloading. Intervals and downtime in case of unauthorized cargo arrival will become known.

REFERENCES

1. Popov, A. T., Suslova, O. A., Voronkova, E. A. Theoretical foundations of optimization of the process of unloading iron ore raw materials on the example of a metallurgical plant [*Teoreticheskie osnovy optimizatsii protsessa vygruzki zheleznorudnogo syriya na primere metallurgicheskogo kombinata*]. *Bulletin of Lipetsk State Technical University*, 2020, Iss. 2 (43), pp. 36–40.

2. Kudrin, V. A. Metallurgy of steel [*Metallurgiya stali*]. Moscow, Metallurgiya publ., 1989, 560 p.

3. Harrison, A., van Hoek, R. Logistics Management and Strategy. Competing through the supply chain. 3rd edition. Prentice hall financial times, 2008, 343 p. [Electronic resource]: https://docviewer.yandex.ru/?lang=en&tm=1600715022&tld=ru&name=Logistics+Management+and+Strategy+Competing+Through+the+Supply+Chain.pdf&text=2.+Alan+Harrison%2C+Remko+van+Hoek.+Logistics+Management+and+Strategy%3A+competing+through+the+supply+chain&url=https%3A//vulms.vu.edu.pk/Courses/MGMT615/Downloads/Logistics%2520Management%2520and%2520Strategy%2520Competing%2520Through%2520the%2520Supply%2520Chain.pdf&lr=213&mime=pdf&l10n=ru&sign=7a09cc4c3f45d00889f1763e4f234aa5&keyno=0. Last accessed 11.12.2019.

4. Ryaboshuk, S. V., Kovalev, P. V., Kur, A. A. Raw materials base of metallurgy [*Syrievaya baza metallurgii*]. St. Petersburg, 2018, 60 p.

5. Galaburda, V. G. Single transport system: Textbook for universities [*Edinaya transportnaya sistema: Uchebnik dlya vuzov*]. Moscow, Transport publ., 1996, 295 p.

6. Rakhmangulov, A. N. Railway transport and technological systems: organization of functioning: Monograph [*Zheleznodorozhnie transportno-tekhnologicheskie sistemy: organizatsiya funktsionirovaniya: Monografiya*]. Magnitogorsk, Nosov Magnitogorsk State Technical University, 2014, 300 p.

7. Kozlov, P. A., Milovidov, S. P., Popov, A. T. Organization of work of technological transport in industrial systems [*Organizatsiya raboty tekhnologicheskogo transporta v promyshlennykh sistemakh*]. *Ekonomika i matematicheskie metody*, 1986, Iss. 4 (22), pp. 697–703.

8. Kozlov, P. A., Vladimirskaya, I. P. Ways to improve validity of technological solutions: problems and judgments [*Puti povysheniya obosnovannosti tekhnologicheskikh reshenii: problemy i suzhdeniya*]. *Bulletin of VNIIZhT: Scientific and technical journal*, 2009, Iss. 3, pp. 8–13.

9. Popov, A. T., Gnedash, M. A. Optimization of transport flows in the system «production–transport–consumption»: Monograph [*Optimizatsiya transportnykh potokov v sisteme «proizvodstvo–transport–potreblenie»: Monografiya*]. Lipetsk, LSTU publ., 2006, 179 p.

10. Popov, A. T., Suslova, O. A., Voronkova, E. A. Optimization of interaction between agglomeration and blast-furnace production on the basis of a dynamic transport problem with delays [*Optimizatsiya vzaimodeistviya aglomeratsionnogo i domennogo proizvodstva na osnove dinamicheskoi transportnoi zadachi s zaderzhkami*]. *Bulletin of Lipetsk State Technical University*, 2018, Iss. 2 (36), pp. 66–74.

11. Popov, A. T. Optimization of interaction of technological railway transport and production (using an example of a metallurgical plant). Ph.D. (Eng) thesis [*Optimizatsiya vzaimodeistviya tekhnologicheskogo zheleznodorozhnogo transporta i proizvodstva (na primere metallurgicheskogo kombinata). Dis ... kand. tekh. nauk*]. Moscow, MIIT publ., 1984, 237 p.

12. Nesterov, E. P. Transport problems of linear programming [*Transportnie zadachi lineinogo programmirovaniya*]. Moscow, Transport publ., 1971, 216 p.

13. Kantorovich, L. V., Gorstko, A. B. Mathematical optimal programming in economics [*Matematicheskoe optimalnoe programmirovanie v ekonomike*]. Moscow, Znanie publ., 1968, 96 p.

14. Phillips, D. T., Garcia-Diaz, A. Fundamentals of Network Analysis. Prentice-Hall, Englewood Cliffs, 1981, 474 p. [Electronic resource]: https://books.google.ru/books/about/Fundamentals_of_network_analysis.html?id=w2FRAAAAMAAJ&redir_esc=y. Last accessed 25.02.2020.

15. Ford, L. R., Fulkerson, D. R. Flows in Networks. New Jersey: Princeton university press Princeton, 1962, 212 p. [Electronic resource]: https://www.rand.org/content/dam/rand/pubs/reports/2007/R375.pdf. Last accessed 25.02.2020.