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CONTENT

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Original article
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Innovative energy sources for Hyperloop high-speed transport

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ABSTRACT This article describes an innovative design of a solar-wind generator for a distributed energy Hyperloop high-speed system. The knowhow of this development is to mount flexible silicon solar panels (SP) on wind turbine blades, thus optimizing the thermal efficiency of solar panels. The basic dimensions of the wind turbine blades and the maximum internal flow velocities at the blade outlet (tips) are presented. At low wind velocities, it is rational to locate solar panels on the outer end (or the tip) of a blade, rather than along the blade length.

The cooling effect can be increased by using materials with low thermal resistance for the SP and blades, or by reducing their thickness.

To increase the heat transfer coefficient, it is recommended to use the airflow turbulence on the solar panel surface. In practice, this can be achieved both by changing the operating parameters and by introducing innovative design solutions.

For better cooling of solar panels, it is recommended to use the technology of a wind flow sucked into the blade inner cavity.

Changing the geometry of the outer end (tip) of the blades and the use of deflectors also give a better panel cooling parameters.

KEYWORDS: hyperloop high-speed transport; solar-turbine generator; flexible silicon solar panel; solar insolation; wind flow; heat transfer coefficient; temperature; blade inner cavity

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Научная статья

Использование инновационных альтернативных источников энергии в трубопроводном высокоскоростном транспорте

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АННОТАЦИЯ Рассматривается инновационная конструкция гелиоветрогенератора, предназначенная для распределенной системы электроснабжения трубопроводного высокоскоростного транспорта. Know how данной разработки заключается в закреплении гибких кремниевых солнечных панелей (СП) на лопастях ветротурбины. За счет этого возможно обеспечение оптимального теплового режима работы СП. Приводятся основные размеры конструкций лопасти и максимальные скорости внутреннего потока на выходе из лопасти. Показывается, что при малых скоростях ветрового потока рационально располагать СП не по всей площади лопасти, а ближе к ее концу.

Усиления эффекта охлаждения можно достичь, применяя материалы для СП и лопастей с малым полным термическим сопротивлением или уменьшая их толщину.

Для увеличения коэффициента теплоотдачи следует реализовывать турбулентный режим течения воздушного потока на поверхности СП. На практике это достигается как за счет изменения режимных параметров, так и с помощью конструктивных решений.

С целью усиления охлаждения панелей необходимо использовать часть ветрового потока, принудительно засасываемого во внутреннюю полость лопасти.

Изменение геометрии оконечных частей лопастей и применение дефлекторов также благоприятно сказываются на интенсивности охлаждения панелей.

КЛЮЧЕВЫЕ СЛОВА: трубопроводный высокоскоростной транспорт; гелиоветрогенератор; гибкая кремниевая солнечная панель; солнечная инсоляция; ветровой поток; коэффициент теплоотдачи; температура; внутренняя полость лопасти

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INTRODUCTION

It is well-known that the advantages of Hyperloop high-speed transport are fully manifested on main lines (at longer distances and with fewer stops). It will be most efficient in a Hyperloop with low-pressure environment inside the tube (the air density is 1.5–2 times lower in comparison with that outside), with passenger capsules (pods) moving at a speed of 500–1000 km/h due to low aerodynamic resistance [1]. This technical solution will make it possible to reduce energy use required for a linear electric drive motor, which is particularly suitable in specific operating conditions. High speeds dictate the replacement of the “rail-wheel” mechanical system by Hyperloop capsules moving in a near-vacuum tube created by electromagnetic force [2].

When the capsule moves along the tube, a boundary air layer is created on its surface. Due to the capsule surface roughness, uneven airflow, capsule vibrations, etc., perturbations of the boundary air layer occur resulting in the turbulent spots that induce a turbulent state of almost the entire boundary air layer over time, thus, increasing sharply the aerodynamic drag of the capsule. To eliminate this and partially reduce the “piston” effect, the engineers of Emperor Alexander I St. Petersburg State Transport University (PGUPS) have put forward an idea of the perforated front surface of the capsule [3]. The incipient turbulent air is sucked through the holes of the perforated shell (*Fig. 1*) and the boundary layer maintains laminar character. This can result in up to 30 % lower frontal aerodynamic drag. At the same time, pressure equalization at the head and tail of the moving capsule (so-called “piston” effect) takes place. The airflow passing through the perforated holes is used for air conditioning and ventilation inside the capsule as well as cooling of the on-board current-carrying elements. Pumps can be used to produce turbulent air suction.

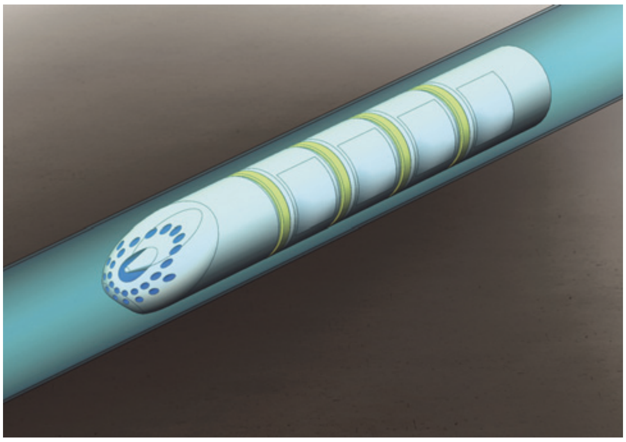

Fig. 1. Passenger capsule with the perforated front

A linear induction motor distributed along the inside wall of the tube is one of the main elements of this transport system. To reduce electric energy losses, energy sources should be distributed along the length of the tube, with each source responsible for their “own” section, electrically independent from the adjacent sections. Each energy source should switch on as soon as the capsule enters the corresponding section.

For energy sources, it is proposed to use solar-wind generators developed at the Electrical Engineering and Heat Engineering department (PGUPS, St. Petersburg, Russia) [4].

The know-how is as follows. Commonly used silicon solar panels have an inherent disadvantage: their efficiency decreases as their temperature exceeds a certain optimal value (about 25 °C) [5]. Thus, it is recommended to cool the solar panel by an incoming airflow. For this purpose, thin-film solar panels (SP) should be mounted on the wind turbine blades.

DESIGN

A horizontal axis wind turbine with three blades is taken as a basis for a solar-wind generator. Two developments have been considered. The first one is based on the AAERA 1500-70 turbine while the second one is based on the Micon 450/530 turbine (*Table 1*). E-Power flexible solar panels (*Table 2*) with Solar Sity photovoltaic cells are used. Solar panels *1* (*Fig. 2*) are attached to the blade *2* front surface. When sunlight hits the solar panels, they generate electric current according to the photovoltaic effect. Through a sliding current collector (not shown in the Figure), this current goes to a storage

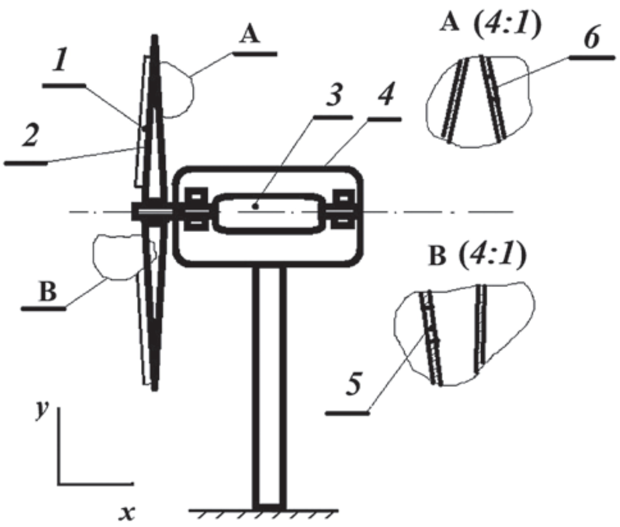

Fig. 2. Design of a solar-wind generator:
1 – solar panels; *2* – blades; *3* – cylindrical rotor; *4* – electric generator; *5*, *6* – holes

Table 1

Wind turbine characteristics

Parameters	AAERA 1500-70	Micon 450/530
Rated power, kW	1500	250
Minimum wind velocity at the beginning of operation, m/s	3	4.5
Rated wind speed, m/s	11.8	14.5
Maximum wind speed, m/s	59	50
Rotor diameter, m	77	26
Specific power, W/m^2	390	471.7
Generator	Asynchronous double-phase	Asynchronous three-phase
Voltage, V	480	400
Frequency	60 Hz	50 Hz

Table 2

E-Power 160 solar panel characteristics

Type	Monocrystalline
Number of cells in the module, pcs.	36
Cell size, mm	156 × 156
Power, W	160
Noload voltage, V	21.6
Operating voltage, V	18
Short-circuit current, A	9.07
Operating current, A	8.89
Cell efficiency, %	20

device (e.g. battery) located at the wind turbine tower base, or, in case of a synchronous generator, to the excitation winding (in this case, the sliding current collector is not used).

The rotation of the blades *2* starts the effective cooling of solar panel *1*. At the same time, the cylindrical rotor *3* of the electric generator *4* rotates; thus, the rotor kinetic energy is converted into electrical energy. It is possible to use electric generators of different types.

HEAT TRANSFER NUMERICAL SIMULATION FOR THE SOLAR-WIND GENERATOR BLADE

To determine the solar-wind turbine performance, the climate conditions with wind speed of 4.2 m/s, solar insolation of 5.79 kW/m^2 and ambient air temperature of 23.8 °C were chosen.

The rotor speed of the solar-wind turbine was ~5.

The solar heat absorbing surface area of three blades (assuming the blades had a rectangular shape) was 427.35 m^2 for AAERA 1500–70 and 49.14 m^2 for 450/530 Micon. The flexible solar cells were assumed to cover the entire surface of the blades. Ambient temperature over the course of a day could be modeled as a sinusoidal function according to the law:

$$T_{air}(t) = \Theta_{avg} + \Delta\Theta \cos\left(2\pi \frac{t-14}{24}\right), \quad (1)$$

where t is time, h; Θ_{avg} and $\Delta\Theta$ are adjustable parameters corresponding to the average temperature and temperature changes respectively during the day and night.

The calculations for Θ_{avg} = 22 °C and $\Delta\Theta$ =10 °C are shown in *Fig. 3*.

In the first part of simulation tests, three rotating blades we presented by a flat rotating disc of homogeneous thickness with a diameter equal to the diameter of the wind turbine rotor. The disc was made of fiberglass reinforced epoxy resin. The rotating speed of the disc was constant and equaled 5.2 rpm. Solar heating and convective heat transfer took place only at the front surface of the blades positioned perpendicular to the solar flux. The back and side surfaces of the disc were thermally insulated.

Temperature distributions along the disc radius for AAERA 1500-70 are shown in *Fig. 4*. Curve *1* corresponds to 6 o'clock, curve *2* to 8 o'clock, curve *3* to 10 o'clock, and curve *4* to 13.5 o'clock (time of maximum temperatures).

As seen from *Fig. 4*, the disc temperatures could be considered acceptable only in the early morning hours. Later in the day, the temperature exceeded its optimal value (25 °C). This fact should not be given much consideration because the equal size of the disc diameter and the wind turbine rotor diameter was of oversim-

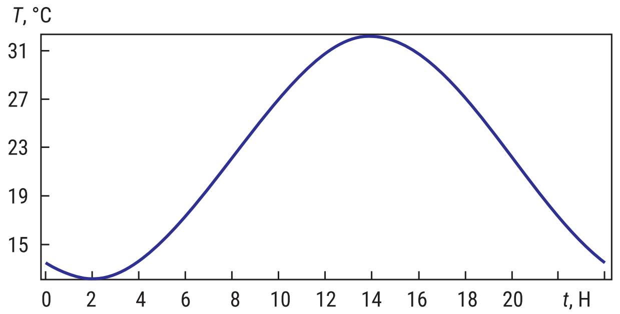

Fig. 3. Daily variations in ambient air temperature

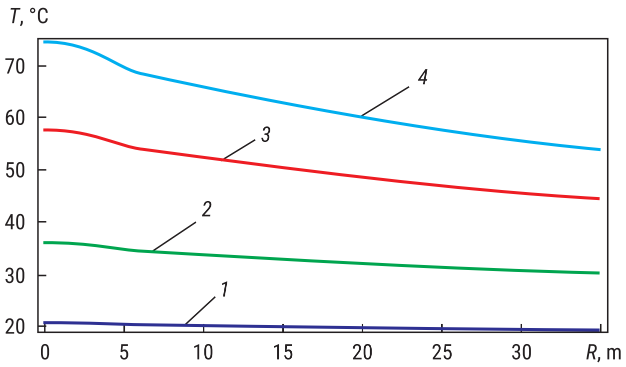

Fig. 4. Temperature distribution along the disk radius

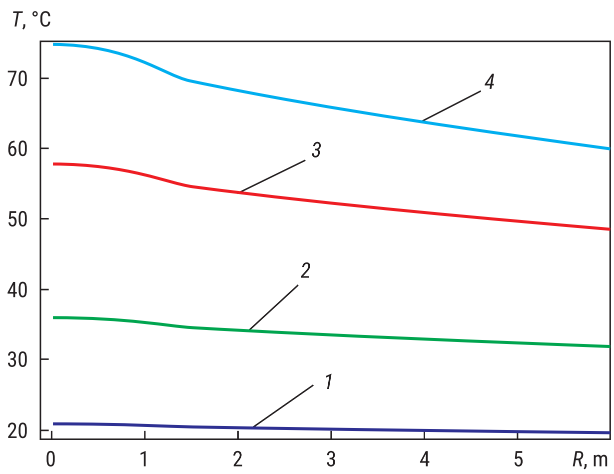

Fig. 5. Temperature distribution along the radius of the equivalent disc

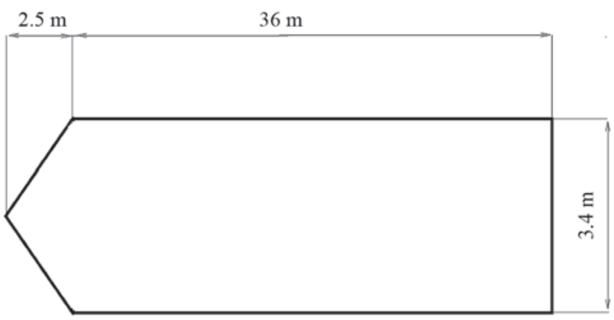

Fig. 6. Blade shape and dimensions

plified assumption. It is interesting to note that the received dependences illustrated the influence of the centrifugal force on the temperature distribution along the disc radius. The temperature decreased steadily towards the disc periphery.

At the second stage of the simulation, the three blades real area was taken into consideration, which was 427.35 m² for AAERA 1500-70. The diameter of the equivalent disk, in terms of the area exposed to solar insolation, was equal to 11.67 m.

The calculations are shown in *Fig. 5*. The dependence numbers correspond to the time points as in *Fig. 4*.

It should be noted that despite a certain temperature excess associated with the reduction of the heat transfer area, the conclusions for the 77 m diameter disc apply to this case as well.

The next issue to be considered was how much the real blade rotation will decrease the solar panel temperature. A blade shown in *Fig. 6* was taken as a model. The blade was assumed to be monolithic made of fiberglass reinforced epoxy resin.

The calculation was based on the heat transfer formula

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p u \nabla T + \nabla q = Q + Q_{ted}; \qquad (2)$$

$$q = -k \nabla T, \qquad (3)$$

where ρ is the density; C_p is the specific heat capacity; the change of temperature field over a period of time; $\partial T / \partial t$ is the temperature field gradient; q is the density of the heat flow transferred from the surface to the environment; Q is the heat flow; $-k$ is the heat transfer coefficient. The minus sign shows that the heat flows in the opposite to the vector direction.

However, even in this case, the blade front surface temperatures reached 140 °C, which can be explained by a very low thermal conductivity of the blade material. Therefore, an additional summand Q_{ted} was introduced to change the external heat flow.

The time dependences of the solar heat flow and the ambient air temperature were the same as those for the disc.

The symmetry condition $-nq = 0$ was set on two blade surfaces located at an acute angle (*Fig. 6*). The other surfaces were thermally insulated, which suited the symmetry condition in appearance.

The dependences in *Fig. 7* show the temperature distribution along the longitudinal axis of the blade at different values of the heat transfer coefficient: curve *1* corresponds to 5 W/(m² · K), curve *2* to 10 W/(m² · K), and curve *3* to 15.5 W/(m² · K).

Fig. 8 shows temperature distributions along the longitudinal axis of the blade of Micon 450/530 wind turbine at different times of the day for the heat transfer coefficient equal to 10 W/(m² · K) and 15.5 W/m² · K respectively. The length of the blade is 13 m; the width

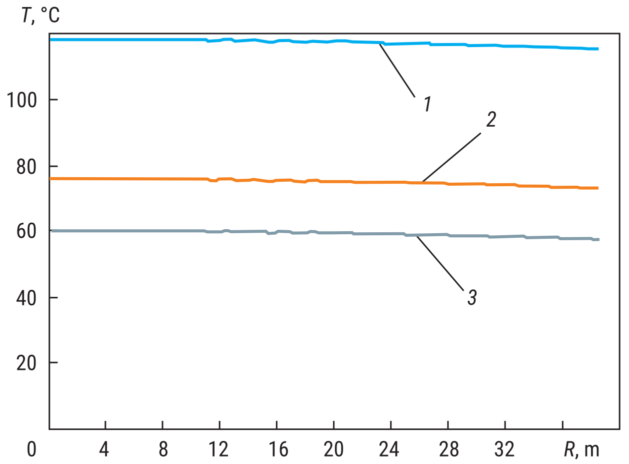

Fig. 7. Graphs of temperature distribution for different heat transfer coefficients (2*R* = 77 m)

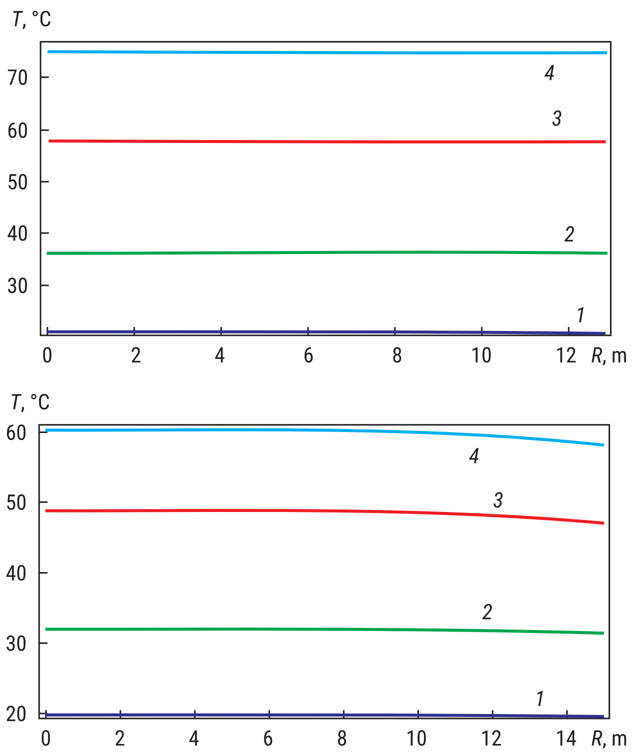

Fig. 8. Graphs of temperature distribution along the longitudinal axis of Micon 450/530 wind turbine blade at different times of the day

is 2.2 m. Curve *1* corresponds to 6 o'clock, curve *2* to 8 o'clock, curve *3* to 10 o'clock, and curve *4* to 12 o'clock.

As was expected, the maximum blade (panel) temperatures were observed in the hours close to noon (*Fig. 9*).

Thus, under the assumed climatic conditions, this design solution, namely, the location of solar panels on the wind turbine blades, does not prove to be efficient for obtaining the optimal temperature of 25 °C, even if a certain temperature reduction was proved to take place. However, the results obtained in the course of simulations allowed making some preliminary conclusions and outlining further research fields.

The heat transfer coefficient can be improved by increasing the wind turbine rotational speed.

The airflow turbulence near the solar panel surface can improve its thermal condition. Turbulent air pulsations increase the panel heat transfer. In practice, the air turbulence can be achieved by changing the operating parameters or by new design solutions. For example, spiral grooves on the blade and solar panel surfaces or artificially created roughness of the solar panel surface can induce airflow perturbations. Aerodynamics and strength factors should be taken into consideration when studying the feasibility of these solutions.

The heating rate of the solar panel decreases towards the blade tip (see *Fig. 7*, *8*), so at low wind velocity, it is rational to place the solar panels closer to the turbine blade end (tip) rather than over its entire area.

The cooling effect can be improved by reducing the thermal resistance of solar panels in the direction perpendicular to their front surface. The use of materials with greater thermal transfer coefficient and thinner solar panels can improve the cooling effect.

INNOVATIVE DESIGN

A cooling mechanism of the blade front surface has been described above. Cooling the blade from inside seems significant as well (see *Fig. 2*). To make it possible, the blade should be hollow inside and have an inlet hole 5 at the rim (on the blade front surface) and an outlet hole 6 at the blade back surface tip (*Fig. 2*) [6].

The "sucking" of the airflow inside the blade occurs as follows. Approaching the sweeping area of the rotating blades (*Fig. 10*, *y*-axis), the wind flow slows down

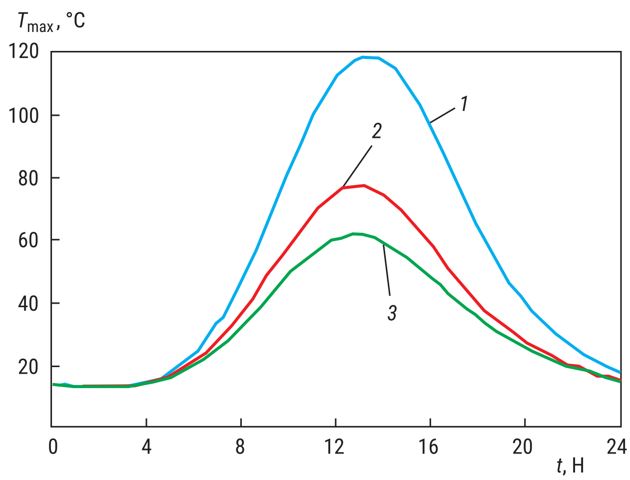

Fig. 9. Change of blade maximum temperatures during the day: curve *1* corresponds to 5 W/(m²·K); curve *2* to 10 W/(m²·K); curve *3* to 15.5 W/(m²·K)

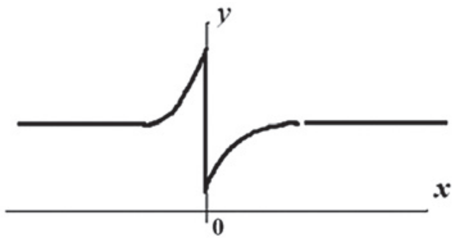

Fig. 10. Pressure diagram

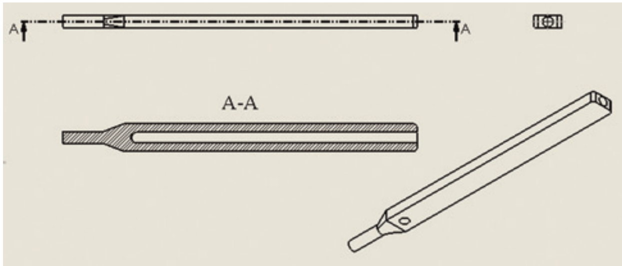

Fig. 11. Straight blade design

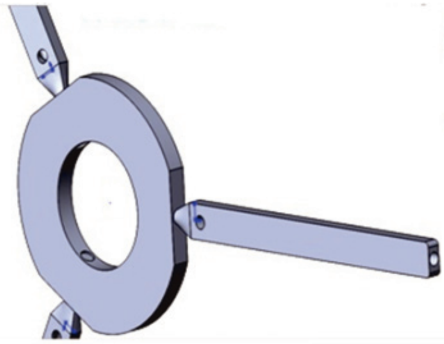

Fig. 12. Wind turbine rotor

and its speed decreases causing the static pressure increase in this area, according to Bernoulli's law. As the wind stream passes through the front area of rotating blades, it meets lower resistance and the air pressure drops suddenly. Because of this pressure drop, the air is partially sucked into hole *5* inside the blade (*Fig. 2*). Passing through the blade inner cavity, the air exits hole *6* (*Fig. 2*). As a result, the blade (panel) is cooled by the inside air.

SIMULATION OF A BLADE WITH AN INTERNAL CAVITY IN SOLIDWORKS

"Straight" blade design

The effect of blade rotation on the airflow velocity inside the blade was studied using SolidWorks.

For simplification, the turbine blade (multilayer heterogeneous structure) was represented as a rectangular hollow parallelepiped with a cylindrical rim. It was called a straight blade design (*Fig. 11*).

Fig. 12 shows a fragment of the wind turbine rotor.

The SolidWorksFlow simulation based on the Finite Volume Method was used to simulate wind flow through the blade inner cavity.

The boundary conditions were set by the "real moving wall" surface. The coordinate system was referenced to the rotor. The model rotated counterclockwise at an angular velocity of –2.62 rad/s.

The simulation analysis showed that with the wind velocity in front of the rotor being 4.2 m/s, the airflow inside the "straight" blade cavity had a velocity as low as 0.2 m/s and was turbulent in nature. This led to further improvement of the blade design.

A flanged blade tip design

The effect of a flanged blade tip on the internal airflow velocity was studied. The flanged tip consisted of a "knee" bend of a certain length attached to the blade tip at an angle relative to the longitudinal axis of the blade.

The basic dimensions of solar-wind generator blade designs under consideration are presented in *Table 3* (*L* is the length of the main part of the blade).

Table 3

Main dimensions of the turbine blade designs and maximum internal flow velocities at the blade output

Blade knee-bend length, % of *L*	Angle of the knee bend, deg.	Maximum airflow velocity at the blade output, m/s
5	90	0.83
10	90	1.20
15	90	1.43
20	90	1.45
5	30	0.70
10	30	1.10
15 The best option	**30**	**1.51**
20	30	1.45
5	–30	1.20
10	–30	1.27
15	–30	1,25
20	–30	1.40
5	45	0.90
10	45	1.12
15	45	1.25
20	45	1.15
5	–45	0.85
10	–45	1.00
15	–45	1.17
20	–45	1.40

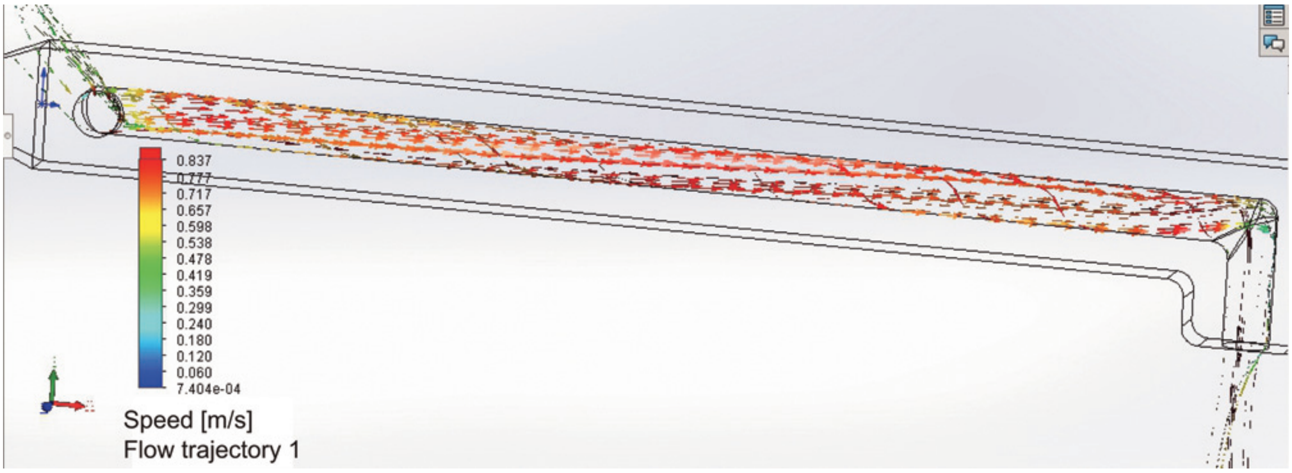

Fig. 13. A blade with a flange length of 0.05*L* bent at an angle 90°

Fig. 13. A blade with a 0.05L-long flange "knee" at an angle of 90° and the calculations of the internal airflow.

As can be noticed, the airflow has a laminar character and the velocity of 0.83 m/s. This value is several times greater than that of a straight blade design.

Increasing the flange "knee" length at a fixed angle of bending led to an increase in the airflow velocity while maintaining its laminar character. However, at greater lengths of the flange, the solar-wind turbine rotor aerodynamics and strength deteriorate. In addition, the study was conducted on how the flange angle variations effected the internal airflow velocity and its character. The optimal parameters were obtained with a flange of 0.15*L* at an angle of 30° (*Fig. 14*). The internal air flow velocity parameters can be seen in this picture as well.

In a flanged tip blade design, the internal airflow remains laminar at a speed of 1.51 m/s, which is about 8 times greater than that in a straight blade design.

A blade design with a tip flange in the opposite direction (at a negative angle) was studied and it showed a lower airflow velocity than that in the optimal design, with the airflow remaining laminar. Wherein the turbine rotational speed is reduced due to brake torque.

A blade with a deflector system

A deflector was assumed to increase the air draft in the blade internal cavity and aerodynamic resistance to rotation.

Using SolidWorks, a deflector in the form of a truncated hollow pyramid was built. An optimal blade design was chosen (see *Table 3*). The results of aerodynamic calculations for this case are shown in *Fig. 15.*

The deflector size allowed a gap spacing between the blade outside surface and the deflector inner wall.

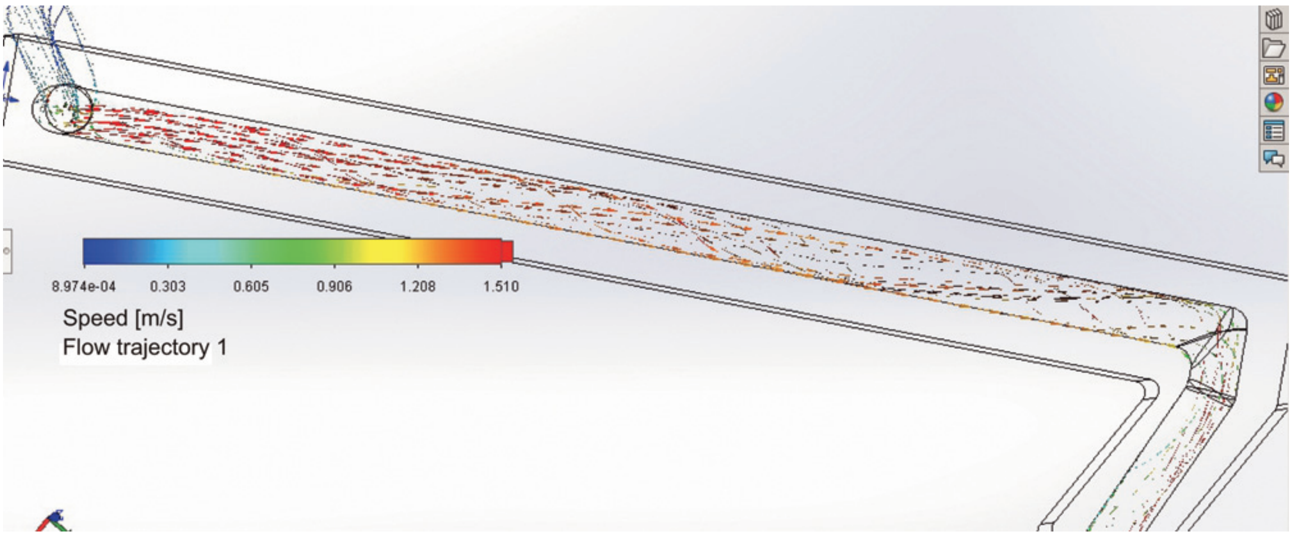

Fig. 14. Blade design and calculation results

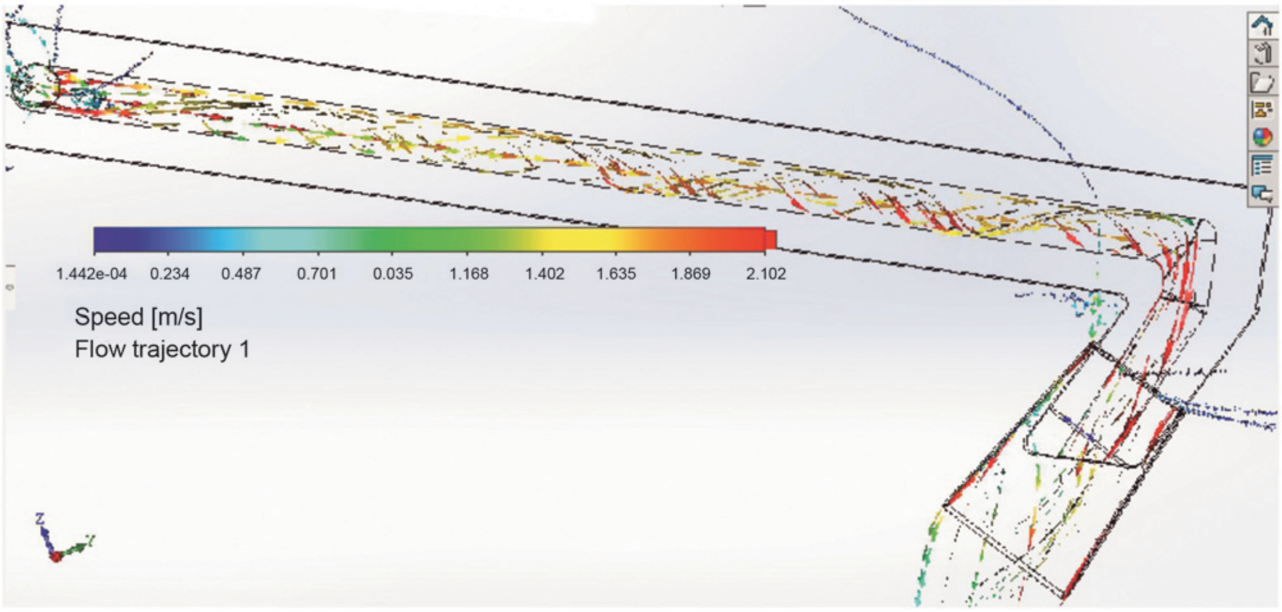

Fig. 15. Calculation results of a deflector blade

Thus, the ambient airflow rushed inside the blade tip through this gap spacing with speed acceleration. It dragged the airflow passing through the blade internal cavity along with (see *Fig. 15*).

The airflow inside the blade remained laminar.

The results showed that the airflow velocity increased 1.3 times and reached an average value of about 2 m/s.

SIMULATION OF HEAT TRANSFER FOR THE SOLAR-WIND GENERATOR BLADE USING COMSOLMULTIPHYSICS

The COMSOL Multiphysics package was used to study the effect of an airflow inside the blade on the solar panel thermal parameters.

The blades were assumed to be made of fiberglass reinforced epoxy resin of uniform thickness. The blade rotated with a constant speed of 2.62 rad/s. The sun heated the blade front surface only. Convective heat transfer was carried out only on the blade front surface. The blade back and side surfaces were thermally insulated.

The calculations were carried out for solar radiation flux of 800 W/m^2, with wind speed being 4.2 m/s and ambient air temperature being 23.8° C.

The blade inteenal cavity had the following dimensions: cavity length was 36 m, wall thickness was 0.02 m, and cross-section width was 0.2 m.

The HeatTransferinSolids interface was used for thermal calculations. Heat transfer equations (2) and (3) were used.

We can note the following regarding the boundary conditions (BC). For the upper boundary of the air flow, BC "Open Boundary" was set up, which took into account the airflow temperature equal to the ambient temperature. BC "Inflow" was used for the left boundary. It indicated the input of the airflow. BC "Outflow" was used for the right boundary and indicated the output of the airflow. BC "Heat Flux" was used to indicate the heated airflow at the blade outer boundary, and the command "Heat rate" was used to account for the flow velocity.

While setting boundary conditions, "Laminar Flow" interface was used to designate the laminar airflow parameters. The laminar air flow boundaries were set up with "Wall 1" command for the lower boundary and "Wall 2" command for its upper boundary.

The airflow velocity at the beginning of the laminar flow was set with "Inlet" command.

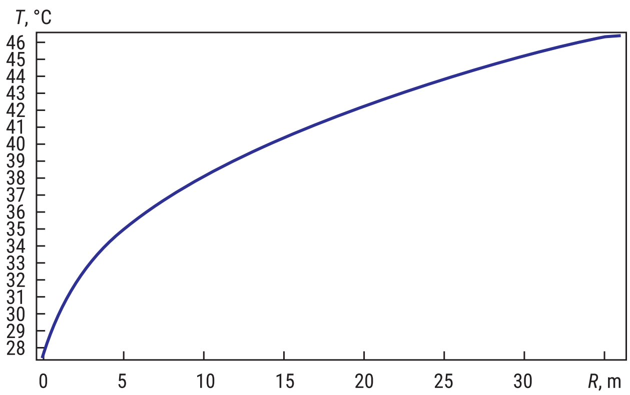

Fig. 16. Thermal calculation results

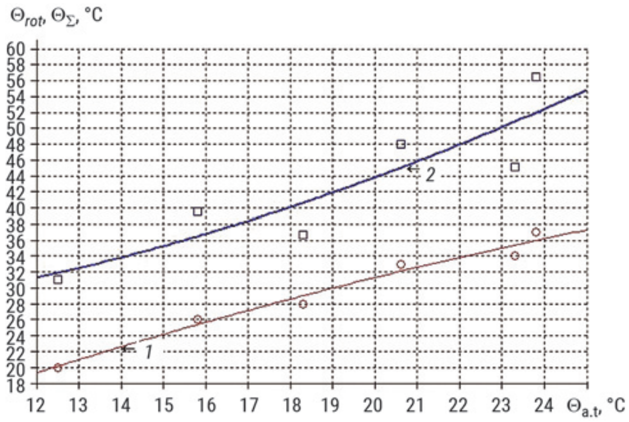

Fig. 17. Graphs show the dependence of the average blade temperature on the ambient temperature: curve *1* is external and internal cooling; curve *2* is external cooling only; Θ_{rot} is average blade temperature resulting from blade rotation; ΘΣ is average blade temperature resulting from blade rotation and internal cooling; $\Theta_{a.t.}$ is ambient air temperature

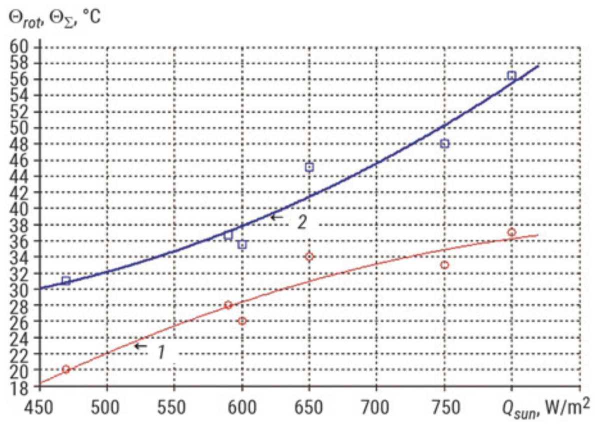

Fig. 18. Graphs show the dependence of the average blade temperature on the solar heating flux value: curve *1* is external and internal cooling; curve *2* is external cooling only; Q_{sun} is solar heating flux

"Outlet" command was used to set up "Suppress Back flow" (pressure suppressing a backflow).

To combine two physical processes "Heat Transfer in Solids" and "Laminar flow", the "Multiphysics" command was used.

The temperature distribution along the length of the blade was obviously similar to the graph of the even-degree root. The minimum temperature of the blade wall heating was 27 °C, and the maximum temperature was about 46.5 °C. This corresponds to an average blade heating temperature of 37 °C. In this case, the steady-state temperature of the blade without internal cooling (only external cooling due to blade rotation) is equal to 56.45 °C for the specified weather conditions [7].

Therefore, the airflow passing through the blade internal cavity reduced the temperature of the blade surface by about 20° C for the considered case.

The results of thermal calculations for different weather conditions are shown in *Fig. 17*, *18*. If we compare these graphs, we can see that the blade temperature reduction due to internal cooling is in the range of 9–20 °C for the considered cases.

CONCLUSION

The optimal solar panel temperature can be effectively achieved by increasing the speed of the wind turbine rotations, which leads to an increase in the heat transfer coefficient.

At low wind speeds, it is rational to place the solar panel closer to the blade tip rather than over the entire area of the blade.

The cooling effect can be increased by using materials with less thermal resistance for solar panels and blades or by reducing their thickness.

To increase the heat transfer coefficient, it is recommended to create the airflow turbulence on the solar panel surface. This can be achieved both by changing the operational parameters and new design solutions.

To increase the solar panel cooling, it is recommended to use part of the wind flow sucked into the inner cavity of the blade. Optimizing the blade tip geometry and using deflectors will also increasethe solar panel cooling.

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High-performance concrete in road pavement construction

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ABSTRACT This paper describes that concrete physical and mechanical properties such as density, crack resistance, durability and reliability can be improved with introducing a high-performance chemical additive based on polycarboxylate polymers modified with electrolytes based on group I metal cations of the main subgroup in D.I. Mendeleev's table. These high mobility polymers facilitate their diffusion ability. It is recommended to use silicon hydroxide nanoparticle dispersion as an additional component as they have such unique properties as increased reactivity.

The superplasticity and reactivity of the complex chemical additive under study proved to increase cement hydration process and enhance the formation of new hydrate phases, which contributed to a greater bending tensile strength and chemical resistance of concrete. The use of this complex chemical additive increased the compressive strength by more than 41 % and the bending tensile strength by 56 %, which contributed to concrete crack resistance.

Concrete water resistance was proved to increase by 75 % and corresponded to W14 class while concrete frost resistance increased by 70 % to the value of F2500, and chemical resistance increased by 16 % to the value Kx.s. l 0.93. According to GOST 58895-2020, this advanced concrete corresponds to the concrete with increased chemical resistance.

According to the test results of physical and mechanical properties, concrete with this complex chemical additive is recommended to use in federal highway pavement construction.

KEYWORDS: concrete; strength; crack resistance; corrosion resistance; water absorption; frost resistance; durability; chemical additives; polycarboxylates; nanoparticle dispersion; silicon dioxide

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Научная статья

Высокоэффективный бетон для дорожных покрытий

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АННОТАЦИЯ Показано, что уровень основных физико-механических свойств бетона — плотность, устойчивость к трещинообразованию, долговечность и надежность можно улучшить использованием высокоэффективной комплексной химической добавки на основе поликарбоксилатных полимеров, модифицированных электролитами на основе катионов металлов I группы главной подгруппы таблицы Д.И. Менделеева, обладающих повышенной подвижностью и, как следствие, диффузионной способностью, а также эффективно использовать в качестве дополнительного компонента добавки нанодисперсии гидроксида кремния, которые отличаются уникальными свойствами, а, именно повышенной реакционной активностью.

Установлено, что исследуемая комплексная химическая добавка обладает суперпластифицирующим и реакционноактивным эффектами действия, которая не только повышает степень гидратации цемента, но и способствует образованию новых гидратных фаз, о чем свидетельствует значительное повышение прочности на растяжение при изгибе, а также значительное повышение химической стойкости бетона.

Показано, что использование исследуемой комплексной химической добавки повышает прочность на сжатие на 41 % и более, на 56 % повышается прочность на растяжение при изгибе, что способствует повышению трещиностойкости бетона.

Определено, что водонепроницаемость бетона увеличивается на 75 % и соответствует марке W14, морозостойкость повышается на 70 % до значения F2500 и химическая стойкость бетона повышается на 16 %, до значения Кх.с. l 0,93 и согласно ГОСТ 58895-2020 данный модифицированный бетон соответствует бетону повышенной химической стойкости.

По результатам физико-механических исследований бетон с комплексной химической добавкой целесообразно использовать и рекомендовать для изготовления верхнего дорожного покрытия автомагистралей федерального назначения.

КЛЮЧЕВЫЕ СЛОВА: бетон; прочность; трещиноустойчивость; коррозионная стойкость; водопоглощение; морозостойкость; долговечность; химические добавки; поликарбоксилаты; нанодисперсии; диоксид кремния

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INTRODUCTION

High-performance concretes (with increased crack resistance, density, water resistance, frost resistance and corrosion resistance) are highly demanded in modern construction, both domestic and foreign, for a wide range of products and structures.

In road construction, especially in the construction of federal highways with a high traffic flow, concrete is preferable as it is more durable than asphalt [1–3].

The traffic density including multi-tonnage traffic is constantly increasing, which leads to increased requirements for the road pavement quality.

Road surfaces are not protected from various negative effects such as increased mechanical stresses, temperature changes from negative to positive in different seasons, precipitations and aggressive salt solutions used in anti-icing mixtures, which require highly reliable and ecologically friendly materials not to have a negative impact on the environment [4–6].

Cement-based concrete can meet these requirements to the greatest extent as its properties can be modified and advanced. In world practice, concrete is being used increasingly for road pavements providing better reliability and durability due to the formation of such properties as:

- enhanced compressive and bending tensile strengths so as to increase crack resistance;
- enhanced hardness so as the riding quality is not affected and the pavement is not deformed under the wheels of multi-tonnage vehicles;
- enhanced density to prevent the penetration of excess moisture and aggressive salt solutions inside, thus improving the concrete water and frost resistance and durability [7–10].

Studies on concrete hardening process have shown that these specified properties can be generated by activating certain chemical processes occurring during concrete mixture hardening.

The number and composition of the generated complex hydrate compounds as well as bonding concrete mix components with the formation of hydrate phases due to generating new chemical bonds have an important impact on the formation of these properties.

In a traditional concrete mixture, cement is a reactive component forming certain complex hydrate compounds as a result of thermal or chemical processes. Stress-strain properties and the structure of the hardened concrete largely depend on these hydrate formations.

MATERIALS AND METHODS

This scientific research describes the concrete with improved properties. During the scientific experiment, B30-class concrete was used. It consisted of PC 500-D0 Portland cement produced at JSC “Pikalevsky cement” according to GOST 10178-85:

- grade (MPa) — 50.0;
- cement average activity in steaming (MPa) — 40.8;
- standard density of cement paste (%) — 25.75;
- soundness (expansion) is standard;
- GOST 8736-2014 construction sand with particle modulus size Mk = 2.6, medium-size, dust and clay particles content is 0.8–1.0 %, bulk density is 1550 kg/m^3;
- GOST 8267-93 crushed granite fractions of 5–20 mm.

The following amount of basic materials per 1 m^3 of concrete mix were used:

- 500-D0 PC Portland cement 410 kg/m^3;
- sand of Mk = 2.6 770 kg/m^3;
- crushed stone fractions (5–20) mm 1000 kg/m^3.

All the investigated mixtures had the same fluidity corresponding to P2 fluidity grade (cone slump was 5–9 cm) according to GOST 7473-2010 "Concrete mixtures. Technical conditions".

The control concrete mixture and the tested concrete mixture with a complex chemical additive were subjected to the following stress-strain tests.

- Tests for compressive and bending tensile strengths were carried out in accordance with GOST 10180-2012. Four 100 × 100 × 100-mm sample cubes and three 100 × 100 × 400-mm sample prisms were made for the experiment. The samples were hardened under standard conditions in accordance with GOST 10180-2020, paragraph 4.3 (with the temperature of 20 ± 2 °C and relative humidity of 95 ± 5 %).
- Water permeability was tested according to GOST 12730.5-2018 "Concretes. Water Resistance Test Methods". For testing, six 150 mm-diameter and 150 mm-height sample cylinders were made and placed in the standard curing conditions for 28 days. For the water penetration test, the samples were placed under the highest water pressure for a period of 16 hours. At least four of the six concrete samples showed resistance against penetration of water.
- Concrete frost resistance was tested by the third accelerated method according to GOST 10060-2012. The samples were pre-saturated and thawed in a 5 % NaCl solution and frozen at the temperature of –50 °C. For the frost resistance test, twelve 100 × 100 × 100-mm cubes were prepared and placed under standard curing conditions for 28 days.
- Concrete abrasion resistance test was carried out according to GOST 13087-2018 "Test Methods for Abrasion".

For testing, two cubes with 70-mm ribs were made. Pre-hardening of the samples to the design age (28 days) was carried out under standard conditions.

Concrete chemical resistance was tested in accordance with GOST R 58896-2020 "Chemically resistant concretes. Test methods".

For testing, three 40 × 40 × 160-mm sample beams were made for each test period of a comparative strength assessment.

As an aggressive medium, a 5 % $MgCl_2$ solution was used and the tests were carried out every 30 days for 360 days.

In order to ensure good workability, various lyophilic additives were used in a concrete mixture. In our opinion, the most effective ones were polycarboxylate-based surfactants (SAA) which had a better plasticizing effect contributing to a greater workability of the concrete mixture and the density of the hardened concrete. A water-soluble polycarboxylate copolymer of methacrylic acid with a density of ρ = 1.027 g/cm^3 and a pH value of 6.0 was used.

The above-mentioned surfactant performance was enhanced with an electrolyte, a 6 % aqueous solution of potassium nitrite (KNO_2). Theoretically, the potassium cation has an increased radius according to the position in D.I. Mendeleev's Periodic Table, hence an increased mobility. The potassium-cation-based electrolyte provided a deeper penetration into Portland cement mineral conglomerates and involved a greater number of Portland cement mineral molecules in the hydration processes. Therefore, the use of a cation-based electrolyte increased the hydration of the mixture forming a stronger concrete paste [11–13].

In order to improve the concrete quality, namely, to increase its crack and corrosion resistance, the unique properties of 1–100-nm nanoparticles were studied. Silicon hydro-dioxide nanoparticles $SiO_2 \cdot nH_2O$ with a particle size of ≈ 60 nm determined by a laser analyzer were investigated. They were included in a colloidal aqueous solution with a density of ρ = 1.021 g/cm^3 and a pH value of 4.0 and were supposed to enhance the hydration processes in the main mineral of Portland cement, for example, tricalcium silicate, following the reaction:

$$3CaO \cdot SiO_2 + (n + 1)H_2O = 2CaO \cdot SiO_2 \cdot nH_2O + Ca(OH)_2,$$

enhancing the bicalcium hydrosilicate $2CaO \cdot SiO_2 \cdot nH_2O$ and calcium hydroxide $Ca(OH)_2$ formation.

In addition, the silicon hydro-dioxide nanoparticles with an improved activity were likely to couple with dicalcium hydro-silicate forming low-base calcium hydro-silicate with a fibrous or needle-like structure reinforcing the bending tensile strength of the concrete structure [14–16].

At the same time, the interaction of silicon hydroxide $SiO_2 \cdot nH_2O$ with the newly formed hydrolysis lime $Ca(OH)_2$ were supposed to take place according to the following scheme:

$$2Ca(OH)_2 + SiO_2 \cdot nH_2O = 2CaO \cdot SiO_2(n + 2)H_2O.$$

As a result, $Ca(OH)_2$-based low-soluble calcium hydrosilicates would be formed improving the concrete corrosion resistance [17].

The above-mentioned chemical additive components were evaluated from the point of view of the water-cement ratio changes required to ensure the homogeneous fluidity of the concrete mixture, of variations in the compressive and bending tensile strengths, and of changes in the concrete density according to the water absorption parameter.

Concrete water absorption was tested according to GOST 12730.3-78 "Concrete. Water absorption test methods".

Results analysis No. 1

The experimental results presented in *Table 1* confirm the theoretical assumption that with the use of an aqueous solution of a methacrylic acid polycarboxylate copolymer with a density of ρ = 1.027 g/cm^3 and a pH value of 6.0 as an additive, a concrete mix acquires more plasticity. As a result, the water content in a concrete mixture of the same fluidity as that of the control mixture decreases by more than 15 %, and the concrete density increases due to a 13 % decrease in water absorption. Meanwhile, the compressive and bending tensile strengths increase by around 14–18 %. A higher concrete structure density results in a higher strength changing the concrete mixture activity only slightly without new hydrate formations.

When a 6 % solution of KNO_2 (potassium nitrite) electrolyte was added to the methacrylic acid polycarboxylate copolymer, the plasticity was not enhanced as the W/C ratio decreased slightly, within 0.02 units, but the concrete water absorption was reduced by 10 % up to W_m = 3.7 % increasing the concrete structure density. Due to an enhanced hydration activity in the concrete structure, the concrete pores were filled with new hydrate compounds formed in an increased amount.

Compressive and bending tensile strength increased by 26–28 % more or less equally, which may be due to increased hydration, the formation of more hydrate complex compounds and a greater number of strong bonds between the concrete mix components without forming new hydrate phases affecting each type of strength.

An additional portion of $SiO_2 \cdot nH_2O$ silicon hydrodioxide nanoparticles in the additive increased the concrete mix reactivity as well as enhanced the formation of new phases. This was due to a greater bending tensile strength in comparison with the compressive strength; thus, new hydrate phases were formed. Low-base hydrous silicates with a higher SiO_2 content having a fibrous or needle structure in the hydrate phase may serve as an example of new hydrate phases.

The results obtained showed that according to the basic laws of chemistry it is possible to change the hydration processes in the concrete mixture using certain materials as additive components ensuring the production of hardened concrete with specified properties.

Having calculated the efficient amount of each additive component, a new high performance complex chemical additive has been established, wt.%:

- aqueous solution of methacrylic acid polycarboxylate copolymer with density ρ = 1.027 g/cm^3 and pH = 6 — 62.5 %
- 6 % aqueous potassium nitrite solution, KNO_2 — 31.25 %;
- colloidal aqueous solution of silicon hydroxide nanodispersions — 6.25 %;

$SiO_2 - nH_2O$, with density ρ = 1.021 g/cm^3 and pH = 4.0.

The aqueous solution of the new nanopolymer modified (NPM) additive had density ρ = 1.031 g/cm^3 and pH = 5.5.

Results analysis No. 2

Further experimental results presented in *Table 2* have shown that the new NPM complex chemical addi-

Table 1

Evaluation of the performance of an additive represented by polycarboxylate-based surfactants with various additional components

No.	Design class of concrete, B (required strength, *Rrq*, MPa)	Design class of concrete Bb (required strength, *Rrq*, MPa)	Consumption of cement and chemical components per m^3 of concrete mixture, kg					W/C	Fluidity grade, *P*	Compressive strength, MPa/%	Tensile strength in bending, MPa/%	Water absorption, *W*, %
			Portland cement, PC5 00-D0	aqueous solution of polycarboxylate copolymer	6 % aqueous solution of KNO_2	$SiO_2 - nH_2O$ colloidal solution	water					
1	2	3	4	5	6	7	8	9	10	11	12	13
1	B30 (38.4)	Btb3.6 (4.6)	410	–	–	–	213	0,52	P2	39,2/100	4,6/100	4,7
2			410	3.28	–	–	180	0.44	P2	44.7/114	5.3/115	4.3
3			410	4.10	–	–	176	0.43	P2	45.9/117	5.4/118	4.1
4			410	4.92	–	–	176	0.43	P2	45.1/115	5.3/115	4.2
5			410	4.10	1.64	–	172	0.42	P2	49.6/126	5.8/125	3.8
6	B30 (38.4)	Btb3.6 (4.6)	410	4.10	2.05	–	168	0.41	P2	50.2/128	5.9/128	3.7
7			410	4.10	2.46	–	168	0.41	P2	49.8/127	5.8/126	3.7
8			410	4.10	2.05	0.328	164	0.40	P2	52.5/134	6.8/148	3.4
9			410	4.10	2.05	0.410	160	0.39	P2	53.7/137	7.0/152	3.3
10			410	4.10	2.05	0.49	160	0.39	P2	52.3/133	6.8/148	3.3

Table 2

Evaluation of the new NPM complex additive performance

No.	Design class concrete, B (required strength, MPa)	Design class concrete Btb (required strength, MPa)	*Consumption of cement and complex NPM additive per 1 m³ of concrete mix, kg			W/C	Compressive strength, MPa /%	Standard class concrete, B	Tensile strength in bending, MPa/%	Concrete actual class, Btb	Crack resistance coefficient, $K_{cr} = R_{ben}/R_{comp}$
			Portland cement, PC500 D0	NPM additive (wt.% of cement weight)	water						
1	2	3	4	5	6	7	8	9	10	11	12
1	B30 (38.4)	Btb3.6 (4.6)	410	–	213	0.52	39.2/100	30	4.6/100	3.6	0,117
2			410	3.28 (0.8)	160	0,39	54.5/139	40	7.0/152	5.6	0.128
3			410	4.10 (1.0)	152	0,37	55.2/141	40	7.2/156	5.6	0.13
4			410	4.92 (1.2)	152	0,37	54.9/140	40	7.1/154	5.6	0.129

Note: * – the fluidity of the concrete mixture in all the cases under study corresponded to the fluidity grade F2.

Table 3

Comparative assessment of the concrete durability of the control mixture and the mixture with a new complex chemical additive

No.	Design concrete class, B	Consumption of cement and complex NPM additive per 1 m³ of concrete mix, kg			W/C	Compressive strength, MPa/%	Standard concrete class, B	Water resistance grade, *W*	Frost resistance grade, F2	Chemical resistance coefficient relative to magnesia corrosion, $K_{ch.r.}$	Abrasion grade, G
		Portland cement, PC 500-D0	NPM additive	water							
1	2	3	4	5	6	7	8	9	10	11	12
1	B30	410	–	213	0.52	39.2/100	B30	W8	F2300	$K_{ch.r.} = 0.8$	G2
2		410	4.1	152	0.37	55.2/141	B44	W14	F2500	$K_{ch.r.} = 0.93$	G1

tive in the rational proportion of 1.0 ± 0.2 wt.% of the cement weight enhanced hyper-plasticity decreasing the water content in the concrete mixture by 29 % as compared to that of the control concrete mix having the same fluidity.

The experimental additive proved to have an enhanced reactivity increasing the compressive strength by up to 40 % and the bending tensile strength even more, thus improving the concrete class by four grades.

Another advantage of the tested additive was its ability to increase concrete crack resistance. It was confirmed by the crack resistance coefficient increase $K_{cr} = R_{ben}/R_{com}$ from 0.117 in the control mixture to 0.13 in the modified mixture. According to GOST 10180-2012 "Concretes. Strength Test Methods by Control Samples", the R_{ben}/R_{com} ratio must be no less than 0.12.

Results analysis No. 3

The theoretical assumptions about the chemical processes in a concrete hardening mixture, the formation of new phases and concrete higher density and strength were tested experimentally and revealed that the concrete quality parameters were improved with the use of a newly developed complex additive.

Additional experimental data on concrete durability parameters are presented in *Table 3*.

CONCLUSION

The experimental research carried out have shown that

- basic physical and mechanical properties of concrete such as density, crack resistance, durability, and reliability can be improved with a polycarboxylate polymers chemical additive in combination with potassium cations-based electrolytes and nanostructured silicon hydroxide;
- the new complex chemical additive has proved to enhance the concrete mixture super-plasticity and reactivity increasing the degree of hydration of its components;
- the experiments have revealed that the use of the tested complex chemical additive increases concrete compressive strength by 41 %, bending tensile strength by 56 %, crack resistance by more than 10 %, water resistance and frost resistance are 1.5 times higher and a chemical resistance coefficient increases by 16 %; thus, the modified concrete durability has proved to be enhanced.

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World Professional Skills Competitions as a Way of Professional Education Internationalization*

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ABSTRACT This article deals with the development of secondary vocational education and training (SVET) in the context of globalization processes. International cooperation is one of the priorities in the development of the SVET system. Constant updating of the educational content and technologies is necessitated by the professional qualification requirements and international standards. A promising area of professional education internationalization could be arrangement of international competitions and professional skills championships in the WorldSkills format. Far East State Transport University (FESTU) took part in organizing the WorldSkills BRICS Championship in the "Rail transport technologies" competence in 2022 and it is described in this paper. The professional skills competitions enhance the development of professional and expert communities, professional development of scientists, engineers, and workers in Russia and globally. Such competitions can become one of the main forms of vocational education internationalization, which will enhance and improve education quality overall.

KEYWORDS: professional education; education internationalization; professional skills competitions

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Научная статья

Международные конкурсы профессионального мастерства как способ интернационализации профессионального образования

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АННОТАЦИЯ Рассматриваются вопросы развития среднего профессионального образования (СПО) в контексте процессов интернационализации. Международное сотрудничество является одним из приоритетных направлений деятельности развития системы СПО. Это обусловлено необходимостью постоянного обновления содержания и технологий профессионального образования в соответствии с актуальными и перспективными требованиями к квалификации работников и международными стандартами. Одним из перспективных направлений интернационализации профессионального образования могут стать международные конкурсы и чемпионаты профессионального мастерства в формате WorldSkills.

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Описан опыт Дальневосточного государственного университета путей сообщения (ДВГУПС) в организации чемпионата WorldSkills BRICS по компетенции «Технологии рельсового транспорта» в 2022 году. ДВГУПС взял на себя функции секретариата при проведении чемпионата WorldSkills BRICS в России по компетенции «Технологии рельсового транспорта». Развитие движения чемпионатов профессионального мастерства влечет за собой развитие профессиональных и экспертных сообществ; повышение квалификации кадров, включая инженерные и рабочие профессии и навыки, в том числе путем организации российских и международных соревнований по профессиональному мастерству. Такие чемпионаты могут стать одной из ведущих форм интернационализации профессионального образования, тем самым значительно повысив его качество.

КЛЮЧЕВЫЕ СЛОВА: профессиональное образование; интернационализация образования; чемпионаты профессионального мастерства

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INTRODUCTION

Vocational education internationalization is a key aspect of professional development in the era of globalization and knowledgeable society. Internationalized education is also recognized as a crucial means of achieving the goals and objectives of innovative vocational education in terms of its interaction with labour market, effective employability of graduates and the development of lifelong learning.

The process of educational internationalization assumes studying the relations between nations, peoples, cultures, institutions and even political systems [1].

For example, J. Knight analyzed the impact of globalization on different countries. He argued that the globalization process depends on the specific historical development, traditions, culture, and priorities of nations, on the one hand, and on the other hand, higher education internationalization is one of the ways a country responds to globalization while maintaining the uniqueness of its own people [2].

In the current studies of Russian scholars, the concept of "education internationalization" is interpreted *"as an integrative process of implementing international educational standards in the educational context of national universities"* based on an active, competent, ethical and strategic approaches, thus contributing to improving education quality [3].

However, the internationalization process depends on the economic level of a country. While developed countries are focusing on personnel training to increase their competitiveness, other countries are creating human resource potential for developed economies resulting in a noticeable brain drain from these countries.

All these processes are reflected in the transport universities activities in Russia. In the context of globalization, the world transport system has been increasing its importance in strengthening the production and business ties between territories, regions, and continents enhancing the development of the global economic space.

MATERIALS AND METHODS

Nowadays, several local and governmental documents map out the internationalization process in transport education such as Federal Project No. 6 "The Development of Export Potential of Russian Education" dated 30.05.2017; Transport Strategy of the Russian Federation for the period up to 2030; the Interaction Programme between JSC "Russian Railways" and universities for the period up to 2025.

In this context, Russian transport universities have now accumulated considerable experience in international activities. All the transport universities have a great number of partner universities abroad and dozens of coordinated international education programmes (EP).

However, while universities have been successfully developing international cooperation, vocational education and training (VET) institutions and colleges have not participated in the internationalization process, which has had negative implications. The content and technologies of vocational secondary education have not been updated in line with international requirements for professional qualification; the attractiveness of vocational education institutions to foreign applicants has been falling; vocational education programmes have not been included in the international education services market. Thus, Russia is missing out on both economic benefits and political opportunities to exert "soft" power internationally through the dissemination of the Russian language, Russian culture, values, and the achievements of Russian science.

Unfortunately, the conceptual and regulatory documents of the Russian Federation do not offer transport vocational education programmes to foreign customers. Education in transport technical schools of Russia has not been in demand in other countries. The share of foreign students in transport vocational schools has not increased (most technical schools do not have foreign students), nor are foreign teachers attracted to work in these schools.

The Department of International Affairs of Far Eastern State Transport University (FESTU) has carried out a rapid analysis of the vocational education indicators in the area of international activities in 2020 (see the *table* below).

For the rapid analysis of VET indicators in the field of international activities, open sources data of the Ministry of Education of the Russian Federation was gathered. A number of vocational and technical schools were chosen, among them:

- Khabarovsk Technical School of Railway Transport (KSRT, a branch of Far East State Transport University);
- the Amur Institute of Railway Transport (AIRT, a branch of Far East State Transport University located in Svobodny, Amur Region);
- the Baikal-Amur Institute of Railway Transport (BAIRT, a branch of Far East State Transport University located in Tynda, Amur Region);
- Primorsky Institute of Railway Transport (PrimIRT, a branch of Far East State Transport University located in Ussuriysk, Primorsky Region);
- Krasnoyarsk Institute of Railway Transport (KIRT, a branch of Irkutsk State Transport University);
- Siberian College of Transport and Construction (SCTC, a branch of Irkutsk State Transport University);
- Omsk College of Railway Transport (OCRT, a branch of Omsk State Transport University);
- Trans-Baikal Institute of Railway Transport (TBIRT, a branch of Irkutsk State Transport University);
- Khabarovsk College of Transport Technologies named after Hero of the Soviet Union A.S. Panov (KCTT).

According to the results of the VET rapid analysis, none of the professional institutions mentioned above fulfilled two of the four indicators. One indicator is Russian students' internship abroad and the second indicator is foreign students' internship at Russian educational institutions. Furthermore, indicators number 2 and 3 coincide because all foreign students studying in professional education programmes are citizens of the Commonwealth of Independent States (CIS). The median indicators for the number of foreign students show that only two out of eight educational organizations mentioned meet the international programme requirements.

The analysis confirms that this is a general tendency for all institutions implementing vocational education programmes including FESTU.

The following issues have been identified:

- why leading universities actively implementing international programmes do not promote them in their branches and technical colleges;
- how the accumulated experience of the leading universities can help develop international activities in their branches;
- what forms of education internationalization programmes are appropriate;
- to what extent SVET institutions want to develop international activities.

Table

Rapid analysis of professional education indicators in the aspect of international activities in 2020

No.	Indicator description	Median value, %, foreign students to the given	KSRT	AIRT	BAIRT	PrimIRT	KIRT	SCTC	OCRT	ZabIRT	KCTT
1	Number of students enrolled in SVET institutions who have completed at least one month of training (internship/apprenticeship) abroad or in foreign companies located in Russia, %	0.72	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2	Number of international students enrolled in SVET institutions, %		0.59	0.01	0.05	0.55	0.20	0.53	2.91	0.07	0.49
3	Number of foreign students from CIS countries enrolled in SVET institutions, %		0.59	0.01	0.05	0.55	0.20	0.53	2.85	0.07	0.49
4	Number of foreign students (except CIS countries) enrolled in SVET institutions, %		0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

RESEARCH RESULTS

In the context of the issues mentioned above, attention needs to be drawn to such a form of education internationalization at the VET level as international professional skills championships. At present, the Autonomous non-profit organization "Professional Skills Development Agency (Worldskills Russia)" that is the functional successor of the Union "Young Professionals (Worldskills Russia)" is working in this direction. However, given a difficult political situation in the world and the high demand in new formats of interaction, one cannot ignore cooperation within the BRICS college alliance (BRICS includes five countries: Brazil, Russia, India, China and South Africa).

At the XIII BRICS summit in September 2021, Chinese President Xi Jinping proposed establishing a BRICS VET union and suggested organising international competitions for confirming the professional competencies of future professionals.

The BRICS member states began hosting WorldSkills competitions in 2017. They are called WorldSkills BRICS competitions. The first competition took place in China. Russia entered the competition in 2018. The WorldSkills BRICS championship is aimed at identifying and developing potential talents and competences, building global network cooperation among partner countries in the field of education and technology development. Its main goal is to train professionals for high-tech production in the context of the transforming economy.

The "Rail Transport Technology" competence was included in the WorldSkills competition in 2022, and students of technical schools, vocational colleges and railway colleges took part in it for the first time. Far Eastern State Transport University functioned as the secretariat for the WorldSkills BRICS championship in Russia in the "Railway Transport Technology" competence. One hundred and fifty two participants and 76 teams from BRICS countries took part in the international championship.

CONCLUSION

The WorldSkills BRICS competition in the competence of "Rail Transport Technology" has provided a unique opportunity for VET institutions to integrate into the international process. Participation in the WorldSkills BRICS competition has been a new experience, but there is every reason to believe that it will be a good start off for the implementation of other international projects. Professional skills competitions enhance the development of professional and expert communities, professional education including engineering and working professions and skills through promoting professional skills competitions in Russia and internationally. They can become one of the leading forms of internationalization of vocational education, thus significantly improving its quality.

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The concept of computer-aided design of railways in the information and digital environment

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ABSTRACT The main objective of this work is the need to develop a new technology for automated solution of railway design problems in the information and digital environment.

For this purpose, the methodology of structural system analysis, the theory of systems, and the principle of decomposition are applied. A brief analysis of the terms related to informatization and digitalization is given, and the interpretation of the concept of "information and digital environment" in relation to the tasks of railway design. The key concepts of information modeling of construction objects in the current regulatory documentation of the Russian Federation, the main qualification features and advantages of information modeling technology are given.

Based on the results of the analysis of the structure and functionality of existing computer-aided design systems of railways and highways, the sequence of procedures of the existing technology of computer-aided design of roads is determined. The concept of automated solution of railway design problems in the information and digital environment based on the use of information modeling technologies and mathematical optimization methods is proposed. The concept is represented by a functional hierarchical model of a computer-aided design system. For its development, the Data Flow Diagrams functional modeling tool was used.

The proposed concept is the basis for the development of a computer-aided design system, which will allow the implementation of a new technology for computer-aided design of railways, reduce labor costs and deadlines for the development of design solutions, improve their quality and efficiency.

KEYWORDS: computer-aided design; railway; information modeling; information model; information and digital environment; digital terrain model; structural system analysis; functional modeling

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Научная статья

Концепция автоматизированного проектирования железных дорог в информационно-цифровой среде

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АННОТАЦИЯ Цель исследования — необходимость разработки новой технологии автоматизированного решения задач проектирования железных дорог в информационно-цифровой среде (ИЦС).

Применены методология структурного системного анализа, теория систем, принцип декомпозиции. Приведен краткий анализ терминов, относящихся к информатизации и цифровизации, трактовка понятия «информационно-цифровая среда» применительно к задачам проектирования железных дорог. Представлены ключевые понятия информационного моделирования объектов строительства в действующей нормативной документации Российской Федерации, основные квалификационные признаки и преимущества технологии информационного моделирования.

По результатам анализа структуры и функциональных возможностей существующих систем автоматизированного проектирования железных и автомобильных дорог определена последовательность процедур технологии автоматизированного проектирования дорог. Предложена концепция автоматизированного решения задач проектирования железных дорог в ИЦС на основе применения технологий информационного моделирования и математических методов оптимизации. Концепция представлена функциональной иерархической моделью системы автоматизированного проектирования. Для ее разработки использовано средство функционального моделирования Data Flow Diagram.

Предлагаемая концепция является основой для разработки системы автоматизированного проектирования, которая позволит реализовать новую технологию автоматизированного проектирования железных дорог, сократить трудозатраты и сроки разработки проектных решений, повысить их качество и эффективность.

КЛЮЧЕВЫЕ СЛОВА: автоматизированное проектирование; железная дорога; информационное моделирование; информационная модель; информационно-цифровая среда; цифровая модель местности; структурный системный анализ; функциональное моделирование

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INTRODUCTION

The scientists and experts of Emperor Alexander I St. Petersburg State Transport University conducts research in the application of digital tools and information modeling technologies for research, design, construction and maintenance of engineering structures [1–7], for the management of technological processes in transport and urban infrastructure [8–11], and other areas of economic activity.

This article is devoted to the use of information and digital environment in the design of railways.

At the present time the terms "information" and "digital", "informatization" and "digitalization" are used various fields of life and professional activity of people. These terms are often identified. In our opinion, it is wrong to consider these terms identical since the term "digital" refers to the form of presentation of information, and "digitalization" is a transition from various forms and means of receiving, recording, processing, storing, presenting and visualizing information to digital form and means.

In the information age new concepts have appeared such as "information society", "informatization", "information technology", "information system", "information environment", "virtual environment", "digital environment" and others, as well as a variety of their interpretations depending on various fields of their application.

The term "information society" means a society that has access unlimited amounts of information. The term "information environment" is interpreted as a systematized representation of the information space based on certain principles. Information processes related to the use of information are implemented in the information environment. At the same time, in the information environment, it is possible to distinguish such a part of it in which information processes are implemented in digital form using digital means. In the work [12], this part is called the digital environment, but in our opinion, it would be more logical to call it the information and digital environment (ICS).

This article discusses the concept of using the information and digital environment in railway design in order to develop a new technology for an automated solution of design tasks.

The standard GOST R 10.0.03–2019/ISO 29481-1:2016 is included in the system of standards of the Russian Federation on information modeling of buildings and structures. In this standard, information modeling of construction objects is considered a *"digital technology for describing and presenting the information necessary for planning, designing, construction and management of constructed objects"*. The application of this technology is possible in the information and digital environment. This environment is necessary for the creation, processing, storage, presentation and visualization of electronic information about buildings and structures at all stages of their life cycle. The result of information modeling of a construction object is an information model of a building or structure.

At each stage of the life cycle of a construction object there should be its own information model: conceptual (sketch), design, construction, executive, operational. The design information model of the construction object should include its design spatial-parametric model, project design and construction documentation.

In SP 333.1325800.2020 "Building information modeling. Modeling guidelines for various project life cycle stages" the spatial-parametric model of a construction object is interpreted as *"a digital information model of a capital construction project (CIM OKS), which is a set of interrelated engineering and technical and engineering-technological data about a capital construction project presented in a digital object-spatial form."* In the same regulatory document, the concept of an engineering digital terrain model (ICMM) is given as *"a set of interrelated engineering-geodetic, engineering-geological, engineering-hydrometeorological, engineering-ecological data, engineering-geotechnical data and data on the territory of a capital construction project presented in digital form for automated solution of process management tasks on the life cycle capital construction projects"*. For the spatial description of CIM OKS and ICMM, coordinate and geometric data are used that determine the position in space, the shape and dimensions of the elements of digital models. In the parametric description, the properties of the CIM OKS and ICMM elements are determined by attribute data.

Currently, the capabilities of modern high-capacity and accessible technical digital means of obtaining, processing, storing, presenting and visualizing large amount of data make it possible to apply digital information modeling technologies in railway design (TIM abbreviation is equivalent to the English-language BIM "Building Information Modeling" (GOST R 10.0.03–2019/ISO 29481-1:2016)).

The basis of TIM is object-oriented design, parametric modeling and an informational 3D model of a construction project, which is used to develop and adjust design solutions to meet changing requirements and conditions.

Based on the analysis of significant world experience in the use of information modeling technology for the development and implementation of projects of complex and unique structures, its main advantages are identified. Significant increase in labor productivity:

1. Significant increase in labor productivity.
2. Multiple reduction in the number of errors in design and construction.
3. Significant improvement in the quality, economic efficiency of space-planning and design solutions.
4. Reduction of time and costs to design and construction by identifying possible errors ("collisions") at the early stages of design, modeling the construction organization process, improving the accuracy of determining the required resources and their rational distribution.

Analysis of the structure and functionality of existing computer-aided design (CAD) systems used for the design of railway and highway (Credo, Robur, CAD PKP, Card/1, GeoniCS, IndorCAD/Road, Bentley Rail Track, Autodesk Rail Layout Module, Trimble Quantm), carried out in [13–20], and generalization of the results this analysis allowed us to determine the following sequence of procedures of the existing technology of computer-aided design of railways:

1) creation of an ICMM based on engineering survey data, construction and analysis of surfaces;
2) design of the horizontal alignment of the railway;
3) design of the vertical alignment of the railway;
4) design of cross direction profile of the railway roadbed;
5) placement of engineering structures;
6) three-dimensional (3D) visualization of the terrain and the projected railway with fixed equipment;
7) visual assessment of the design position of fixed equipment on 3D views of terrain and roads;
8) correcting the design position of the railroad (paragraphs 2–5);
9) formation and printing of project design documentation.

As you can see, the existing technology implements the design of the railway in the projections (paragraphs 2–5), on the basis of which 3D views of the terrain and the projected railway are created for visual evaluation of the design solution.

The use of information modeling technologies, data mining and mathematical optimization methods in the design of capital construction projects requires a radical revision of the existing technology of railway computer-aided design.

In this article, the authors propose a conceptual model of CAD for the design of railway (CAD Railway), which will allow the implementation of a new technology for computer-aided design of railways in an information and digital environment.

MATERIALS AND METHODS

The development of CAD Railway is a complex task. The solution to this problem begins with the construction of a conceptual model of the system. At the first stage, research and analysis of information, functional, technical and technological requirements and capabilities are carried out. At the second stage, based on the results of the analysis, a functional CAD model is developed using functional modeling tools that allow describing the processes performed on the system and the information flows connecting them.

The basis of the information and digital environment is the ICMM. It is formed from the input data stream, which is a description of the engineering-geodetic, engineering-geological, hydrographic, climatic, permafrost and seismic conditions of the design site.

The ICS for railway design also includes:

- construction and technical standards;
- library of structural and technical solutions for devices, structures and technical equipment of the construction project;
- technical, technological, socio-economic and environmental requirements;
- variants of design solutions with technical and economic indicators for their comparison;
- digital information model of the railway (CIM railway).

Functional computer-aided railway design can be represented as a set of interrelated processes of the information transformation of input data stream output. Structural analysis methodologies are widely used to describe such processes. These methodologies are based on the principles of decomposition, abstraction, hierarchical structuring, formalization and consistency.

Based on the decomposition method, each process in the functional CAD model of the railway is divided into subprocesses by abstraction levels, within which only the components and elements of the system that are essential for this level are used.

Thus, on the basis of the principle of hierarchical structuring, sequential detailing of processes from the first level to the subsequent ones is performed.

The number of sub-processes is limited from 3 to 8 at each level of process decomposition. This is determined by the holistic perception of the totality of the components and elements of the system connected by information flows. Each process in the model must have input data streams and output streams generated in it, which are necessary to consistently achieve the ultimate goal of computer-aided railway design.

To ensure the requirements of completeness and consistency in the decomposition of a functional model, it is necessary to apply strict rules for the formalization of system components, which allow you to control the consistency of its elements with the help of their information links.

For a formalized description of the functional CAD model, we use data flow diagrams DFD (Data Flow Diagrams) in the Yodan notation (Yourdon) [21]. DFD consist of logical functions (processes) and data stores (information storage) interconnected by data streams, as well as external entities.

A logical function is the process of processing input data streams and generating output. It is given a name in accordance with the essence of the process that it models. Each logical function is assigned a unique number for references to it in the diagram.

The data warehouse is used as an information storage device in the processes of information transformation of data flows. The repository is given a name that must match its contents.

Data flows are used to model the transfer of information between processes, data warehouses and external entities. Data streams are indicated by name arrows, while the name of the stream entering or exiting the data warehouse and corresponding in structure to the storage, cannot be displayed in the diagram.

External entities are sources and/or receivers of data flows and are considered an external objects or subjects in relation to the process (logical function).

When the functional model is decomposed, logical functions are detailed at each subsequent hierarchical abstraction level. To do this, use a lower-level DFD or mini specifications. The mini specification describes the logic of the function at the last level of the hierarchical structuring of the model.

The lower-level DFD at the input and output should have only those external entities and data store with which the detailed function is connected using information flows on the parent diagram.

When detailing logical functions, the hierarchical numbering rule is applied, i.e., detailing the DFD process with number 3, the lower-level functions are designated by numbers 3.1, 3.2, 3.3, etc.

RESULTS AND DISCUSSION

At the analysis stage, the structure and functionality of existing CAD systems of railways and highways, technical and technological capabilities of modern hardware and software, prospects for their development were investigated and the concept of computer-aided design of railways in the information and digital environment based on the use of information modeling technology and mathematical optimization methods was proposed.

The concept is represented by a functional hierarchical model of a railway computer-aided design system in an information and digital environment, which includes:

- the context diagram with the main process (see *Fig.*), defining the main purpose of the system — the creation of a digital railway project;
- DFD diagrams, with the help of which the decomposition of the main process "Railway Design" is performed.

The components of DFD diagrams are:

- functions — processes of processing input and output information flows necessary for the formation and updating of the information and digital environment and the creation of a digital railway project;
- data warehouses: STM — construction standards; ICMM — digital information model of the terrain; CIM Railway — digital information model of the railway; BKTR — library of structural and technical solutions for devices, structures and technical equipment of the construction project; VPR TEP — variants of design solutions with technical and economic indicators;
- external entities — objects or subjects outside the context of the main process used to form and update the information and digital environment for railway design;
- input and output information flows between processes, data warehouses and external entities.

SP 328.1325800.2020 "Building information modeling. Rules for describing information model components" contains the term "library of components of information model" and the definition of information

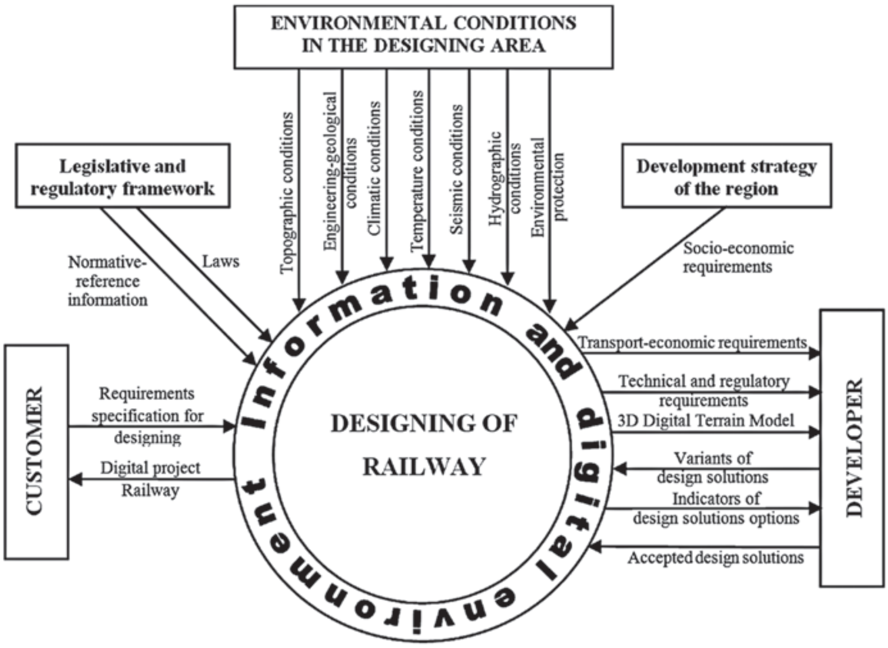

Fig. Context diagram

model component (CIM) *"a digital representation of a part of a capital construction object or territory characterized by attributive and geometric data intended for multiple use"*.

The KIM library is a structured repository of components that are used to build an information model of a construction project as a set of three-dimensional elements interconnected by attributive, geometric and spatial parameters.

The library of KIM is a library of constructive and technical solutions in the proposed CAD Railway. It is used to develop variants of design solutions of the VPR TYPE, from which a CIM Railway is formed as a result.

The context diagram (*Fig.*) shows the information interaction of the main process "Railway Design" with external entities "Customer" and "Designer" through the information and digital environment. The ICS is formed on the basis of the design specification, legislative acts, the system of construction design and estimate documentation (SND), socio-economic requirements, data on topographic, engineering-geological, climatic permafrost, seismic and hydrographic conditions, environmental requirements, structural and technical solutions for devices, structures and technical equipment of the railway.

Based on the use of ICS, the "Designer", taking into account the natural conditions of the design site, transport, economic, technical and regulatory requirements, develops variants of design solutions, according to which technical and economic indicators are calculated [22], necessary for making effective decisions. From the accepted design decisions, the "Designer" forms the final version of the railway CIM, which is transferred to the "Customer" with the developed digital project of the railway.

The next stage in the construction of a functional model of CAD Railway is the decomposition of the contextual process "Railway Design". Using the principles of abstraction and hierarchical structuring, the functional model of the system is divided into levels of abstraction. At the first level, the processes defining the main stages of the new technology of railways computer-aided design in the information and digital environment are presented:

1) creation of an ICS for railway design;

2) creation of a CMM based on engineering survey data, construction and verification of a visual three-dimensional terrain model (3D ICMM);

3) the design of the railway alignment on 3D ICMM using parametric 3D modeling;

4) placement and parametric 3D modeling of engineering structures and maintenance service of the railway;

5) comprehensive analysis and examination of the railway CIM to identify "collisions" (design errors);

6) elimination of "collisions" (correction of design solutions and CIM railway — paragraphs 2–5);

7) generation of drawings in orthographic and perspective projections, specifications and other project documentation.

The processes of the first and subsequent levels of the functional model of CAD railway will be considered in a series of articles devoted to the implementation of the concept of computer-aided design of railways proposed by the authors in the information and digital environment.

CONCLUSION AND DISCUSSION

The proposed concept is the basic basis for technological modernization of computer-aided design of railways based on the application of the following innovations:

- information modeling technologies;
- data mining;
- mathematical optimization methods [23–33].

The technology of railway computer-aided design in the information and digital environment will allow solving the following tasks:

- conceptual 3D design of the railway in connection with the local conditions of the design site;
- analysis and expertise of railway infrastructure facilities at the early stages of their life cycle;
- detailed design of railway infrastructure facilities based on the use of parametric 3D modeling;
- optimization of design solutions based on data mining, mathematical optimization methods, as well as three-dimensional visualization and simulation;
- feasibility study of design solutions;
- managing the collaboration of project participants at all stages of its life cycle.

The development and implementation of a new technology for computer-aided design of railway is carried out within the framework of the strategic project No. 3 "Development of transport infrastructure facilities in the Arctic Zone of the Russian Federation" — part of development program of the Emperor Alexander I St. Petersburg State Transport University "Priority 2030" project.

The purpose of "Priority 2030" project is to create scientific, technical and personnel support for the implementation of investment construction projects for the development of transport infrastructure in the Arctic zone of the Russian Federation to achieve the priorities of the State Program of the Russian Federation "Socio-economic development of the Arctic zone of the Russian Federation".

To achieve the stated goal, the university plans to create new and modernize existing research and testing laboratories, testing centers to solve specific narrowly focused tasks within the framework of scientific projects: "Digital transformation of engineering and geodetic survey data of transport infrastructure facilities"; "Design of railway infrastructure in the information and digital environment"; "Development of a catalog of standard solutions for the roadbed that ensure the stability of the lower structure of the track in extremely difficult natural and climatic conditions of the Russian Arctic"; "New technologies for maintenance of railway facilities in the Arctic zone of Russia"; "Development of the composition of concrete sleepers designed for the harsh conditions of the Arctic zone of Russia"; "Automated monitoring of the technical condition of rolling stock and the railway track on the train in the Arctic zone of Russia"; "Investigation of the processes of snow sticking and ice formation on the chassis and ways to prevent them"; "Effective ways of installing water supply and sanitation systems in the Arctic zone of Russia".

The realization of the announced scientific projects will ensure the development and implementation of know-how for the formation and development of land transport networks; accessibility and connectivity of remote territories of the Russian Federation; improvement of conditions for the mobility of the country's population; timely training of specialists for the design, construction and operation of transport infrastructure; adaptation of transport facilities to the ongoing and predicted climate changes; acceleration of transport and economic development and creation of competitive conditions for the implementation of large-scale investment projects in the Arctic zone of the Russian Federation.

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A Study of Wagon Turnaround in the Current Context

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ABSTRACT Wagon turnaround remains the key performance indicator of railway transport operations characterizing the efficiency both of a wagon fleet owner and of "Russian Railways" Company (RZD). Freight logistics efficiency in the railway sector can also be assessed using this indicator. For determining the wagon turnaround time, the duration of operations at technical stations, freight handling time and the time in motion are taken into account. "Russian Railways" company and operator companies control the three components of the wagon turnaround time. The synergies of railways, intermodal types of transport, and private railways belonging to major freight owners are of particular interest. Their interaction efficiency can be calculated using the wagon turnaround formula that considers the freight idle time and the local operations factor. The local operations at the station for serving private tracks and port sidings are regulated by a number of documents that determine the procedure for supply and departure of wagons, the number of wagons in supply, the regularity of these operations, the number and series of shunting locomotives, etc. The optimal number of wagons in supply will be determined by the minimum cost of wagon movement and wagon idle time on the station tracks. The calculation of the cost function sensitivity will make it possible to determine the limits in the optimal wagon movement changes.

KEYWORDS: logistics; freight flow logistics; wagon turnaround; local operations; optimal wagon supply; private tracks; port sidings; inventory management theory; cost function; function sensitivity; wagon fleet

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Научная статья

Исследование оборота вагона в современных условиях

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АННОТАЦИЯ Оборот вагона остается ключевым эксплуатационным показателем работы железнодорожного транспорта, характеризующим эффективность деятельности владельца вагонного парка и ОАО «РЖД» Логистический процесс продвижения грузопотока с участием железнодорожного транспорта также может быть оценен с использованием этого показателя. При определении оборота вагона учитывается продолжительность операций на технических станциях и под грузовыми операциями, время в движении. Все три составляющих времени оборота вагона находятся в области управления и ОАО «РЖД», и операторской компании. Интерес вызывает стык взаимодействия железнодорожного и смежных видов транспорта и путей необщего пользования крупных грузовладельцев. Эффективность такого взаимодействия можно оценить составляющей произведения грузового простоя и коэффициента местной работы в формуле оборота вагона. Проведено исследование оптимального количества вагонов в подаче на пути необщего пользования или портовые пути. Оптимальность количества вагонов в подаче будет определяться минимумом затрат на передвижение вагонов и простой на станционных путях с использованием теории управления запасами. Оценка чувствительности функции затрат позволит установить пределы изменения оптимального количества вагонов в подаче, которое даст возможность минимизировать грузовую составляющую в обороте вагона.

КЛЮЧЕВЫЕ СЛОВА: логистический процесс; передача грузопотока; оборот вагона; местная работа; оптимальное количество вагонов в подаче; пути необщего пользования; портовые пути; теория управления запасами; функция затрат; чувствительность функции; вагонный парк

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INTRODUCTION

"Russian Railways" Company (RZD) is the largest carrier and infrastructure owner that interacts with the operators of railway rolling stock at all stages of transport management [1]. Rail transport performance is evaluated by quantitative and qualitative operational indicators [2]. Operational indicators include such an important parameter as wagon turnaround, which is defined as the time interval between two successive loadings [3]. The interaction between "Russian Railway" Company (RZD), the railway transport operator, large freight owners, and other types of mainline transport traditionally have always been of particular interest for research [4–6]. Such interaction efficiency is reflected in the wagon turnaround indicator, because its main components are wagon time in motion along the section, time of wagon handling at sorting stations and loading/unloading operations. With the transfer of wagon fleet management to the operator companies, wagon empty runs have significantly increased. The operating companies have been adjusting the transportation operations but additional studies are necessary to amend the fundamental works of a number of scientists in the current situation context [7]. However, efficient freight train routing will improve the wagon turnaround indicator and allow assessing the participants' interaction efficiency and increasing the attractiveness of domestic rail transport in the context of international transport corridors [8–10]. In this study, the wagon turnaround is investigated in terms of freight idle time on private tracks and port sidings. The efficient technical, technological and organizational interaction between a railway station, the starting point and the destination of freight flows are the concepts of logistics to be observed. It will improve operational performance and bring additional profits [11–13]. It is difficult to overestimate the importance of transport terminal service [14–16]. Largely, it has an impact on the entire process of freight flow movement on national railways. The loading of wagons at freight flow starting points can also be attributed to terminal services. Yard time of freights is a component of wagon turnaround and it describes the efficiency of wagon handling on private tracks, which requires further research [7, 12, 17].

MATERIALS AND METHODS

The study of wagon turnaround is conducted in the context of local operations at the station and the interaction of the station with private tracks or port sidings. Inventory management theory, where wagons at the station are represented as inventory is used for calculating the optimal wagon handling. The optimal number of wagons for loading is investigated taking into consideration the cost function minimization. The function sensitivity is determined using a differential. The necessity to transfer the wagon fleet under the management of operator companies was caused by objective reasons such as shortage of rolling stock, high depreciation of the wagon fleet, insufficient funds for providing the required traffic volume. Today, "Russian Railways" Company (RZD) is the main carrier and owner of the infrastructure, but the transfer of the wagon fleet management to the operator companies had a negative effect on the railway industry as a whole. In spite of the positive aspects such as investing more money in the industry and creating a system of corporate transport service in order to improve customer orientation and competitiveness, it is necessary to highlight a number of drawbacks. The main and most sensitive one is the loss of wagon versatility, i.e., the ability to be loaded at any time at any place. It leads to the accumulation of wagons and their unproductive idle time resulting in an increase of empty wagon runs and turnaround time. Thus, financial losses of the operator companies, which inevitably affects the operation of "Russian Railway" Company (RZD) as a whole. That is why it is necessary to adjust the theory of intermodal transportation and interaction in current conditions [7]. It is important for railway transport partners to reduce the costs of wagon fleet operation and maintenance. The interaction of "Russian Railways" Company (RZD) with major freight owners, rolling stock operators, and other mainline modes of transport includes four major issues: freight traffic transfer issue; information transfer issue; station facilities layout and private tracks or port sidings; spatial facilities layout (*Fig. 1*). Therefore, the interaction process is a complex concept, which includes a number of parameters such as organizational, technological, technical, legal and informational.

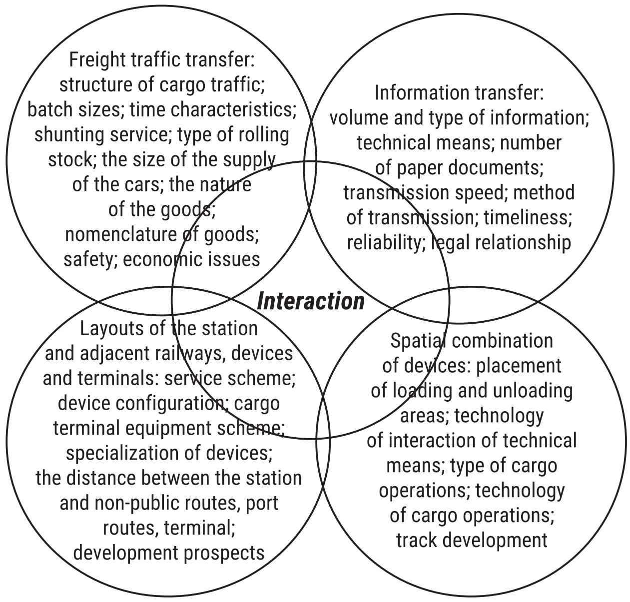

Fig. 1. Interaction diagram

Let us analyse freight logistics issues. The freight chain delivery consists of terminal services and freight movement by different modes of transport (T). Freight loading can be performed either directly, from vehicle to vehicle (which is potentially disadvantageous for one of them), or at a terminal. The terminal can be used for loading/unloading of wagons from origin to destination points. An important link in the logistics chain freight delivery is the interaction of railway stations with freight owners' private tracks and port sidings. The transfer of the wagon fleet management to the operator companies has intensified the need for the competent transportation management to ensure rhythmic operation of rail transport. The freight traffic operation should be comprehensive, i.e. it should ensure uninterrupted operation of the railway network at the planning, operative regulation and performance assessment stages. Under Soviet-era state management, this was achieved by planned economy methods [7]. At present, these methods of regulating the interaction between different modes of transport is not possible. World practices show that the Total Quality Management system used by many companies including railway transport companies have been very successful. This system is based on international ISO quality standards. The TQM approach assumes that the result of a process is a product or, in this case, a transport service. Every product or service is the result of a process, so improving the process is an effective way of improving quality. If we consider rail freight transportation as a process, it is appropriate to apply the Deming-Schuchart "Plan – Do – Check – Act" or PDCA. The application of the Deming-Schuchart cycle in transport operation is deemed an effective tool that will ultimately improve the quality of transportation services (*Fig. 2*).

The analysis of the introduced improvements should include several parameters. Traditional performance indicators could be taken into consideration. Accordingly, planning and performance improvement belong to the "Plan" and "Do" parts of the Deming-Schuchart cycle. The introduction of transportation standards and process replanning belong to the "Act" part. Operational parameters that can also act as key performance indicators should be taken into consideration [3, 16]. For example, the transport route speed; average distance of freight delivery; freight loading idle time; empty wagon run ratio; number of empty grouped departures and outbound routes; out-of-service-wagon average time; number of outbound freight shipping based on permanent contracts with consignor and those at single requests; number of double-run operations when arranging the wagon fleet management layouts.

The key parameter of rail transport operation efficiency is wagon turnaround. It is the time required for performing a full freight handling cycle from loading/unloading operations at one point to those at the next point, duration of loading operations at sorting stations, and wagon movement time on sections. Obviously, the wagon turnover reflects the rolling stock operators' efficiency. Thus, "Russian Railways" Company (RZD) efficiency as the main carrier and infrastructure owner can also be assessed in terms of wagon turnaround evaluating at least two parameters such as transit time and load handling time at sorting stations. "Russian Railways" Company (RZD) is also responsible for wagon supply in freight operations.

Studies on the rail transportation market show that the main factors having a negative effect on wagon turnaround growth are the abundance of wagon fleet; inefficient operation of wagon fleet; lack of cooperation between the participants of rail transportation; lack of cooperation between railways and intermodal kinds of

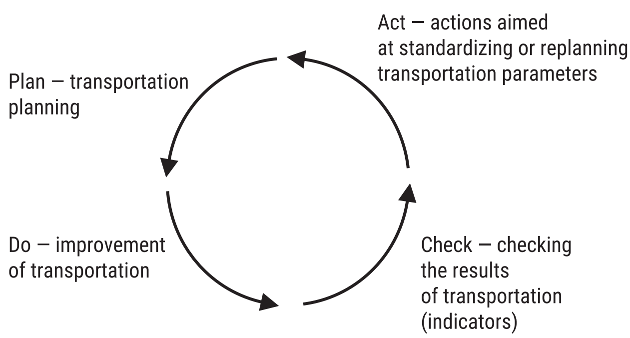

Fig. 2. The PDCA cycle in rail transport operation

transport including sea transport. The three-part formula for wagon turnaround is defined as

$$\vartheta = \frac{1}{24}\left(\frac{l}{v_{uch}} + \frac{l}{L}t_{tec} + k_m t_{gr}\right), \qquad (1)$$

where l is the wagon run; v_{uch} is the speed on the section; L is the wagon haul; t_{tec} is the transit car idle time at sorting stations; k_m is the local operations coefficient; t_{gr} is a single freight operation idle time.

Let us analyse a single freight operation idle time and local operations coefficient. Freight idle time is the time per cargo operation, which is calculated as quotient of dividing the total number of local wagon idle hours by the number of loaded/unloaded wagons.

$$t_{gr} = \frac{\Sigma Ut_m}{U_p + U_v}, \qquad (2)$$

where ΣUt_m is the total local wagon idle time; U_p and U_v are the volumes of wagon loading and unloading respectively.

Local wagon idle time is the time from the moment of wagon arrival at the station till the moment of its departure. In this regard, it is interesting to study the process of interaction between the railway station and private tracks or port sidings.

In accordance with Article 2 of the Rail Services Charter, the legal entity or individual entrepreneur who owns or has other rights to the railway track of non-public use, as well as buildings, structures and facilities, and other objects related to transport operations and provision of railway transport services. Freight owners interact with the carrier under the contract for the wagons supply and departure. Private tracks are serviced on the contract basis depending on the ownership of the private track and the locomotive serving that track. The process of wagon loading/unloading on a private track is usually included in process charts specifying the conditions and facilities. Largely, it is convenient to present this process as an algorithm a fragment of which is shown in *Fig. 3*.

It is recommended to determine the number of wagons in supply by the formula

$$m = \frac{U}{n_{pod}}, \qquad (3)$$

where U is the daily volume of the freight flow inbound to the private tracks or port sidings, n_{pod} is a number of shipments per day.

In this case, the number of wagon supplies is recommended to calculate according to the availability and readiness of wagons for delivery at the station, the chosen order of private tracks service and so on. However, the number of wagons in supply on a private track for freight operations is important in determining the freight idle time parameter of freight idle time and wagon turnaround. It is necessary to determine the optimal number of wagons in supply to minimize idle wagon-hours and, as a result, time and money costs. Various methods can be used to determine the optimal number of wagons in supply. This study suggests using inventory management theory. Wagons are represented as inventory so that to make the above-mentioned theory applicable to them.

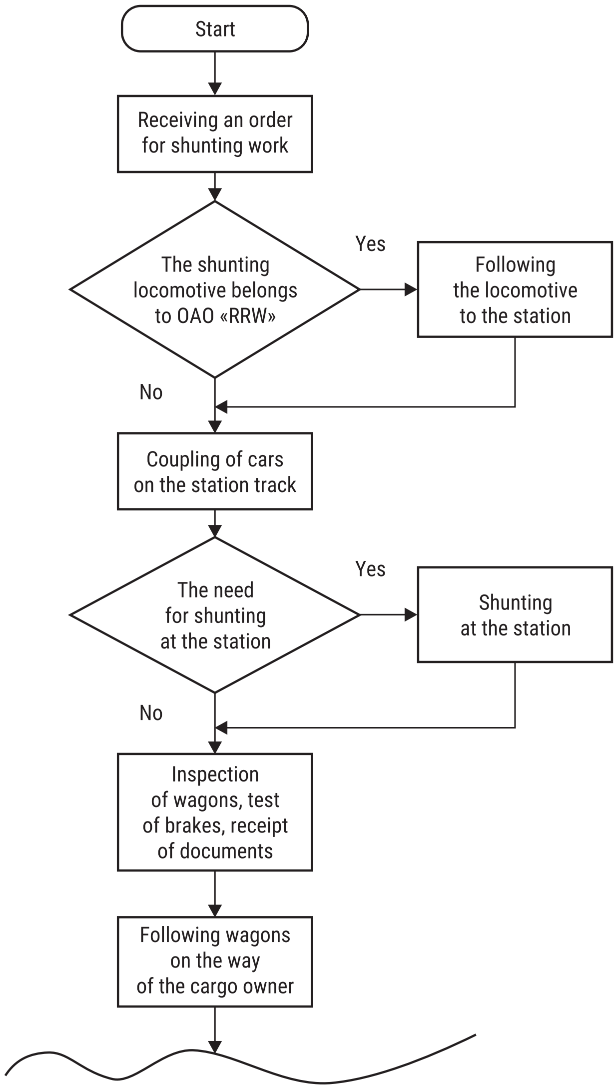

Fig. 3. Interaction of the railway station and the freight owner's tracks

Let us assume that in the wagon supply process on private tracks, there are two types of costs, constant (not conditionally dependent on the wagons number in supply) costs of load/unload operations c_l and costs of unproductive wagon idle time on the station tracks in supply c_s. We assume that the wagon stock at the station for the time interval Θ is equal to U (the daily volume of the freight flow inbound on private tracks or port sidings). We will calculate the wagon number in supply m so as to minimize the private track service cost. The following constraints $m \neq 0$ will be accepted; otherwise, the wagon supply will not make sense. The upper limit will be determined by the capacity of the enterprise (port) tracks and the shunting locomotive capacity depending on what services have been included in the station operations and the service contract. Let us assume that

$$1 \leq m \leq 60. \quad (4)$$

The average wagon stock during the time period T is equal to $m/2$ according to the inventory management theory.

The total costs for the whole period of time Θ will be

$$C(n) = \frac{UC_l}{m} + \frac{\Theta C_s}{2} m. \quad (5)$$

Therefore, the cost function is a function of the variable m for the specified time interval, number of wagons at the station as well as variable and fixed costs. The first summand of formula (5) is the total cost of wagon supply on private tracks or port sidings C_l, and the second summand is the total cost of wagon idle time on the tracks of "Russian Railways" Company (RZD) C_s. With a certain number of wagons in supply, the value of the cost function will be minimum. This number of wagons in supply will be the optimal one.

The minimum of two variables, namely, the costs of wagon supply and wagon storage on the station tracks with their constant product is achieved if these two types of costs are equal. Then the optimal number of wagons in supply m_0 will be

$$m_0 = \sqrt{2 \frac{U}{\Theta} \frac{C_l}{C_s}}. \quad (6)$$

The cost function sensitivity is expressed by the differential

$$dC = Cdm = \frac{1}{2}\Theta C_s - \frac{UC_l}{m^2}. \quad (7)$$

If the optimal number of wagons in supply varies from (n_0 – 10 %) to (n_0 + 10 %), then

$$\partial C = \frac{1}{2}\left[C(0.9m\ ) + C(1.1m_0) - 2C(m_0)\right] \quad (8)$$

we obtain

$$\frac{\partial C}{C_0} = \frac{1}{2}\left(\frac{C(0.9m_0) + C(1.1m_0)}{C_0}\right). \quad (9)$$

The total cost of wagon supply on private tracks or port sidings given the function sensitivity is therefore reflected in *Fig. 4*.

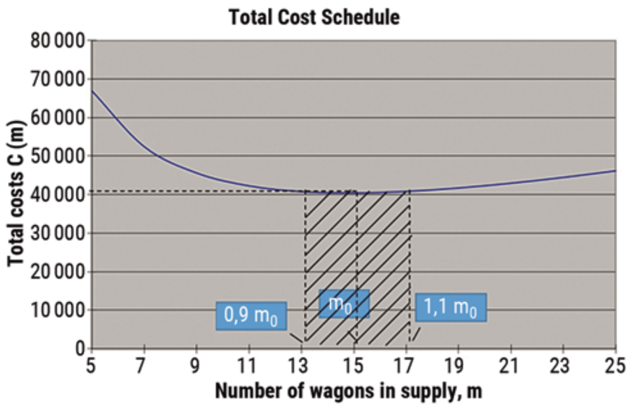

Fig. 4. The chart total cost changes depending on the number of wagons in supply

RESEARCH RESULTS

This study analyses the aspects and technology of the interaction between the railway station and private tracks (port sidings). Freight idle time due to the interaction between railway infrastructure facilities and the freight flow origin/ delivery points is an integral part of the wagon turnaround. Freight idle time reduction can be achieved by determining the optimal number of wagons in supply. The inventory management theory can help to find the function minimum of total expenses for private track services, to determine the function sensitivity, and to calculate the optimal number of wagons in supply as well as its variation limits.

CONCLUSIONS

The study has classified the issues of freight movement interaction into four groups. A study of freight movement interaction between "Russian Railways" Company (RZD), rolling stock operators, tracks of major freight owners, port sidings and terminal complexes has been of particular interest. Improving the freight transportation process using the TQM tools will help to improve the quality of transport services. Analysis of the transportation cycle involves assessing a number of operational indicators. The main operational indicator of wagon turnaround includes the efficiency of interaction between the railway station and private tracks in terms of freight idle time. It is possible to minimize the costs reducing freight idle time by finding the best option for servicing private tracks or port sidings. The presented methodology of finding the optimal number of wagons in supply allows minimizing the total costs of local operations. All participants of railway freight traffic can use the mentioned above methodology.

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Bionotes

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Foreign trade as a factor influencing the development of transnational transport and logistics systems

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ABSTRACT BRICS, an international association of countries with the greatest potential for economic growth is an example of a promising international alliance capable of effectively integrating economic interests and processes to provide a serious alternative to the developed countries in terms of the international trade scale and efficiency. At the same time, the existing format for discussing intentions and statements requires the targeted institutionalization of economic interactions and the creation of international economic, primarily transport and logistics, systems. These systems should be capable of using advanced transport and logistics concepts in terms of full consumer value chains to ensure effective support for international trade commodity flows based on real-time requests and existing import-export specialization of the participating countries.

The article provides statistical data characterizing the volumes of Russia's foreign trade with key international partners in non-CIS countries including the BRICS countries. The Federal State Statistics Service of the Russian Federation provided the statistical information in the field of foreign trade and its main aspects.

The analysis of existing international commodity flows unequivocally demonstrates a possibility of increasing international trade through the creation of transnational transport and logistics systems capable of ensuring the functioning of international value chains and efficient international exchange.

KEYWORDS: BRICS; import-export specialization of countries; international partnership; international trade

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Научная статья

Внешняя торговля как фактор развития транснациональных транспортно-логистических систем

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АННОТАЦИЯ Международное объединение стран с наибольшим потенциалом экономического роста БРИКС является образцом перспективного внешнеполитического союза, способного при эффективной интеграции экономических интересов и процессов обеспечить серьезную альтернативу развитым странам в части масштабов и эффективности международной торговли. В то же время существующий формат обсуждения намерений и заявлений требует целенаправленной институционализации перспективных экономических взаимодействий, создания международных экономических, в первую очередь транспортно-логистических систем, способных на основе перспективных и прогрессивных транспортных и логистических концепций в контуре полных цепочек создания потребительской ценности, обеспечить эффективное сопровождение товарных потоков международной торговли на основе актуальных запросов и сложившейся импортно-экспортной специализации стран-участников.

Приведены статистические данные, характеризующие объемы внешней торговли РФ с ключевыми международными партнерами дальнего зарубежья, в том числе странами БРИКС. Данными для расчетов послужили сведения Федеральной службы государственной статистики Российской Федерации в части внешней торговли и ее основных направлений.

Проведенный анализ сложившихся товарных потоков международной торговли однозначно указывает на возможность роста их масштабов на основе формирования перспективных транснациональных транспортно-логистических систем, способных обеспечить функционирование международных цепочек создания ценности и эффективный международный обмен.

КЛЮЧЕВЫЕ СЛОВА: БРИКС; импортно-экспортная специализация стран; международное партнерство; внешняя торговля

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INTRODUCTION

The new geopolitical reality that emerged in 2022 requires updating of theoretical and applied approaches to the creation, operation and modernization of transnational transport and logistics systems that will ensure the most effective implementation of the international division of labor, specialization and competitive advantages of the countries ready to implement active competitive strategies in international markets. One of the main aspects of such systems is handling of foreign trade commodity flows between countries-members of international economic alliances and associations including the BRICS group that represents the countries with the highest economic growth rates within the global economy.

MATERIALS AND METHODS

As an objective justification for the necessity of effective transnational transport and logistics systems, the Customs statistics data reflecting the structure of export and import flows between the Russian Federation and the key international partners including BRICS countries have been used. In conditions of global geopolitical transformations, the creation of reliable transport and logistics corridors based on effective infrastructure capacities will ensure regular, fair and efficient international trade. It will help to overcome unjustified discriminatory restrictions of certain international entities and to promote the international competitiveness of Russian goods.

RESEARCH RESULTS

Statistical data characterizing the volume of Russia's trade with the key international partners in non-CIS countries including BRICS countries are presented in *Table 1*, analyzed and summarized in *Table 2*, and visualized in *Fig. 1*, *2*. The statistical information in the field of foreign trade and its main aspects was provided by the Federal State Statistics Service of the Russian Federation.

The dynamics and structure of Russia's foreign trade with non-CIS countries in 2010–2018 are shown in *Table 1*[1].

The official Rosstat website has not been publishing the statistical data for 2019–2022 in the public currently. Nevertheless, the presented data analysis shows the main trends in the development of Russia's international trade with non-CIS countries.

Looking at the Russian Federation export business in 2010–2018, Russia's main trading partners were non-CIS European countries. The Russian-European partnership has been steadily declining, whereas the Russian-Chinese export operations have been steadily increasing. Over the period of 2010–2018, the export volumes to Europe fell from 61.1 to 48.5 %, while similar export trade indicators concerning China increased from 6.0 to 14.2 %. These tendencies took place against the background of growing export cooperation with India (as of 2010, 1.9 % and as of 2018, 2.0 % of total Russian exports) and Brazil (as of 2010, 0.53 %, and as of 2018, 0.65 %). South Africa was not one of Russia's key foreign trade partners in terms of exports in 2010–2018.

Russia's import volumes with Asian countries saw a rapid growth over the period of 2010–2018 as compared to the falling import volumes from Europe and steady import commodity flows from America. In 2010, the import volume from Europe exceeded 48.3 % and by late 2018, it had dropped to 41.8 % in specific terms. Alternatively, import volumes from Asia amounted to 35.3 % of the total import operations in 2010 and exceeded 40.7 % in 2018. The tendency was likely to have continued in 2021, and Asian countries have become the main trading partners — importers to the Russian Federation.

[1] The main indicators of the Russian Federation foreign trade. URL: ttps://rosstat.gov.ru/folder/11193

Table 1

Dynamics and structure of Russia's foreign trade with non-CIS countries in 2010–2018, USD, mln. (according to Rosstat[1])

Continents/Countries	Years								
	2010	2011	2012	2013	2014	2015	2016	2017	2018
1	2	3	4	5	6	7	8	9	10
Export									
Total	336 959,0	437 282,8	447 276,5	452 902,1	433 172,9	298 419,8	247 686,6	309 687,5	394 675,0
Europe	205 749,1	258 327,4	266 538,1	264145,7	236105,1	152 629,4	120 861,6	149 910,1	191 320,0
as % of the total	61,1	59,1	59,6	58,3	54,5	51,1	48,8	48,4	48,5
Asia	69 600,6	92 285,1	97 602,1	97 594,5	89 723,5	59 867,5	61 953,4	79 121,0	86 279,5
as % of the total	20,7	21,1	21,8	21,5	20,7	20,1	25,0	25,5	21,9
Including India	6392,6	6079,8	7915,6	6885,6	6343,2	5575,2	5311,7	6455,5	7752,0
as % of the total	1,9	1,4	1,8	1,5	1,5	1,9	2,1	2,1	2,0
Including China	20 324,6	35 030,1	35 727,2	35 630,5	37 492,3	28 600,9	28 011,9	38 918,6	56 019,0
as % of the total	6,0	8,0	8,0	7,9	8,7	9,6	11,3	12,6	14,2
Africa	3903,9	6395,2	7498,8	5216,0	7098,3	6500,3	8852,5	12 119,4	13 607,0
as % of the total	1,2	1,5	1,7	1,2	1,6	2,2	3,6	3,9	3,4
America	16 082,3	20 760,4	16 609,0	15 123,9	15 391,4	13 156,3	12 873,6	15 308,8	18 454,6
as % of the total	4,8	4,7	3,7	3,3	3,6	4,4	5,2	4,9	4,7
Including Brazil	1794,1	2124,9	2304,5	1984,9	2365,6	1923,7	1786,0	2031,5	2584,0
as % of the total	0,5	0,5	0,5	0,4	0,5	0,6	0,7	0,7	0,7
Australia and Oceania	131,9	71,1	115,4	403,7	550,1	505,7	142,0	203,6	168,1
as % of the total	0,0	0,0	0,0	0,1	0,1	0,2	0,1	0,1	0,0
Import									
Total	197 439,0	260 919,9	272 507,7	276 496,2	242 044,4	161 692,7	162 657,9	202 608,2	212 026,0
Europe	95 310,9	127 331,1	132 326,7	133 393,1	116 866,5	69 702,2	69 265,4	85 665,1	88 612,0
as % of the total	48,3	48,8	48,6	48,2	48,3	43,1	42,6	42,3	41,8
Asia	69 600,6	92 285,1	97 602,1	97 594,5	89 723,5	59 867,5	61 953,4	79 121,0	86 279,5
as % of the total	35,3	35,4	35,8	35,3	37,1	37,0	38,1	39,1	40,7
Including India	2142,5	2786,5	3041,5	3091,1	3172,3	2257,9	2402,5	2902,9	3225,0
as % of the total	1,1	1,1	1,1	1,1	1,3	1,4	1,5	1,4	1,5
Including China	39 036,1	48 201,8	51 843,9	53 211,5	50 773,4	34 948,0	38 021,9	48 055,9	52 225,0
as % of the total	19,8	18,5	19,0	19,2	21,0	21,6	23,4	23,7	24,6
Africa	676,5	1018,4	912,8	1043,7	1175,0	908,6	964,0	1127,9	1118,7
as % of the total	0,3	0,4	0,3	0,4	0,5	0,6	0,6	0,6	0,5
America	18 156,6	22 766,8	23 553,6	24 970,0	25 928,9	16 680,8	15 294,8	18 426,1	17 548,2
as % of the total	9,2	8,7	8,6	9,0	10,7	10,3	9,4	9,1	8,3
Including Brazil	4080,4	4389,0	3358,8	3493,1	3969,4	2915,2	2523,2	3199,1	2471,0
as % of the total	2,1	1,7	1,2	1,3	1,6	1,8	1,6	1,6	1,2
Australia and Oceania	919,9	1231,8	1111,1	1053,3	913,1	693,1	619,3	727,0	807,0
as % of the total	0,5	0,5	0,4	0,4	0,4	0,4	0,4	0,4	0,4

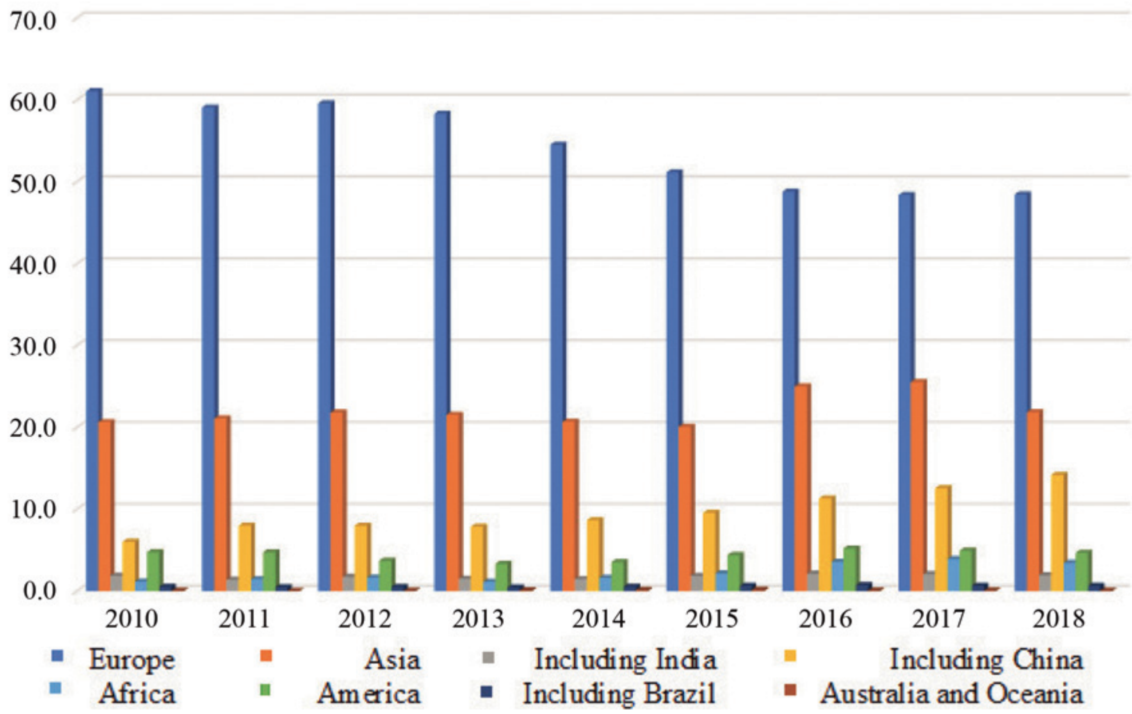

Fig. 1. Dynamics and structure of Russia's export flows to the main continents and BRICS countries (author's visualization)

Table 2

Structure of Russia's foreign trade with non-CIS countries including BRICS countries, 2010–2018, % (calculations are based on Rosstat data[1])

Continents/Countries	Years								
	2010	2011	2012	2013	2014	2015	2016	2017	2018
Export									
Europe	61,1	59,1	59,6	58,3	54,5	51,1	48,8	48,4	48,5
Asia	20,7	21,1	21,8	21,5	20,7	20,1	25,0	25,5	21,9
Including India	1,9	1,4	1,8	1,5	1,5	1,9	2,1	2,1	2,0
Including China	6,0	8,0	8,0	7,9	8,7	9,6	11,3	12,6	14,2
Africa	1,2	1,5	1,7	1,2	1,6	2,2	3,6	3,9	3,4
America	4,8	4,7	3,7	3,3	3,6	4,4	5,2	4,9	4,7
Including Brazil	0,53	0,49	0,52	0,44	0,55	0,64	0,72	0,66	0,65
Australia and Oceania	0,04	0,02	0,03	0,09	0,13	0,17	0,06	0,07	0,04
Import									
Europe	48,3	48,8	48,6	48,2	48,3	43,1	42,6	42,3	41,8
Asia	35,3	35,4	35,8	35,3	37,1	37,0	38,1	39,1	40,7
Including India	1,1	1,1	1,1	1,1	1,3	1,4	1,5	1,4	1,5
Including China	19,8	18,5	19,0	19,2	21,0	21,6	23,4	23,7	24,6
Africa	0,3	0,4	0,3	0,4	0,5	0,6	0,6	0,6	0,5
America	9,2	8,7	8,6	9,0	10,7	10,3	9,4	9,1	8,3
Including Brazil	2,07	1,68	1,23	1,26	1,64	1,80	1,55	1,58	1,17
Australia and Oceania	0,47	0,47	0,41	0,38	0,38	0,43	0,38	0,36	0,38

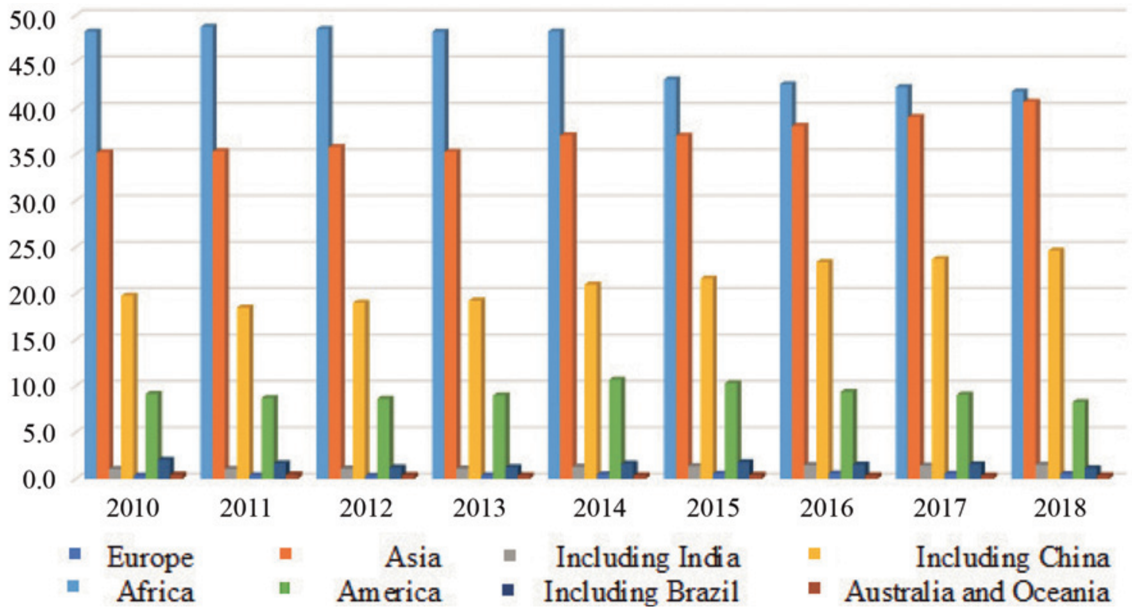

Fig. 2. Dynamics and structure of import flows to the Russian Federation from the main continents and BRICS countries (author's visualization)

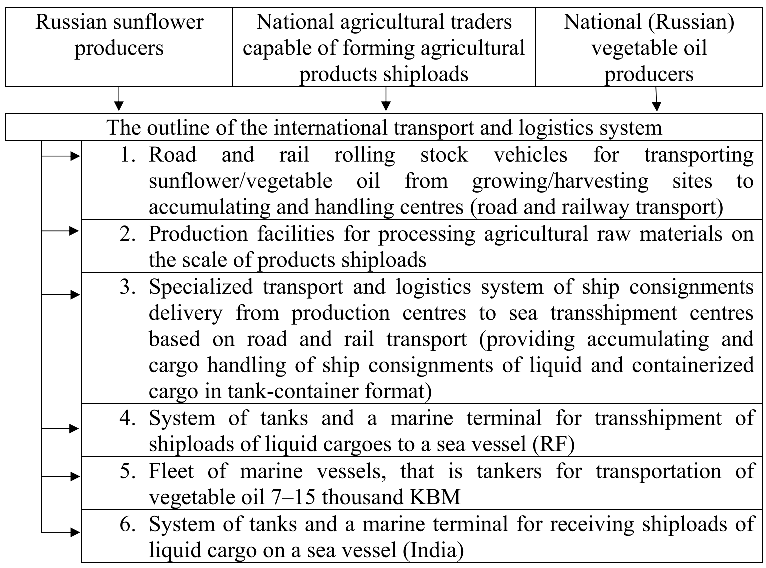

Fig. 3. The outline of the international transport and logistics system for sunflower oil shipments between Russia and India (proposed by the authors)

Import volumes from China amounted to 19.8 % of Russia's total import trade goods in 2010 and grew as high as 24.6 % in 2018. The Chinese import flows are envisaged to reach 30–35 % in 2022–2023.

Import volumes from India increased almost 1.5 times in 2010–2018, but accounted for 1.5 % only of the total import goods at the end of 2018. Nevertheless, it shows that there is a potential for international trade growth between our countries and requires the development of transnational transport and logistics systems that can improve the interaction efficiency on certain types of goods, among other things.

Russia's import volumes from Brazil decreased from 2.07 to 1.17 % in specific terms in 2010–2018. This was because of raw-material orientation and the lack of raw-material movement between our countries in the absence of large internationally competitive manufacturing centers.

The analysis of existing international commodity flows expressly demonstrates that their growth potential lies in the creation of promising transnational transport and logistics systems ensuring international value chains and efficient international exchange. Let us explain the above on the example of Russian-Indian cooperation prospects in terms of export/import of vital food industry products.

India is the world's largest player in the vegetable oil market: at the end of the 2020–2021 season, the import volume of this important industrial product amounted to more than $15.71 billion, an increase of 63 % compared with the previous year, while the natural volume of imports (i.e., driven by rising prices) remained unchanged[2]. The share of sunflower oil import was more than 14.04 %, or 1.9 million tons, with a 25 % drop in natural volume compared with the previous year. It happened due to a sharp increase in the oil export price in the Russian Federation and Ukraine and other countries.

A model of an effective transnational transport and logistics system capable of ensuring vegetable oil products movement is shown below (*Fig. 3*).

The system described above may serve as a model for the development and implementation of specialized transport and logistics systems, or international trade "bridges" in the BRICS architecture, ensuring infrastructure support of international commodity flows with high indicators of reliability and transparency of goods movement. It may be a good way of introducing modern container technologies allowing the transportation of liquid cargo in tank-containers.

CONCLUSION

According to the results of the BRICS 2022 Summit in Beijing, China, it is worth noting that this foreign economic union is a platform for discussion and statements of intentions rather than a real foreign economic alliance with integrated transport and logistics systems capable of implementing the international competitive advantages of member-countries. At the same time, the emergence and functioning of the New Development Bank, as well as the positive interaction experience between Russian Railways Company and this international financial structure on the infrastructure projects implementation indicate a positive dynamics in institutionalization of international economic intentions of the BRICS countries and the prospects of their functional support.

Bionotes

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[2] India increased vegetable oil import expenses by more than 60% in 2020/21. URL: https://www.oilworld.ru/analytics/worldmarket/325361