DIGITAL TRANSFORMATION OF TRANSPORT INFRASTRUCTURE: EXPERIENCE OF EUROPEAN AND MOSCOW METRO SYSTEMS

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Abstract

The article is devoted to the consideration of the digital transformation processes of the world's metro systems based on Industry 4.0 technologies. The aim of the study is to determine the social, economic and technological effects of the use of digital technologies on transport on the example of the metro, as well as to find solutions to digitalization problems in modern conditions of limited resources. The authors examined the impact of the key technologies of Industry 4.0 on the business processes of the world's subways. A comparative analysis of the world's metros digital transformations has been carried out, a tree of world's metros digitalization problems has been built, a reference model for the implementation of world's metros digital transformation is proposed. As the results of the study, the authors were able to determine the social, economic and technological effects of metro digitalization.

Keywords: Industry 4.0 technologies, digital transformation, transport, metro

Introduction

The coming era of the digital economy requires a revision of business models, methods of production in all spheres of human life in order to maintain competitive advantages in the world arena. The transport industry is no exception, as it plays an important role in the development of the country's economy and social sphere.

The Metro is a complex engineering and technical transport enterprise, dynamically developing taking into account the prospects for expanding the city's borders, with an ever-increasing passenger traffic and integration into other public transport systems. With the metro development, the increase in the load of passenger

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traffic, the volume of processed information in the management of technological processes is increasing every year, which requires a modification of control technologies - digital transformation (Lapidus, 2015). The experience of the metro systems of world megacities shows that digital technologies are effectively implemented and aimed at automating traffic control, developing unmanned technologies, ensuring security, technological innovations, identifying, implementing and developing promising digital solutions, developing transport infrastructure, increasing the efficiency of the transport system, in this regard, along with the development of innovative digital solutions, it is necessary to study international experience, adapt, deploy successful turnkey solutions and services, taking into account the specifics of the metro in each individual country.

1. Key advantages of digital technologies on transport

1.1. Internet of Things

The Internet of Things (IoT) is a network of various devices interconnected and capable of interaction. The IoT has become an integral part of modern life. A huge number of devices that we use every day have the ability to communicate without human intervention. The IoT provides a huge amount of real-time data on how different vehicles function and are used around the world (Lapidus, 2017).

The development of IoT is not only an increase in the penetration of “connected” devices, but also the creation of a technological ecosystem - a set of technological solutions for collecting, transferring, aggregating data and a platform that allows you to process data and use it for solutions.

The number of “connected” devices in the world is growing (according to industry analysts, their number will reach 20-50 billion units by 2020) and with it - the number of examples of the use of the “Internet of Things” in the economy: energy, industry, housing and communal services, agriculture, transport, health care, etc[1].

In foreign practice, there are successful examples of IoT implementation at the initiative of both the state and business. For example, with the support of the state in the countries of the European Union, South Korea, China and India, smart city technologies are being introduced, which make it possible to increase the efficiency of energy consumption and traffic management. In the UK and the US, large-scale programs have been implemented to introduce smart meters to remotely control energy consumption in households. In Russia, IoT technologies have a number of features and application restrictions associated with the economic, technological, legislative, geographical and cultural specifics of the country.

[1]Presentation “Internet of Things (IoT) in Russia. The technology of the future, available now”(2017), Electronic resource (retrieved fromhttps://www.pwc.ru/ru/publications/iot/iot-in-russia-research-rus.pdf).

IoT allows businesses to gain a competitive advantage by reducing costs and developing new sources of income. The constant and increasing exchange of data requires the development of new services that should connect us to the physical world around us. These services must also be built on completely new business models and provide new financial flows. With the help of the Internet of Things, the interaction of objects, the environment and people will be intertwined in many ways, which promises to make the world "smart" - more comfortable for humans.

The use of IoT for the digitalization of technological processes in the metro will provide and combine the main trends:

- improving customer service;
- reducing the cost of maintaining computing power and operating equipment;
- development of cloud technologies and Big Data (Vajgend, 2018);
- reducing the cost of data transmission;
- growth of labor productivity;
- the ability to increase the number of "connected" devices.

The usefulness of the implementation and development of IoT in metros lies in the use of visualization tools and the expansion of the functions of using mobile devices, which, in symbiosis, will improve the quality of passenger transportation. Also, with the help of IoT, it becomes possible to quickly identify serial flaws and analyze the trip.

Adjusting timetables and providing personalized services across modes of transport are helping crowded cities encourage public transport instead of personal transport and reduce traffic congestion. Technology can reduce costs and speed up service delivery. The issues of using the capabilities of "smart" systems in areas where extreme weather events, for example, floods, can cut off entire settlements from the mainland and block the operation of transport are being developed.

The road infrastructure includes many components - transport itself, security systems, electronic boards, surveillance cameras, and so on. Technologies that connect all these elements together are sensors and sensors (for example, GPS), as well as wireless data networks: Wi-Fi, Bluetooth, 3G, 4G, NB-IoT.

The organization of a transport network in metropolitan areas would be simply impossible without the IoT. The data collected by the turnstile sensors allow not only assessing the congestion, but also predicting the hourly passenger traffic. Metro trains also transmit information to a single server, which allows improving track parameters - for example, in this way it is possible to adjust train schedules in real time, reduce waiting intervals, and inform passengers about alternative routes. And all this is possible with minimal human involvement - in London, a network of sensors transmitting information to the cloud center independently monitors the entire underground transport system, including escalators, elevators and rolling stock. At the first signs of a malfunction, an alert is automatically triggered in the system, which indicates the need for preventive repair or emergency measures.

For example, the Moscow Metro has been operating since 1935 and during this time the infrastructure on the first lines (Sokolnicheskaya, Zamoskvoretskaya, Arbatsko-Pokrovskaya, etc.), as well as on the first lines of the London Underground

(Hammersmith and City, District, Ring, etc.) etc.), has reached its obsolescence. The risk of a system going out of control is enormous, as is the danger of inefficient operation. Therefore, the introduction of technologies based on the Internet of Things in the coming years will make it possible to modernize the maintenance of the transport system, improve travel conditions and increase the efficiency of the metro. Transport of London (TFL) is implementing IoT in the London Underground[2]. The project has installed sensors on escalators, elevators, ventilation systems and subway tunnels. The result is monitoring of public address systems and video surveillance. In addition, the project has begun work to move isolated legacy applications to an improved cloud environment, making it easier to manage, monitor, and automate individual tasks.

In the metro, the IoT will be able to digitally transform data on the operation of the Infrastructure Directorate's operational divisions: energy supply, electromechanical and escalator services, track and artificial structures, signaling, centralization and blocking services, forming a large-scale centralized system and digital interconnection of these divisions. This will allow planning the utilization of capacities, in particular, energy. However, it should be noted that at present in the information technology market in Russia, the “Internet of Things” is at an initial level (Dobrynin *et al*., 2016).

In the power supply sector, the widespread introduction of intelligent technologies, especially taking into account the length of linear facilities, can lead to increased reliability and lower operating costs. This will allow you to switch to network management “as per condition”, and not to carry out repairs in accordance with strict regulatory terms.

In the generation of elements of the “Internet of Things”, asset management systems of the ICS class are also used. They are installed in various combinations at all power plants in Russia and allow remote control and information on the operation of key systems. In the context of the Moscow Metro, as a major consumer of energy resources, the capabilities of the Internet of Things will not only save electricity, but also receive data on current costs (smart meters) in real time (Kranc, 2018).

In Europe, the task was to provide 80% of consumers with “smart meters” by 2020, which amount to 200 million electric and 45 million gas meters. In the United States, each state independently determines the policy for their implementation, but the number of “smart meters” in the country as a whole is already approaching 50% of the total (in six states, the share of “smart meters” was more than 80%)[3].

The Internet of Things has penetrated much deeper into the transportation industry. In the industry, where the length of various types of tracks exceeds 1.6 million km., And the number of freight transport (road, rail, etc.) - 7 million units, in principle, it is impossible to do without remote monitoring (Public Transport

[2]CISCO (2019), Electronic resource (retrieved fromhttps://www.cisco.com/)

[3]Smart manufacturing (2020), Electronic resource (retrieved fromhttps://iot.ru/wiki/umnoe-proizvodstvo).

Magazine, 2018). The “Internet of Things” is also used by the state to organize the transport system of Russia.

Cloud technology will also lead to platform solutions, which in turn will lead to new business models such as virtual forwarding. It will also contribute to the scalability and standardization of processes (Sutherl *et al*., 2018). Therefore, in the world, logistics companies plan to direct 5% of their revenues to the digitalization of logistics. In logistics, the introduction of IoT technologies allows solving such urgent problems for the industry as reducing the cost of freight and delays in transit, increasing the transparency of transportation (including using RFID tags) and minimizing the influence of the human factor. The vehicles connected to the Internet and remote monitoring of the vehicle fleet will reduce operating costs by optimizing the repair and maintenance of equipment. In addition, the “uberization” of cargo transportation is widespread, which makes it possible to refuse the services of forwarding companies. At the same time, the potential for the implementation of the Internet of Things in the transport industry in Russia is very significant - both in railways, pipeline and other modes of transport. There are three markets for the application of IoT technologies:

1. Mass market B2C. This market is receptive to new innovative technologies and products based on these technologies. Consumers are shopping on trends. In the medium term, products based on “cloud” IoT solutions are expected to be in demand, for example, monitoring public transport, monitoring the load of public infrastructure (roads, subways, etc.), etc. Such products will be monetized through the sale of related services, advertising, and gaining access to large amounts of user data. The solutions of this market are mostly focused on “smart insurance”, “smart home”, monitoring of vital functions, telemedicine.
2. Market of commercial companies B2B. This market is more inert compared to the B2C market. Such a market is characterized by time for analyzing the external environment, realizing the need to apply new technologies, agreeing on investments and implementing projects. In Russia, there are a number of factors that complicate decision-making in favor of IoT, since a return on investment is not expected in the horizon of 2-3 years. Many Russian companies are not ready to increase flexibility, because in addition to the lack of return on investment in the short term, this requires a culture of transformation of the team, business partners and contractors.
3. Market for government agencies (B2G). Such a market has the maximum economic potential for the introduction of IoT technologies in terms of improving energy efficiency and reducing the cost of maintaining industrial assets. The main reason for the inertia of the market is a worn-out infrastructure, which requires high costs for renovation, repair and maintenance.

The IoT has entered a period of significant change in 2019. Promising trends that prevail in the IoT market:

1. Boundary calculations. Devices will become even more powerful, providing local data processing and artificial intelligence capabilities. This will reduce the amount of data transfer and dependence on cloud computing, as well as provide

more flexibility. The impact will be on industries where an immediate response is needed based on sophisticated real-time data analysis (manufacturing and community activities), and where cloud communications may be limited.

2. Increased competition in the field of information security. The rivalry of large companies in the development of the most efficient and secure IoT solutions. The IoT market will focus on addressing key security challenges and addressing the Internet of Things vulnerabilities that previously hindered technology adoption.
3. Dominance of large companies. Competition between tech giants like Amazon Web Services (AWS), Microsoft and Google is expected to intensify as large IoT platforms become commonplace. These companies will be able to capture most of the market and continue to expand their area of influence at the expense of adjacent small organizations, since they will be forced to focus on niche areas to survive.
4. The growing use of “smart devices”. Especially relevant for the automotive industry. Market participants will implement IoT technologies to provide vehicles with data collection and monitoring, as well as their interaction with smart city services and other transport facilities.
5. 5G helps to strengthen the interconnection of the elements of the modern world. This will drive IoT innovation further and provide the ability to collect, analyze and manage data in near real time.

According to the forecasts of the international consulting and audit network PricewaterhouseCoopers (PwC) in Russia, by 2025 the cumulative effect of the implementation of the Internet of Things in 6 segments (electricity, healthcare, agriculture, transportation and storage of goods, segments of the smart city and smart home) will be about 2.8 trillion. rubles, of which 542 billion rubles. in logistics, of which 39 billion rubles. - connected transport (railways)[4].

1.2. Mobile applications

Another equally important technology generated by the digital economy is mobile applications. London Underground passengers receive real-time travel information (including train movements) using the Tube Map mobile application (see Table 1), which allows them to plan trips and perform many other operations. Since 2014, London's passengers have been able to pay for travel via smartphones that support the NFC short-range communication standard. The new cloud solution is expected to further enhance the passenger experience through improved infrastructure planning, process automation and proactive fault detection (Mesenbourg, 2018).

[4]Presentation “Internet of Things (IoT) in Russia. The technology of the future, available now”(2017), Electronic resource (retrieved fromhttps://www.pwc.ru/ru/publications/iot/iot-in-russia-research-rus.pdf).

Table 1. Applied mobile applications in subways

№	City, Country	Mobile applicationname	Passenger rating, 5-point scale	Number of survey participants, thousand people
1	Moscow, Russia	Moscow metro	4,7	28
2		Yandex.Metro - metro map and route times Yandex	4,5	141,9
3	SaintPetersburg, Moscow, Russia	Metro and transport with Citymapper Limited	4,5	68,5
4	Minsk, Belarus	Minsk - guide and travel guide TingBY Team	4,5	4,03
5	Kiev, Ukraine	Kiev Metro Guide KorsTech Inc.	4,4	2,5
6	Poland	Jakdojade: public transport CITY-NAV sp. z o.o.	4,5	64,6
7	Helsinki, Finland	HSL - Tickets, route planner and information Helsingin seudun liikenne	3	0,96
8		SL:Journey planner and tickets AB StorstockholmsLokaltrafik	2,6	2,4
9	London, GreatBritain	Tube Map London Underground Visual IT Limited	4,3	12,9
10		Tube Map – TfL London Underground route planner Mapway	4,2	13,3
11	Berlin, Germany	BVG FahrInfo Plus eos.uptrade GmbH	4,1	16,1
12	Germany	DB Navigator Deutsche Bahn	4,0	125,3
13	NewYork, USA	My Transit NYC Subway, Bus, Rail (MTA) My Transit™	4,7	20,6
14		New York Subway – Official MTA map of NYC Mapway	4,4	8,2
15	Paris, France	Next Stop Paris - RATP	4,5	13,9
16		RATP : Subway Paris	3,5	54,3
17	Tokyo, Japan	Tokyo Subway Navigation 東京地下鉄株式会社	4,2	3,5
18	Japan	TABIMORI	4,4	545
19		Japan Travel –Route, Map, JR NAVITIME JAPAN CO., LTD.	4,5	5,3
20		Japan Official Travel App Japan National Tourism Organaization	4,7	3,8
21	SouthKorea	KakaoMetro - Subway Navigation Kakao Corporation	4,1	42,7
22		지하철정보 :메트로이드HDmetroid	4,2	14,9

23		지하철종결자 : Smarter Subway TeamDoppelGanger	4,4	75,9
24	Singapore	Singapore MRT and LRT FREE RoarApps	4,4	4,7
25	SaoPaulo, Brazil	São Paulo Metro - Official	4,3	7,2
26	Alma-Ata, Kazakhstan	Almaty-Metropolitan	3,9	0,9
27	Copenhagen, Denmark	Rejseplanen Rejseplanen A/S	4,1	17,2
28	Canada	Canadian Mortgage App Bendigi Technologies Inc.	4,7	2,5
29	Madrid, Spain	Transporte Madrid - EMT Interurbanos Metro TTP JSVM	3,2	2,2
30		Metro de Madrid Oficial Metro de Madrid, S.A.	4,0	5,5
31	Aroundtheworld	MAPS.ME –Офлайнкарты	4,5	995,8
32		GPS Navigation & Maps – Scout	4,3	57,1
33		Google LLC Maps: navigation and public transport	4,3	9713
34	Aroundtheworld	Transit: Real-Time Transit App Transit App, Inc.	4,2	46,6
35		Moovit Transportation App	4,4	673,4

Source: Google.Play.

In the future, passengers with disabilities will be able to subscribe to an online service informing about the availability of certain services, for example, an escalator or an elevator. The cloud-based approach has a much broader scope: it will enable aviation, transport and logistics companies to improve their performance in the face of increasing regulatory requirements, cost burdens and competition.

1.3. Artificial intelligence and smart solutions

All industries - from the financial sector to retail, from mechanical engineering to healthcare, are striving to adopt artificial intelligence technologies. Public transport is no exception. It is here that smart technologies extend not only to technical solutions, but also have a social orientation.

The UITP Asia-Pacific Research Center conducted a study on the role of artificial intelligence in the development of public transport. The main objectives of the project, which began in December 2017, are to analyze the use of artificial intelligence in the sector, to study how technology can contribute to the development of the industry (including new opportunities for staff training), to study trends in technology adoption in the industry.

Artificial Intelligence is designed to improve productivity and set high standards for service delivery. How it will be used in the field of urban public transport largely depends on the policy of the transport company - whether it is planned to use artificial intelligence to increase its competitiveness or expand its market share (Kazakov *et al*., 2016).

When implementing smart solutions technologies, organizations need to understand what the employees who are assisted by artificial intelligence are capable of, and make development plans based on these abilities. The resource-based approach involves the transfer of personnel from performing routine tasks to a higher functionality, where creativity, empathy, and parallel thinking are present. In this sense, people will be ahead of artificial intelligence for a long time, if not always.

Currently, the city of Moscow, as one of the brightest examples of modern cities in the world with a complex infrastructure, where transport interchange hubs (TPU) are gaining relevance and development, does not do without the introduction of smart transport technologies, and this is especially true of the metro, as the most popular type of public transport. Most experts adhere to a complement strategy, where computer technology complements the human work, but does not replace it. High requirements for the safety of the transportation process, a large number of objects of control and management, the need for a quick, prompt response in response to constantly changing conditions in a huge, geographically distributed system make this type of transport truly intelligent. This is especially true of the Moscow Metro, as the main form of public transport. Man and artificial intelligence have to learn to work with each other.

For example, an urgent task for the Moscow Central Circle is to enter electric trains into the schedule in the event of various disruptions and delays in movement, which ensures prompt recalculation of the schedule of electric trains on the entire ring and selects the optimal solution to eliminate the backlog. To help dispatchers, it is necessary to develop an automated conflict resolution system based on multi-agent technologies.

Meeting the spirit of the times, in France, Systra offers the concept of a “smart” station, which implies online communication with the external and internal environment using sensors, CCTV cameras, as well as setting up information systems, lighting, ventilation (Public Transport Magazine, 2018). This technology lies in the same plane as the concept of a smart city. It promotes the development of new modes of transport and changes in the usual behavior of passengers. With the help of this concept, the integration of the metro into urban life is laid, to move away from the closed functioning of the transport circuit. Here the transition to a more friendly (less stressful) environment in relation to the consumer (passenger) is laid, as well as the issue of improving navigation and redistribution of passenger traffic. In real time, the work of the station elements that influence or control the passenger flow is adjusted - navigation elements, escalators, elevators, entry and exit groups.

To create a friendly environment, Systra has adopted an environment design methodology based on 3 main steps:

1) determine the parameters of the room and its functional load;
2) design the environment for the needs of various groups of passengers inside the premises;

3) ensure the coordination of the design of the room with the general design of the TPU.

An indicator of successful work is the behavior of passengers, when they, being unaware of the different "settings" of different TPU rooms, moving from one room to another, feel comfortable in each of them. The station or TPU should become a living place, where there would be a desire to come not only for the sake of changing to another mode of transport. An offer for the consumer (passenger) of a safe and comfortable environment in line with the modern trend - the desire of a person to be "flexible", i.e. prefer to decide for themselves how they spend their time at the station.

Passengers note the demand for TPUs built by the Dutch agency ProRail. In 2018, 72.8% of passengers rated TPU services 7 out of 10, while in 2014 this figure was 65.7%. But TPU Nuevos Ministerios in Madrid pays special attention to the human factor. At the station, which occupies 7,600 square meters on five levels, there is a transfer to 3 metro lines and 5 directions of the commuter train. There are 12 elevators, 47 escalators, 30 ticket machines at the service of passengers. The station is equipped with tactile surfaces for the blind and visually impaired. Corridors and passages are wide enough for easy passage of passengers. Travolators on long passages facilitate the rapid movement of passengers and avoid congestion. Passages through the turnstiles are of standard width, there are also increased widths for passengers with luggage and disabled people. This is important because Nuevos Ministerios transfers to the metro line towards the airport. Passengers with bulky luggage pass without hindrance (Public Transport Magazine, 2018).

A new security system is being installed in the metros of developed countries of the world: cameras that scan passengers' faces, digital video analytics, thermal imagers and other accessories that will allow law enforcement agencies to monitor the movements of any of the passengers and be aware if a citizen of interest appears in the subway. Intelligent video surveillance systems will automatically receive notifications about emergency situations - from a simple bag forgotten in the lobby to smoke. The number of passengers in each seat is estimated by a video camera, the data is processed in a special center - the conventional "brain" of TPU. In case of an unauthorized hit of any object on the path, the camera "understands" this and raises an alarm (Lapidus*et al*., 2016).

1.4. Smart мanufacturing

The concept of smart manufacturing was formed quite recently and can be used to describe the implementation of robots, information technology, or any other innovation in production. One of the fundamental definitions of smart manufacturing was formulated by scientists from the University of Stuttgart - it is a production system that can take into account the context and help people and machines in solving their problems, thanks to the large-scale implementation of information and communication technologies in the workflow management system (Smart manufacturing)[5].

Smart manufacturing is inextricably linked to “Industrie 4.0” - a concept that appeared in the German government's strategy for the development of high technology, which involves the computerization of production. Industry 4.0 is a modern trend towards automation of production with widespread use of cloud technologies, the Internet of things and cyber-physical systems. Thus, the arrival of Industry 4.0 is impossible without the massive spread of smart manufacturing.

Many associate the development and establishment of Industry 4.0 with the fourth industrial revolution. Interestingly, the concept of the fourth revolution already exists, despite the fact that the third has not yet been completed.

Smart manufacturing involves the use of the following technologies:

- smart machines that can exchange information with other production systems and work with a high degree of autonomy, and advanced robots;
- industrial Internet of Things (IIoT). Devices and technologies that provide an Internet connection for all machines in production;
- cloud services that provide convenient and continuous network access to a common pool of configurable computing resources;
- enterprise integration platforms, the task of which is to receive data from equipment, analyze and aggregate them;
- Big Data technologies

2. Comparative analysis of the automation of the world's subways and barriers hindering digital transformation of the metro

2.1. The scale of the world's metros digitalization

Automation of traffic control processes plays the most important role in digital transformation of the metro. SAUP M are designed to automate the process of train control, including starting, acceleration, selection of the driving mode on the tracks, braking at platforms in order to improve the accuracy of the schedule.

According to the UITP classification, SAUP M is divided into 4 levels of automation (Grade of Automation):

1. GoA1 - manual control of rolling stock with the use of automatic train traffic safety (ATP). The driver controls the movement of trains, the position of doors and other elements;
2. GoA2 - semi-automatic rolling stock control. The driver controls the start of movement and the closing of doors. Automatically following the tracks, stopping at the station and opening doors. Full functionality of the ATP and ATO systems with the train driver in the control cabin is provided;

[5]Smart manufacturing (2020), Electronic resource (retrieved fromhttps://iot.ru/wiki/umnoe-proizvodstvo).

3. GoA3 - automatic control without the direct participation of the driver, but with the presence of the personnel who operate the doors and are able to take control in the event of emergency situations. The ATP and DTO systems are operational;
4. GoA4 - fully automatic control of rolling stock without the participation of any personnel on board (UTO) (Nikul'chikov, 2015).

As of 2016, according to the UITP, there are automated metro lines in 37 cities around the world. The number of such lines is 55, the deployed length is more than 800 km, and the number of served stations is 848. Thanks to the launch of new automated lines, their total length in 2017 was increased to 1000 km, lines were built in Beijing, Istanbul, Santiago, Seoul and Kuala Lumpur, which added to the total number of cities and lines where the metro operates using innovative train control technologies. In 2018, the total length of automatic metro lines was 1,030 km. By 2025, the rapid growth in the total length of automated metro lines is expected to continue, which will amount to about 2,300 km.

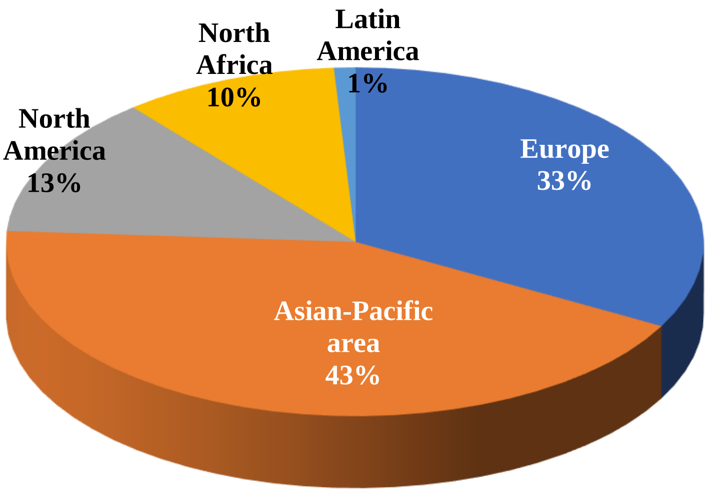
The first subway, where train traffic was organized without the participation of a driver, opened in 1981 in the city of Kobe, Japan. Regional analysis shows that the share of fully automated lines is noticeably higher in the Middle East and Europe, where they occupy 15% and 10% of the total length, respectively. In Asia - the leading region in the implementation of automated systems in the metro - the share of such lines is only 5%. Asia (43%) and Europe (33%) have 76% of the world's automatic metro. Only 13% are in North America, even though the region can be described as a pioneer in automation. Over the past decade, Latin America (1%) and the Middle East (10%) have become actively involved in this issue, with the latter showing the highest rates of development (see Figure 1).

50% of the automatic metro infrastructure is located in 4 countries: France, South Korea, Singapore and the United Arab Emirates (UAE). France continues to lead with a share of 16%, South Korea is approaching these indicators, reaching 15%. The three cities with the longest automatic lines are not in Europe. These are Singapore (93 km), Dubai (80 km) and Vancouver (68 km).

Initially, the usage decisions were mainly for lightly loaded lines, but in the last decade they have been increasing for medium to heavily loaded systems.

The busiest metro lines in Europe and Asia - with the exception of the 4th line in São Paulo in Latin America: with more than 32 thousand passengers per hour, it is one of the busiest lines in the world. Over the next 10 years, the introduction of automated systems in the metro is mainly concentrated in the Middle East, Europe and Asia - together they account for 88%. Only 11% of the planned growth will come from Latin America.

Figure 1. Distribution of automated metro systems in the regions of the world



Source: authors' representation.

In Europe, 26% of the length of new lines to renovated projects. Following the successful conversion of the U2 line in Nuremberg in 2009 and the L1 in Paris in 2012, European cities have announced preparations for metro conversion projects in the next decade: Glasgow - G. Subway line, London - Docklands, Lyon - LA & LB, Marseille - L1 & L2, Paris - L4, Vienna - U5.

The London Underground is expected to become fully automatic by 2022. By 2025, Asian countries will have 33% of the total length of modern automated metro systems, 30% in Europe and another 25% in the Middle East.

Most subways in Russia have implemented the so-called "simple" (Traditional) first-level systems with manual control, equipped with ALS-ARS (ATP - Automatic Train Protection). If the permissible speed is exceeded, the train is forced to stop. Separate lines of St. Petersburg, as well as the line of the Kazan metro, equipped with security and driving systems, to the second level systems (road train operation - ATR + ATO). In them, the driver controls the arrival and departure of the train from the station, takes control in emergency situations. So, in the complex system "Movement" developed by the St. Petersburg "Research Institute of Precision Mechanics" in the automatic mode, when approaching the station, it can manually urgently reduce the speed of the train, for example, in the event of a person falling on the track. The driver also has access to the function of confirmation (permission) of departure from the station in case of emergency (when the doors are closed).

On the trains of the third level Driverless Train Operation - DTO (Driverless with onboard staff - without a driver, but with the presence of personnel on board) often there is not even a driver's workplace, nevertheless, there are specially trained personnel. In emergency situations, specialists can manually remove the damaged train from the line under the control of the security subsystem or without its participation.

Level 4 systems have become widespread over the past 15 years. More than 50 Unattended Train Operation - UTO (Driverless Unattended) projects have already been implemented in 25 cities around the world. This number is expected to increase fivefold over the next ten years. Today systems of the third and fourth levels are not used in Russia. In 2011, for the first time in the CIS, the Korean system of the third level ATDP SVTS-class (Communication Based Train Control - control of trains using telecommunication technologies, in particular, a radio channel with Wi-Fi of the Hyundai-Rotem corporation) was implemented. It has been introduced on the line of the Almaty Metro. The system of the fourth level of SVTS-class of the French company “Alstom” is included in the project of the Omsk metro line.

Systems of the second - fourth levels are based on modern hardware and software. They differ in the algorithms for the use of on-board safety equipment and automatic guidance in case of its malfunction. On some foreign lines with the highest level of automation of technological processes, the functions of station attendants are transferred to line dispatchers and automation. In this regard, it is very important that the personnel - dispatchers, “escorts”, station attendants - are well trained.

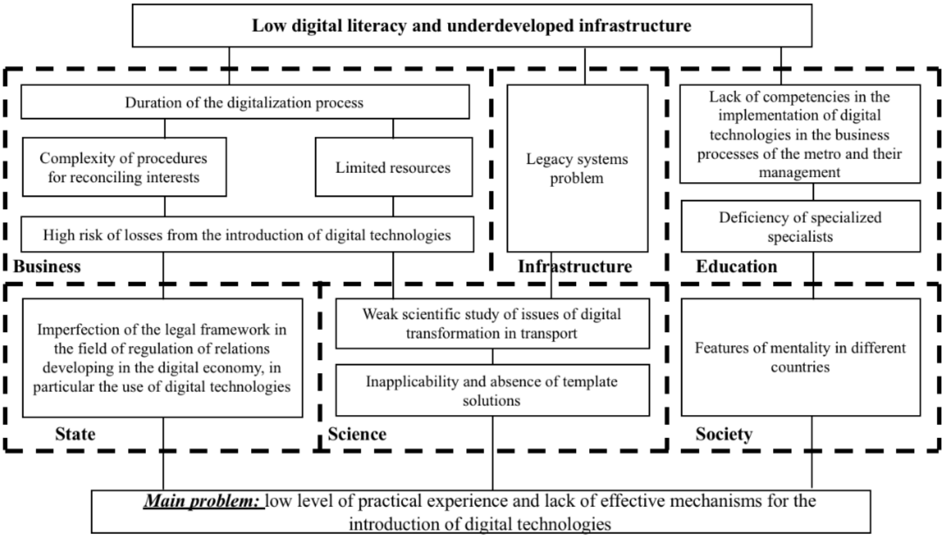
In the systems of the fourth level of leading foreign manufacturers, priority is given to traffic safety, tranquility of passengers and comfortable work of dispatchers. At the same time, other aspects of operation are provided for. For example, from the workplace of any line dispatcher, you can urgently disconnect the voltage from the contact rail. Thanks to the linking of the TETRA standard radio communication system with the on-board devices, dispatchers can negotiate with passengers, and notify them via loudspeaker communication.

Data exchange channels are organized between the train and traffic control points. They are designed to receive and transmit automatic fire alarm signals from the equipment diagnostics subsystem on trains and transmit images from video cameras installed in carriages to the dispatch center to the station.

2.2. Problems of world’s metro digitalization

Digital transformation on transport is a complex, multi-level process that requires a certain level of development of technologies, infrastructure and society as a whole. However, at present, all countries are faced with different problems of digitalization of metros, which can be structured, highlight common problems, as well as “problems of cause” and “problem-effect” based on decomposition modeling. All problems are categorized into 6 groups: “state”, “business”, “society”, “science”, “education” and “infrastructure” (see Figure 2).

Figure 2. "Problem tree" of the world's metros digitalization



Source: authors' representation

The main problem of digitalization of subways is determined - the low level of practical experience and the lack of effective mechanisms for the introduction of digital technologies. At the same time, solving the problem of low levels of digital literacy and underdeveloped infrastructure will make it possible to solve most of the identified problems in all of these six categories.

For example, the development of relevant educational programs for students, graduate students, as well as advanced training of employees of all levels will expand competencies in the new digital reality and use the acquired skills for business development in the context of mass digitalization of all spheres of life.

Underdeveloped infrastructure is at the heart of all the identified problems. The solution to this problem is possible with the help of state subsidies for underground enterprises, as well as targeted investments in research and development, accompanied by scientific research in this area (Baranov*et al*., 2019).

The introduction of digital technologies is also often associated with the imperfection of the legal framework of countries in the field of regulation of relations developing in the digital economy, as well as the peculiarities of the mentality in different countries. In this case, it is advisable to develop template solutions for the digitalization of individual business processes that can be adjusted to the specifics of conducting production activities, depending on the region and legislative norms.

3. A reference model for the implementation of metro digital transformation

In order to increase the level of development of the digital economy in the world, traffic safety and the quality of passenger transportation, a model has been built for implementing the digital transformation of the metro by introducing modern information technologies for the transmission, storage and processing of large amounts of data, digital modeling of objects and processes, generation of decisions of a statistical and event nature. forecasting and planning the activities of the enterprise, taking into account the dynamic changes in external and internal conditions (Kitaev *et al*., 2017).

The metro digital transformation implementation model is a system of measures aimed at optimizing business processes and improving the quality of the provision of passenger transportation services based on the massive introduction of digital technologies.

Figure 3 shows the constructed model, which includes 6 stages of digital transformation, i.e. transition of the metro from the state “analog” to “digital”. Let's take a closer look at each stage of digital transformation.

Stage 1. Preparation of infrastructure and rolling stock for the implementation of digital control systems:

Inspection of infrastructure facilities and rolling stock to determine the volume of analog and digital equipment with the aim of subsequent modernization for inclusion in digital process control systems.

Survey of existing control and safety systems in order to determine the possibility of integration into digital process control systems.

Description of the existing technological processes for managing the maintenance and repair of infrastructure facilities and the rolling stock in order to determine the need for adaptation in the event of the introduction of digital process control systems.

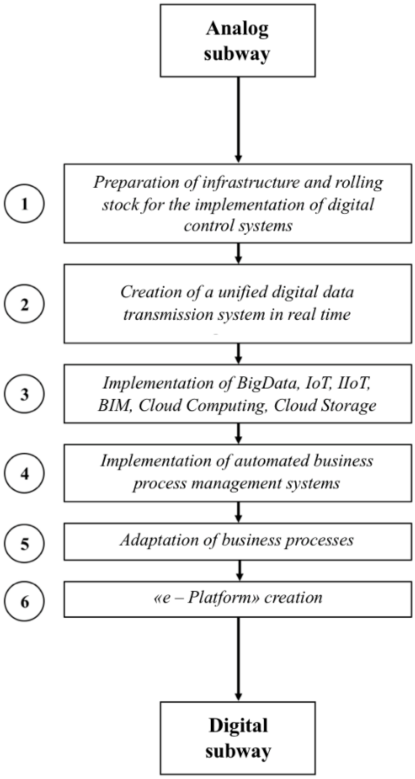
Determination of the degree of readiness (qualification) of personnel for the implementation and operation of digital process control systems.

Updating the normative and technical documentation governing the existing business processes of management, maintenance and repair of infrastructure facilities and the rolling stock fleet.

Stage 2. Creation of a unified high-speed data transmission system:

1. Survey of infrastructure and rolling stock for equipping with analog and digital devices and communication systems in order to determine the volume of construction of digital technological and corporate data transmission systems.
2. Creation of a digital technological (high-speed) data transmission system to ensure operability and real-time control of technological processes and services that ensure the transportation of passengers.
3. Creation of a digital corporate (high-speed) data transmission system that provides management of passenger services and enterprise resources.
4. Creation of a high-tech center for storing and processing large amounts of data.

Figure 3. Model of digital transformation of the metro and the creation of an "e-Platform"



Source: own representation.

Stage 3. Implementation of Big Data, IoT, IIoT, BIM, Cloud Computing, Cloud Storage technologies:

• Implementation of Big Data technology:

1. Formation of a strategy for the phased implementation of technology as an information technology tool that allows parallel processing of large arrays of unstructured data of business processes carried out by an enterprise in real time, with the ability to statistically predict negative and positive trends.
2. Creation of a working group for the organization of implementation and formation of a responsible subdivision at the enterprise to support the technology, appointing the owner of the process of ensuring the operation of the technology.
3. Preparation of the enterprise hardware and software infrastructure for the implementation of the technology. Mostly - the creation of a single digital, high-speed data transmission network and high-tech data processing centers (stage 2

of the model) using cloud technologies, integration with existing information systems.

4. Step-by-step implementation of the technology in test mode, development of the “work without failures” resource.
5. Updating the existing and forming new normative and technical (legal) documentation regulating the work and operation of the introduced technology.
6. Training and advanced training of the personnel of the enterprise involved in the work and operation of the introduced technology.
7. Putting the technology into operation in full.

• Implementation of technologies “Internet of Things” and “Industrial Internet of Things”:

1. Formation of a strategy for the phased implementation of technologies as a technological tool that allows real-time interaction of digital devices, machines, equipment, mechanisms and systems (programs) involved in the business processes of the enterprise.
2. Creation of a working group to organize the implementation of technologies.
3. Restructuring of the existing ones and the formation on their basis of a new responsible subdivision at the enterprise to support the technology, appointment of the owner of the process of ensuring the management and operation of the technology.
4. Preparation of infrastructure facilities and rolling stock, software and hardware infrastructure of the enterprise for the implementation of technology. Mainly - equipping or retrofitting with built-in digital technologies for autonomous control and self-diagnostics (technical) with the ability to analyze the health status and generate proposals for the further management and operation of digital devices, machines, equipment, mechanisms and systems (programs) involved in supporting the business processes of the enterprise in the real time, integration with existing information systems.
5. Step-by-step segment introduction of the technology in test mode, development of the “work without failures” resource. When implementing technologies, it is necessary to provide for segmentation based on the level of responsibility for ensuring the operation of technological processes and services, passenger and corporate services.
6. Updating the existing and forming new normative and technical (legal) documentation regulating the work and operation of the technologies being introduced.
7. Training and professional development of the personnel of the enterprise involved in the work and operation of the introduced technology.
8. Putting the technology into operation in full.

• Implementation of the Building Information Modeling technology:

1. Formation of a strategy for the phased implementation of information modeling technology for enterprise facilities and management of their life cycle (at all stages: construction and reconstruction, operation and repair) based on digital

data about the object and data related to the object, considered together at one point in time.

2. Creation of a working group to organize the implementation of technology.
3. Restructuring of the existing ones and the formation on their basis of a new responsible subdivision at the enterprise to support the technology, appointment of the owner of the process of ensuring the management and operation of the technology.
4. Preparation of infrastructure facilities and rolling stock, software and hardware infrastructure of the enterprise for the implementation of technology. Mostly - the formation of digital passports of objects: buildings, technological structures, tunnels, bridges, stations, transport hubs, electric depots, etc. etc., creation of a unified electronic register of enterprise objects, integration with existing information systems.
5. Updating the existing and forming new normative and technical (legal) documentation regulating the work and operation of the introduced technology.
6. Training and advanced training of the personnel of the enterprise involved in the work and operation of the introduced technology.
7. Phased introduction of technology into operation.

• Implementation of technologies “Cloud data storage” and “Cloud computing” (perspective):

1. Formation of a strategy for the use of technology as an online storage of data not related to the operation of the enterprise's technological processes.
2. Appointment of a responsible subdivision at the enterprise for technology maintenance, appointment of the owner of the process of ensuring the technology operation.
3. Preparation of the enterprise hardware and software infrastructure for the implementation of the technology. Mostly - the creation of a single digital, high-speed data transmission network and high-tech data processing centers (stage 2 of the model), integration with existing information systems.
4. Updating the existing and forming new normative and technical (legal) documentation regulating the work and operation of the introduced technology.
5. Training and professional development of the personnel of the enterprise involved in the work and operation of the introduced technology.

Stage 4. Implementation of automated business process management systems:

1. Development of a strategy for the implementation of automated business process management systems (technological and corporate).
2. Creation of a working group to organize the implementation of automated systems.
3. Restructuring of the existing ones and the formation on their basis of a new responsible subdivision at the enterprise for the maintenance of automated systems, the appointment of an owner of the process of ensuring the management and operation of automated systems.
4. Preparation of the hardware and software infrastructure of the enterprise for the implementation of automated systems. In the areas of automated dispatch

control of infrastructure and train traffic, automated control of technological and production processes (maintenance and repair), automation of diagnostics of the technical condition of infrastructure and rolling stock, automation of corporate processes and enterprise management processes, etc.

5. Step-by-step implementation of automated systems in the indicated areas in test mode, development of the “work without failures” resource.
6. Updating the existing and forming new normative and technical (legal) documentation regulating the work and operation of the automated systems being introduced.
7. Professional retraining (retraining) of dismissed personnel, training and advanced training of the personnel of the enterprise involved in the work and operation of the automated systems being introduced.
8. Phased commissioning of automated systems.

Stage 5. Adaptation of business processes:

1. Development of the concept of enterprise management as an interconnected set of business processes in real time.
2. Conducting an audit of the current business processes for duplication of the functionality of the company's divisions.
3. Carrying out the actualization of the existing business mechanisms for the maximum efficiency of the implementation of business processes.
4. Conducting an audit of existing business processes for the need and the possibility of automation (mathematical modeling).
5. Development of new business processes (tools) necessary for the formation of analytics and assessment of existing business processes, development of proposals for the optimization and improvement of business processes.
6. Redistribution of business process management.
7. Updating the normative and technical documentation regulating the implementation of business processes (functions and operations).
8. Professional development and training of the company's personnel.
9. Creation of a subdivision for the implementation and maintenance of the “e-Platform”.

Stage 6. Development of the “e-Platform”:

1. Development of a strategy for the phased implementation of the “e-Platform” using the management concept of process management of the organization, considering business processes as enterprise resources.
2. Modeling business processes of an enterprise and creating a unified automated platform for managing business processes in aggregate in real time.
3. Software and hardware preparation of the enterprise IT infrastructure and the implementation of the “e-Platform”.
4. Organization of training for personnel to acquire competencies in the digital economy.
5. MTBF of the e-Platform in test mode.

6. Updating and revising the mechanisms for the implementation and management of business processes.
7. Putting the "e-Platform" into commercial operation, the formation of analytics about the work of the system.

Automation of all business units of an enterprise can be achieved through the introduction of digital technologies that will optimize and improve the quality of the metro's activities, all business processes of which can be controlled on a specialized virtual platform in real time. Thus, the introduction of digital technologies into the business processes of the metro is an integral process in the modern world to improve the methods and methods of ensuring safety, comfort and reducing the time for transporting passengers. The study made it possible to identify the following effects of digitalization of metro business processes.

Social Effects:

- increasing the attractiveness of the metro as a public transport in terms of increasing comfort, mobility and the level of transport safety;
- increasing the attractiveness of work at the enterprise for young professionals.

Economic effects:

- reduction of overhead costs of the enterprise as a result of the introduction of equipment maintenance technology "on condition";
- reducing the need for space for the placement of telemechanics devices and hardware for automation, signaling, communications and security;
- optimization of the personnel of the enterprise of operational services and the release of areas (rest rooms for drivers, first-aid posts and other premises at the stations) by automating the business processes of the enterprise;
- reduction of power consumption for traction due to the automation of train traffic control;
- the use of resource-saving techniques to reduce the consumption of electricity for traction of trains.

Technological effects:

- reducing the time for coordinating the actions of the participants in the passenger transportation process due to the introduction of a unified information platform for the exchange of statistical and operational dispatch information;
- increasing the uniformity of train movement intervals in case of disruption of the normal operation of the line, reducing the time for restoring normal movement after the elimination of the violation;
- minimization of the influence of the "human" factor in the implementation of business processes of the enterprise through automation;
- minimization of the voice commands of the dispatcher and negotiations on train and dispatch communications;
- transition from planned maintenance of equipment to maintenance technology "on condition", reducing the time for maintenance and repairs due to the automation of diagnostic systems;

- timely diagnostics of the technical condition of infrastructure equipment and rolling stock and its systems, reducing the risk of rolling stock malfunctions during operation on the line;
- decrease in the number of violations of the timetable by a single train, as well as violations of the timetable in general;
- rejection of traffic light signaling as the main train traffic control system.

Conclusions

In the context of the digital race for leadership in digitalization, many countries are developing draft laws and state programs for the development of the digital economy, paying special attention to those industries that have reached the greatest readiness for digital transformation.

As the results showed, each of the European countries considered in the research, including the Russian experience of digitalization of the Moscow metropolitan, has achieved some success in one form or another of digitalization. However, at present, the key problem of digitalization of European and Russian metropolitan is the lack of a comprehensive digital transformation of this transport infrastructure object. In this regard, this study presents a reference model of digital transformation of the metropolitan, which, according to the authors, will allow in the short term and at the lowest cost to switch from an" analog "metro to a "digital" one.

In addition, as an innovative solution for automating metropolitan management, it is proposed to create a specialized e-Platform that will allow to monitor all metro business processes in real time, as well as to make decisions in emergency situations, which will increase the safety and comfort of passenger transportation.

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