UDC 681.5

Lapidus A.A.
Adamtsevich L.A.

Digital transformation of life cycle management processes for residential and engineering infrastructure facilities in complex development of territories

Modern projects of complex development of territories are characterized by technological, organizational and informational complexity. Technological challenges stem from the need to integrate heterogeneous systems while ensuring safety, reliability and sustainability of residential buildings and infrastructure facilities. Organizational complexity arises from the increasing number of participants in complex territory development projects, while information complexity results from exponentially growing volumes of heterogeneous data and requirements for rapid decision-making.
In this regard, the issue of ensuring end-to-end life cycle management of objects and consistency of decisions for the efficient use of resources is relevance.
The purpose of the research work is to analyze digital technologies for optimizing the life cycle management of residential buildings and infrastructure facilities in projects of complex development of territories.
As part of the presented study, an analysis of publications was conducted, according to keywords defined by the authors in the context of the topic under consideration. The international Scopus database served as the basis for forming specimens, according to keywords.
The analysis demonstrates that the introduction of digital twins, IoT, Big Data, BIM and machine learning allows achieving significant optimization in managing the life cycle of residential and engineering infrastructure facilities in projects of complex development of territories. Digital transformation fundamentally changes the approach to life cycle management, moving it from reactive to predictive and adaptive, which ensures the sustainability, reliability and safety of objects, resource savings and improved quality of the urban environment.
Keywords: *digital transformation, information modeling, digital twin, Internet of things, data analysis, artificial intelligence, life cycle of an object, sustainable development of territories*

Lapidus Azariy Abramovich,
Doctor of Technical Sciences, Professor, Head of the Department of Technologies and Organization of Construction Production; Moscow State University of Civil Engineering (National Research University) (MGSU); 26 Yaroslavskoe shosse, Moscow, 129337, Russian Federation; ID RSCI: 364784; lapidusaa@mgsu.ru

Adamtsevich Liubov Andreevna,
Candidate of Technical Sciences, Senior Lecturer Department of Information systems, technologies and automation in construction; Moscow State University of Civil Engineering (National Research University) (MGSU); 26 Yaroslavskoe shosse, Moscow, 129337, Russian Federation; ID RSCI: 2537-0511, Scopus Author ID: 57190342498; WoS Researcher ID: M-5000-2016, ORCID: 0000-0002-5843-0076; AdamtsevichLA@mgsu.ru

INTRODUCTION

Modern projects of complex development of territories are characterized by technological, organizational and informational complexity. Technological complexity is justified by the need to integrate heterogeneous systems, ensure the safety, reliability and sustainability of residential buildings and infrastructure facilities. Organizational complexity arises due to the increase in the number of participants in the implementation of projects of complex development of territories, and informational complexity arises from the exponential growth of heterogeneous information volumes, as well as requirements for the speed of decision-making.

In these conditions, the issue of ensuring end-to-end life cycle management becomes relevant and critically important to ensure the continuity of the project implementation process from the building design to its disposal, the consistency of decisions at different stages of the life cycle, as well as increasing the efficiency of resource use and ensuring sustainable development.

Thus, the purpose of this study is to analyze digital technologies to optimize the life cycle management of integrated territorial development projects.

MATERIALS AND METHODS

As part of the presented study, an analysis of publications was conducted, by keywords defined by the authors in the context of the topic under consideration. The basis for forming specimens, by keywords, was the international Scopus database. In this case, the first specimen was formed by all publications presented in the database, and the remaining ones for a period of 10 years from 2014 to 2024. The logic of forming specimens is described below.

At the first stage, to identify key digital technologies in managing the life cycle of residential and engineering infrastructure facilities in complex territorial development projects, specimen 1 was formed, by keywords, life cycle, construction, Industry 4.0. The cluster map of the relationship of keywords is shown in the figure (Fig. 1) below.

From the figure, we can conclude that there is a close connection between the life cycle of construction projects and sustainable development, Industry 4.0 technologies. A lot of attention is paid to the issues of building materials and technologies, considering their environmental friendliness.

At the same time, based on the initial analysis of publications, the following technologies are seen as key ones in the context of digital transformation of the processes of managing the life cycle of residential and engineering infrastructure in complex territorial development projects:

- BIM at all stages for creating, managing and analyzing digital information about buildings or infrastructure (specimen 2 — BIM + life cycle);

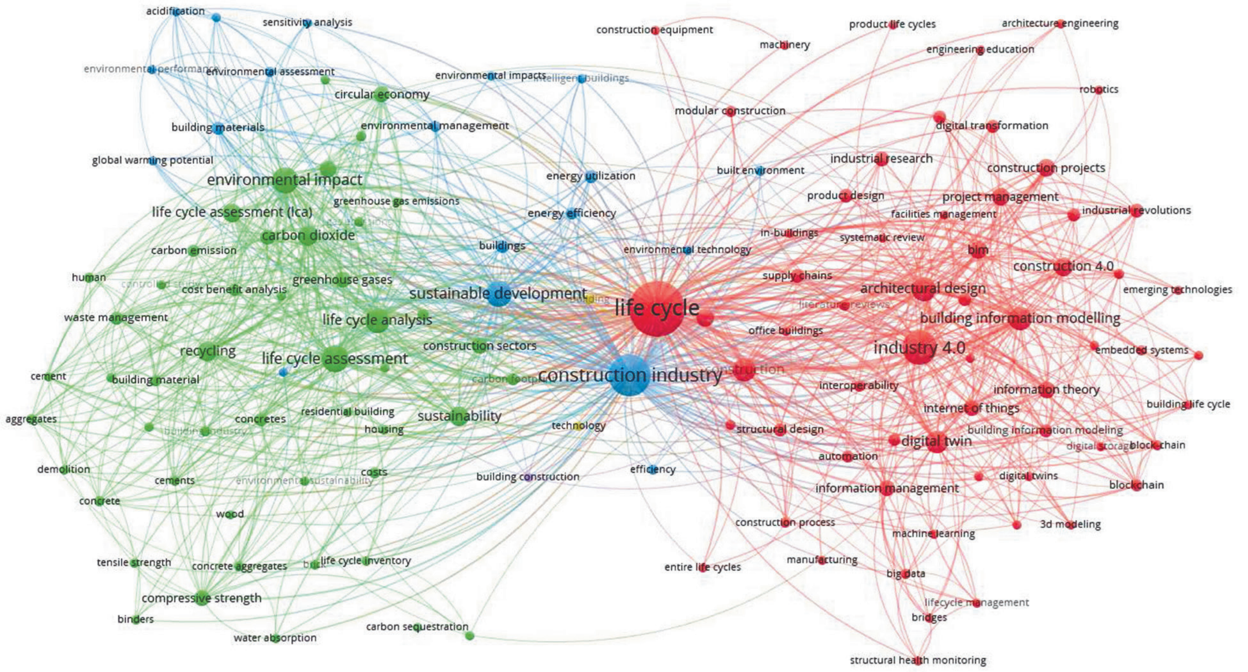


Fig. 1. Cluster map of the relationship of keywords of the formed specimen 1

- using digital twins to monitor and predict the state of an object (specimen 3 — digital twins + buildings);
- implementation of IoT and Big Data to manage the operational characteristics of an object (specimen 4 — IoT, Big Data + + construction);
- using Machine Learning to assess demand for infrastructure (specimen 5 — machine learning + buildings).

Thus, at the next stage of the study, specimens 2–5 were collected and analyzed, and the main aspects of the digital transformation of the life cycle management processes of construction projects were identified.

At the same time, within the framework of this study, the life cycle of a capital construction project, which includes residential and engineering infrastructure facilities, is defined as the stages regulated by CP 333.1325800.2020[1]. According to the document, the life cycle of a capital construction project is the following time periods:

1. Engineering surveys.
2. Architectural and construction design.
3. Construction.
4. Operation.
5. Reconstruction.
6. Major repairs.
7. Demolition.
8. Disposal.

The specified structure is presented in the Fig. 2 and is a methodological basis for the analysis of digital control technologies during the existence of the facility.

The choice of this classification of life cycle stages is justified by the fact that it includes all key stages from surveys to disposal, and CP 333.1325800.2020[1] is a current regulatory document in the Russian Federation, developed for the application of information modeling technologies.

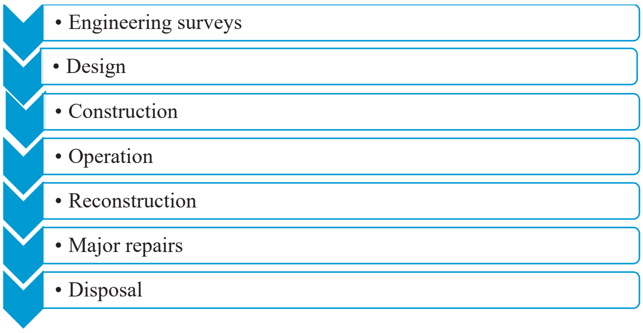


Fig. 2. Stages of the life cycle of a construction project

To conduct a system analysis of the possibility of optimizing the management of objects at all stages of their existence, considering digital tools, for each of these stages, management tasks, performance indicators for the use of digital technology, as well as key problems of digital transformation of processes will be identified.

RESULTS

Specimen Analysis 2 — BIM + life cycle

During the period under review, 2729 documents are displayed in the Scopus database (Fig. 3). The dynamics of changes in the number of publications by year are presented below, in addition, the trend line indicates a growing interest in life cycle management issues using information modeling technologies. At the same time, the leaders in publications are authors from China. The figure shows the top 15 countries.

The analysis of specimen 2 allowed us to identify the main areas of BIM application at the stages of the construction project life cycle (Table 1).

[1] CP 333.1325800.2020. Information modeling in construction. Rules for the formation of an information model of objects at various stages of the life cycle.

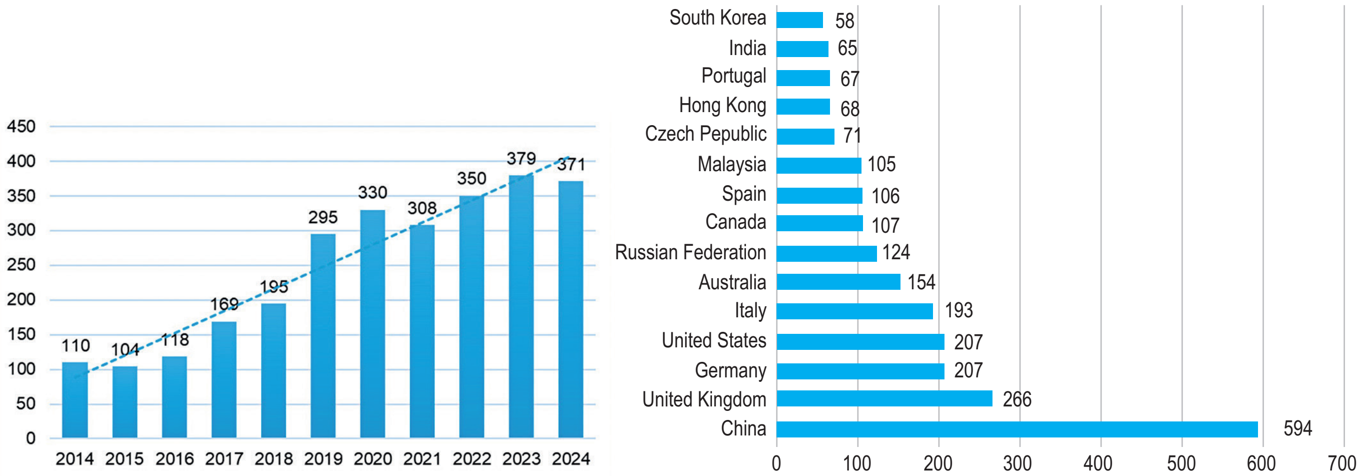


Fig. 3. Dynamics of changes in the number of publications for BIM + life cycle, top 15 countries by publications

Table 1. Application of BIM at the stages of the construction project life cycle

Life cycle stage	Application area	Examples	Links
Design	3D visualization, coordination	• creation of detailed digital models of residential buildings and infrastructure facilities; • automatic detection of collisions before construction begins	[1–4]
	Calculations and analysis of parameters	Optimization of structures considering loads and materials; calculation and analysis of energy efficiency, illumination, acoustics, etc.	
Construction	Logistics and planning	4D BIM for work schedule optimization; 5D BIM for budget control, etc.	[5]
	Quality control	Conducting a comparative analysis of the information model with the results of laser scanning to identify deviations	
Operation	Asset Management	• integrated use of BIM and CAFM (Computer-Aided Facility Management) systems; • access to communications via AR/VR for repairs	[6–8]
	Predictive maintenance	Monitoring the condition of structures through the integration of IoT sensors	
Disposal	Dismantling and recycling	• analysis of the information model for the selection of environmentally friendly waste disposal methods; • calculation of volumes of materials for recycling	[9,10]

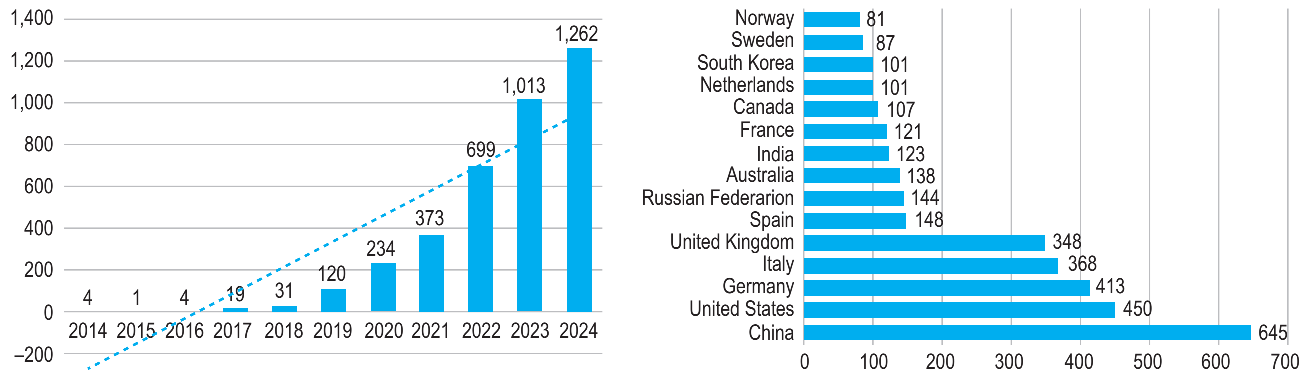


Fig. 4. Dynamics of changes in the number of publications for Digital Twins + Buildings, top 15 countries by publications

The results obtained indicate that the use of information modeling technologies is considered in combination with digital twins, machine learning methods, etc.

At the same time, the authors point out such positive aspects as a reduction in costs by up to 20 % due to the minimization of errors, as well as a reduction in time by 15–30 % due to the provision of clear coordination of contractors [8, 11, 12].

Specimen Analysis 3 — Digital Twins + Buildings

During the period under review, 3,375 documents are displayed in the Scopus database. The dynamics of changes in the number of publications by year are presented below, in addition, the trend line indicates a growing interest in the use of digital twins of buildings. At the same time, the leaders in publications are also authors from China (Fig. 4).

An analysis of publications revealed that digital twins, which are a copy of a physical object reflecting its condition and interaction with the environment, in the context of life cycle management of residential buildings and infrastructure facilities are used for:

- monitoring the condition of an object in real time, using IoT sensors measuring temperature, vibration, humidity, etc.;

Table 2. Integrating digital twins with other technologies

Technology	Appointment in the digital twin	Links
BIM	Base for 3D model and data	[13–17]
IoT	Providing information in real time	[18–19]
Big Data + AI	Analysis and forecasting of the development of the object's state	[20–21]
Cloud Computing	Storage and processing of data	[22–23]

Table 3. Areas of application of IoT and Big Data in construction

Direction	Application	Examples
Monitoring the state of the object in real time	Using IoT sensors to collect data	Vibration, deformation and corrosion sensors in load-bearing structures
	Application of IoT sensors in engineering systems	Sensors for measuring temperature, humidity, pressure in engineering systems
	Using Big Data for Analysis	Equipment wear forecast
Optimization of energy consumption	Adaptive control systems	Dynamic regulation of heating, lighting, air conditioning systems depending on weather conditions
Predictive maintenance	Failure Prediction Using Machine Learning Models	Analysis of temperature and noise in equipment to justify spot repairs based on sensor data
Security Management	Providing comprehensive monitoring of fire safety, access control	Smoke detectors and cameras with computer vision models for open fire analysis

- predicting emergency situations, wear and tears through intelligent data analysis using artificial intelligence;
- optimizing the operation of facilities by simulating various energy consumption scenarios, analyzing the occupancy of premises — offices, hospitals, shopping centers, resource distribution, etc.;
- justifying decisions on modernization before implementing changes through virtual verification of reconstruction, assessing economic efficiency.

At the same time, several works note that the synergistic effect of the introduction of digital twins is achieved only through integration with other technologies (Table 2).

In fact, digital twins make it possible to bridge the gap between the design and operation of facilities.

Specimen Analysis 4 — IoT, Big Data + construction

This specimen reflects only 197 publications, which is generally not much given the time interval under consideration. At the same time, an analysis of current publications has shown that the oint use of IoT and Big Data allows for the transfer of residential buildings and infrastructure facilities management to a predictive and adaptive level, minimizing costs and increasing their energy efficiency (Table 3) [20, 24–27].

Specimen Analysis 5 — Machine Learning + Buildings

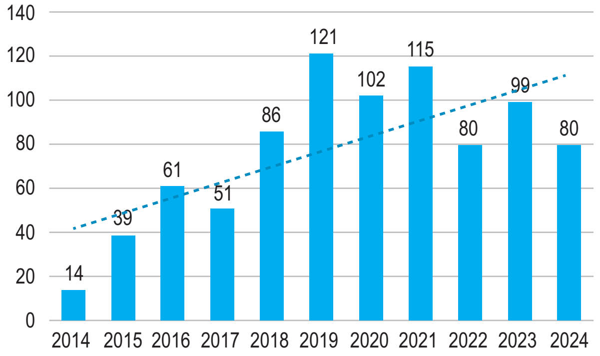
During the period under review, the Scopus database displays only 848 documents. The dynamics of changes in the number of publications by year are presented below, in addition, the trend line indicates an increase in interest in the issue of using technology under consideration. At the same time, the leaders in publications are authors from the United States (Fig. 5).

In this context, machine learning is used to assess the demand for housing, transport and social infrastructure in complex territorial development projects, which allows for optimized planning.

Based on historical census data, a machine learning model can predict population growth, migration, and therefore the need for housing. The model can segment the market by solving the clustering problem and identifying the types of housing in demand.

The load on transport infrastructure can be assessed by modeling traffic flows and planning new routes.

Algorithms can predict the congestion of roads and public transport considering the density of buildings and pendulum migration routes, and graph neural networks, by analyzing the points of



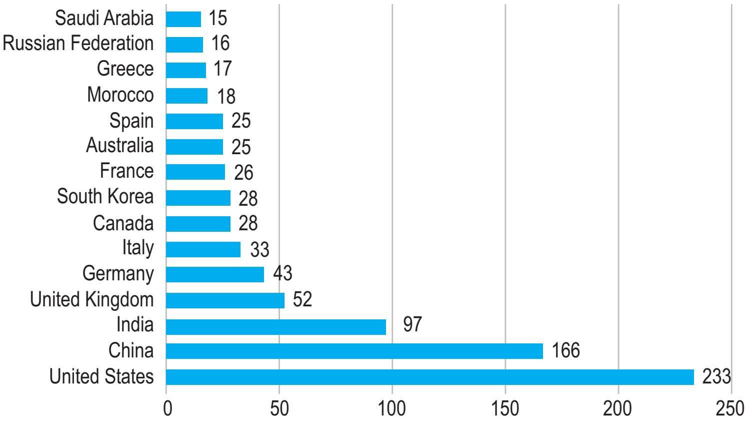


Fig. 5. Dynamics of changes in the number of publications for Machine Learning + Buildings, top 15 countries by publications

Table 4. Directions for optimizing lifecycle management processes for residential and engineering infrastructure facilities in the context of digital transformation

Direction	Technology	Result	Effect
Reducing construction and operating costs	BIM + digital twins	Minimizing design errors	Budget cuts upto 20 %
	IoT + predictive analytics	Reduce repair costs by predicting failures	Reduce operating costs by up to 35 % through smart maintenance
Reducing project implementation time	BIM	Optimization of logistics and budget	Reduction of construction time by up to 15 %
	Planning with Artificial Intelligence	Automatic budget allocation	
Increasing reliability and safety	Digital twins + IoT	Monitoring of deformations, corrosion, etc.	Increasing the service life of objects by 20–20 %
	Machine learning	Analysis of emergency situations	Reducing the risk of accidents by up to 40 %
Energy efficiency and environmental friendliness	Digital twins	Analysis of the applicability of green solutions	Conformity Analysis LEED/BREAM
	Algorithms based on artificial intelligence	Setting up energy consumption	Reduce energy costs by up to 25 %

attraction of the population, can determine the locations for the design of public transport stops.

In addition, regression models can consider the birth rate and age composition of the population, which will allow for a forecast of the population's need for social infrastructure — schools, hospitals.

CONCLUSIONS

The analysis conducted revealed that digital transformation of life cycle management processes for residential and engineering infrastructure facilities in complex territorial development projects through the introduction of digital twins, IoT, Big Data, BIM, and machine models will ensure optimization in the following areas (Table 4).

Digital transformation of life cycle management processes for residential and engineering infrastructure facilities in complex territorial development projects changes reactive life cycle management of facilities into predictive and adaptive management, ensuring sustainability, reliability and safety of facilities.

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Цифровая трансформация процессов управления жизненным циклом объектов жилой и инженерной инфраструктуры в проектах комплексного развития территорий

Современные проекты комплексного развития территорий характеризуются технологической, организационной и информационной сложностью. Технологические вызовы включают интеграцию разнородных систем и обеспечение устойчивости объектов, организационных — полную координацию участников проекта иинформационных — обработку значительных объемов данных в условиях необходимости оперативного принятия решений. В этойсвязи особую актуальность имеет вопрособеспечения сквозного управления жизненным циклом объектов и согласованности решений для эффективного использования ресурсов.

Целью исследования является анализ цифровых технологий для оптимизации управления жизненным циклом жилых зданий и объектов инфраструктуры в проектах комплексного развития территорий.

В рамках представленного исследования проведен анализ публикаций по ключевым словам, определенным авторами в контексте рассматриваемой темы. Базой формирования выборок по ключевым словам стала международная база Scopus.

Проведенный анализ демонстрирует, что внедрение цифровых двойников, IoT, BigData, BIM и машинного обучения позволяет достичь значительной оптимизации при управлении жизненным циклом объектов жилой и инженерной инфраструктуры в проектах комплексного развития территорий.

Цифровая трансформация принципиально меняет подход к управлению жизненным циклом, переводя его от реактивного к прогнозному и адаптивному, что обеспечивает устойчивость, надежность и безопасность объектов, экономию ресурсов и повышение качества городской среды.

Ключевые слова: *цифровая трансформация, информационное моделирование, цифровой двойник, интернет вещей, анализ данных, искусственный интеллект, жизненный цикл объекта, устойчивое развитие территорий*

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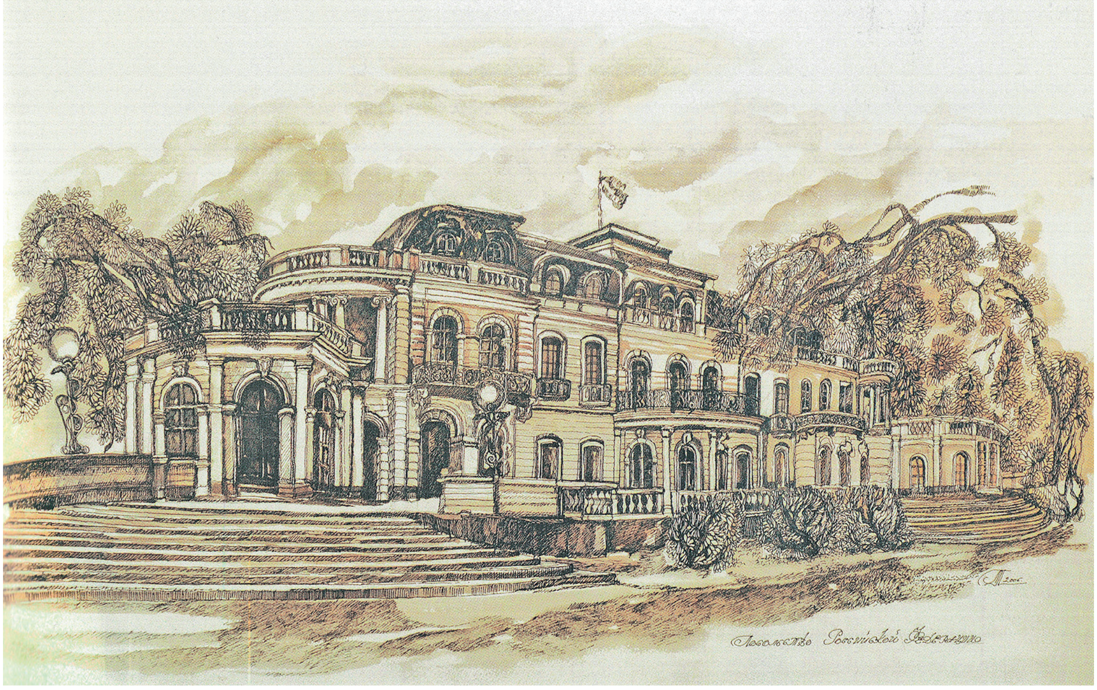
Об авторах: **Лапидус Азарий Абрамович** — доктор технических наук, профессор, заведующий кафедрой «Технологии и организация строительного производства»; **Национальный исследовательский Московский государственный строительный университет (НИУ МГСУ)**; 129337, г. Москва, Ярославское шоссе, д. 26; РИНЦ ID: 364784; lapidusaa@mgsu.ru;

Адамцевич Любовь Андреевна — канд. техн. наук, доцент кафедры ИСТАС; **Национальный исследовательский Московский государственный строительный университет (НИУ МГСУ)**; 129337, г. Москва, Ярославское шоссе, д. 26; РИНЦ ID: 2537-0511, Scopus AuthorID: 57190342498, WoS ResearcherID: M-5000-2016, ORCID: 0000-0002-5843-0076; AdamtsevichLA@mgsu.ru.

For citation: Lapidus A.A., Adamtsevich L.A.Digital transformation of life cycle management processes for residential and engineering infrastructure facilities in complex development of territories. *Real Estate: Economics, Management.* 2025; 2:6-12.

Для цитирования: *Лапидус А.А., Адамцевич Л.А.* Digital transformation of life cycle management processes for residential and engineering infrastructure facilities in complex development of territories // Недвижимость: экономика, управление. 2025. № 2. С. 6–12.



Прага. Посольство Российской Федерации в Чехии