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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

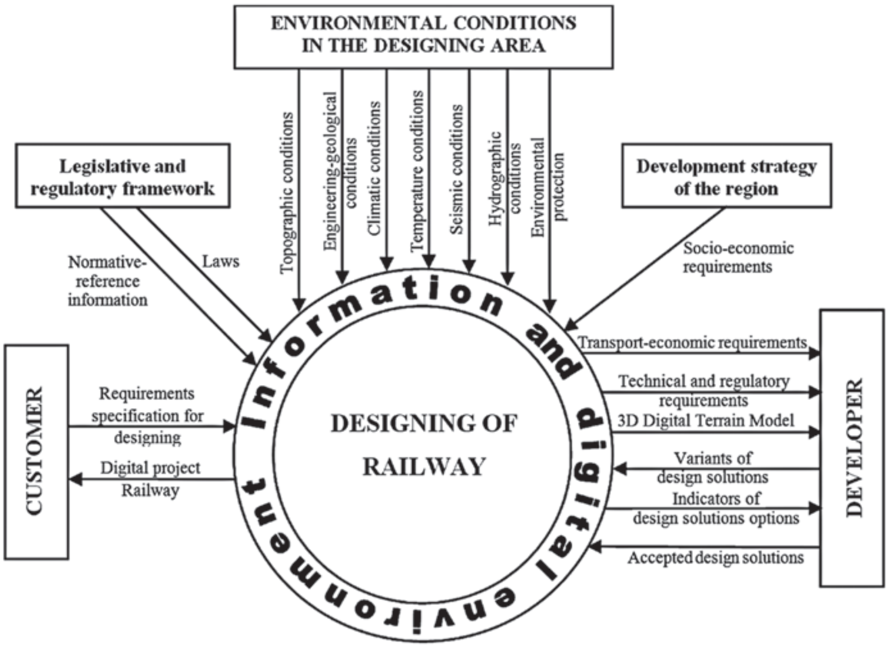

Fig. Context diagram

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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Bionotes

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