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DEVELOPMENT POTENTIAL OF CONSTRUCTION COMPANIES: TECHNICAL AND ECONOMIC ASPECTS

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Abstract

Introduction: The construction industry represents the priority area of the economy, which affects the quality of life of the population and other industries as well. Currently, many construction companies in Russia show low competitive ability (in 2016, their competitiveness index was lower than 400). The value of this index depends on the ability to adapt the internal organizational structure and applied technologies to the requirements of the market, i.e. on the innovative activity. At the present time, introduction of technical as well as organizational and economic innovations is complicated. This is due to the fact that most Russian companies do not focus on qualitative changes in the production structure and processes as well as in the management practices applied. Those factors result in low labor efficiency as unqualified workers are engaged, long lead time, etc. **Methods:** Scientific novelty lies in the development of methods for innovation potential assessment at a construction company, based on technical and economic indicators. The originality of the paper lies in the fact that the results of the authors' research on construction companies in Russia are used for analysis. **Results and discussion:** The present paper analyzes key factors of construction companies' development and its barriers. The paper aims at substantiating resources facilitating development of construction companies. The research data obtained allow for qualitative and quantitative assessment of the construction industry state in Russia.

Keywords

construction, competitive ability, potential, innovative development.

Introduction

Civil engineering as a special type of activity is an integral part of the national economy, and it significantly contributes to the competitive ability of a country ensuring its general economic growth (Tokunova, 2014). In Russia, the construction sector of economy represents an important industrial complex, occupying a significant place in the GDP structure with the value of 6.4% (2016–2017). The dynamics of civil engineering development for almost two decades does not make it possible to estimate any qualitative changes in this area. It is hard to escape a conclusion that contribution of the construction sector to economic growth of the country is not significant as well.

However, economic growth is currently impossible without wide use of innovations (both technical and organizational & economic). Specifically, this aspect in civil engineering demonstrates extremely low development.

Methodology

Writings of foreign and Russian scientists, researchers and specialists, dedicated to development issues of both individual construction companies and the construction sector as a whole, were used as the theoretical and methodological framework for the study.

Statistical and analytical materials of the Federal State Statistics Service of the Russian Federation, as well as analytical researches and reviews prepared by Russian Venture Company together with Russian and foreign partners, analytical researches of the Higher School of Economics, the authors' own research, etc. were also used in the study. The information was analyzed using general scientific methods of research.

Results

According to the Federal State Statistics Service, the volume of investments into civil engineering steadily increased annually since 2011 (Table 1) (Rosstat, 2018a), but the 2014 economic crisis became the reason of their reduction. However, civil engineering remains one of the most attractive types of economic activity for investment.

Table 1 Investments into fixed capital for "civil engineering" foreign-economic activity (in actual prices at the time)

Year	2011	2012	2013	2014	2015	2016	2017
Investments into fixed capital	336.8	348.6	438.1	469.3	401.2	443.8	266.5

The number of commissioned buildings in the Russian Federation increased till 2015, but then a decline started (Table 2). In 2017, this figure was 272.6 thous. and it dropped by 11% as compared to 2015 (Rosstat, 2018a).

Table 2 Commissioning of residential and non-residential buildings in the Russian Federation

Year	2012	2013	2014	2015	2016	2017
Commissioned buildings – total number, thous.	241.4	258.1	304.2	306.4	278.3	272.6
including:						
residential buildings	223.0	239.1	283.0	286.1	259.5	253.8
non-residential buildings	18.4	19.0	21.2	20.3	18.8	18.8
Overall construction volume – total number, mln m3	485.6	526.7	617.8	622.8	608.5	599.4
including:						
residential buildings	316.9	343.5	404.4	415.7	400.4	401.3
non-residential buildings	168.7	183.2	213.4	207.1	208.1	198.1
Overall building area – total, mln m2	110.4	117.8	138.6	139.4	135.8	137.3
including:						
residential buildings	82.0	87.1	104.4	106.2	103.4	104.6
non-residential buildings	28.4	30.7	34.2	33.2	32.4	32.7

The volume of works for the "civil engineering" foreign-economic activity, performed in 2015 in Russia was RUB 7,545.9 bln (Rosstat, 2018a), which is 98.6% as compared to the previous year (Table 3).

In 2000–2008, the volume increased annually, on average, by 12.4%. However, a dramatic drop happened in 2009: by 13.2% as compared to the previous year. The situation then returned to normal in 2010. Starting from 2014, there was a decline (by 2.3%), but the volume of works increased in 2017, and the drop was 1.4% only.

Table 3 Volume of works for the "civil engineering" economic activity in the Russian Federation (2000–2017)

Period	RUB bln in actual prices at the time	In percent (in comparable prices) as compared to the previous year	Period	RUB bln in actual prices at the time	In percent (in comparable prices) as compared to the previous year
2000	503.8	113.5	2009	3,998.3	86.8
2001	703.8	110.4	2010	4,454.1	105.0
2002	831.0	102.9	2011	5,140.3	105.1
2003	1,042.7	112.8	2012	5,714.1	102.5
2004	1,313.6	110.1	2013	6,019.5	100.1
2005	1,754.4	113.2	2014	6,125.2	97.7
2006	2,350.8	118.1	2015	7,010.4	96.1
2007	3,293.3	118.2	2016	7,204.2	97.8
2008	4,528.1	112.8	2017	7,545.9	98.6

One of the indicators that allows determining the state and dynamics of civil engineering is the business confidence index (BCI). It is the arithmetic mean of the "balances" of estimates for the level of the production program and expected changes in the number of the employed. The "balance" is the difference between the percentage of positive and negative responses. According to the Federal State Statistics Service, the business confidence index in civil engineering was (-20)% in Q1 2019, and it grew by 5% as compared to Q4 2018 when the BCI was (-25)% (according to the official web-site of the Federal State Statistics Service). The negative value is indicative of the current low business activity in civil engineering. Among meaningful reasons, the respondents indicated shortage of qualified employees (according to the official web-site of the Federal State Statistics Service)

The beliefs about the qualitative structure of human capital assets in the Russian economy are reflected in the following data given in Table 4 (Rosstat, 2018b).

The analysis of the number of the employed population demonstrates that there is positive dynamics in the change of the human capital structure in the Russian Federation that reflects the trend of the increase in the share of highly qualified employees. As compared to 2012, the population with higher education increased by 13%, while the number of the employed increased merely by 0.83%.

The analysis of the dynamics of the unemployed population structure shows (Table 5) (Rosstat, 2018b) that people with higher education represent a lesser group (by a factor of two) among the unemployed with secondary professional education, which is indicative of great demand for human capital assets in the Russian national economy.

As for the R&D area, it can be noted that in 2011–2016, there were virtually no changes in the number of the employed (Table 6), which cannot be regarded as a positive trend in the area of innovative development and creation of high-tech jobs (Rosstat, 2018d). Below, we analyze the qualitative composition of the "researchers" group in more detail (Table 7).

Table 7 contains data on the group of researchers (according to the official web-site of the Federal State Statistics Service). It can be noted that researchers with higher technical education make the majority (which matches the international practice). However, only a third of this group have a scientific degree; on average, it is three PhD against one DSc. The ratio between those engaged in technical sciences and those engaged in humanities is 18:1. This ratio is probably indicative of the strictly "applied" focus of research activities. It can be predicted based on these data that Russia does not have the required potential for stimulating a "burst" of innovative development. Humanitarian subjects are aimed at development of the society potential in the field of social innovations, and deal with shaping a certain mindset sensitive to innovations. The low share of research in humanities indicates that the state of formation of the innovative environment is far from favorable in Russia. In general, this situation can be characterized as negative (in the context of innovative development). Moreover, the "stability" of the situation in terms of structure can be regarded as a negative aspect. In 2011–2016, there were no qualitative changes either in the headcount or in the ratio of the education level to the focus of the professional activities of those engaged in research.

Table 4 Employed population by the education level

Year	2012	2013	2014	2015	2016	2017
the employed – total number (thous. people)	71,545	71,391	71,539	72,324	72,393	72,142
among them, with education:						
higher education	21,740	22,616	23,045	23,847	24,216	24,698
secondary professional education	32,703	31,634	32,104	32,521	32,624	32,359
secondary general education	14,236	14,446	13,745	13,322	13,107	12,534
basic general education	2,671	2,511	2,484	2,485	2,315	2,397
no basic general education	196	181	160	147	129	154

Table 5 Unemployed population by the education level

Year	2012	2013	2014	2015	2016	2017
the unemployed – total number (thous. people)	4,131	4,137	3,889	4,264	4,243	3,967
among them, with education:						
higher education	676	721	709	839	868	819
secondary professional education	1,638	1,608	1,551	1,744	1,716	1,590
secondary general education	1,355	1,376	1,223	1,257	1,266	1,155
basic general education	416	395	372	385	368	361
no basic general education	46	38	35	40	27	41

Table 6 Personnel engaged in R&D

Year	2011	2012	2013	2014	2015	2016
Russian Federation						
Personnel – total number (persons)	736,540	735,273	726,318	727,029	732,274	738,857
including:						
researchers	368,915	374,746	372,620	369,015	373,905	379,411
technicians	59,276	61,562	58,905	61,401	63,168	62,805
support staff	183,713	178,494	175,790	175,365	173,554	174,056
other personnel	124,636	120,471	119,003	121,248	121,647	122,585
Saint Petersburg						
Personnel – total number (persons)	79,813	81,000	80,660	78,773	78,727	79,076
including:						
researchers	43,555	44,676	45,503	43,932	43,317	42,956
technicians	5,549	5,001	4,528	5,063	4,852	5,104
support staff	17,376	17,416	17,993	17,372	17,773	18,149
other personnel	13,333	13,907	12,636	12,406	12,785	12,867

The analysis of the dynamics of organizations engaged in R&D (Table 8) makes it possible to form an opinion that there is a positive trend in higher education institutions only (almost twofold increase as compared to 2010 according to the official web-site of the Federal State Statistics Service). Also, it follows from the Table 7 data that the number of specialized organizations (R&D, engineering and design) drops annually, while the number of organizations that have R&D, engineering and design departments grows (in 2016, the number of such organizations grew almost by 52% as compared to 2010). On the one hand, this trend can be regarded as positive, because integration of science and education is evident. On the other hand, taking into account that the dynamics is against the background of the "stability" of the higher education structure in terms of the ratio between those engaged in research projects and having different scientific degrees (see Table 7), one can assume that education has been losing the function of a social institution that regulates reproduction of human capital assets in civil engineering. Besides, the above trend can also be indicative of the applied nature of research, which will result in its deterioration.

Table 7 Headcount of researchers by fields of science

Year	2011	2012	2013	2014	2015	2016
Russian Federation						
Researchers – total number (persons)	374,746	372,620	369,015	373,905	379,411	370,379
of which:						
engaged in technical sciences	226,492	225,118	225,082	226,682	231,809	225,038
engaged in humanities	11,828	12,631	11,740	12,565	12,891	12,328
Researchers with a scientific degree – total number	109,493	109,330	108,248	109,598	111,533	108,388
among them, with the following scientific degree:						
PhD	78,325	81,818	81,546	80,763	81,629	83,487
DSc	26,789	27,675	27,784	27,485	27,969	28,046

Table 8 Number of organizations engaged in R&D, by types of organizations in the Russian Federation

Year	2011	2012	2013	2014	2015	2016
Russian Federation						
Organizations – total number (pcs.)	3,682	3,566	3,605	3,604	4,175	4,032
including:						
R&D organizations	1,782	1,744	1,719	1,689	1,708	1,673
engineering organizations	364	338	331	317	322	304
design and surveying organizations	38	33	33	32	29	26
pilot plants	49	60	53	53	61	62
higher educational institutions	581	560	671	702	1,040	979
industrial organizations with R&D, engineering and design departments	280	274	266	275	371	363

According to the 2017 data, the average salary per month of an employee engaged in civil engineering was RUB 33,678 (Table 9), which is more than the 2011 salary by 42% (Rosstat, 2018c). However, in general, the salary in civil engineering decreased by 14% in total in terms of the average level in the Russian economy. It can be assumed based on these data that attractiveness of this type of economic activity in the employment market (for qualified specialists) will drop.

The average annual number of employees involved in civil engineering in 2017 (Table 10) was more than 5 mln persons and increased by 4% as compared to 2010 (Rosstat, 2018b).

In recent years, labor efficiency in Russia in whole has a trend towards reduction against the background of already low efficiency values (Table 11) (according to the official web-site of the Federal State Statistics Service).

Table 9 Average monthly nominal salary of employees

Year	2011	2012	2013	2014	2015	2016	2017
Total in the economy (RUB)	23,369	26,629	29,792	32,495	34,030	36,709	39,144
civil engineering	23,682	25,951	27,701	29,354	29,960	32,322	33,678

Table 10 Average annual number of employees engaged in civil engineering

Year	2011	2012	2013	2014	2015	2016	2017
the employed – total number (thous. people)	70,857	71,545	71,391	71,539	72,324	72,393	72,142
civil engineering	5,106	5,320	5,392	5,419	5,475	5,201	5,258

Table 11 Labor efficiency index in Russia in whole and in the civil engineering sector of the Russian Federation (in percent as compared to the previous year)

Year	In economy in whole	In the civil engineering sector
2010	103.2	99.6
2011	103.8	105.2
2012	103.2	101.6
2013	101.8	99.8
2014	100.7	98.4
2015	98.9	100.8
2016	100.2	102.3
2017	101.9	97.6

Also, the share of migrant workers in civil engineering who compensate a significant part of labor resources deficit in the sector should be taken into account. As of the end of 2012, the share of migrant workers with an effective work permit who were engaged in the economy of Saint Petersburg and the Leningrad Region was 12.9% and 3.0% of the total number of all migrant workers in Russia with a work permit, respectively (Shcherbakova, 2013). Besides, only 96,000 migrants working in the civil engineering sector in the Saint Petersburg agglomeration out of 296,000 people had a work permit in 2011 (Vedomosti, 2017). In H1 2013, according to the Directorate of the Federal Migration Service, only 100,000 people out of almost 800,000 migrants (with only 352 persons being highly qualified specialists) received a work permit (Sadkova, 2013). As of the beginning of 2016, there were 400,000–450,000 migrant workers in the city (Saint Petersburg Vedomosti, 2016). According to Petrostat, for this period in 2017, the number of migrants (including those who migrated from other Russian regions and non-CIS countries) grew by 15% (Vedomosti, 2017). However, only 132,000 migrants received a work permit in H1 2017.

The following conclusions can be made on the basis of the analysis of the civil engineering sector state:
- poor qualification of workers engaged in civil engineering, and, as a consequence, low labor efficiency, which is in many aspects caused by obsolete management and production technologies (Faltinsky, Tokunova, 2018);
- low level of the innovations used, which does not ensure economic growth of the construction sector;
- no comprehensive approach to management of the organization's resource portfolio that would take into account rapid development factors.

Thus, intensification of civil engineering production requires initiation and implementation of innovative processes, structural reorganization for creation and development of the most innovative activity both on a scale of the organization, sector and on a scale of the state as a whole. Integrated programs for planning and development of innovative activities, that can provide coordination of works performed, shall serve as a basis for activities on reorganization of the civil engineering sector.

We believe that to develop an integrated method for assessment of the resource portfolio and innovation environment of a construction organization, it is reasonable to use as a basis the assessment method proposed by Goran Roos. According to Roos, there is an individual set of resources in every organization, and these sets of resources affect the results of activities. However, since there is no clarity concerning the reasons for success or failure, it is hard to establish the contribution of an individual resource to the success without taking into account the interdependence with other resources.

Management of material and immaterial resources of an organization is aimed at the growth of the organization's market value (creation of the organization's value). The essence of the immaterial resources' management technique lies in transformation of the resource portfolio and search for its most preferable configuration. It is therefore necessary to use not only business processes' management tools, but also the organization's resource

portfolio when elaborating a technique to create and manage development of the organization's innovation environment.

Civil engineering as a type of activity has a significant influence both on the organizational structure and the structure of the resource portfolio of a construction organization. As opposed to industrial organizations, in the civil engineering sector, the design and development stage (usually connected with innovative activity as the greater share of R&D in the industry occurs during this stage) is externalized and represents an independent professional activity. Therefore, various organizations performing design, construction, implementation and operation can be engaged in implementation of a single civil engineering project for fulfillment of its individual stages.

Thus, an integrated method of resource portfolio estimation in civil engineering should be structured on the basis of the project life cycle stages. They are described in more detail below.

During the pre-investment phase, the organization faces the need to solve non-standard, unique tasks, to make managerial decisions c and within limited timeframe. Therefore, the main focus should be on solving a unique problem of a client. The efficiency of organization activity lies not only in the solution (a result (innovative concept)) but also in individuals who suggested the given solution and in the way it was conceived (innovation environment). Operations performed during this stage are consistent and cycled. Capability for permanent re-configuration of the existing resource portfolio for resolving non-standard problems is required, thus, the organization acts as per the "economy of scope" logics. Organization's activity is estimated based on its efficiency (it does not mean that it is efficient; it means that the most attention is paid to efficiency), consequently, main efforts of the management are aimed at reduction of coordination costs that define organization's activity efficiency. Thus, the main resource of a construction organization at the pre-investment stage is human assets in the form of skills, knowledge, expertise and competences of personnel involved in the production process. Therefore, the education and qualification level of personnel (estimation of the human assets' level) significantly identifies the volume of the civil engineering organization innovative potential.

During the investment phase of the life cycle of a construction project, two scenarios are implemented: preparing design and estimate documentation (DED) and performing construction works. Conclusion of an agreement with a General Contractor, works acceptance and acquisition of a permit for civil engineering activities are performed during the documentation preparation stage. The production logics is similar to the previous (pre-investment) stage, thus, resource transformation technologies represent the most important management tools.

The leading resource at these two stages is human assets facilitating the accomplishment of organization's goals and increasing the organization's activity efficiency level.

An agreement with a General Contractor for fulfillment of construction and installation works with subsequent works acceptance is concluded at the construction stage. Operations performed at this stage are consistent and linear. Efficiency of organization's activity at the construction stage is defined by standardization and formalization of production processes, repetition (economy through training) and mass production (economy through scale). Commitment to economic efficiency is naturally created in the logics of the construction stage (the main criterion for estimation of production activity that is in constant focus of managerial attention). Therefore, main efforts are aimed to reduce transaction costs (related to efficiency). The concept of decrease in labor intensity of production processes shall be applied in accordance with the logics of this stage, and, therefore, innovative development shall be arranged at the expense of implementation of the corresponding technologies that minimize labor of workers and replace them by robots and equipment. For example, more than 550 various automation and robotization systems for civil engineering works and unattended civil engineering technologies were developed and implemented in Japan within the last two decades (Vin'kov et al., 2007).

A facility is commissioned at the post-investment stage of the civil engineering project life cycle.

In summary, it can be said that the specifics of civil engineering activity has a direct impact on innovative development of civil engineering organizations. In the context of development and implementation of an innovative idea, there is a pronounced difference in the structure and the size of the resource portfolio. Based on the above, we determine the weights of resources in the resource portfolio structure (Figs. 1, 2).

All resources 100%				
Immaterial resources 75%			Traditional economic resources 25%	
Organizational resources (25%)	Human resources (30%)	Relationship resources (20%)	Monetary resources (15%)	Material resources (10%)
Public image (25%)	Competences (18%)	Subcontractors (10%)	Cash (35%)	Raw materials (18%)
Business processes (40%)	Attitudes (11%): - behavior (28%) - motivation (40%) - traits (32%)	Suppliers (10%)	Investments (45%): - attraction of investors / lending activities (49%) - proceeds from owners/shareholders (51%)	Land (28%)
Intellectual property (35%): - patents (31%) - regulations (18%) - projects (26%) - quality standards (25%)	Personal relations (10%)	Clients (13%)	Guarantees (20%)	Structures (30%)
	Knowledge (18%)	Customers (12%)	Subsidies (51%)	Equipment (24%)
	Skills (18%)	Owners/shareholders (12%)	Public funding (49%)	
	Intellectual flexibility (25%): - innovations (45%) - problem statement (25%) - problem solution (30%)	Competitors (11%)		
		Financial institutions (12%)		
		State (15%)		
		Local communities (5%)		

Fig. 1. Determining the weights for the resource portfolio of a construction organization during life cycle stages of a construction project (pre-investment, preparation of design and estimate documentation)

All resources 100%				
Immaterial resources 75%			Traditional economic resources 25%	
Organizational resources (25%)	Human resources (30%)	Relationship resources (20%)	Monetary resources (15%)	Material resources (10%)
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		Financial institutions (12%)		
		State (15%)		
		Local communities (5%)		

Fig. 2. Determining the weights for the resource portfolio of a construction organization during life cycle stages of a construction project (investment, construction)

Conclusion

In the course of this study, the analysis of the construction sector was conducted, and the extremely low level of innovative activity in construction organizations was identified (among other things, due to the conservative nature of civil engineering as a type of economic activity). However, at the current stage of the society development, it is innovations that are the driving force behind the economic growth both at the level of the organization and the economy as a whole. The nature and areas of use of the innovative component radically differ from the implementation stage of a construction project. In the context of the work done, the difference in the structure and size of the resource portfolio with the weight for each resource was given. This approach should be included in the integrated method of assessment of the resource portfolio and innovative environment of a construction organization.

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SPECIFICS OF UTILITIES DESIGN USING INFORMATION MODELING

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Abstract

Introduction: Building information modeling is currently intensively used in the construction industry, helping to automate design processes starting from the development of drawings and ending with the BOM preparation. BIM technologies are useful in the design and development of documentation for various design sections (heating, ventilation, outdoor gas and water supply systems) as they make it possible to avoid project mistakes. **Purpose of the study:** The paper is aimed to review the specifics of developing information models for utilities and analyze issues arising in the course of design. **Methods:** In the present paper, methods of theoretical research are used. **Results:** The authors studied mechanisms of information modeling for utilities, identified issues arising during design documentation development, and suggested methods of solving staffing problems.

Keywords: information modeling, BIM platform, utilities, technologies, innovations.

Introduction

BIM (Building Information Modeling) is a process of information creation and management at all stages of the facility's life cycle. Steps taken by various countries give a boost to the rapid development of BIM technologies. In some countries, implementation of BIM standards is state-regulated, while in others it is advisory rather than mandatory. However, in all cases, those are detailed documents intended to improve the economic efficiency of investment construction projects. In the last few years, some new approved standards were introduced into the Russian regulatory framework: State Standard GOST R 57310-2016 "Building information models. Information delivery manual. Methodology and format" (ISO 29481-1:2010); State Standard GOST R 57563-2017 "Buildings and structures information modeling. General principles for the development of buildings and constructucions information modelling standards" (ISO/TS 12911:2012); State Standard GOST R 57311-2016 "Building information modelling. Requirements for operation and maintenance documentation for built asset"; State Standard GOST R 57309-2016 "Guidelines for knowledge libraries and object libraries" (ISO 16354:2013); State Standard GOST R ISO 12006-2-2017 "Building. Model of construction works data organization. Part 2. Basis of information classification" (ISO 12006-2:2015); State Standard GOST R 12006-3-2017 "Building. Model of construction works data organization. Part 3. Basis for object-oriented information interchange" (ISO 12006-3:2007); State Standard GOST R ИСО 22263-2017 "Model of construction works data organization. Framework for management of design information" (ISO 22263:2008); Regulations SP 301.1325800.2017 "Building information modeling. Rules for the organization of work by the production and technical departments"; Regulations

SP 333.1325800.2017 "Building information modeling. Modeling guidelines for various project life cycle stages"; Regulations SP 328.1325800.2017 "Building information modeling. Components. Guidelines and requirements"; Regulations SP 331.1325800.2017 "Building information modeling. Modeling guidelines and requirements of exchange data between building information models and application package models", etc. A review of national and international scientific literature revealed a large number of publications dedicated to BIM implementation efficiency (Blanco and Chen, 2014; Kannan and Santhi, 2014; Kristianto et al., 2014; Reizgevičius et al., 2013; Ziganshin and Ziganshin, 2018, and others). Russian literature has enough sources describing work with BIM tools as well as challenges associated with the implementation of BIM in Russia (Boykov et al., 2015; Chervova and Lepeshkina, 2018; Lyalin et al., 2017; MGSU report, 2016; Pykhtin et al., 2017; Sharmanov et al., 2015; Ziganshin and Ziganshin, 2018, and others). One of the main advantages of information modeling over computer-aided design (CAD) is a possibility to track changes in adjacent design sections, exchange data, and introduce changes in real time (Boykov et al., 2015; Chervova and Lepeshkina, 2018; Lyalin et al., 2017; Pykhtin et al., 2017; and others).

Nowadays, most employers in the construction industry expect graduates to have basic skills in using software tools and working with BIM elements.

Subject, tasks and methods

According to some experts (Chervova and Lepeshkina, 2018; MGSU report, 2016; Astafieva et al., 2017), among the main reasons hindering wide BIM implementation in Russia, the following shall be mentioned: significant initial expenses for necessary equipment and software

(most construction companies are not ready to spend 200,000–1,000,000 rubles per employee); shortage of qualified specialists having relevant competencies and experience in the BIM field; a need to restructure the company when stepping away from traditional design methods and implementing the teamwork principle in a particular information environment (which is often accompanied by some decrease in labor efficiency due to training to work under new conditions, longer design time, and lack of significant economic effects when starting to use new technologies); a need to adapt foreign software supporting the BIM process to the requirements of the domestic regulatory framework, etc. Despite some difficulties, the following advantages of new technologies are beyond question: an increase in the speed of design documentation development and improvement of its quality; detailed estimation of construction and installation works; a possibility to reduce errors (e.g. detect interferences between structural units and utilities, which is impossible in case of 2D drawings); improvement of project quality in general; a capacity to construct and operate a facility in a virtual space.

A study performed by Autodesk (Autodesk. Building Information Modeling in industrial and civil engineering) presents the following results of using BIM: cost reduction by 10%; a decrease in project delivery time by 7–15%; estimate accuracy improvement by 3%; a decrease in construction estimate development time by 80%; reduction in construction rejects and waste by 30%. Presenting results of its studies, the Ministry of Construction Industry, Housing and Utilities Sector (Minstroy) of the Russian Federation argues that BIM implementation improves a number of performance indicators. It reduces construction and operation costs by 30%; errors in design documentation – by up to 40%; project delivery time – by up to 50%; time spent for model checking – by a factor of 6; the percentage of error upon budget planning – by a factor of 4; coordination and approval time – up to 90%; construction period – by 10%; design period – by 20–50%.

The following methods of using BIM are the most common:

- 3D visualization. Using this function, it is possible to create a 3D model of a facility (building, structure), perform a visual analysis of a facility, print a mock-up on a 3D printer, test a structure, and edit such a model.
- Clustered data storage and integrated data management. All data on a designed facility are within the same group of linked drawings (within the same program). Therefore, a change in one of the parameters automatically leads to changes in other elements, thus reducing the error probability.

Currently, 3D modeling is a standard tool in the design of boiler houses, utilities, linear facilities, including gas pipelines (Figure 1). A geo-referenced 3D model of an actual plant, based on its 2D master plan, involving all its utilities, improves visualization of data on the plant and its performance.
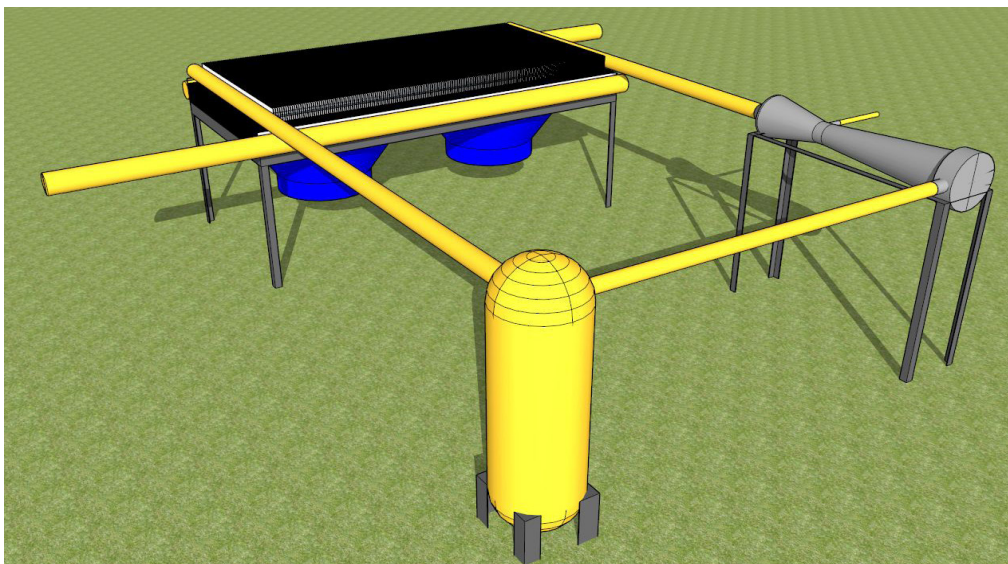

Figure 1. 3D model of a heat exchanger

For automated design and work with utilities (heat, gas and water supply; sewerage; storm drainage), several software programs are proposed, e.g. ENGCAD by ZWSOFT with BIM application in the ZWCAD Professional, AutoCAD, BricsCAD environment (see https://www.zwsoft.ru/): With regard to each type of utilities, the program solves the following tasks: utility summary plan formation, detailed design of water-conduit wells, development of a table of wells, generation of initial data for a facility specification, determination of borehole location, development of volume tables showing cut and fill volumes. It is also possible to choose from various

templates of tables under the profile. The utility route location is performed in the ZWCAD, AutoCAD (or any other graphic editor) environment, based on an available underlay drawing (Figure 2).

Using a special function, a designer can mark restricted areas (a table of minimum distances is provided

in the program). During utility route location, a user shall only specify wells and bending points; the program automatically detects intersections with existing and designed utilities (Figure 3).
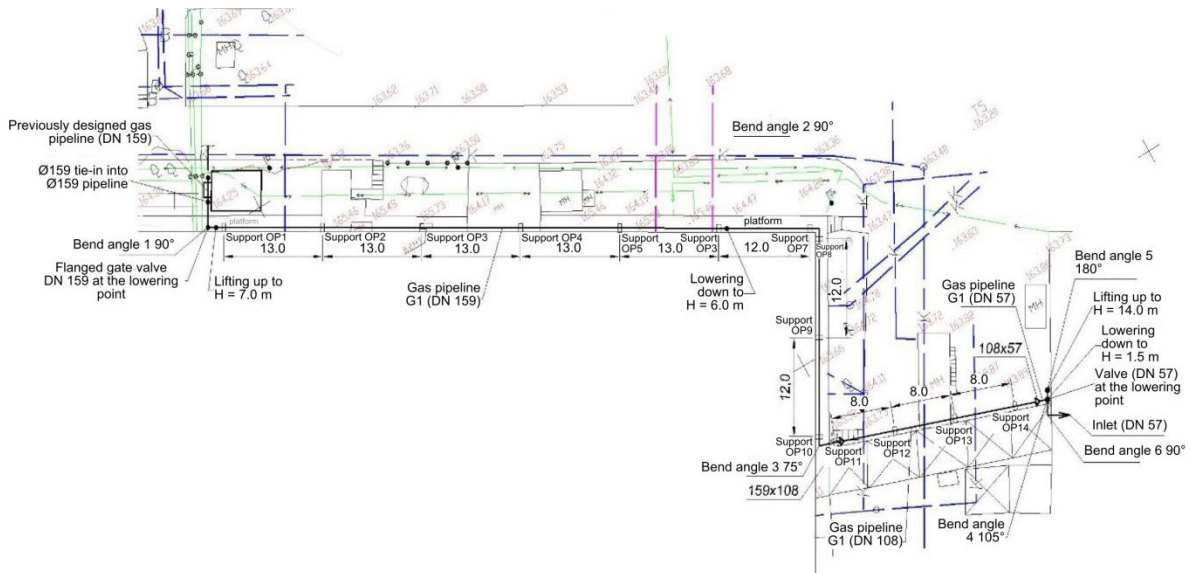

Figure 2. Gas pipeline route being designed
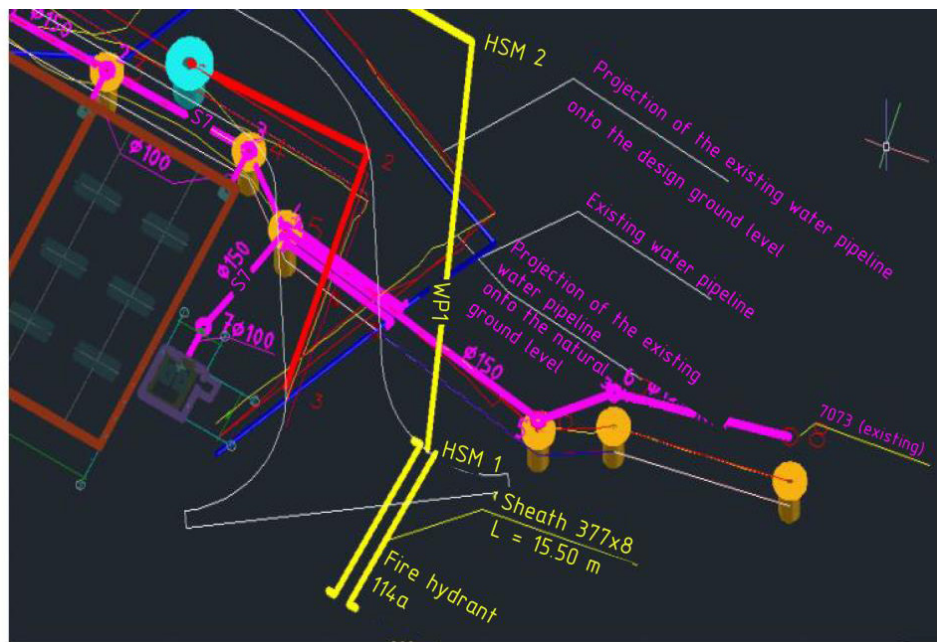
Figure 3. Axonometric diagram of underground utilities being designed (see https://www.zwsoft.ru/eng)

To perform 3D design of intrasite, intradepartmental and interdepartmental pipeline systems, including process pipelines, steam and hot water pipelines, water and gas supply systems, heating systems, and sewerage, it is convenient to use Model Studio CS Pipelines software suite developed by CSoft Development. With its help, it is possible to perform all necessary checks to detect collisions, intersections, and violations of minimum

distances. Besides, the collision check system provides a possibility to analyze distances between pipelines and their elements, equipment, structures, cables, and other objects.

Results and discussion

One of the most essential components of proper switching to BIM technologies is training of skilled

specialists able to work with information models, which requires mandatory training of students in the use of BIM-oriented programs. In most educational institutions, the training process is still limited to 2D design. In most cases, to write term papers and graduation theses, students use Autodesk family programs (AutoCAD, ArchiCAD). However, they do not allow for full BIM introduction in the educational process at all design stages. Meanwhile, Autodesk family programs offering integrated solutions to implement BIM technologies (e.g. Autodesk Revit, Autodesk Design Review, Autodesk BIM 360; Autodesk Revit MEP to manage utility infrastructure projects; Autodesk Navisworks to develop "Technology and Organization of Construction and Installation Works" design sections, etc.) can be used in the educational process.

Specialists emphasize that it is necessary to create an educational environment close to the professional one, develop teamwork skills in students, teach them how to master new computer tools and adapt promptly to shifts and changes.

The interest of students in education, development of a professional mindset, gaining of initial practical experience is an important condition of their successful adaptation to future professional activities. To ensure such adaptation to the fullest extent possible, on-the-job training and research activities are required. Training of students majoring in civil engineering shall be based on the wide use of information technologies in the educational process, mastering of CAD systems and 3D models of various technical objects.

Let us provide several examples of implementing practice-oriented assignments within the framework of basic training of students majoring in civil engineering. Students are offered to perform not only obligatory assignments in 2D (e.g. design of a construction site, development of a building plan and section views, preparation of drawings with the design of utilities, structural

units) but also creative assignments implying independent work and use of innovative design technologies.

Creative work on an assignment consists of the following stages:

1. Stage 1 – analysis of initial data.
2. Stage 2 – 3D modeling of an object.
3. Stage 3 – execution of design documentation and preparation to project presentation:
   – project visualization;
   – generation of an associate drawing with structural elements;
   – 3D mockup printing.
4. Stage 4 (final stage) – presentation of the project and its submission for critical review (e.g. at annual competitions of scientific and technical creativity of youth).

Projects can be developed individually or in a team.

For instance, in the course of their research, students at the Department of Heat and Gas Supply, Ventilation, Water Supply, and Applied Fluid and Gas Dynamics of the Yuri Gagarin State Technical University of Saratov designed a laboratory installation to study hydraulic modes of gas supply systems (Izotova and Fominykh, 2017). For a comprehensive study of gas pipeline operation, it is necessary to measure pressure and, based on those measurements, construct pressure maps (a piezometric graph). Using those maps, it is easy to determine areas with the maximum differential pressure and areas with pipe clogging.

The project concept was as follows:
– to develop an appearance model of a gas distribution pipeline;
– to make it possible to model gas consumption by various users in case of changes in demand in separate areas;
– to engage students (including school students) in processes of simulation modeling.

A diagram and a 3D model of the installation, a laboratory bench photo are presented in Figures 4–7.
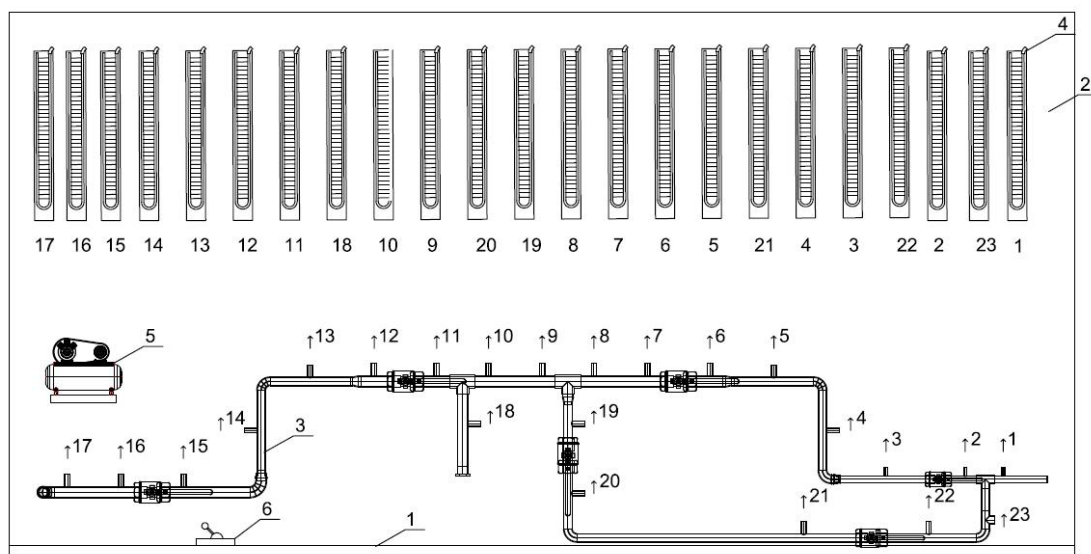

Figure 4. Diagram of the experimental installation

A low-pressure gas supply system is assembled on bench 1 (Figure 4). Gas supply system 3, which consists of bends, reducers, and valves, is fixed to wall 2. To measure pressures in characteristic points, liquid pressure gauges connected to pressure taps with flexible tubing are fixed to the bench. To feed air to the gas pipeline, compressor 5 is used, which is connected to a tank through a pressure control valve. Start and shutdown of the installation are performed with switch 6.

With the help of that installation, it is possible to obtain dependences of gas velocity on pressure and determine the gas flow rate.
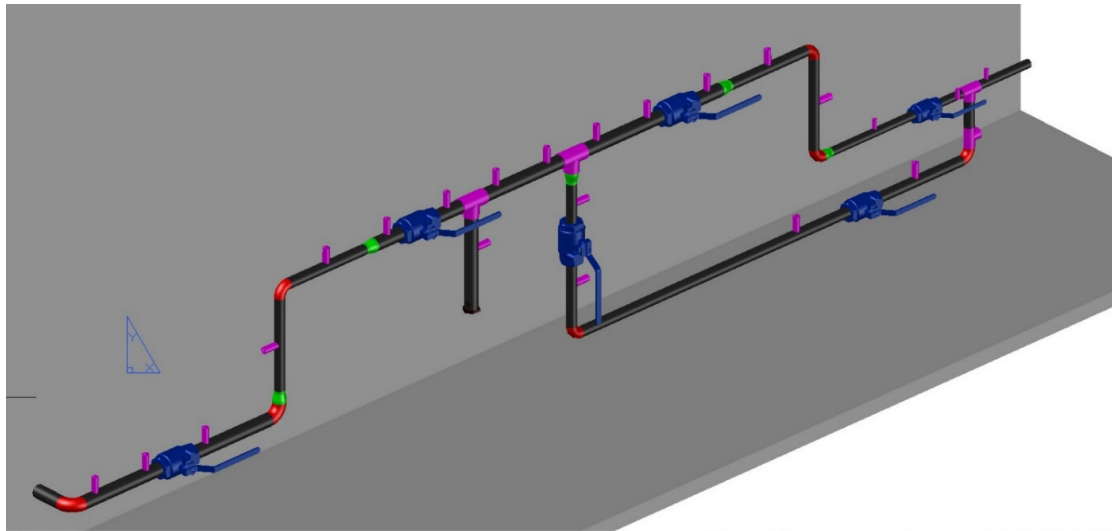
Figure 5. 3D model of a section of the experimental installation
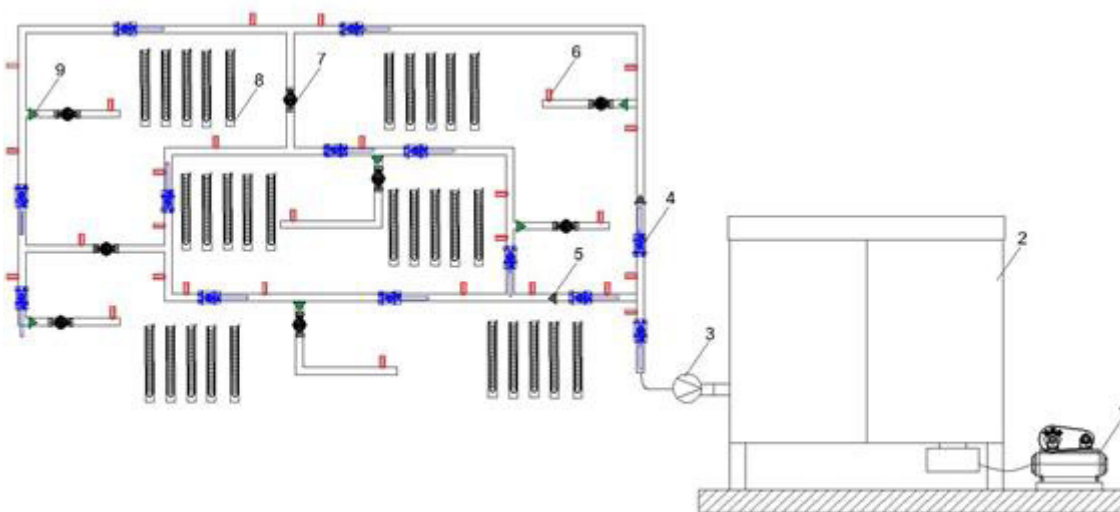
Figure 6. Diagram of the laboratory bench: 1 – compressor unit; 2 – reducing unit; 3 – gas meter; 4 – ball valve; 5 – reducer DN 32/35; 6 – outlet for a pressure gauge; 7 – globe valve; 8 – U-shaped pressure gauge; 9 – reducer DN 25/20

Final results of the project are as follows:

– manufacturing of an experimental prototype simulating a low-pressure gas supply system in a populated area;

– analysis of medium pumping intensity effect on the pipe friction and local drag coefficients;

– clear demonstration of pressure changes upon various system configurations.

In their practical activities, engineers and technicians need to address issues related to the design of gas distribution and gas use equipment, studies of their operation. Experimental data allow for additional analytical studies. Using the installation proposed, it is possible to study the behavior of gas traveling in a pipeline. It is also possible to create such conditions, under which students will be able to apply their knowledge in the field of structural design.

Figure 7. Laboratory bench assembly

Conclusions

– Information modeling technologies have changed the process of facility design, construction and operation since design is performed in a 3D space with account for the time factor (4D), i.e. an object-oriented digital model includes the object itself, the process of its construction and further disposal.

– Information modeling improves profitability, reduces time and money expenditures.

– A BIM model contains information on the facility designed, which can be used at all stages of its life cycle, and that is very important.

– When utilities are designed using BIM platforms, it is necessary to perform regular checks to detect intersections and, thus, prevent collisions.

– Using BIM principles, it is possible to visualize, design, detail, and manufacture utilities of complex configuration.

– A BIM model is needed to be shared among all construction participants.

– Due to BIM technologies, it is possible to reduce the number of errors in design documentation, thus optimizing the construction process.

– The use of Green BIM (symbiosis of green construction and information modeling) results in the minimization of expenses for energy resources and utilities.

– BIM technologies allow companies to control the quality of initial design documentation and estimates, organize safe construction works, optimize logistics, and make quality control easier.

– It is necessary to improve knowledge of BIM technologies in both professional designers and future specialists.

– Implementation of BIM training in the educational process requires teachers to improve their skills and take training courses in specialized organizations.

– Purchasing of the necessary software (offering an integrated solution to work with BIM projects at all design stages, and determine construction duration and cost) by universities on special terms will allow such institutions to establish a system of professional training with the use of innovative technologies with account for the life cycle of a construction facility.

– To train sought-after technical experts, it is required to create a realistic educational

environment.

– Students welcome with interest improved educational technologies, which promote professional competencies, demanded by the Federal State Educational Standard, in accordance with real needs in the construction industry.

– It is required to mobilize potential employers around the issue of implementing BIM technologies in the educational process and training specialists based on the modular competency-based approach.

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ОСОБЕННОСТИ ПРОЕКТИРОВАНИЯ ИНЖЕНЕРНЫХ СИСТЕМ С ИСПОЛЬЗОВАНИЕМ ИНФОРМАЦИОННОГО МОДЕЛИРОВАНИЯ

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Аннотация
Введение. На сегодняшний день технологии информационного моделирования зданий и сооружений активно применяются в строительной индустрии и помогают автоматизировать процессы проектирования, начиная с процесса формирования чертежей и заканчивая составлением спецификаций. Большую помощь использование BIM технологий оказывает при проектировании и оформлении разделов инженерных систем (отопления, вентиляции, наружных сетей газо-, водоснабжения), поскольку позволяют избежать возникновения различных проектных ошибок. Цель исследования: Цель данной статьи – обзор особенностей создания информационной модели инженерных систем и анализ возникающих проблем в процессе проектирования. Методы: использованы методы теоретического исследования, Результаты: изучены механизмы информационного моделирования инженерных систем, отмечены проблемы, возникающие в процессе разработки проектной документации, предложены пути решения кадровых проблем.

Ключевые слова
Информационное моделирование, BIM-платформа, инженерные системы, технологии, инновации

MODELING FRACTURE OF REINFORCED CONCRETE STRUCTURES UNDER IMPACT

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Abstract

Introduction: The papers presents results of an integrated experimental and numerical study on behavior of reinforced-concrete beams under impulse loading. The beams under study had three layers. The upper and lower layers were of fiber-reinforced concrete with a carbon fiber volume fraction of 0.2%. The middle layer was of concrete with metal reinforcement. **Methods:** Experimental studies were performed using a pile driver. A falling weight of 450 kg was dropped on a beam from a height of 0.7 m. The authors performed numerical studies based on the finite element method in a full dynamic 3D setting, using the proprietary EFES software suite considering structure fragmentation, formation of contact and free surfaces. **Results:** In numerical modeling, the reinforcement mesh was clearly defined. The authors studied changes over time in the stress-strain state, and fracture of reinforced-concrete beams under short-term impact loading. They developed a calculation algorithm and procedure that made it possible to analyze and predict behavior of actual structures in a full dynamic 3D setting. They also proposed a model of concrete and fiber-reinforced concrete behavior, considering anisotropy, bimodularity with regard to strength characteristics, plastic properties, and relations between strength and strain rate / pressure. Fracture dynamics in concrete beams reinforced with metal bars was studied. Good agreement of the results with the experimental data was observed.

Keywords

Model, fracture, strain, stress, concrete, fiber-reinforced concrete.

Introduction

Describing behavior of solid bodies during their high-speed interaction is one of the most complex problems in mechanics of deformable solids. A system of equations describing dynamic behavior of deformable solids does not have an analytical solution, and it is not always appropriate to use simplified engineering approaches, especially when wave processes have a defining role. In that case, simplifying hypotheses can distort the actual state of things. Therefore, deformation and fracture of solids under impact and impulse loading are studied using mainly experimental and numerical methods.

Experiments show that final fracture of structures under impact loading is caused by a combination of mechanisms. However, they do not allow us to evaluate contribution of those fracture mechanisms at different stages of the process. After the final fracture, it is not always possible to identify fractures that occurred at the initial stages of impact interaction. Thus, mathematical modeling plays an essential role. In structure behavior analysis, mathematical modeling has some advantages over experiments: e.g. it is possible to obtain data on stresses, shock wave processes, transient processes, as well as on material and structure fracture at any specific time. A computational experiment cannot replace a physical experiment, but it can complement it. Computer development significantly

extended the scope of numerical modeling application. Among the main tasks of mathematical modeling are the following: development of adequate models for behavior of materials and structures, accurately describing crack formation and fracture processes under impact and impulse loading; development of numerical methods for structural analysis that make it possible to consider actual loads taken by structures. Therefore, it is very important to perform numerical studies on behavior of concrete structures of various applications. Their practical significance lies in the fact that numerical modeling allows us to predict behavior and fracture pattern of materials and structures under dynamic loading.

Lately, non-metallic carbon-fiber or glass-fiber composite reinforcement (which is significantly anisotropic) has been used for concrete strengthening. Developing a model for behavior of materials with anisotropy under static loading is a complex and labor-intensive task. They differ from isotropic materials in a complicated internal structure depending on fiber orientation in the material, different strength characteristics along different axes, number of elastic constants (up to 21 in anisotropic materials, while only 3 in isotropic materials). Orientation of fibers relative to the loading direction, and the stress pattern significantly affect the fracture pattern in anisotropic

materials. Under certain conditions, in different directions, fracture can be both plastic and brittle. Moreover, upon fracture of anisotropic materials (in contrast with isotropic materials), it is necessary to take into account the impact of hydrostatic pressure. Despite distinctive features, which shall be considered, anisotropic materials have a major advantage – they allow for creation of materials to be used in pre-determined conditions.

These days, anisotropic materials are widely used but their properties – especially under dynamic loading – are not sufficiently studied. Both in Russia and abroad, anisotropic materials are mainly studied in terms of static loading, and solutions are based on approximations of the theory of thin shells. What is more, they are studied both experimentally and numerically. In anisotropic materials, wave phenomena significantly affect crack formation and fracture processes, but modern engineering methods based on simplified approaches cannot demonstrate their evolution under dynamic loading. In the present paper, the authors analyze fracture of a laminated reinforced-concrete beam. The upper and lower layers of the beam are of fiber-reinforced concrete, the middle layer is of concrete with a reinforcement mesh.

The authors perform numerical modeling based on the finite element method (Johnson, 1977; Anderson et al., 1994; Johnson, 1977) in a dynamic 3D setting, using a proprietary high-performance algorithm and software suite (Radchenko et al., 2014) implementing an algorithm of mesh generation for complex geometric objects.

Basic equations of the mathematical model

A general system of continuum mechanics equations in an arbitrary system of coordinates($i = 1,2,3$)consists of the following equations (Sedov, 1976; Radchenko et al., 2015; Buzyurkin et al., 2015):

– mass conservation equation

$$\frac{\partial \rho}{\partial t} + \rho \nabla_i \upsilon^i = 0;$$

(1)

– motion equation

$$\rho a^k = \nabla_i \sigma^{ik} + F^k,$$

(2)

where $a^k = \frac{\partial \upsilon^k}{\partial t} + \upsilon^i \nabla_i \upsilon^k$, $\nabla_i \sigma^{ik} = \sigma_{,i}^{ik} + \Gamma_{im}^k \sigma^{im} + \Gamma_{im}^m \sigma^{ik}$;

– energy equation

$$\frac{dE}{dt} = \frac{1}{\rho} \sigma^{ij} e_{ij}.$$

(3)

Here,F^k– mass force vector components; Γ_{ij}^k– Christoffel symbols; σ^{ij}– contravariant components of the symmetric stress tensor; E – specific internal energy; ρ– medium density; υ^i– velocity vector components; e_{ij}– components of the symmetric strain rate tensor:

$$e_{ij} = \frac{1}{2}\left(\nabla_i \upsilon_j + \nabla_j \upsilon_i\right).$$

(4)

Behavior of metal and concrete was described by an elastic-plastic model. The stress tensor was represented as the sum of deviatoric S^{ki} and spherical P components:

$$\sigma^{ij} = -Pg^{ij} + S^{ij}$$

where g^{ij}– metric tensor.

Pressure was calculated using the Mie–Grüneisen equation as a function of specific internal energy E and density ρ:

$$P = \sum_{n=1}^{3} K_n \left(\frac{V}{V_0} - 1\right)^n \left[1 - K_0 \left(\frac{V}{V_0} - 1\right)\bigg/2\right] + K_0 \rho E$$

(5)

where K_0, K_1, K_2, K_3– material constants, V_0– initial specific volume, V– current specific volume.

Assuming that the principle of least work of true stresses with respect to plastic incremental strains is true for the continuum, we can represent the relation between strain rate tensor and stress deviator components as follows:

$$2G\left(e_{ij} - \frac{1}{3}e_{kk}\delta_{ij}\right) = \frac{DS^{ij}}{Dt} + \lambda S^{ij} , \ (\lambda \geq 0)$$

(6)

Here, time derivatives of stress tensor components, considering medium element rotation, are taken according to the Jaumann's formulation:

$$\frac{DS^{ij}}{Dt} = \frac{dS^{ij}}{dt} - S^{ik}\omega_{jk} - S^{jk}\omega_{ik}$$

where, $\omega_{ij} = \left(\nabla_i \upsilon_j - \nabla_j \upsilon_i\right)\big/2$, G – shear modulus.

The material behaves in an elastic manner ($\lambda = 0$) if the von Mises condition is met:

$$S^{ij} S_{ij} \leq \frac{2}{3}\sigma_d^2$$

(7)

and in a plastic manner ($\lambda > 0$) if it is not met. Here, σ^d– dynamic yield stress that, in the general case, can be the strain rate, pressure and temperature function. For concrete, a dependence of yield stress on pressure was considered (Belov et al., 2008):

$$\sigma_d = \sigma_s + \frac{11.398P}{13.9 + 0.82P}$$

(8)

If condition (7) is violated, then to find stress deviator components, a procedure of reducing to the yield circle is applied. For those purposes,S^{ij} components are multiplied by the normalizing factor, which is equivalent to description of medium behavior in the plastic range by equations of the Prandtl–Reuss theory.

The limiting value of plastic strain intensity is taken as a local criterion of shear fracture in steel reinforcement:

$$e_u = \frac{\sqrt{2}}{3}\sqrt{3T_2 - T_1^2}$$

where T_1, T_2– the first and second invariants of the strain tensor.

To describe concrete fracture, the authors use the Hoffman criterion (Hoffman, 1967; Tsai and Wu, 1971) that considers differences in ultimate tensile and compressive strength, anisotropy of strength properties:

$$C_1\left(\sigma_{22}-\sigma_{33}\right)^2+C_2\left(\sigma_{33}-\sigma_{11}\right)^2+C_3\left(\sigma_{11}-\sigma_{22}\right)^2+$$
$$+C_4\sigma_{11}+C_5\sigma_{22}+C_6\sigma_{33}+C_7\sigma_{12}^2+C_8\sigma_{23}^2+C_9\sigma_{31}^2\le1$$

(9)

where C_i is determined as follows:

$$C_1=[(\,Y_tY_c)^{-1}+(\,Z_tZ_c)^{-1}-(\,X_tX_c)^{-1}]/2$$
$$C_2=[(\,X_tX_c)^{-1}+(\,Z_tZ_c)^{-1}-(\,Y_tY_c)^{-1}]/2$$
$$C_3=[(\,X_tX_c)^{-1}+(\,Y_tY_c)^{-1}-(\,Z_tZ_c)^{-1}]/2$$
$$C_4=(\,X_t^{-1}-X_c^{-1})\ ;\ C_7=S_{yz}^{-2}$$
$$C_5=(\,Y_t^{-1}-Y_c^{-1})\ ;\ C_8=S_{zx}^{-2}$$
$$C_6=(\,Z_t^{-1}-Z_c^{-1})\ ;\ C_9=S_{xy}^{-2}$$

where X_t, X_c, Y_t, Y_c ,Z_t ,Z_c– ultimate strength along X, Y, Z axes under tension and compression, respectively, and S_{XY} ,S_{YZ} ,S_{zx} – ultimate shear strength along the corresponding axes. In case of an isotropic material X_t= Y_t=Z_t=R_t, X_c=Y_c=Z_c=R_c.
S_{XY}=S_{YZ}=S_{zx}=R_{SH}

It is believed that concrete fracture under intensive dynamic loading occurs as follows (Radchenko and Radchenko, 2015):

- if strength criterion (9) is violated under compression ($e_{KK}\le0$), then the further behavior of the material is described by the hydrodynamic model $\sigma_{ij}=-P$;

- if criterion (9) is violated under tension ($e_{KK}>0$), then the material is considered to be completely fractured and stress tensor components are taken to be equal to zero.According to experimental results, dynamic loading leads to improvement of concrete strength characteristics. It should be noted that the dependence of the ultimate tensile strength on the strain rate and the dependence of the ultimate compressive strength on the strain rate are different. The ratio between the static and dynamic ultimate strength can be represented by a dynamic response factor: K_d = R_d /R_s where R_d – dynamic strength, R_s – static strength.

Based on experimental data (International Atomic Energy Agency, 2015), approximation dependences for dynamic response factors of concrete under compression (10) and tension (11) were plotted. The corresponding dependence curves of K_d versus the strain rate (in s^{-1}) are given in Figure 1, where curve 1 describes a dependence of the dynamic response factor under tension, and curve 2 – under compression.

$$K_{dt}=0.00158333e^5+0.0252855e^4+0.15255e^3+0.47898e^2+$$
$$+1.01959e+2.36037$$

(10)

$$K_{dc}=0.0008832308e^5+0.0110547e^4+0.0447734e^3+0.0475887e^2+$$
$$+0.0184316e+1.20895$$

(11)

To find the ultimate shear strength of concrete, ratio (Belov et al., 2008) $R_{sh}=0.55\sqrt{R_cR_t}$ is used, where R_c – compressive strength, R_t – tensile strength. The materials had the following basic characteristics: concrete: ρ=2,450 kg/m³, Poisson's ratio ν=0.2, R_t=1.75 MPa, R_c = 22 MPa, G=10.8 MPa, σ_s=7.7 MPa; fiber-reinforced concrete: ρ=2,450 kg/m³, Poisson's ratio ν=0.2, R_t=3.4 MPa, compressive strength R_c = 41 MPa, G=17.1 MPa, σ_s= 7.7 MPa; steel: ρ=7,850 kg/m3, Poisson's ratio ν=0.3, G=78.5 MPa, σ_d = 390 MPa.
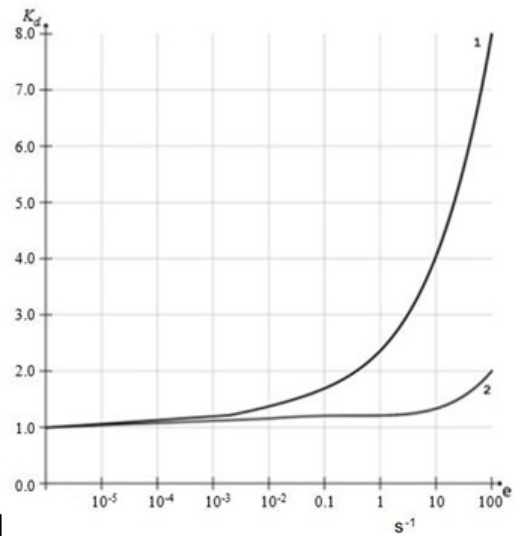

Figure 1. Dependence of steel strengthening on the strain rate

Discussion

In order to determine the stress-strain state, crack formation and fracture processes, the authors conducted studies on behavior of three-layer fiber-reinforced concrete beams under dynamic loading. The beams under study had three layers in a cross section: the upper and lower layers were of fiber-reinforced concrete with concrete in the middle. The experimental studies were performed using a pile driver imposing short-term dynamic loading.

The test specimens had a length of 2.2 m, distance between the centers of bearing – 2 m, cross-section dimensions – 0.22 x 0.15 m. Each test specimen had three layers in a cross section: the upper and lower layers were 20 mm thick and had carbon-fiber reinforcement, and the middle layer of concrete was 110 mm and had metal reinforcement. The carbon fiber volume fraction in the upper and lower layers was 0.2%.

In the middle layer, 8Ø10 A400 reinforcement was placed. It was supported by wire (Ø4 B500) stirrups. The fiber-reinforced concrete layers were reinforced with a tied mesh (Ø4 B500 wire, mesh spacing – 66 mm).

To measure the load and deflection of the test specimens, a system of primary transducers of measurement data was used.

The value of dynamic load under short-term impact was determined using a dynamometer gauge. To

determine specimen displacements, linear displacement transducers were used. Accelerations were measured using accelerometers.

To determine concrete and fiber-reinforced concrete deformations, resistive strain gauges (PKB-20 and PKB-50 (constantan alloy, paper base)) were placed on the surface of the test beams.

Reaction at the supports was measured using dynamometers. A falling weight of 450 kg was dropped on the beams from a height of 0.7 m with the help of a bomb-dropper.

In the course of the studies, the following was established: beam fracture occurs along the section, which is orthogonal to the longitudinal axis, with crack formation in the area of pure bending (Figure 2). The ultimate load resulting in concrete element fracture Fud was equal to 120 kN.

In mathematical modeling, contact action of the falling weight was replaced by an impulse load determined experimentally (Figure 3).

Numerical modeling was performed with clear defining of reinforcement, i.e. contact interaction between concrete and metal reinforcement was considered. Formation of contact and free surfaces in concrete and fiber-reinforced concrete upon crack formation and fragmentation was taken into account as well. Concrete and fiber-reinforced concrete behavior is described by equations (1)–(11) with strength criterion (9).

Behavior of the steel reinforcement mesh was described by the elastic-plastic model (6), (7). A structural design and reinforcement details were specified in accordance with the experimental design (Figure 4). The structure was divided into finite elements – tetrahedra. The total number of finite elements in calculations amounted to 1.8×10^7.
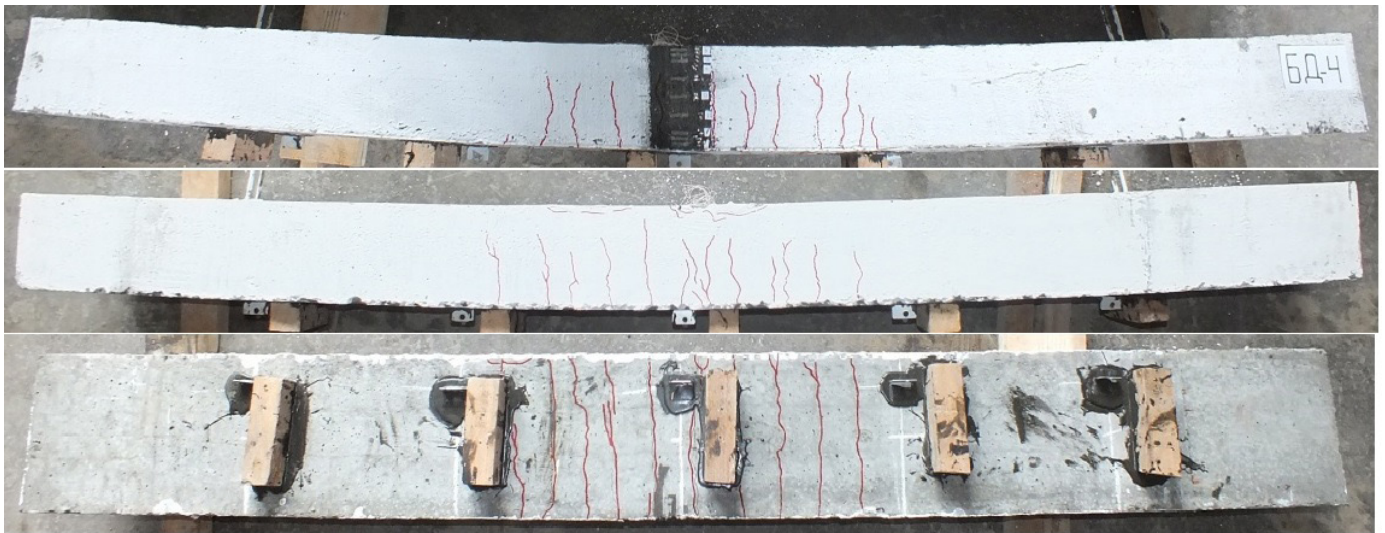

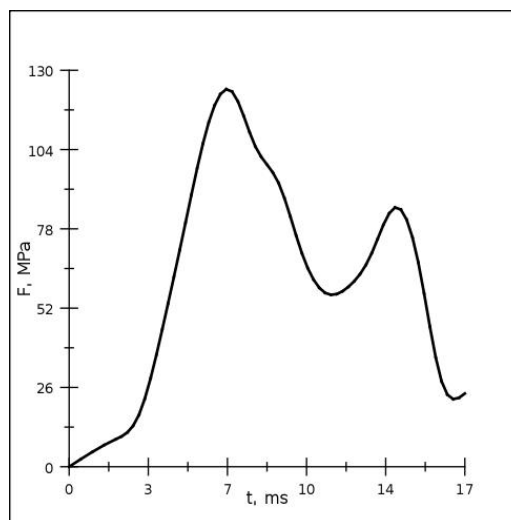Figure 2. Concrete beams after loading during the experimental study

Figure 3. Load dependence on time

To implement the structural design and evaluate the influence of reinforcement on the material fracture pattern, numerical studies on impact fracture of a laminated beam without a reinforcement layer were conducted.

Figures 5 and 6 show results of the numerical studies on a three-layer beam without reinforcement (a) and with reinforcement (b) under impact loading at different periods of time. It is clear that patterns of crack formation and fracture in beams with reinforcement and without it differ significantly. In the beam without reinforcement, main cracks generate on the back surface under the area of load application. Those cracks lead to beam fragmentation into three pieces (Figure 6a). In the beam with reinforcement, cracks propagate along the entire specimen and its total destruction is less. Maximum stresses in the beam are observed in the areas adjacent to metal reinforcement. Concrete fracture is caused by occurring fracture tensile and shear stresses in the areas of contact between concrete and the reinforcement mesh. That results in crack formation and further stress relaxation in concrete that was not fractured.
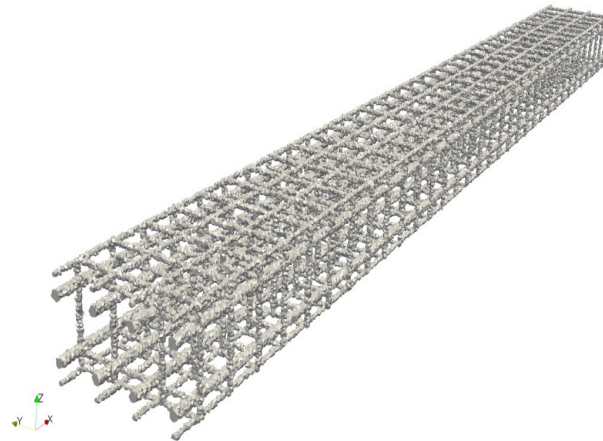
Figure 4. Structural design of beam reinforcement

Figure 7 shows comparison of experimental (solid curve) and numerical (dashed curve) changes over time in displacement of back surface points in a reinforced-concrete beam. Divergence was 12%. Agreement with the experimental data is satisfactory.
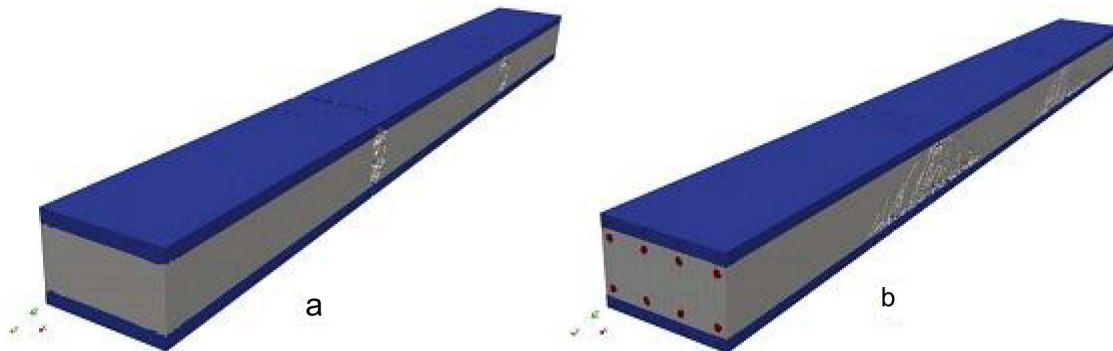

Figure 5. Computational configurations of a three-layer beam without reinforcement (a) and with reinforcement (b) (t = 3 ms)
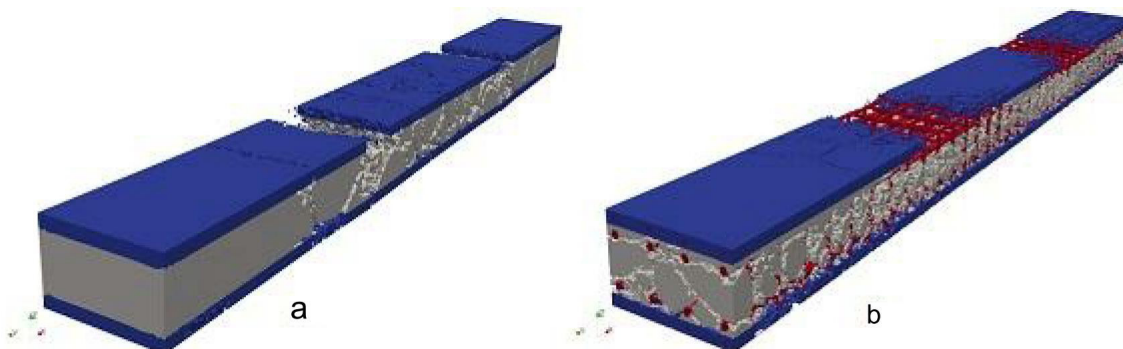

Figure 6. Computational configurations of a three-layer beam without reinforcement (a) and with reinforcement (b) (t = 6 ms)
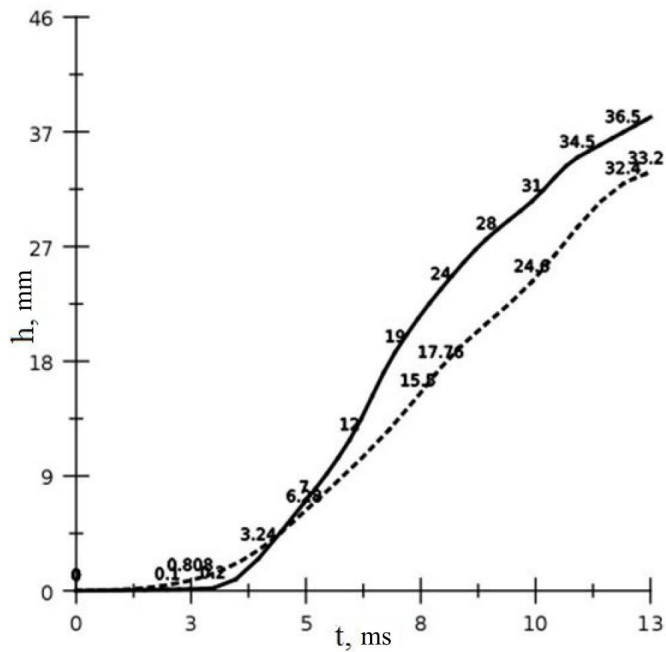
Figure 7. Displacement of points on the beam back surface over time

Conclusions

As a result of the conducted experimental and numerical studies, the following conclusions can be made:

1. The model of concrete and fiber-reinforced concrete behavior, considering bimodularity with regard to strength characteristics, plastic properties, and relations between strength and strain rate, was suggested.

2. The developed calculation algorithm and procedure make it possible to analyze and predict behavior of actual structures in a full dynamic 3D setting with account for material fracture and structure fragmentation, formation of contact and free surfaces.

3. Fracture dynamics in concrete beams reinforced with metal bars was studied. Good agreement of the results with the experimental data was observed.

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МОДЕЛИРОВАНИЕ РАЗРУШЕНИЯ АРМИРОВАННЫХ БЕТОННЫХ КОНСТРУКЦИЙ ПРИ УДАРЕ

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Аннотация

Введение: В работе представлены результаты комплексного экспериментального и численного исследования поведения железобетонных балок при импульсных нагрузках. Балка состояла из трех слоев: материал верхнего и нижнего слоя – фибробетон, с объемной долей углеродной фибры 0.2%. Материал среднего слоя – бетон с металлической арматурой. **Методы:** Экспериментальные исследования проводились на копровой установке. Груз весом 450 кг сбрасывался на балку с высоты 0.7 м. Численные исследования проводились методом конечных элементов в полной трехмерной динамической постановке с использованием в авторского программного комплекса EFES, учитывающий фрагментацию конструкций, образование новых контактных и свободных поверхностей. **Результаты:** Арматурная сетка при численном моделировании выделяется явным образом. Исследовано изменение во времени напряженно-деформированного состояния и разрушение железобетонных балок при кратковременных ударных нагрузках. Разработан алгоритм и методика расчета позволяющие исследовать и прогнозировать поведение реальных конструкции в полной трехмерной динамической постановке Предложена модель поведения бетона и фибробетона, учитывающая анизотропию, разномодульность прочностных свойств, пластические свойства и зависимость прочности от скорости деформации и давления. Исследована динамика разрушения бетонных балок, армированных металлическими стержнями. Проведено сравнение с экспериментальными данными, показавшее хорошее согласование результатов.

Ключевые слова: модель, разрушение, деформация, напряжение, бетон, фибробетон.

REVIT DYNAMO: DESIGNING OBJECTS OF COMPLEX FORMS. TOOLKIT AND PROCESS AUTOMATION FEATURES

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Abstract

Introduction: Design of objects of complex forms (non-linear, round, dynamic in their geometry) currently causes difficulties in the construction of geometry and documentation of various project stages. In this paper, proven approaches towards modeling objects of complex forms are presented. Here, the authors mean forms that represent planes bent in three directions, which shall be built according to the rules of the graphical display of drawings. **Methods:** A toolkit of the *Autodesk Revit software* (Masses, Model In-Place) is considered together with an additional script created using a visual-programming add-on – *Dynamo.* The authors formulate approaches to work with complex geometry in *Revit* that make it possible to model objects of complex forms correctly. Examples of using standard program tools in unusual application logic are given. Since standard tools have limited functionality, it is shown how to use a *Dynamo*-based script that automates and speeds up the process of creating geometric forms. **Results and discussion:** Optimization of work with non-standard instances of the project geometry is performed, and a subsequent paradigm for the design of non-standard construction objects is formulated.

Keywords

Masses, Model In-Place, automation, complexity of forms, adaptability

Introduction

Architecture and structural elements are shifting away from simple linear forms. Such tendency is apparent in the modern construction sector. More and more emphasis is put on generative design, mathematical modeling of facades, analytical description of structures. All these approaches have an important common idea – a transition from structures of simple form, which are easy to design, present graphically, and manufacture, to structures, forms of which are determined not by simplicity but by content.

Requirements for modern buildings become more advanced, the economy forces designers to develop structures with the minimum material consumption but with the maximum areas. Previously, only great architects who had plenty of time and money could do that (Figures 1, 2). Such a situation in the construction market dictates its rules, thus creating progress in design and, in particular, the growing development of *BIM* technologies (Garber, 2014).

Figure 1. Mila House (Casa Mila). Architect: Antoni Gaudi i Cornet

Figure 2. Heydar Aliyev Center building. Architect: Zaha Mohammad Hadid

When using the information modeling technology, it is required to build processes of creating elements of complex and information-rich forms, as that is the major problem of the designer.

When analyzing difficulties at the beginning of object design, it is necessary to answer the following questions:

1) What stages of documentation are covered by the design of the object? It is required to establish levels of detail *(LOD/LOI)* (The American Institute of Architects, 2019).

2) Based on the principles of the concept (in particular, the purpose of the building, its approximate volumes, and general style), it is required to identify the most complex regions that will require the most time for elaboration.

3) Is the general logic of modeling the most complex regions elaborated (monolithic structures, dynamically modifiable facade structures, etc.)?

4) Is it needed to adapt templates to the current requirements, adding means of automation?

Therefore, the formation of model requirements represents an important stage of process planning. Approaches towards modeling and enriching elements with information will depend on those requirements. The requirements shall be analyzed at the very beginning of works to avoid altering large blocks of geometry at the detailed documentation stage (Kensek, Noble, 2014).

Methods of working with complex geometry in *Autodesk Revit* are described below. The basic tools are Masses and Model In-Place, which are the main replacement for system families in case of constructing complex geometry. Since standard tools have limited functionality, a Dynamo-based script is implemented, which automates and speeds up the process of form creation. In turn, these forms serve as the basis for the positioning of several categories of elements: subsystems of facades, monolithic structures, finishes of stairs.

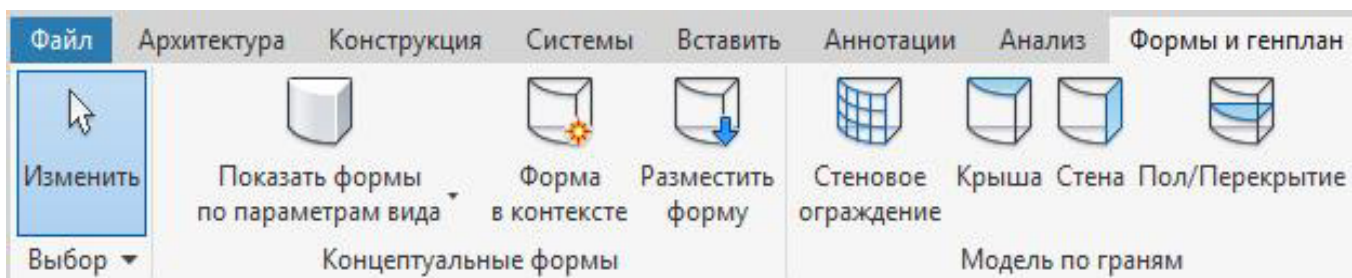Masses. They are located on the Massing and Site panel in Revit (Figure 3).

Figure 3. Location on the Revit ribbon

Let us consider three main applications of Masses in the design of objects:

1. Masses as a tool of conceptual design.

2. A basic tool when designing "complex" architectural forms.

3. A tool of automation using visual programming.

There is a lot of guidelines on the construction of forms for conceptual design, which describe methods of work at the conceptual design stage in detail (Vandezande, Krygiel, Read, 2013; Read, Krygiel, Vandezande, 2011; Lantsov, 2014).

For instance, in residential construction, which currently occupies a very large niche in the construction business, forms are often used in conceptual design for the extraction of certain volumes.

Mass Floor Schedules contain information on the following mass characteristics: Floor Volume, Floor Perimeter, Exterior Surface Area with account for the Level, Floor Area. Using calculation formulae, it is also possible to derive Floor Area *(S_floor)* percentage of the total Floor Area *(S_total)* and Exterior Surface Area *(S_exterior surface)* percentage of the total Exterior Surface Area *(S_total surface)* of a building (Figure 4). Using a standard tool to calculate energy performance of a building through the forms, it is possible to derive and calculate total facade glazing percentage (Figure 5) and approximate energy performance (it should be noted that *Revit* uses data of *ASHRAE* tables) (Shariq, 2010).
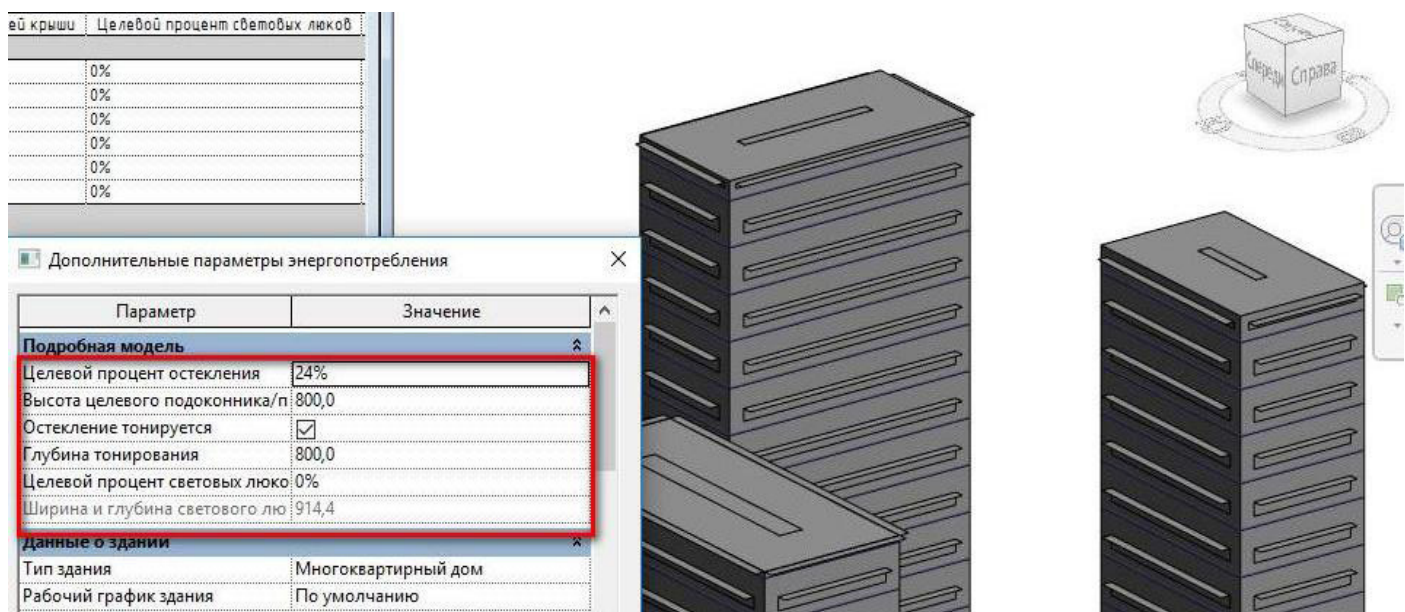

Figure 4. Mass Floor Schedule

Figure 5. Masses when creating an Energy Model

There are ways to introduce basic requirements of standardizing documents and basic calculation formulae through the *Dynamo* add-in or calculation formulae in schedules, and also use the interaction of the *Autodesk Revit, MS Project,* and *Excel* toolkits to calculate energy consumption at the stage of conceptual design. The process is based on the integration of data from *Autodesk Revit* into *MS Project* (Oolacay, 2015).

It is possible to integrate *Dynamo* in the *Revit* environment. *Dynamo* is an open-source add-in for Revit. Such functionality allows us to create masses with the help of visual programming. There is a lot of such examples in design, and the logic of scripts is based on customer's requirements (Mogilina, 2018; Poddorogina, 2018; Vandezande, Krygiel, Read, 2013).

Capabilities of such toolkit have many advantages for developers (e.g. obtaining initial data items required for construction). Variability of its use makes it possible to compile a catalog of existing layouts used by the developer, thus standardizing its approach to the site development, getting an idea of the future of the object at the conceptual design stage. Company specialty determines the use of various approaches to the creation of mass families (Krygiel, Nies, McDowell, 2008).

But this way of using forms is not a major one. If forms are viewed as the basis for the construction of various elements within the project, then, normally, the following categories are used:

A. Monolithic structures (ramps, passages, tunnels, structures bending in three planes).

B. Complex parametric facades (shells, exterior glazing grids with different in-fills, bionics).

C. Stairs and railings.

Monolithic structures. When designing monolithic structures of diverse complexity, it is important to consider basic documentation requirements. For example, plans and section views shall have uniform graphics without additional separators (Figure 6). Such graphics shall be suitable for future use by designers (if we take into account the copying of elements from the architect's model).
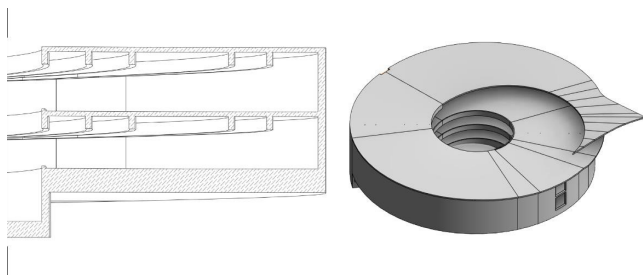

Figure 6. Example of the parking ramp section view

While no difficulties generally arise if straight objects are drawn, when designing objects of non-standard forms, it is required to shift away from using system tools of modeling and utilize the Model In-Place tool or masses. As for the parking ramp presented above, Model In-Place was applied, or more specifically, the Swept Blend tool, using profiles describing the start and end levels of the structure. It is impossible to model the structure using system tools in such a way as to display it correctly in section views and ensure that it is geometrically correct in general (Figures 7, 8).

A separate collection of materials covering design using the Model In-Place tool can be developed as it is important to know about its features and capabilities to ensure its beneficial use. Its main function is to replace system tools. When drawing of a complex geometry element is planned and a tool is selected, according to the initial data, it is necessary to bear in mind the following:

a. Elements created in the Model In-Place space that have a single path, coinciding in one of the faces, cannot be joined together.

b. Elements, the area of which is to be accounted for in a schedule, shall be made in one layer in the space of one Model In-Place, or, depending on the number of layers, the corresponding formula shall be introduced to the schedule.

c. To avoid mistakes, Model In-Place void forms, cutting through system elements, need to cut only one appropriate element.

d. A void form cannot cut through a solid if faces of their sketches coincide.

When applying a certain logic of building elements, it is necessary to bear in mind the processes of automation and exchange of information between adjacent structures, existing in your company. It should also be remembered that many scripts centered around a certain logic of interaction between elements may fail to work with the elements, which were modeled not according to the logic of reading information from automation tools. In such cases, it is better to convert scripts and plugins, transforming the conditions and logic of action within the add-in, to avoid execution of the object on a case-by-case basis.
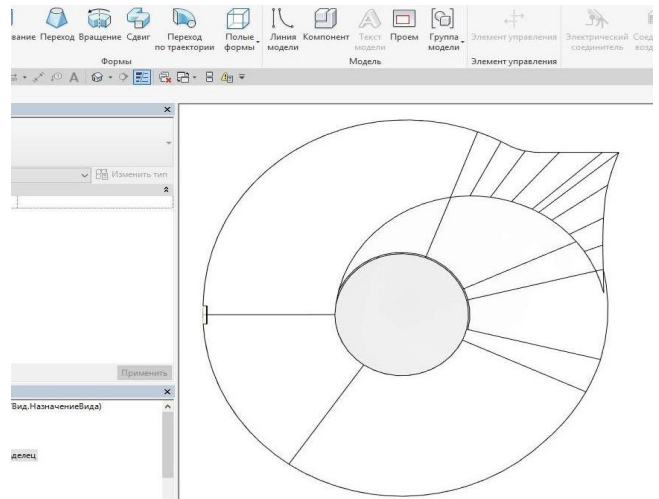

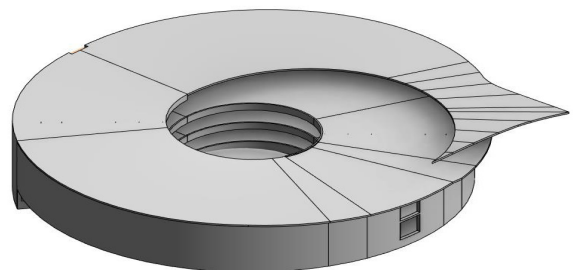Figure 7. Plan view of the parking ramp when using the Swept Blend tool

Figure 8. 3D view of the parking ramp when using the Swept Blend tool

Similar curved structures can also be built using forms. The same form can serve as the basis both for monolithic walls and for the facade subsystem structure (Figures 9, 10, 11).
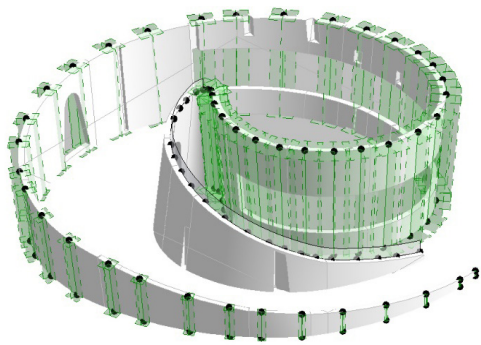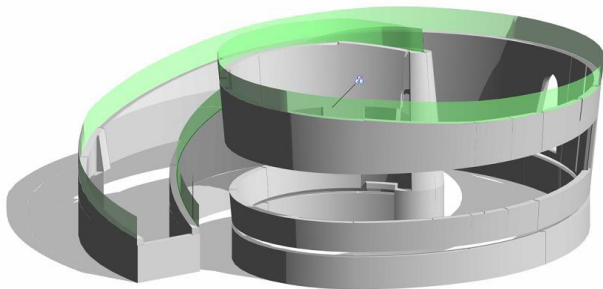
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Figure 9. Form sketching process (1)

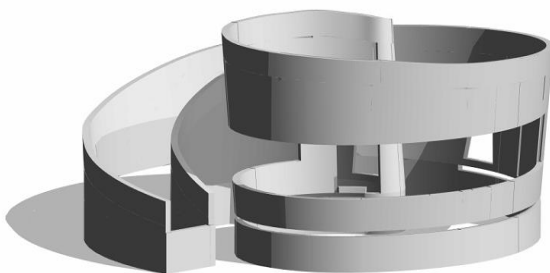Figure 10. Form sketching process (2)

Figure 11. Form-driven monolith

In this object, the walls at each point have a certain slope and a certain height relative to the plane of the level. To achieve the desired height and shape, additional constructs in the form of splines were required (combining two points with a spline – a straight line) to further fix the slope of the parapet points. It is important to understand the effect of reference points as in most cases they are critical in the creation of reference lines tied to the geometry of another object.

When *Dynamo* is used during the design process (which makes it possible to generate the building volume at the preliminary design stage or create a complex parametric shell with adaptive inserts), this, of course, simplifies it and makes it more automated, but this is only one of the application options. To make full use of all mass advantages, it is necessary to utilize masses in parallel with the detailed documentation stage. We will consider an example of such an application below.

Stairs + masses. It is actually an unusual application of the tool, which, however, plays a significant role in the development of detailed documentation for the project. Let us consider the following task: it is needed to read the stairs finishing, and, if the finishing consists of several layers, display the "pie" graphics in section views (Figure 12). In order to do that, it is necessary to use a stock Stairs object, based on which a form following the form of the stairs (Figure 14) is created using a script (Figure 13). Based on the form, the Roof by Face tool is used, which reproduces the multi-layer "pie" of the structure. Due to this method, the finishing of stairs does not require high labor intensity.
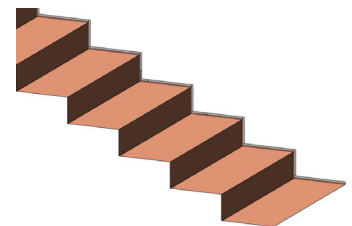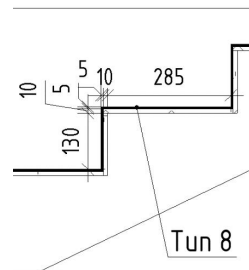

Figure 12. Stairs finishing "pie"

It should be added that the end parts of the finishing are modeled with fascias, and then, upon changes in the width of the roof by face, the fascia adjusts according to its host element. Calculations are carried out through assemblies, fascias form particular parts, and, eventually, material takeoff schedules are generated. It is possible to model forms every time when a host element changes its geometry, in which case the new form completely replaces the old one as it has the following structure in its name: "Selection category _ID".

The script is quite easy to execute. Depending on the complexity of tasks, its transformations can create a required interface for work with elements. It is possible to add pop-up windows in the main body of the script, using additional *Dynamo* packages, transform it in a way so that it could work with multiple objects simultaneously, insert initial data on the geometry offset, etc. The basic logic will be uniform and, depending on the complexity of elements' geometry, it will be transformed in the *python script* body code.
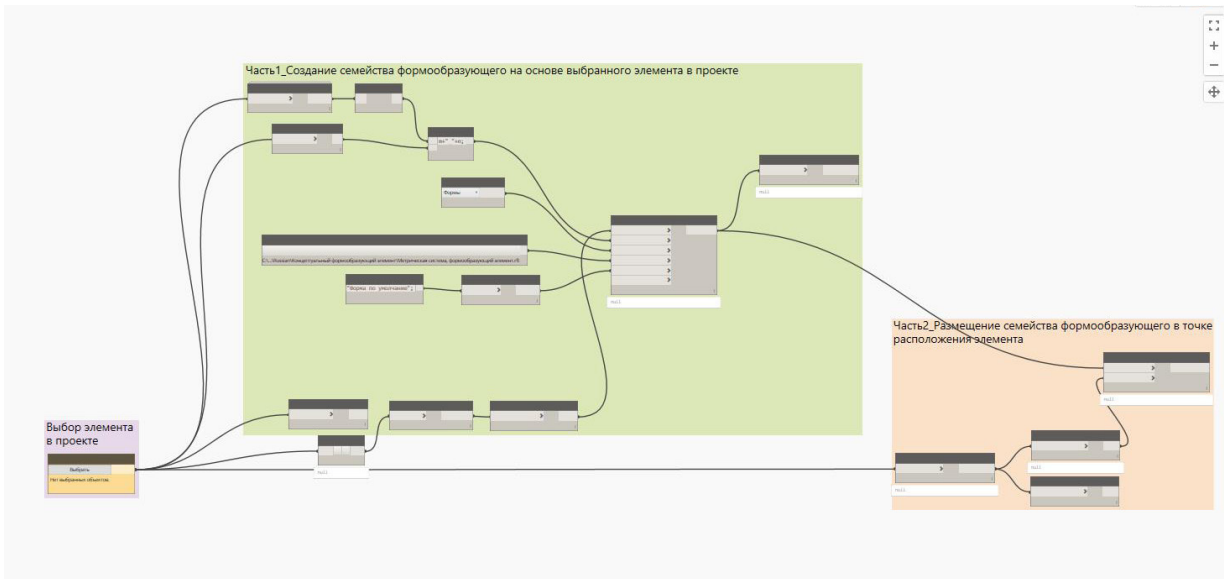
```python
import clr
clr.AddReference('ProtoGeometry')
from Autodesk.DesignScript.Geometry import *
clr.AddReference("RevitAPI")
from Autodesk.Revit.DB import *

clr.AddReference("RevitNodes")
import Revit
clr.ImportExtensions(Revit.GeometryConversion)

element = UnwrapElement(IN[0])
solids = []

GeomOpt = Options()
geom1 = element.get_Geometry(GeomOpt)
enum1 = geom1.GetEnumerator() ; enum1.MoveNext()
geom2 = enum1.Current.GetInstanceGeometry()
for g in geom2:
    s1 = g.Convert()
    if s1 != None: solids.append(s1)
OUT = solids
```

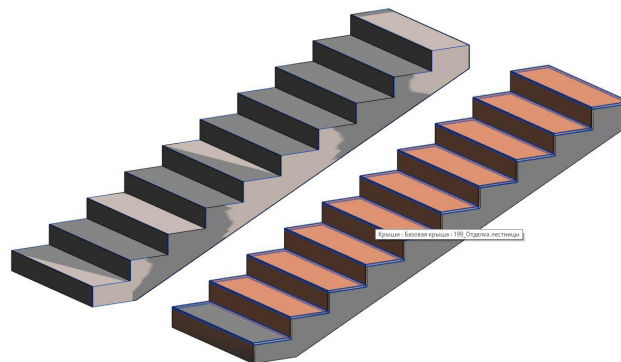Figure 13. Dynamo script + Python

Figure 14. On the left: system stairs with a superimposed form, on the right: form + Roof by Face

Facades and their metal subsystems. There can be a wall in the initial data, connected to a sloped floor, on the basis of which a form element will be created, and then an element of the facade subsystem will be constructed (Figure 15).
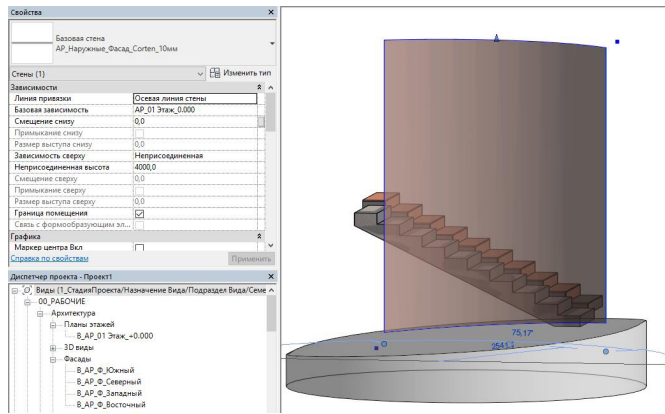

Figure 15. Initial geometry

After the script launch, a form repeating the geometry of the wall is superimposed on that wall. Then a customized curtain system with profiles of metal guides is built covering the form (Figure 16).
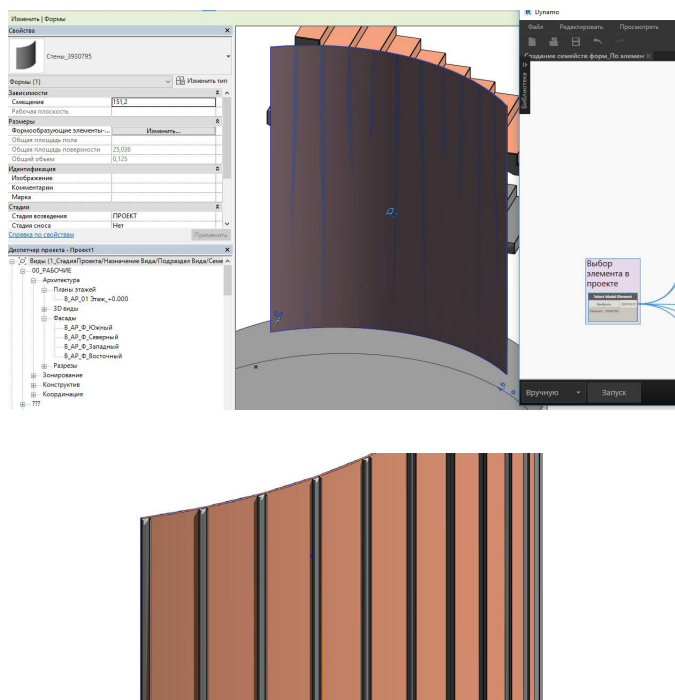

Figure 16. Form repeating the geometry of the wall. Curtain system created on its basis

Thus, the combination of these tools will help to avoid some problems associated with the development of detailed documentation. It should also be remembered that *Dynamo* reads the geometry of elements in different ways, depending on the complexity of the selection geometry. Depending on the complexity of the source element available in the project, either standard geometry

extraction nodes or *python script* are used. For the convenience of writing the latter, it is better to use *NotePad++* and *PyCharm* (Foord, Muirhead, 2009; Van Rossum, Drake, 2001; Vysotskiy Consulting, 2019).

Only the host is subject to manual modeling, therefore, the speed of introducing changes is the most important advantage of such binding since continuous change and transformation represent object constants (Hardin, McCool, 2015).

This method makes the process of introducing changes (when designing forms of curved geometry) easier and faster. In fact, only the initial mass is subject to alteration, while the rest undergo changes according to the presented logic.

Railings. There is wide variability in the creation of railings, following the same principle of action as in case of the form + curtain system binding (Figure 17). The process of calculating balusters, rails, and guides is significantly simplified as all elements of such railings are curtain wall mullions. Of course, it all depends on the structural complexity of railings, but, as experience shows, work with curtain grids and imposts is much easier in terms of the process of introducing changes to the railing structure and in the way of calculating their elements. Usually, to calculate elements of railings created using a curtain system, assemblies are used. When calculating rails/balusters, to distinguish them from each other, it is possible to use calculation formulae depending, for example, on the impost length.
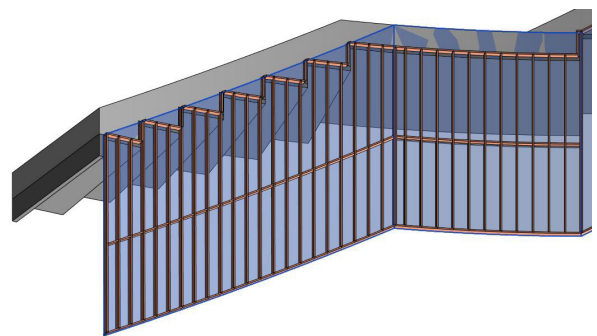
Figure 17. Curtain system (railings) + mass

Conclusions

When designing objects of complex geometric forms, the use of such Autodesk Revit tools as masses, Model In-Place elements (categories replacing system families), as well as the interaction between toolkit products and objects of process automation (using Dynamo) create a new paradigm of modeling non-standard objects. Such approach combines correct geometry and information content. Clear formation of the project structure, logic of modeling with regard to each aspect of the total geometry volume and use of automation methods ensure that geometrically complex objects are designed without losing additional time to edit and make changes, and the total timing budget to model volumes of complex forms is optimized.

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«REVIT DYNAMO: ПРОЕКТИРОВАНИЕ ОБЪЕКТОВ СЛОЖНЫХ ФОРМ. ОСОБЕННОСТИ ИНСТРУМЕНТАРИЯ И АВТОМАТИЗАЦИИ ПРОЦЕССОВ»

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Аннотация

Введение: Проектирование объектов сложных форм (непрямолинейных, округлых, динамичных в своей геометрии) на сегодняшний день вызывает сложности при построении геометрии и выпуске документации различных стадий проекта. В работе представлены зарекомендовавшие себя подходы в моделировании сложных форм. Подразумеваются формы, представляющие собой плоскости с изгибами в 3 направлениях, выполнить которые необходимо в соответствии с правилами графического отображения чертежей. **Методы:** Рассматривается инструментарий программы *Autodesk Revit* (формообразующие, модель в контексте) в совокупности с дополнительным скриптом, созданным с помощью дополнения для визуального программирования – *Dynamo*. Сформулированы подходы к работе со сложной геометрией в *Revit,* позволяющие корректно смоделировать объекты сложных форм. Приведены примеры использования стандартных инструментов программы в нетипичной для них логике применения. Так как стандартные инструменты имеют ограниченный функционал, показан способ использования скрипта на базе *Dynamo,* который автоматизирует и ускоряет процесс создания геометрических форм. **Результаты и обсуждение:** Произведен процесс оптимизации работы с нестандартными экземплярами геометрии проекта, а также на основе наработанных материалов сформулирована дальнейшая парадигма проектирования нестандартных объектов строительства.

Ключевые слова

Формообразующие, модель в контексте, автоматизация, сложность форм, адаптивность

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INVESTMENTS IN PRESERVATION AND DEVELOPMENT OF REGIONAL CULTURAL HERITAGE: A LIBRARY OF BIM ELEMENTS
REPRESENTING NATIONAL ARCHITECTURAL AND URBAN-PLANNING LANDMARKS

Urban Planning

INVESTMENTS IN PRESERVATION AND DEVELOPMENT OF REGIONAL CULTURAL HERITAGE: A LIBRARY OF BIM ELEMENTS REPRESENTING NATIONAL ARCHITECTURAL AND URBAN-PLANNING LANDMARKS

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Abstract

Introduction: The paper presents a methodology for reduction of expenses within investment projects aimed at the preservation and development of cultural heritage sites, based on the combined use of methods of scientific restoration, laser scanning and information modeling, as well as creation of a library of unique BIM elements of ancient city buildings, identified at protected sites of the urban environment, using restoration of a building in the Old Tatar Quarter (Staro-Tatarskaya Sloboda) in Kazan as an example. **Methods:** The authors performed standard (traditional) scientific restoration activities and innovative field studies using laser scanning and built a parametric information model of the cultural heritage site for further development of a restoration plan with account for site adaptation to modern functions. **Results and discussion:** Point cloud processing is carried out to create an information model and a library of unique BIM elements, which can be used repeatedly in restoration and reconstruction, thus reducing costs for BIM-model development in future investment projects. The practical significance of the study lies in the creation of a public good – a library (encyclopedia) of ancient architectural elements in the form of a library of BIM elements for BIM models of architectural and urban-planning landmarks in the region, as well as in the development of recommendations (by individuals, regional and local regulatory authorities) for an efficient policy in urban planning and restoration with regard to similar historical and cultural, architectural and urban-planning landmarks.

Keywords

Investments, preservation of cultural heritage, national color, surface laser scanning, information modeling technology, library of cultural heritage sites' BIM elements, social infrastructure, tourism potential, urban planning, regional economy

Introduction

Generally, investments aimed at preserving and developing cultural heritage sites of the peoples of Russia under conditions of integrated territorial development in cities and regions are made by state, regional and local authorities, legal entities and individuals. They are intended for implementation of investment projects on the preservation of the public good – the property of the people living in their historical lands: identification, preservation, and protection of the cultural and historical environment in settlements, nature reserves and territories of other significant national sites. Care for spiritual and material values makes it possible to achieve social development goals (in terms of charity, culture, education, and socially useful activities) and material goals (attractiveness of urban areas, tourism potential growth in regions, increase in regional and city budget income, regional economic growth).

Implementation of the cultural heritage site's life cycle concept based on the information modeling technology results in the reduction of expenses for reconstruction, restoration, and management of regional architectural and urban-planning facilities.

In the course of the study, the following main advantages of the combined use of traditional and innovative methods for reconstruction and restoration of cultural heritage sites were identified: improvement of building design quality and accuracy; cost reduction at the stage of construction operations due to work activity management and material control; prospective reduction of expenses for management of facilities with new qualitative characteristics due to the use of automated systems of integrated building utilities control.

BIM-model development for investment restoration projects differs from the development of such models for new construction projects in labor intensity as time spent

for the creation of BIM elements (windows, doors, stairs, and other building members that underwent substantial changes over time) increases significantly. Modern information systems and CAD systems used in construction utilize catalogs (libraries) of BIM-model elements for construction projects, which consist of standard elements of various manufacturers (both domestic and foreign).

Government regulation of information modeling technology development in the field of architecture, design, construction, and operation requires infrastructure set-up and development to describe construction products and help manufacturers of building materials to introduce the digitized products into state information systems. Manufacturers have access to the Russian Federal State Information System of Pricing in Construction. Introducing their products in the system, they can subsequently use cost indicators in a BIM model upon expert cost estimation for each element of the model submitted for state expert review.

Works on restoration of cultural heritage sites are the most labor-intensive as each building member becomes unique over time and, in most cases, requires artistic work when BIM elements are created. Problems related to object geometry determination to create a BIM element for subsequent use in an information model arise. Field studies of cultural heritage sites using laser scanning, and modeling of BIM elements, typical for ancient objects, based on the point cloud obtained can serve as an essential complement to traditional analytical methods of research, scientific restoration, and reconstruction of the historical development.

Subject, tasks and methods

The paper presents a methodology for reduction of expenses within investment projects aimed at the preservation, renovation, restoration and reconstruction of historical, cultural and natural sites upon design of cultural heritage sites with the use of an integrated scientific restoration approach, new laser scanning technologies, information modeling technology and development of an object BIM-model to make a thorough restoration plan, through the example of the cultural heritage site of republican significance located in the Old Tatar Quarter (Staro-Tatarskaya Sloboda) in Kazan, which is a historical and architectural landmark: the house of B.-F.Ya. Bagautdinova (Marjani)–B.-Kh.Sh. Apanayeva, architect: P.I. Romanov (1873). The building was owned by a daughter of Shihabeddin Marjani (Shihabeddin bin Bagautdin al-Kazani al-Marjani, 16.01.1818–18.04.1889) – a Tatar enlightener, theologian, philosopher and historian, who laid the foundations for renewal of the Tatars' life: getting secular education, studying ancient, Arab, Russian and Western European culture, achievements of the world culture and science in educational institutions called madrasas[1].

The study was aimed at the following: a system analysis of field studies of the site using a laser scanning technology, point cloud, BIM model of the cultural heritage site; search for a solution to reduce time spent by restoration architects on development of a building information model when modeling unique elements of the ancient site (as new elements of the BIM model); drafting of recommendations for reduction of expenses within investment projects aimed at the reconstruction and restoration of cultural heritage sites due to creation of a public good – a library of unique BIM elements of regional cultural heritage sites for repeated use in investment projects.

The field study of the cultural heritage site in the Old Tatar Quarter in Kazan revealed damage resulting from a fire (Figure 1), construction of a new building on the adjacent land plot, and growth of plants (Figure 2). The damage was initially analyzed during training design at the Kazan State University of Architecture and Engineering by a team of faculty members and students of the Department of Reconstruction, Restoration of Architectural Heritage and Principles of Architecture (using traditional methods of scientific restoration[2]). Then the study was continued with a view to a more accurate analysis of the building based on modern information technologies.

Figure 1. Effects of a fire at the cultural heritage site of republican significance located in the Old Tatar Quarter in Kazan. Source: photo by the authors.

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[1]Official Tatarstan website, National Library of the Republic of Tatarstan. Available at: http://kitahane.tatarstan.ru/mardzhani.htm (accessed on 01.06.2019).
[2]Sadykova D., Garayeva L., Minnegulova Z., Shakirova A., Amirova A., Kuzmichev N. (2018). Architectural description of the building located at 44 Sh. Marjani St. as of September 2018. Advisors: Mukhitov R.K., Fazleyev M.Sh. Kazan, 22 p.

Figure 2. Effects of new construction on the adjacent land plot and wildlife on the cultural heritage
site of republican significance located in the Old Tatar Quarter in Kazan.
Source: photos by the authors.

Initially, the following task was set: practical evaluation of developing a unified BIM model of a real object under the project for reconstruction of the cultural heritage site, applying the method of teamwork involving restoration architects, designers, and building utilities engineers, using methods of laser scanning for high-precision architectural measurements, information modeling to develop design and operation BIM models of the building during inter-disciplinary course design at the Kazan State University of Architecture and Engineering. In the course of the study, another task was set: search for a solution to reduce costs for the creation of ancient buildings' unique elements in the BIM environment.

Historical background

Three cities of the Republic of Tatarstan have sites included in the UNESCO World Heritage List: Kazan (Kazan Kremlin), ancient city Bolgar and Sviyazhsk town-island. Preservation and development of cultural and historical sites in the territory of the Republic are of integrated nature:

1) at the regional level, the Republican Fund for the Revival of Historical and Cultural Monuments of the Republic of Tatarstan was established. As a result of its activity, Sviyazhsk town-island and Bolgar city were restored. In 2014, ancient city Bolgar was included in the UNESCO World Heritage List. The Bolgar historical and archaeological complex is represented by architectural examples of the medieval Islamic city of Volga-Bolgars[3]. In 2017, the Assumption Cathedral of Sviyazhsk town-island was included in the UNESCO World Heritage List (building date: 1556–1560; Pskov architect: Postnik Yakovlev). Thus, the world universal value of Eastern Orthodox Church historical treasures – frescoes of the 16th century, the historical significance of which is in representing decisions of the Council of Hundred Chapters held in 1551, – was acknowledged[4]. Scientific studies and restoration of sites were carried out by archaeologists, historians, surveyors, restoration artists, and other specialists. The spatial and planning structure of a city typical for the middle of the 14th century was developed based on a graphic reconstruction of Bolgar city (Nadyrova, Troepolskaya, 2013).

2) at the municipal level, city authorities and individuals are responsible for the development of historical territories. In an area where the Kazan Tatars historically

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[3]Zubkov I. (2014). Rossiyskaya Gazeta official website. Available at: https://rg.ru/2014/06/23/bulgar-site-anons.html (accessed on 12.02.2019).
[4]Rodionov V. (2017). UNESCO included the Assumption Cathedral in Sviyazhsk in the World Heritage List. Available at: RIA Novosti official website https://ria.ru/20170709/1498159565.html (accessed on 12.03.2019).

resided, the "Old Tatar Quarter of Kazan" Prefect's Office and the non-commercial Fund for Development of the Old Tatar Quarter and Kaban Lake Improvement operate. The purpose of the Fund is to develop the historical area of the Old Tatar Quarter in Kazan and improve Kaban Lakes. The Fund ensures the preservation, renovation, and re-creation of the typical historical urban environment in the area of Kazan city beyond Kaban Lake. Its tasks are improvement, renovation, and restoration of historical sites, creation of new landmarks, maintenance of cultural traditions, arrangement of public events and development of tourism potential with regard to the Kaban Lake embankment [5].

The Ministry of Culture of the Republic of Tatarstan in collaboration with the City Hall and the "Old Tatar Quarter of Kazan" Prefect's Office implemented investment projects for the development of the quarter territory, renovating blocks of buildings in the historical area. Among those projects are the following: re-creation of a typical Tatar town mansion, renovation of the Sredny Kaban Lake embankment, formation of an eco-system for water birds, revival of cultural traditions (Sabantuy festival, which means "celebration of the plough"), Gabdulla Tukay

Literature Club project, renewal of Tatar intelligentsia meetings in the Eastern Club (beginning of the 20th century) to hold evenings with poets, writers, composers, artists developing the Tatar musical and visual art, and literature.

Analysis of investment directions with regard to projects for the development of historical territories as well as urban-planning projects in the Republic of Tatarstan shows that investments are systemic and integrated, their sources are budgets of all levels and private funds, aimed at the reconstruction and restoration of unique architectural and urban-planning facilities, re-creation of the typical historical urban environment in old quarters of cities.

Let us review possibilities of the combined use of traditional and innovative methods for preservation and reconstruction of the architectural and historical heritage of the Republic using the example of such cultural heritage site of republican significance as the historical and architectural landmark "House of B.-F.Ya. Bagautdinova (Marjani)–B.-Kh.Sh. Apanayeva, architect: P.I. Romanov (1873)" located in the Old Tatar Quarter in Kazan (Figure 3).

Figure 3. Historical part of the city near the cultural heritage site of republican significance "Historical and architectural landmark "House of B.-F.Ya. Bagautdinova (Marjani)–B.-Kh.Sh. Apanayeva, architect: P.I. Romanov (1873)" located in the Old Tatar Quarter in the central part of Kazan city, on the embankment of Sredny Kaban Lake.
Source: photo by the authors.

Scientific restoration of cultural heritage sites requires complete, reliable and accurate measurement documentation. Besides drawings and photos[6], it is possible to build a BIM model based on the surface laser scanning technology:

1) a 3D point model of a landmark as a result of its laser scanning (exact geometry) and use of photogrammetry (color data);

2) an ortho-photo plan – an orthogonal projection of a 3D model to a given plane, combining geometric characteristics of the measurement drawing and imagery of photos;

3) point cloud projections used for fixation and measurement of convoluted surfaces. The type of projection depends on the surface form and makes it possible to project the surface with minimal distortions.

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[5] Charter of the Fund for Development of the Old Tatar Quarter and Kaban Lake Improvement. Available at: http://fond-sts.ru/regulations (accessed on 12.03.2019).
[6] Architectural measurements (2018). Research and Production Company "Photogrammetria". Available at: https://photogrammetria.ru/18-arkh-itekturnye-obmery.html (accessed on 25.03.2019).

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INVESTMENTS IN PRESERVATION AND DEVELOPMENT OF REGIONAL CULTURAL HERITAGE: A LIBRARY OF BIM ELEMENTS
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Results and discussion
Use of laser scanning

Based on a set of works on the scientific restoration of the cultural heritage site, performed by restoration architects, the authors set a task of studying the site using surface laser scanning. Surface laser scanning makes it possible to build models of urban areas (Usikov et al., 2009), study cultural heritage sites precisely (Seredovich, 2009), develop a precise digital model of a site or terrain (Akulova, Krutikov, 2009; Komissarov, 2006), use possibilities of non-destructive analysis methods to evaluate the state of a cultural heritage site (Potapov, Pavlov, Verkhovskaia, 2019), conduct non-destructive testing (Yakovlev et al., 2013). It also can be used in archaeological studies (Prokopieva, 2006). Software analysis aimed at the processing of surface laser scanning results (Shevchenko, Gura, Glazkov, 2016) and analysis of the combined use of laser scanning and photogrammetry (Komissarov, Kalinina, 2016; Pavlov, Vinogradov, 2011) showed the high efficiency of modern technologies in studies of architectural monuments. Scanning for building construction is applied to existing structures (Shevchenko et al., 2016), used for inventory control, measurements of objects (Minaev, 2013) and in new construction. Scanning technology is becoming a critical function necessary to complete the integrated BIM cycle and provides a clear value-add for the integrated BIM workflow (Gleason, 2013). It is assumed that the transfer of BIM models to state expert review authorities will make it possible to reduce the time spent on project analysis and expert review (Lyapina, Borodin, 2018).

A surface laser scanning system consists of a laser scanner (laser range finder and laser scanning unit deflecting the laser beam) and a laptop with special software. Due to laser scanning, it is possible to perform a topographic survey, take geo-referenced building facade measurements, and analyze the obtained point cloud promptly and accurately:

1) scanner settings' management: spatial coordinates of points on the surface of an object are determined by measuring the distance to all points captured by a reflectorless pulse laser range finder:

beam direction (vertical and horizontal angles) is registered;

a distance from the scanner to the points is measured;

for building facades, measurements from four angles are taken;

2) scan recording: high accuracy of the tool makes it possible to take numerous measurements and replicate the surface of the object scanned in the form of a point cloud, creating a 3D raster image (scan) of the object. Each pixel can be an element of a three-component vector (distance; reflected signal strength; real color of each point, expressed as RGB) or a five-component array of points of laser reflections from the object in the sight of the scanner (x, y, z spatial coordinates; reflected signal strength; real color);

3) processing of results: the generated point cloud is transferred to the BIM environment to develop a parametric information model of the object.

The object was studied according to the following algorithm: 1) collection of data on the object (construction and topographical survey), database formation; 2) building siting directly on site using the BIM technology[7].

Results of the study based on the analysis and interpretation of the point cloud generated during in-situ laser scanning of the building facades from four points are presented in Figure 4.
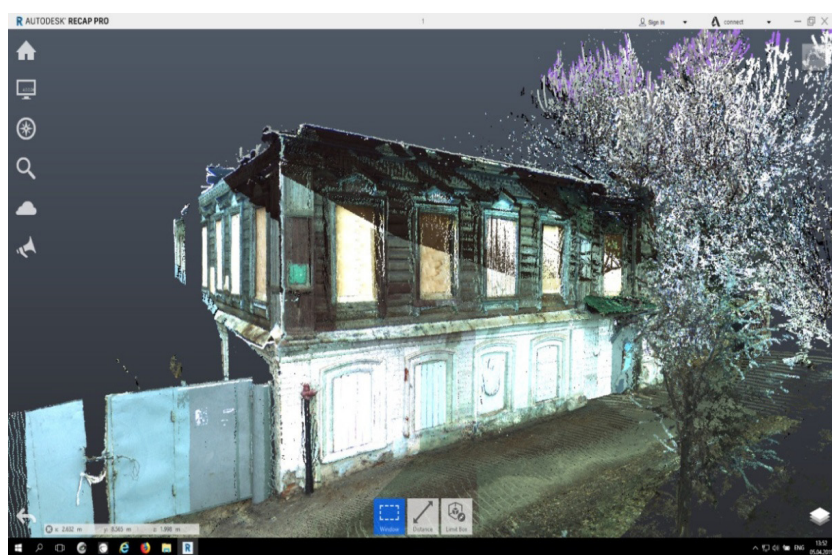

Figure 4. Results of the cultural heritage site's field survey.Source: the results were processed and submitted by M.V. Efremov, TSNRU JSC (Tatar Special Scientific Restoration Department).

[7]Lakin P. (2017). BIM technologies in preservation of heritage sites. Available at: https://www.kgasu.ru/customer/bim/news/universitet-skaya-zhizn/v-kgasu-startovali-master-klassy-po-bim-tekhnologiyam-v-ramkakh-grantovoy-programmy-rt-algarysh-/ (accessed on 15.03.19)

The following advantages of obtaining spatial information using surface laser scanning of a cultural heritage site were revealed: high accuracy of measurements and speed of field survey; non-destructive information gathering; safety of works in hard-to-reach areas generated due to dilapidation or partial loss of structures (e.g. using radio-controlled devices).

After completion of surface laser scanning and recording of several scans, studies continue as the development of an information model of the object in the BIM environment, which makes it possible to combine two technologies to create a precise digital model and improve the information accuracy for the corresponding investment project.

Specifics of developing a BIM model for a cultural heritage site

Development of a comprehensive information model for a cultural heritage site located in the historical part of a city shall be performed after its scientific restoration, field studies using surface laser scanning, subsequent design and development of a BIM model for the efficient implementation of the corresponding investment project and further building adaptation to modern functions (a wire-frame model, a surface or solid model in black and white or color with account for the need to preserve, replace or re-create BIM-model elements at the next stages of the architectural monument's life cycle).

The next step is model checking. It is especially important in case of joining the preserved building elements and attaching the old elements to new structures and joints. Tolerances and clearances are also essential.

At this stage, it is possible to avoid or reduce expenses associated with actual restoration. Location-based scheduling allows us to perform production control on-site and make teams proactive when managing a project schedule. The combined pro-activeness of scanning information and production control is a key component to mitigating schedule delays on renovation projects. Laser scanning results in a BIM model based on the exact number of elements and allows for more accurate investment project evaluation with account for new and existing elements of the architectural monument (Gleason, 2013).

Building a BIM model of a cultural heritage site, it is possible to obtain measurement drawings of facades, floor plans, drawings in longitudinal section, roof and wall plans, decoration drawings with the indication of actual measurements, elevations of various building elements with the indication of deviations from design values; identify defects and other information depending on the object and objectives.

Information modeling technology allows owners, specialists, facility managers to make right and effective decisions related to facility management due to the precision of information models, possibilities of detecting, monitoring and correcting collisions in a project, scenario forecasting with respect to various restoration options, investment control within a project for reconstruction or restoration of a cultural heritage site.

It has been revealed that a BIM model of a cultural heritage site (Figure 5) is characterized by high labor intensity associated with the creation of unique BIM elements by restoration architects.
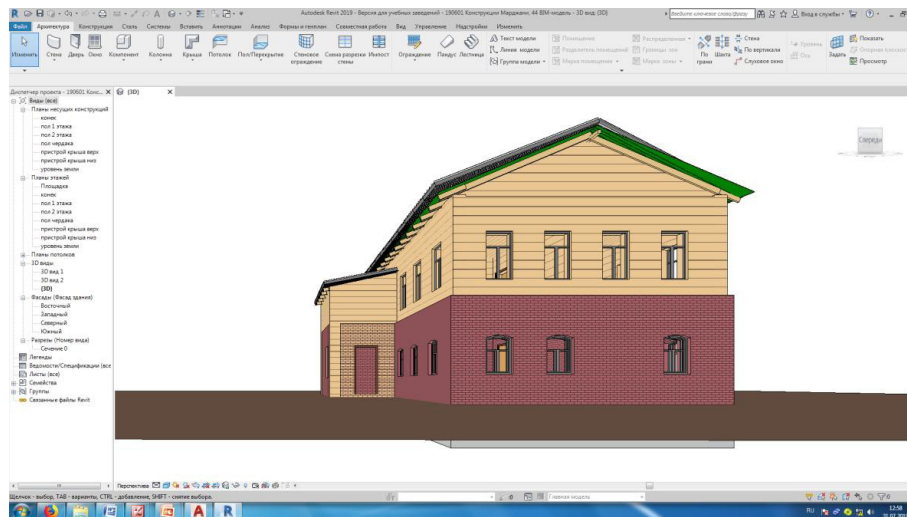

Figure 5. BIM model of a cultural heritage site.

When restoration architects create a unique element of a building of architectural heritage in the BIM environment, the following is considered:

firstly, the geometry of standard elements used during initial construction distorts over time; secondly, similar elements (e.g. windows) could initially have different dimensions; thirdly, plants could also change

the geometry of the object (as exemplified by the fire wall of the house) over time; fourthly, modern catalogs of software for BIM modeling and catalogs of building materials lack unique ancient architectural elements to be used to re-create a cultural heritage site, whereas the creation of a unique element is a labor-intensive process (Figure 6).

Figure 6. Examples of unique elements of a building as a part of an actual cultural heritage site and BIM model.
Source: photo by the authors, BIM model.

It is possible to resolve issues related to the efficient development of a cultural heritage site's BIM model by restoration architects, using the following methodology:

1) based on ancient guides, create a library of BIM elements of regional cultural heritage sites and utilize it as a public good within the regional policy of urban planning and preservation of cultural heritage sites;

2) provide the library of BIM elements of regional cultural heritage sites (as elements of repeated use) for the public use.

It will allow all concerned parties to projects aimed at the restoration and reconstruction of cultural heritage sites to use the library in architectural design, perform scenario forecasting, and assess restoration options and site's possibilities for adaptation. Changes in a BIM model make it possible to obtain documentation needed at the subsequent stages of the object life cycle and respect the interests of the society and investors when preserving the architectural heritage of the region.

The following advantages of information modeling with respect to cultural heritage sites (possibilities of implementing the concept of the full life cycle of a cultural heritage site) were revealed: cost-efficient design works due to the development of a unified BIM model; possible repeated use of a library of unique BIM elements related to regional cultural heritage sites in an information model for the purposes of architectural and engineering design, construction management, operation, and repair.

Considering the high cultural value of unique BIM elements created by restoration architects for ancient mansions, natural, cultural and historical monuments, the authors suggest implementing a regional investment project to create a library of unique BIM elements of cultural heritage sites located in the Republic of Tatarstan and developing measures of state support for the creation of such library (digital architectural and urban-planning encyclopedia) as a public good with free access to it (as a cultural layer of historical elements) for the next generations of restoration architects, historians, and art experts, based on repeated use of BIM elements for artwork, restoration and reconstruction of cultural heritage sites, including typical housing development in the historical part of cities and villages of the region.

Conclusions

The combined use of traditional scientific restoration methods, advanced technologies of surface laser scanning, and information modeling for investment projects aimed at the preservation, reconstruction, and restoration of cultural heritage sites made it possible to assess possibilities of implementing the cultural heritage site's life cycle concept (with regard to sites being restored) upon object creation in the BIM environment by specialists of related fields.

Investments in preservation and development of cultural heritage sites based on the combined use of traditional restoration methods, advanced methods of surface laser scanning, and information modeling make it possible (due to high accuracy of design methods) to reduce investment project costs and expenses for operation of buildings, including historical and cultural monuments of the region.

Social and institutional significance of the suggested investment project to create a library of unique BIM elements of cultural heritage sites located in the Republic of Tatarstan lies in the following:

1. Preservation of cultural heritage sites and sites portraying the history of the peoples in the region.

2. Preservation and development of the national color of cities using the example of the Old Tatar Quarter in Kazan.

3. Use of non-destructive technologies of scientific restoration as well as the effective, cost-efficient and high-precision re-creation of historic buildings based on surface laser scanning and BIM.

4. Development of the social infrastructure in a city due to the adaption of sites to socially beneficial functions.

5. Development of tourism potential in the region.

The combined use of traditional restoration and reconstruction methods as well as advanced information technologies will make it possible to implement investment projects aimed at comprehensive restoration, provide conservation of buildings to prevent their subsequent

destruction, and develop projects to renovate historic buildings and adapt them to the improving social infrastructure in the historical part of the city, preserve the national color of the Old Tatar Quarter in Kazan, and improve tourism potential with regard to the regional economy.

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ИНВЕСТИЦИИ В СОХРАНЕНИЕ И РАЗВИТИЕ КУЛЬТУРНОГО НАСЛЕДИЯ РЕГИОНА: БИБЛИОТЕКА BIM-ЭЛЕМЕНТОВ ПАМЯТНИКОВ НАЦИОНАЛЬНОЙ АРХИТЕКТУРЫ И ГРАДОСТРОИТЕЛЬСТВА

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Аннотация

Введение: В статье представлена методология снижения издержек инвестиционных проектов сохранения и развития объектов культурного наследия на основе комплексного применения методов научной реставрации, лазерного сканирования, технологии информационного моделирования объекта и создания BIM-библиотеки уникальных элементов старинных городских зданий, выявленных на охраняемых объектах городской среды, на примере проекта реставрации дома в Старо-татарской слободе города Казани. **Методы**: В исследовании проведён комплекс традиционных мероприятий научной реставрации объектов, инновационных натурных исследований с применением лазерного сканирования с последующим созданием параметрической информационной модели объекта для разработки плана реставрации с учетом современного приспособления объекта культурного наследия. **Результаты и обсуждение:** Обработка облака точек для создания информационной модели и библиотеки уникальных BIM-элементов модели, которые могут быть повторно использованы для реставрации и реконструкции объектов, что снизит стоимость создания BIM-модели в последующих инвестиционных проектах. Практическая значимость работы заключается в постановке задачи создания общественного блага - библиотеки (энциклопедии) старинных архитектурных элементов в форме библиотеки BIM-элементов для BIM-модели памятников архитектуры и градостроительства в регионе, а так же разработке рекомендаций частными лицами, муниципальными органами, региональными органами власти по государственному регулированию эффективной и качественной политики городского планирования и реставрационной деятельности на аналогичных объектах историко-культурного, архитектурного и градостроительного наследия.

Ключевые слова

Инвестиции, сохранение культурного наследия, национальный колорит, наземное лазерное сканирование, технология информационного моделирования, библиотека BIM-элементов объектов культурного наследия, социальная инфраструктура, туристический потенциал, городское планирование, региональная экономика

Surface Transportation Engineering Technology

PRACTICAL USE OF BIM MODELING FOR ROAD INFRASTRUCTURE FACILITIES

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Abstract

Introduction: The subject of the study is transport infrastructure. The paper describes engineering solutions suggested by Hexagon Geosystems Rus and other large companies that conduct construction monitoring using BIM technologies and develop software solutions, services and equipment. It also addresses implementation of such engineering solutions. **Purpose of the study:** to achieve high level of road maintenance, preserve the existing road network, ensure traffic safety, switch to new methods of infrastructure facilities management by implementing BIM-based projects. **Methods:** Domestic products keep up with capabilities of modern information technologies and demonstrate BIM capabilities during its use in road infrastructure projects. Russian experts suggest software solutions to create a new environment for economic development, including in the road industry. **Results**: Documentation based on 3D laser scanning makes it possible to schedule maintenance and repair of transport infrastructure facilities. Data obtained are relevant and objective as the human factor is removed from final drawings and 3D models, thus improving the efficiency of the transport infrastructure facilities management system.

Keywords: BIM-modeling, transport infrastructure, road information model, geographic information system, digital transformation of roads

Introduction

Linear facilities are managed using transport infrastructure geographic information systems (GIS). Though GIS have been used for road and road facilities management since the 1990s (e.g. ArcGIS (ESRI), MapInfo (MapInfo Corp.), free QGIS, IndorRoad (IndorSoft), DorGIS (Intelnova), etc.) (Boykov, Kuzovlev, Barannik, 2017), the regulatory framework, which is much needed for successful Building Information Modeling (BIM) implementation in Russia, is still being developed (Shamraeva, Kuzovlev, Barannik, 2018a). It is required to transform the entire construction industry and, in particular, ensure interaction with all existing information systems created within the framework of the Digital Economy of the Russian Federation program (Decree No. 1632-R of the Government of the Russian Federation dd. 28.07.2017 "On Approval of the Digital Economy of the Russian Federation Program").

Currently, computer-aided design (CAD) and 3D modeling are quickly developing. As a result, a demand arises to exchange 2D and 3D data between various CAD systems. Therefore, a standard is needed that could register changes in an infrastructure facility at all stages of its life cycle, i.e. a data bank containing such information as infrastructure facility requirements, a facility project and alterations thereof, as well as physical assets comprising such infrastructure facility and alterations regarding those assets. Researchers dealing with the issue in other countries also acknowledged the lack of national standards for BIM and software interoperability (Sandeep, Criminale, 2017). Expectations from different stakeholders involved in construction projects where BIM is utilized are different and can lead to misunderstandings (Abbasnejad, Moud, 2013). Upon introduction of ISO 15926 standard, a traditional software concept based on task issue and execution control is replaced with a flexible and adaptive collaboration concept.

For Russia, introduction of BIM technologies is just a matter of time as new engineering models supported by open data protocols are already being implemented. It is possible to provide a formal description of the BIM process at each stage of the life cycle of a construction and operation facility based on particular assumptions and suggestions. At the first stage, a BIM Execution Plan (BEP) is developed. It sets a procedure for collaboration between different teams within a BIM project. At the second stage, a Project Implementation Plan is developed, which, in particular, includes a Supply Chain Capability Summary (SCCS). Finally, at the third stage, levels of information model development (LOD) in terms of geometry and

attributes are determined. Design companies, software and hardware developers, etc. introduce information modeling into their business processes using a BIM planning process map (Barannik, 2017).

The conditions listed above offer a BIM team an opportunity to prepare smooth transition to the next stage of the life cycle, ensuring BIM process continuity. The present paper demonstrates implementation of BIM-based projects using the example of practical activities carried out by Hexagon Geosystems Rus and other companies that conduct construction monitoring using BIM technologies and develop software solutions, services and equipment. Use of BIM in the road industry in general makes it possible to form a unified approach to the structure and special library of elements of a digital road model. Therefore, we can draw the following conclusion: GIS of roads reaches the highest maturity (according to the British classification) – iBIM (Shamraeva, Kuzovlev, Barannik, 2018b) and demonstrates BIM capabilities during its use in road infrastructure projects. Russian experts not only suggest optimal unique software solutions. They create a new environment for economic development, including in the road industry.

Subject, tasks and methods

The subject of the study is transport infrastructure, which is considered as an object intended for safe and comfortable movement of its users. Digitalization of transport infrastructure is one of the most important conditions for its development. Within the framework of digital transformation of roads, the following constituent elements can be distinguished:

- mobility (increase in speed, volume and efficiency of transportation; development of user services and integration into national and transnational transport corridors);

- safety (traffic safety; transportation safety, public safety; anti-terrorism security);

- efficiency (digitalization of public services; increase in public mobility; elimination of digital inequality; traffic situation awareness enhancement due to navigation services).

In the current circumstances, it is required to provide conditions to develop the services indicated above. Issues related to optimization of transport communications and upgrade of integrated transportation safety based on intelligent transport systems become more and more important and relevant. Main tasks of the road industry for the next few years are the following: to switch to new methods of infrastructure facilities management, achieve high level of road maintenance, preserve the existing road network, and ensure traffic safety. The road industry has experience in using digital technologies and implementing intelligent transport systems on Russian roads (national projects: ERA-GLONASS, Digital Transport and Logistics, Caravan, Platon system, Russian Railways infrastructure, etc.). The process for informatization of domestic transport enterprises is no less important. At the facilities of the Avtodor State Company, during construction of

the Moscow–Saint Petersburg M-11 road sections and the Central Ring Road in the Moscow Region, Hexagon and Leica Geosystems 3D machine control systems are used. It should be noted that surveyors, designers and contractors work at the facilities using a unified coordinate system (Eastman, Teicholz, Sacks, Liston, 2011). In this regard, let us consider a number of Hexagon Geosystems Rus products. The company was established in 1997 in accordance with a development strategy for new businesses. Hexagon Geosystems Rus is engaged in introduction of advanced global technologies to reduce time and money expenditures of manufacturers during various topographic and geodetic works with the use of GPS equipment, traditional equipment and 3D laser scanning technologies. Using Leica Geosystem geodetic tools (GPS receivers and total stations), the company develops and adapts technologies to specific tasks of customers (Znobishchev, Shamraeva, 2019).

a)   b)

Figure 1. Leica Geosystem geodetic tools: a) FlexLine TS02plus total station; b) Leica GS07 NetRover with a Leica CS20 3.75G Captivate controller

Leica GR geodetic receivers are able to receive signals from GPS and GLONASS satellite systems as well as from Compass and Galileo being designed. To control and operate a network of reference stations with Leica GNSS Spider software, modularity is applied, which ensures automation of the process of transmitting satellite data to users for post-processing or in real time with the LEICA GEOSYSTEMS technology. For the purposes of data management, visualization, import and export, Leica Geo Office multi-functional software suite, which is able to process geodetic measurements, is used. Leica Geosystems experts are constantly working to improve their tools and software. GPS/GLONASS receiver signal quality, sensor and control unit frequency, and total station accuracy are improving, and it is becoming easier to use the tools.

It shall be noted that for more efficient road facilities management, a single platform is required. Such platform is intended to provide timely and reliable information, namely:

- consolidated data on the current traffic situation;
- data (stored in data bases) on the condition of roads and movable facilities to prepare analysis reports and make forecasts;

- up-to-date information on the condition of roads for a wide variety of customers;
- feedback from traffic participants with regard to incidents, road pavement condition and other important information.

Based on the domestic software, a single point of contact between the state and business during transportation will be developed. The platform will set uniform standards, rules and regulations for exchange of data, including legally relevant data on transport infrastructure and vehicles. That is another benefit of BIM modeling when designing transport infrastructure facilities (Bryde, Broquetas, Volm, 2013). The platform will serve as an aggregator of data on transport (without privatization of such data), providing non-discriminatory access to such data for all concerned members of the transport industry. Finally, it will allow us to preserve our national sovereignty over information flows within the transport system of the country. Use of the global positioning technology based on GLONASS/GPS systems takes us to a whole new level in terms of construction machinery operations' automation when road works are performed (without labor-intensive location survey), ensuring design accuracy and high quality of works at any stage of a project.

Such system is based on the use of a 3D digital terrain model (DTM), which is uploaded to the on-board computer in a cabin. In the course of machine operation, location of the attachment is determined in real time on the basis of data obtained from GLONASS/GPS receivers and sensors installed on the machine. The location obtained is compared with the DTM, and the corresponding calculated required movement is displayed on the screen. In automatic mode, the attachment is always kept in a permanent position. Practical use of the comprehensive technology (from design to its implementation) at the facilities of the Avtodor State Company (on road sections of the M4 Don Highway: facilities of Avtoban Road Construction Company, Transstroymekhanizatsiya, Donaerodorstroy, Krasnoarmeyskoye Road Maintenance and Construction Department; on road sections of the M-11 Moscow–Saint Petersburg Highway: facilities of Transstroymekhanizatsiya, Avtoban Road Construction Company) showed the following advantages:

- human factor reduction;
- no material overconsumption for road grading;
- schedule reduction: each machine operates 2–2.5 times as fast; logistics of moving trucks loaded with materials, and other machines is optimized;
- reduction of machinery out-of-service time during preparatory works (e.g. geodetic survey, stationing and elevation setting-out are not required). The automated control system for road construction machinery copies the design to the actual surface;
- reduction of time and money expenditures for geodetic works (up to 90%). No geodetic survey is required.

Such developments represent information society trends and support national sovereignty over information flows within the transport system of the Russian Federation.

Method development

At the current stage of road digitalization in Russia, practical use of BIM modeling for road infrastructure facilities plays a significant part. Tools and software developed and used for road diagnostics serve as the information basis that could be integrate into intelligent transport systems. Machinery efficiency increase, provision of required accuracy and quality, and schedule reduction are the main reasons to equip contractors with 3D automated control systems for road construction machinery. In those companies, only 20% of operated machinery are equipped with 3D technologies. In Northern Europe, average equipment with such systems is 60%; in Central Europe and in the USA – 30%. Moreover, it is currently legally required to use 3D automated control systems for road construction machinery at all stages of cement concrete road construction.

In 2018, during construction of road infrastructure facilities, monitoring was implemented on the Central Ring Road, where data of the GNSS geodetic service and data of 3D automated control systems for road construction machinery were used in a single cloud. Prompt control over earthwork levels allowed foremen to arrange for delivery of materials in the right quantities and optimize transportation logistics. On a case-by-case basis, contractors implemented BIM systems at the site. Those systems provided real-time processing of data on construction stages and allowed employees to maintain as-built documentation. BIM systems ensured the following:

– remote project management from the office;

– remote work control, including control of actual marks with respect to the design surface, and monitoring of the current location;

– storage of location history with time marks to determine where and when machines and surveyors were located;

– remote uploading of design data to the machine; that way a machine operator can get design data and start operations earlier;

– performance evaluation, collection and processing of data on machine passes, and display of those data made it possible to evaluate quality of works and track the progress with respect to design data.

Due to data analysis within the BIM system using various data collection systems (from UAV and mobile laser scanning systems), it became possible to promptly track changes in design data, control material supply needs, and achieve the following:

– improvement of accuracy and speed of works;

– constant real-time monitoring of design elevations;

– reduced number of passes: economy of fuel, lubricating oils and liquids; reduced machinery depreciation;

– reduction of time and money expenditures for geodetic works, geodetic survey, monitoring; reduction of machinery out-of-service time;

– possibility of night works;

– safety of works.

BIM systems are intended to perform tasks related not only to road infrastructure but to various economic branches as well.

Road diagnostics is based on principles of radiation technologies as well as competencies accumulated in the industry. In an integration laboratory, 3D models of roads in section view can be developed. Using a scanner, it is possible to collect data from a road section with a width of 7 m (at a speed up to 100 km/h), including from a depth of 7 m under the road pavement. The data obtained are processed automatically by special software and uploaded to the global information system. Using that system, concerned individuals and entities can get necessary information for design, construction, maintenance and repair of the Russian transportation network. Not only engineers and qualified operators but car enthusiasts as well can join the process of data registration. They will be able to make photos of any road pits and unevenness, violations in traffic sign installation and, using a special app, send those to the shared data base. It is expected that large arrays of information (hundreds of TB) will be accumulated.

In 2017, the State Company began creating systems for monitoring of transport and operating conditions of roads, and constructing a network of observation stations registering all parameters of road pavement elements 24/7 at all sites of new construction. Therefore, it is possible to obtain and accumulate data on actual road deformations caused by traffic load, increase efficiency in forecasting performance indicators, and model energy of roads to propose design alternatives (Stumpf, Kim, Jenicek, 2011).

As a result of a meeting of the Government Commission regarding use of information technologies to improve quality of life and business environment dd. December 18, 2017, a plan of actions in the field of formation of research competencies and technological foundations within the Digital Economy of the Russian Federation program was approved (in particular, activity 03.00.000.001.18.11 "Development of a software suite for instrumental monitoring of the diagnostic condition of roads, intended for collection, accumulation, storage, consolidation, analysis and interactive visual display of data on the condition of roads, obtained from instrumentation, control units and population" (see https://www.sbras.ru/files/news/docs/tex_zadely_d_e_plan.pdf)).

Conclusion

Engineering solutions suggested by Hexagon Geosystems Rus and their implementation can contribute to intense development of digitalization and expansion of Russian companies into foreign markets with the following proposals:

- creation of regional GIS systems, target monitoring systems in various economic branches for public and commercial companies;
- creation of a system for monitoring of transport and movable facilities for companies maintaining and operating mobile vehicles;
- use of a system for monitoring of the condition of roads in the road industry.

Data obtained using unique products of Hexagon Geosystems Rus can be used for the purposes of strategic and operational management of the national transport system, formation of architecture and infrastructure foundations for a digital environment of the transport system, strategic management in related industries (Hardin, McCool, 2015). Those technologies will ensure design, construction and operation of infrastructure facilities, as well as processes of design monitoring and management at a new level.

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ПРАКТИЧЕСКОЕ ПРИМЕНЕНИЕ BIM МОДЕЛИРОВАНИЯ ДЛЯ ОБЪЕКТОВ ДОРОЖНОЙ ИНФРАСТРУКТУРЫ

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Аннотация

Введение. Предметом исследования в данной статье является транспортная инфраструктура. В статье представлены технологические решения ООО «Гексагон Геосистемс Рус», других крупных компаний, занимающихся строительным контролем с помощью технологий информационного моделирования и разработкой программных решений, сервисов и оборудования и их практические реализации. **Цель исследования:** достижение высокого уровня содержания автомобильных дорог, сохранности существующей дорожной сети и обеспечения безопасности дорожного движения, переход на новые формы управления инфраструктурными объектами путём реализации проектов на основе BIM-технологий. **Методы:** продукты отечественных компаний соответствуют возможностям современных информационных технологий и демонстрируют возможности BIM-моделирования при практическом применении в дорожной инфраструктуре. Предложены программные решения, которые позволяют создать новую среду для развития экономики, в том числе и в дорожной деятельности. **Результаты:** документация, созданная на основе работ по 3D лазерному сканированию, позволяет осуществлять планирование работ по содержанию и ремонту объектов транспортной инфраструктуры. Актуальность и объективность полученных данных очевидна в виду исключения человеческого фактора в конечных чертежах и 3D моделях и приводит к повышению эффективности системой управления объектами транспортной инфраструктуры.

Ключевые слова

BIM-моделирование, транспортная инфраструктура, дорожная информационная модель, географическая информационная система, цифровая трансформация дорог

GRAPHICAL-AND-ANALYTICAL BASIS FOR QUANTOMOBILE NEAR-GROUND MOTION STUDIES

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Abstract

Introduction. Development of a graphical-and-analytical basis to perform optimization calculations for quantomobile motion control will contribute to studies on vehicle creation. **Purpose of the study.** It is required to develop a methodology for graphical representation of thrust vector realization as a graphical-and-analytical basis for optimization calculations of quantomobile trajectories. **Methods.** The thrust vector is decomposed into orthogonal components. A generalized quantomobile force balance equation is used. A mode of partial hovering of a vehicle is distinguished as the basic mode of near-ground motion. 2D modeling of force balance for a particular velocity slice is performed. 3D modeling of force balance with velocity sweeping is carried out. 2D and 3D models of force balance are developed using Maple software. Images of surfaces with regard to road and wind resistance with limits to the maximum thrust are built. Examples of calculation as well as graphical-and-analytical studies are provided. **Results.** A graphical-and-analytical basis for optimization calculations of quantomobile trajectories, changes in QE thrust and corresponding control actions is developed. Results of calculations with visualization are presented using specific examples. **Discussion.** Development of a program in the graphical environment required combining knowledge of the software tools and programmed field. Development of the quantomobile simulation model as well as its graphical-and-analytical basis in the direction of increasing complexity is the only way. Corresponding development stages are described. Two hypothetical areas for the minimization of sufficient thrust are distinguished: in the middle of vehicle hovering and after its full hovering. It shall be taken into account both in quantomobile takeoff and its near-ground motion with partial hovering.

Keywords

Quantum engine, quantum thrust, quantomobile, near-ground motion, force balance, graphical-and-analytical basis

Introduction

Extraction of energy from the physical vacuum (Leonov, 2002, 2010, 2018) will change the motion mechanics of vehicles equipped with quantum engines (QEs). In contrast to ICEs, QEs generate thrust, which can be applied directly to the vehicle body to create motion (Leonov, 2010, Brandenburg, 2017, Tajmar, 2007).

Changing the thrust vector position from horizontal to inclined will make it possible to create a vertical component of thrust, which can be used to overcome gravitation and get the quantomobile above the bearing surface (Kotikov, 2018a).

In earlier papers (Kotikov, 2018a, 2018b, 2018c, 2019a, 2019b, 2019c), the author described individual aspects of vehicle force balance. Development of a graphical-and-analytical basis to design control over QE thrust and vehicle motion will contribute to further studies on this topic.

Purpose and tasks of the study

1. To develop a methodology for 2D and 3D graphical representation of thrust vector realization in the pitch plane as a graphical-and-analytical basis for future optimization calculations of quantomobile trajectories, changes in QE thrust, and corresponding control actions. 2. To consider specifics of using the generalized quantomobile force balance equation (derived by the author) when modeling the vehicle near-ground motion. 3. To provide numerical and graphical examples. 4. To discuss results and prospects for further development.

Methods

Thrust vector decomposition

The thrust vector in the pitch plane can be decomposed into unit vectors (Leonov, 2018, Kotikov, 2019c):

$$F_T = F_{Tx} + F_{Tz}. \tag{1}$$

The scalar form of this equation is as follows:

$$F_T = \sqrt{F_{Tx}^2 + F_{Tz}^2} \qquad (2)$$

The first quadrant of the circle formed by the thrust vector tip corresponds to the translational motion of the quantomobile (Figure 1).
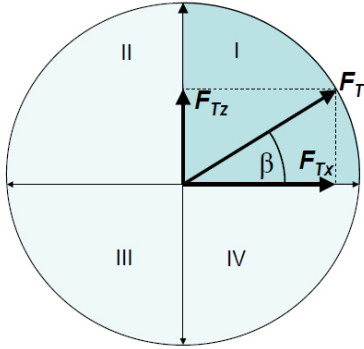

Figure 1. Decomposition of $\boldsymbol{F_T}$ thrust into horizontal ($\boldsymbol{F_{Tx}}$) and vertical ($\boldsymbol{F_{Tz}}$) components: β – $\boldsymbol{F_T}$ thrust inclination angle

Quantomobile and automobile force balance analyses differ. This is due to the fact that the quantomobile force balance equation involves entities, which are unique for land vehicles and manifest when vertical forces (gravity, hovering, wind resistance to vertical motion, vertical accelerations) are taken into account.

These aspects are considered in aircraft and helicopter engineering with regard to vertical takeoff and landing (VTOL) as well as short takeoff and landing (STOL) (Schmitz, 1971, Cerbe and Reichert, 1989, Century of Flight, 2007). Let us develop a unique model based on that experience.

Generalized quantomobile force balance equation and its reductions

As a result of equation (2) detalization, we obtain the following (Kotikov, 2019c):

$$F_T^2 = F_{Tx}^2 + F_{Tz}^2 = \left(P_f + P_{w.x} + P_{j.x}\right)^2 + \left(P_{w.z} + P_{j.z} + P_g\right)^2 =$$

$$\left(f_{wh.0}\left(1 + f_{wh.v}\cdot V_x^2\right)\cdot\left(G_q - F_{Tz}\right)\Big|_{F_{Tz} \le G_q} + k_{w.x}\cdot S_{front}\cdot V_w^2 + \frac{G_q}{g}a_x\cdot\left(1 + \delta_{wh}\right) \right)^2 +$$

$$+\left((k_{w.z}\cdot S_{plan}\cdot V_z^2 + \frac{G_q}{g}a_z)\Big|_{F_{Tz} > G_q} + \min(F_{Tz}, G_q) \right)^2, \qquad (3)$$

where:

P_f – a force of resistance to the rolling of wheels, N;
$P_{w.x}$ – wind resistance to the horizontal motion, N;
$P_{j.x}$ – a force of resistance to horizontal acceleration, N;
$P_{w.z}$ – wind resistance to the vertical motion, N;
$P_{j.z}$ – a force of resistance to vertical acceleration, N;
$P_g = \min(F_{Tz}, G_q)$ – a part of the vertical component of thrust used to neutralize g portion of hovering vehicle's gravity ($y = F_{Tz} / G_q$), N;

$f_{wh.0}$ – a coefficient of resistance to the rolling of driven wheels at a speed close to zero, and $F_{Tz} = 0$;
$f_{wh.v}$ – a velocity coefficient of resistance to the rolling of driven wheels;
V_x – velocity of longitudinal (course) motion of the vehicle, m/s;
G_q – quantomobile weight, N;
$k_{w.x}$ – a horizontal (longitudinal) wind shape coefficient, N×s²/m⁴;
S_{front} – frontal area of the vehicle, m²;
V_w – longitudinal velocity of the vehicle relative to the wind (in the present study, $V_w = V_x$), m/s;
g – gravitational acceleration, m/s²;
a_x – longitudinal acceleration of the vehicle, m/s²;
δ_{wh} – a rotational inertia coefficient of driven carrying wheels;
$k_{w.z}$ – a vertical wind shape coefficient, N×s²/m⁴;
S_{plan} – vehicle area in plan view, m²;
V_z – vertical motion velocity of the vehicle, m/s;
a_z – vertical acceleration of the vehicle, m/s²;
$| F_{Tz} \le G_q$ – a range of F_{Tz} values in the mode of partial hovering of the vehicle;
$| F_{Tz} > G_q$ – a range of F_{Tz} values in the mode of full hovering of the vehicle (with possible breakoff from the bearing surface).

When considering force balance in uniform steady motion, upon contact with the bearing surface but without breakoff (at $F_{Tz} \le G_q$), it is possible to use the following reduced equation:

$$F_T^2 = F_{Tx}^2 + F_{Tz}^2 = \left(P_f + P_{w.x}\right)^2 + \left(P_{w.z} + P_g\right)^2 = \qquad (4)$$

$$= \left(f_{wh.0}(1 + f_{wh.v}\cdot V_x^2)\cdot(G_q - F_{Tz}) + k_{w.x}\cdot S_{front}\cdot V_x^2 \right)^2 + \left(k_{w.z}\cdot S_{plan}\cdot V_z^2 + F_{Tz} \right)^2.$$

Moreover, if we take the vertical motion velocity V_z as negligible (as compared with V_x), the equation can be reduced to the following form:

$$F_T^2 = F_{Tx}^2 + F_{Tz}^2 = \left(f_{wh.0}(1 + f_{wh.v}\cdot V_x^2)\cdot(G_q - F_{Tz}) + k_{w.x}\cdot S_{front}\cdot V_w^2 \right)^2 + \left(F_{Tz}\right)^2. \quad (5)$$

Equation (5) is implicit with regard to $x = F_{Tx}$, $z = F_{Tz}$, $y = V_x$ arguments. In case of calculation studies, explicit equations may be required.

Equation (5) can be reduced to the explicit form with regard to F_{Tx}:

$$F_{Tx} = \left(f_{wh.0}(1 + f_{wh.v}\cdot V_x^2)\cdot(G_q - F_{Tz}) + k_{w.x}\cdot S_{front}\cdot V_x^2 \right). \quad (6)$$

with regard to F_{Tz}:

$$F_{Tz} = G_q + \frac{k_{w.x}\cdot S_{front}\cdot V_x^2 - F_{Tx}}{f_{wh.0}(1 + f_{wh.v}\cdot V_x^2)}. \qquad (7)$$

with regard to V_x:

$$V_x = \sqrt{\frac{F_{Tx} - f_{wh.0}(G_q - F_{Tz})}{f_{wh.0} \cdot f_{wh.v}(G_q - F_{Tz}) + k_{w.x} \cdot S_{front}}}. \qquad (8)$$

With account for $\gamma = F_{Tz} / G_q$, after $(G_q - F_{Tz}) = G_q(1-\gamma)$ substitution, equation (8) will take the following form:

$$V_x = \sqrt{\frac{F_{Tx} - f_{wh.0} \cdot G_q \cdot (1-\gamma)}{f_{wh.0} \cdot f_{wh.v} \cdot Gq \cdot (1-\gamma) + k_{w.x} \cdot S_{front}}}. \qquad (9)$$

When analyzing the moment of quantomobile breakoff from the bearing surface ($F_{Tz} = G_q$), accepting that $\delta_{wh} = 0$, $V_z = 0$, $a_z = 0$, equation (3) can be reduced to the following form:

$$F_T{}^2 = F_{Tx}{}^2 + F_{Tz}{}^2 = \left(k_{w.x} \cdot S_{front} \cdot V_x{}^2 + \frac{G_q}{g} a_x \right)^2 + (G_q)^2. \qquad (10)$$

Taking into account that $F_{Tz} = G_q$, the balance of horizontal forces can be simplified as follows:

$$F_{Tx} = k_{w.x} \cdot S_{front} \cdot V_x{}^2 + \frac{G_q}{g} a_x. \qquad (11)$$

If the balance conditions in equation (11) are maintained, the following can be written for the longitudinal acceleration of a vehicle in the mode of full hovering (at $F_{Tz} = G_q$):

$$a_x = \frac{g}{G_a}\left(F_{Tx} - k_{w.x} \cdot S_{front} \cdot V_x{}^2\right). \qquad (12)$$

The maximum possible velocity of a hovering vehicle can be determined by setting $a_x = 0$:

$$V_{x.max} = \sqrt{F_{Tx}\big/ k_{w.x} \cdot S_{front}}. \qquad (13)$$

The acceleration at the initial moment of longitudinal motion of a hovering vehicle can be determined by setting $V_x = 0$:

$$a_x = \frac{F_{Tx} \cdot g}{G_q}. \qquad (14)$$

We can complement the analysis based on equations (1)–(14) with corresponding graphical models.

Thrust representation for a particular velocity slice. 2D modeling

Figure 1 shows a calculation example and graphical representation for a particular quantomobile force balance.

Let us analyze a hypothetical quantomobile having specifications of a similar automobile (KamAZ-4326) with a QE, under extremely severe conditions of motion: G_q = 88 kN; $f_{wh.0}$ = 0.3; $f_{wh.V}$ = 4×10-4 s²/m² ; $k_{w.x}$ = 0.5 N×s²/m⁴; S_{front} = 7 m²; δ_κ = 0.04; $k_{w.z}$ = 0.8 N×s²/m⁴; S_{plan} = 17.5 m² (Kotikov, 2019a, 2019b).

We consider a situation where a practical coincidence of the thrust values is observed: for steady motion at a speed of 67.2 m/s in the automobile mode (F_{Tz} = 0, $F_T = F_{Tx}$ = 89.9 kN) and for full hovering of the vehicle ($F_T = (F_{Tz}{}^2 + F_{Tx}{}^2)^{1/2} = (88^2 + 15.8^2)^{1/2}$ = 89.4 kN) (Figure 2). In an earlier paper (Kotikov, 2019c), the following was quantitatively substantiated: at $f_{wh.0}$ = 0.3, the course speed of 67.2 m/s can be achieved through the actualization of the same thrust value ~90 kN, but by different methods: a) horizontal thrust (point 1 in Figure 2); b) thrust is inclined at angle β = 79.8° to the horizon, providing full hovering of the vehicle (point 8 in Figure 2).

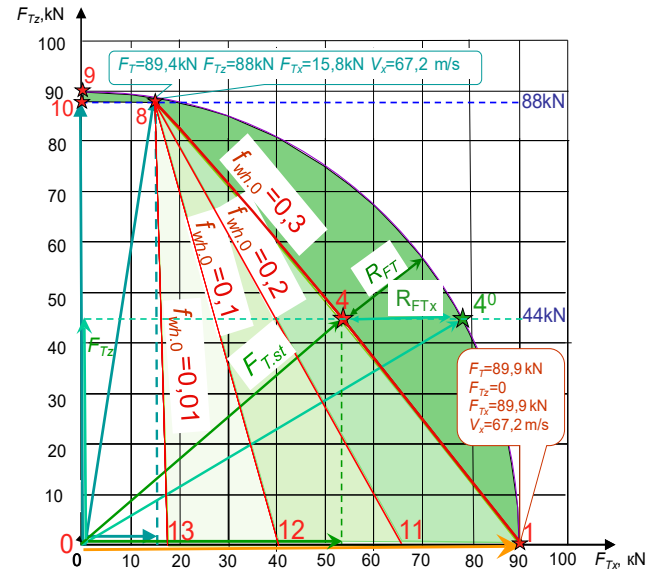Figure 2. Diagram of force balance and possible use of thrust upon quantomobile motion along the bearing surfaces with $f_{\kappa0}$ = 0.3…0.01 at a speed of 67.2 m/s

The following question arises: what value and direction shall thrust take to maintain the speed of 67.2 m/s upon partial hovering? The answer can be obtained from Table 1 and Figures 2 and 3. Let us state that upon partial hovering (γ = 0.4…0.7, β = 30…60°) the thrust required to maintain the set speed shall be 15–25% less than in extreme cases: $\gamma \approx 0$ and $\beta \approx 0°$, or $\gamma \approx 1$ and $\beta \approx 90°$ (see a red curve in Figure 3). If constant thrust is maintained (e.g. 90 kN), then the maximum speed of steady motion can also be achieved upon intermediate hovering ((g = 0.7–0.9 – see a blue curve for $V_{x.max}$ in Figure 3).

Table 1
Thrust characteristics in case of quantomobile motion along the surface with $f_{wh.0}$ = 0.3

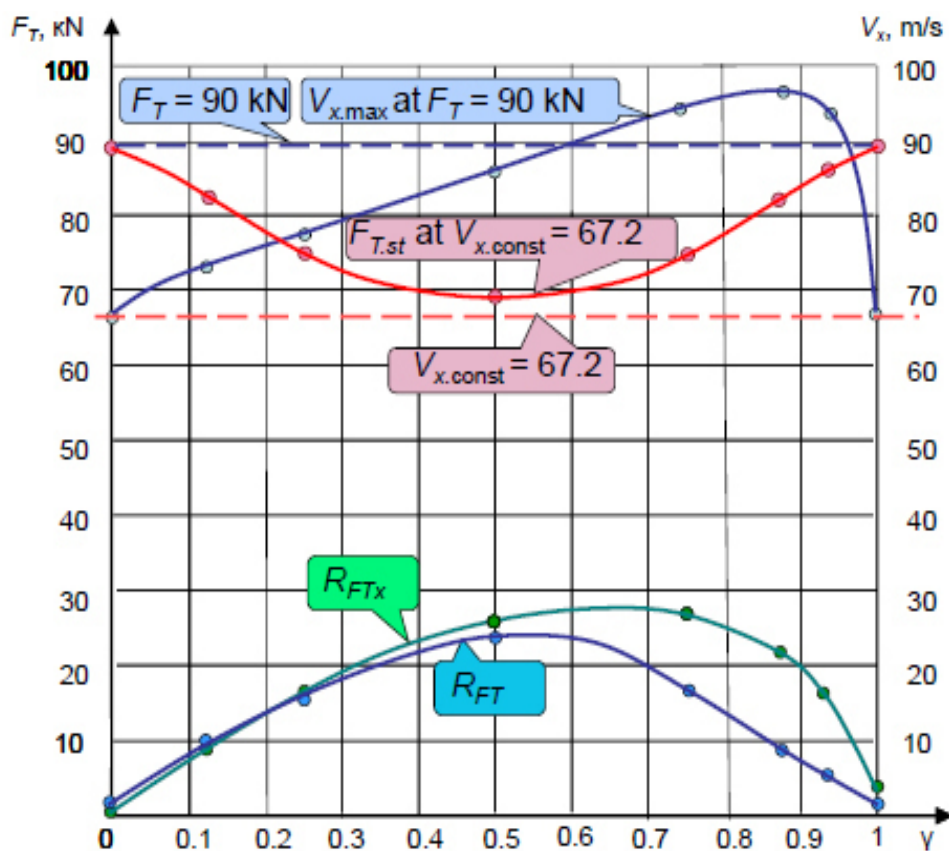| Point No. in Figure 2	Hovering rate γ	Maximum speed, m/s	Thrust components, kN							Thrust inclination angle relative to the horizon, degrees	
		V_{xmax}	F_{Tz}	$F_{Tx.ac}$	$F_{TX.ST}$	R_{FTx}	$F_{T.st}$	R_{FT}	β_{ac}	β_{st}
1	0	67.2	0	90	89.89	0.11	89.9	0.11	0	0
4	1/2	86.4	44	78.52	52.85	25.7	68.7	21.23	29.26	39.8
8	1	67.2	88	18.87	15.80	3.07	89.4	0.59	77.90	79.8

Figure 3. Dependence of motion characteristics on the vehicle hovering rate

The following designations are taken in Table 1 and in Figures 2 and 3:

$F_{Tx.ac}$ – a horizontal component of the maximum thrust that ensures the set rate of vehicle hovering, speed (67.2 m/s) maintenance, and the possibility of further acceleration;

$F_{Tx.st}$ – a horizontal component of the sufficient thrust, necessary and sufficient to maintain the steady speed of the vehicle of 67.2 m/s;

R_{FTx} – the difference between the values ($F_{Tx.ac} - F_{Tx.st}$) that ensures further horizontal acceleration ax when the speed of the vehicle of 67.2 m/s is achieved;

$F_{T.st}$ – sufficient thrust to maintain the steady speed of 67.2 m/s;

R_{FT} – the difference between the vector values ($F_T - F_{T.st}$) that can ensure acceleration of the vehicle (ax and/or az) when the horizontal speed of the vehicle of 67.2 m/s is achieved;

β_{ac} – maximum FT thrust angle relative to the horizon;
β_{st} – sufficient FT.st thrust angle relative to the horizon.

An algorithm to calculate the mentioned values is provided in one of the author's articles (Kotikov, 2019c).
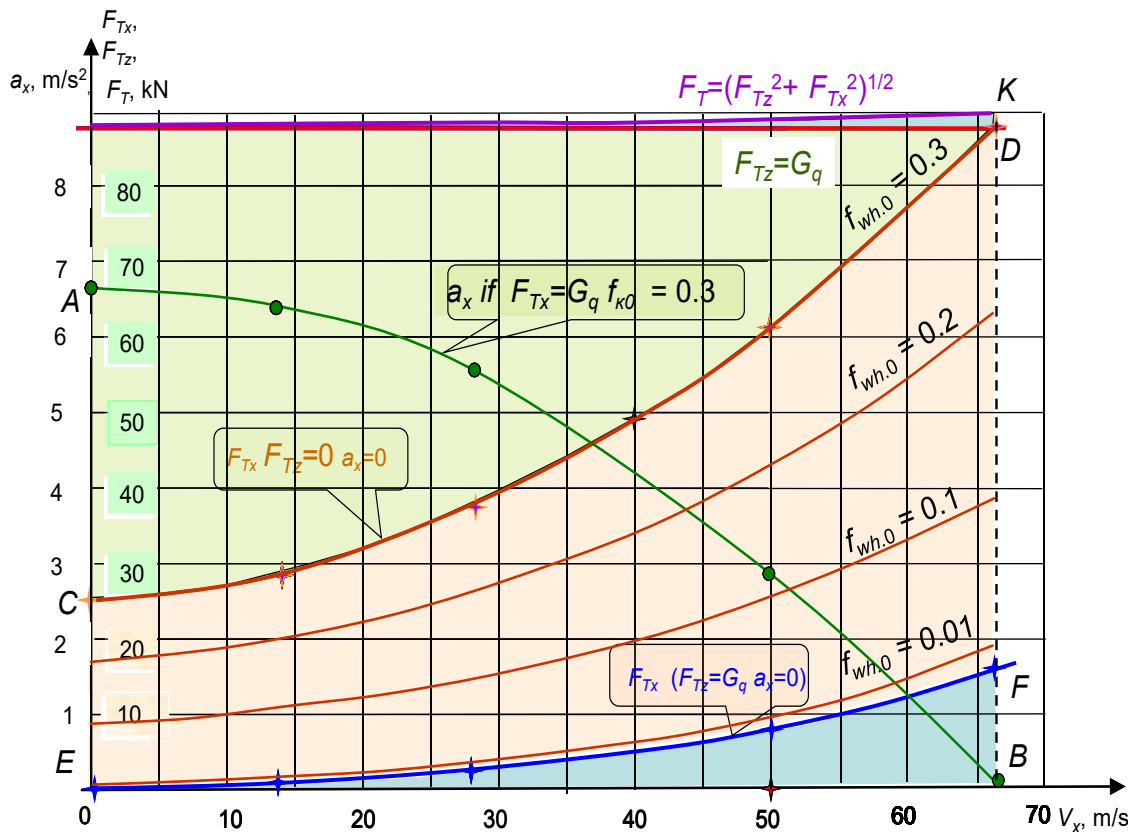

Figure 4. Speed characteristic curve with regard to the force balance of the quantomobile moving along the bearing surfaces with $f_{wh.0}$ = 0.01–0.3

For $f_{wh.0}$ = 0.3, three zones are highlighted in color in Figure 4: wind resistance (blue), resistance of the bearing surface (beige), remaining vehicle acceleration margin (green). The Figure also shows the acceleration curve AB upon complete depletion of the thrust margin highlighted in green.

3D modeling of the quantomobile force balance

It is possible to combine the capabilities of the diagrams in Figures 2 and 4 with the help of a 3D model. Let us build a 3D model using Maple software. Let us decompose the F_T thrust vector into two orthogonal components F_{Tx} and F_{Tz}, and direct the vehicle speed axis normally to the plane F_{Tx}–F_{Tz}. Let the de-identified variables be $F_{Tx}=x$, $F_{Tz}=z$, and $V_x = y$.

We programmed equations (5-9) to be used in the Maple environment in the form of $F_T^2=f(x, y, z)$ implicit function (see (5)) as well as coordinate functions $x=f(y,z)$, $z=f(x, y)$, $y=f(x, z)$ (see (6–8)). Final graphic images were similar; however, differences in build time, specifics of coloration and surface grids were observed. The following explicit model was chosen by the mentioned factors as a basic one:

$$z = f(x, y), \text{ i.e. } F_{Tz}= f(F_{Tx}, V_x). \tag{15}$$

The simple graphic images are given in Figure 5.

$F_{T.\max}^2 = F_{Tx.\max}^2 + F_{Tz.\max}^2$ cylindrical surface representing QE limit capabilities is highlighted here (and below) in blue. The sum of wind resistance and bearing surface resistance to vehicle motion (corresponding surface) is highlighted in red.

The isolines correspond to tens of kN of the vertical component of thrust. Surfaces related to lower resistances to the rolling of wheels $f_{wh}.0$ occupy the half-space to the left of the red surface of the thrust required for steady motion. QE power for vehicle acceleration and maneuvering occupies the half-space to the right of the red surface of thrust (up to the cylindrical surface of maximum thrust). All future studies on searches for optimal trajectories shall be performed in this spatial domain.

It can be seen that the line segment between points 10 and 8 in Figure 2 corresponds to the force of wind resistance P_w = 15.8 kN. This value is constant for a particular slice of velocity. With changes in the resistance of the bearing surface ($f_{wh.0}$ = var), 8-1 line inclination will

change as well. Moreover, due to the stable position of point 8, line 8-1 will rotate about it. Dependence between the position of the surface of the required thrust and $f_{wh.0}$ coefficient can be seen in Figure 6.
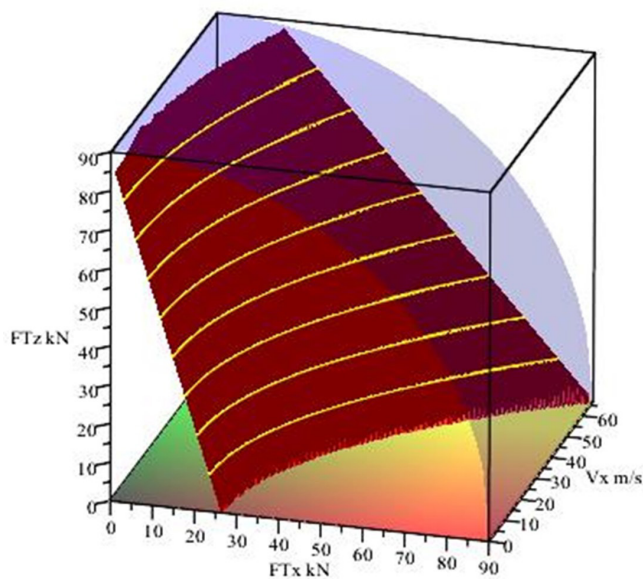

Figure 5. Surfaces: maximum QE thrust (blue, cylindrical) and thrust required for steady motion along the bearing surface with the coefficient of resistance $f_{wh.0}$ = 0.3 (red)
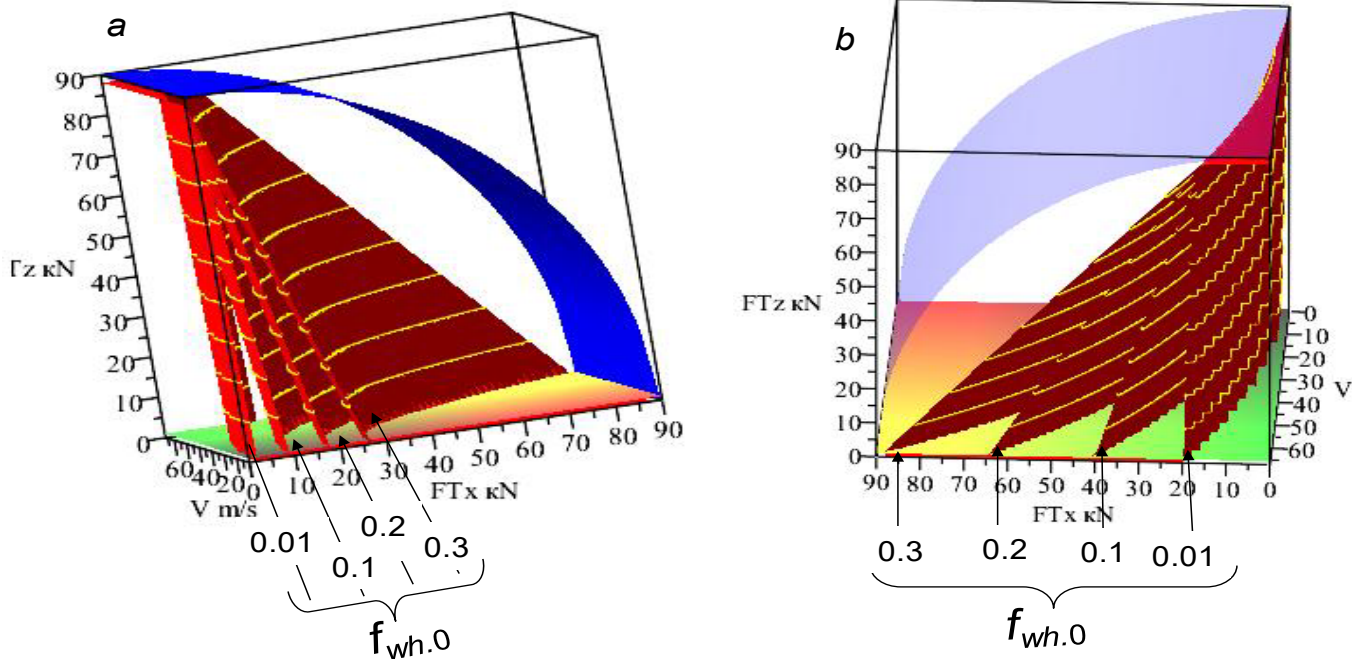

Figure 6. Surfaces of the thrust required for steady motion of a quantomobile on roads with various $f_{wh.0}$ coefficients

The addition of resistance to the rolling of wheels and wind resistance, resulting in total resistance to uniform longitudinal motion of a vehicle, is represented in a model based on equation (6). It is graphically shown in Figure 7. Forces of wind resistance (area to the left of the blue surface) and resistance to the rolling of wheels (area between the blue and red surfaces) are added to form total resistance to uniform vehicle motion (red surface). The area limited by the red and blue surfaces is a subspace for the use of thrust for vehicle acceleration and maneuvering.
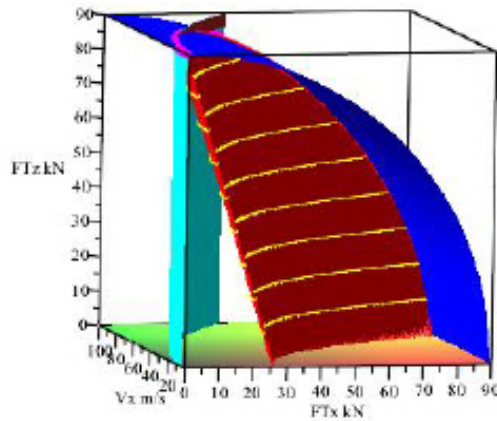
Figure 7. Addition of forces of wind resistance (to the left of the blue surface) and resistance to the rolling of wheels (between the blue and red surfaces), forming total resistance to vehicle motion (red surface).
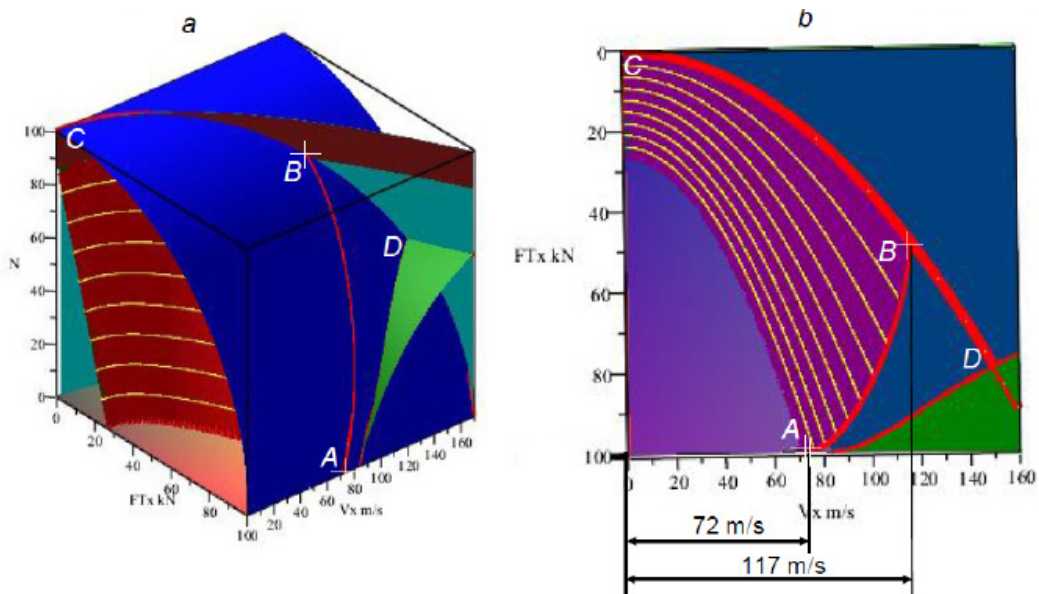

Figure 8. Set of surfaces and lines in the developed model: one of the options

Results

The main result of the study is a graphical-and-analytical basis for optimization calculations of quantomobile motion, changes in QE thrust and corresponding control actions. Its analytical component is a generalized quantomobile force balance equation taking into account the decomposition of the thrust vector into orthogonal component, which is a key element when determining optimal combinations of energy consumption for vehicle hovering and gains from a decrease in driven wheels resistance upon such hovering. While in case of aircrafts and helicopters, vertical takeoff (VTOL) and short takeoff (STOL) modes represent a small share of their relatively long-lasting operation, for quantomobile, near-ground motion can be the main long-term mode. Therefore, it is important to search for optimal combinations of the vertical and horizontal thrust components.

Maple software tools provide a rotating view of graphical 3D images, allow for interactive model modification, creation of animations. Besides the mentioned graphical functions, numerous additional options embedded in the model can be noted: surface intersection lines, surface limits along those lines, and surface extension outside the set limits (Figure 8).

With this figure as an example, the following conclusion can be drawn: if a quantomobile with the indicated characteristics and QE with a maximum thrust of 100 kN moves along the bearing surface with $f_{wh.0}$=0.3 in the automobile mode (without hovering), it is possible to achieve speed V_x=72 m/s, while the maximum achievable speed upon partial hovering V_x=117 m/s (Figure 8*b*). In the first case, point A represents an "exit" of line AB (intersection of the red surface of the required thrust and blue surface of the QE maximum thrust) onto the plane F_{Tz}=0. In the second case, point B represents a point of intersection between line *AB* and line *CD* (intersection of the blue (+ brown in the upper part) surface of wind resistance with the dark blue surface of maximum thrust).

Therefore, at the same thrust, the maximum speed of a vehicle upon partial hovering is 50% more than the speed of a vehicle in the automobile mode, and that is due to the thrust vector direction only.

Discussion

Maple software is a powerful and flexible system with a wide mathematical apparatus, multi-parameter analytics of problem solving, and nice business graphics. It may seem that due to the lack of a real object being modeled (quantomobile), we are actually using a sledgehammer to crack a nut. However, its deep understanding is possible only with the use of such powerful tools.

Development of the quantomobile simulation model as well as its graphical-and-analytical basis in the direction of increasing complexity is the only way. At the next stage, it is required to program the generalized equation of qauntomobile motion, turn to differential models of vehicle motion, introduce a model of QE control, then turn to optimization models of trajectory control, develop special quantomobile aerodynamics, combine course and lateral motion, and, finally, switch to the concept of a "flying saucer". At all those stages, it will be necessary to form a graphical-and-analytical basis using Maple software tools.

Exit from the mode of near-ground motion is ensured by inequation $F_{Tz}>G_q$. Several tests with the use of the model showed the following: in case of road resistance disappearance (at $F_{Tz}>G_q$), the formation of the second zone of thrust minimization is possible. A vehicle passes some crest in the force balance, which is related to hovering in the area $\gamma\approx0.8…1.0$. The latter circumstance is likely to matter when choosing a type of quantomobile takeoff: vertical (VTOL), short (STOL), or combined.

The numerical examples are based on the use of geometry, weight and aerodynamics parameters of similar KamAZ-4326. On the one part, this racing truck with more than a thousand HP happened to be the most similar to the hypothetical laboratory quantomobile (Kotikov, 2018b) in terms of force balance (Kotikov, 2018c, 2019a). On the other part, the mentioned parameters (in particular, aerodynamics parameters) will be unsatisfactory for the quantomobile. In that respect, all numerical examples and graphical images presented in this paper characterize the worst options of force balance and required thrust. Nevertheless, high design speeds of quantomobile near-ground motion (117 m/s and more) are due to the quantomobile thrust, which exceeds the automobile thrust significantly (Kotikov, 2018c, 2019a).

Conclusions

Based on the generalized quantomobile force balance equation (derived by the author), the graphical-and-analytical basis was developed to study quantomobile near-ground motion. The calculations, analysis, and visualization were based on the equation implementation in the Maple environment.

According to the calculation studies, in the middle of the full range of thrust vector inclination angles (0−90°), a zone of the most beneficial use of thrust upon partial hovering of a vehicle is located. This creates opportunities for developing methodologies to substantiate thrust control when a vehicle interacts with the bearing surface.

The Maple graphical tools allowed us to perform a visual analysis of the space topology with regard to thrust resources in a vehicle with a QE, and confirm the possibility of using the software analytical tools in further studies.

At the current stage (with the simplest linear algebraic model for vehicle interaction with the road and simplified aerodynamics of the "flying box"), the first step of quantomobile near-ground modeling using Maple can be considered sufficient and adequate.

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ГРАФОАНАЛИТИЧЕСКИЙ БАЗИС ИССЛЕДОВАНИЯ ПРИЗЕМНОГО ДВИЖЕНИЯ КВАНТОМОБИЛЯ

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Аннотация

Введение. Продвижению исследовательских работ по созданию квантомобиля будет способствовать создание графоаналитического базиса для оптимизационных расчетов управления движением этого транспортного средства. Цель. Сформировать методику графического отображения области реализации вектора траста (thrust) – как графоаналитического базиса для будущих оптимизационных расчетов траекторий движения квантомобиля. **Методы**. Разложение вектора траста на ортогональные компоненты. Использование обобщенного уравнения силового баланса квантомобиля и его упрощения. Определение 6 характерных режимов движения квантомобиля, выделение из них режима частичного вывешивания как основного в приземном движении. 2D-моделирование силового баланса для скоростного среза. 3D-моделирование силового баланса с разверткой по скорости. Программирование 2D и 3D моделей силового баланса в ППП Maple. Построение образов поверхностей сопротивлений дороги и аэродинамических сил, максимального и достаточного траста. Расчетные и графоаналитические исследования на примерах. **Результаты.** Сформирован графоаналитический базис для оптимизационных расчетов траекторий движения квантомобиля, изменения траста его КвД и соответствующих управляющих воздействий. Представлены результаты вычислений с визуализацией на конкретных примерах. **Обсуждение.** Создание программы в среде графического ППП потребовало комплексирования знаний как средств пакета, так и программируемой области знаний. Естественным будет путь развития расчетной модели квантомобиля и его графоаналитического базиса по пути возрастающей сложности, приводятся этапы развития. Отмечены две предположительные зоны минимизации достаточного траста: в срединной части степени вывешивания экипажа и после его полного вывешивания. Это необходимо учитывать при реализации как взлета квантомобиля, так и при приземном движении с частичным вывешиванием.

Ключевые слова

Квантовый двигатель, квантовая тяга, квантомобиль, приземное движение, силовой баланс, графоаналитический базис