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Suvorova M.O.
Avilova I.P.
Naumov A.E.

Reducing the carbon footprint of buildings to improve sustainable development mechanisms of the construction complex

The construction industry's impact on the environment is overwhelming. Construction and industrial activities account for about 40 % of the global energy consumption that translates into about one third of global greenhouse gas emissions. The rapid growth of property development and attention to global climate change make the reduction of greenhouse gas emissions a promising area of research. The importance of the carbon impact assessment throughout the life cycle of buildings implies the improvement of emission reduction methods associated with the production and transportation of building materials, selection of optimal design solutions. Evaluation becomes key to the economic modeling of green low-carbon construction. The article addresses the current methods of the eco-economic assessment of the carbon impact of residential buildings at early stages of construction projects. Key construction resources, critically affecting the eco-performance of buildings, are identified. The comparative analysis of functionally equivalent design solutions for mid-rise residential apartment buildings, designed and constructed in the Belgorod region, is carried out. The study shows that the introduction of low-carbon principles into the design of residential buildings should and can be supported by the improved eco-economic evaluation of the construction project efficiency. This allows to capitalize the carbon impact of residential buildings and stimulate the use of effective green low-carbon motivation tools in the building market.

Keywords: *sustainable development, green building, low-carbon construction, carbon footprint of buildings, cost efficiency of construction projects*



Suvorova Maria Olegovna,
Lecturer of the Department of Construction Management and Real Estate; Belgorod State Technological University named after V.G. Shukhov (BSTU named after V.G. Shukhov); 46 Kostyukova St., Belgorod, 308012, Russian Federation; ID RISC: 811292; Scopus: 57196246833; ResearcherID: AAC-4403-2019; ORCID: 0000-0001-7423-6866; marykrutilova@gmail.com



Avilova Irina Pavlovna,
Candidate of Economic Sciences, Professor of the Department of Construction Management and Real Estate; Belgorod State Technological University named after V.G. Shukhov (BSTU named after V.G. Shukhov); 46 Kostyukova St., Belgorod, 308012, Russian Federation; ID RISC: 646843, Scopus: 57164826800; kafeun@mail.ru



Naumov Andrey Evgen'evich,
Candidate of Technical Sciences, Assistant professor, Chief of the Department of Construction Management and Real Estate; Belgorod State Technological University named after V.G. Shukhov (BSTU named after V.G. Shukhov); 46 Kostyukova St., Belgorod, 308012, Russian Federation; ID RISC: 683551, Scopus: 56448117200, ResearcherID: K-1704-2018, ORCID: 0000-0002-8162-1946; andrena@mail.ru

INTRODUCTION

The construction sector, being a material and energy intensive manufacturing industry, has a significant impact on the environment and a direct impact on the development of sustainable territories and the implementation of the concept of low-carbon state development [1]. Residential construction grows year-by-year thanks to the implementation of the state programs, focused on providing affordable and comfortable housing and directly related to the increase in the production of building materials and construction machinery. Hence, this trend emphasizes the critical importance of the construction industry as the principal indicator of the state development, in general, and the core constituent of the manufacturing and construction sector of the economy, whose eco-sustainability is impossible without effective economic motivation tools[1]. Construction intensification, being a tool for attaining the social objectives of national development, must cause a minimal increase in the environmental impact, since environmental safety is an equally important priority of the future public development. Since construction and manufacturing are among the main sources of global greenhouse gas (GHG), emissions and residential construction rise every year. Effective widescale decarbonization of construction of residential buildings and civil engineering facilities is the way to reduce GHG emissions and implement the Strategy for the long-term development of the Russian Federation through 2050, that entails low greenhouse gas emissions (according to the 2018 report of the Intergovernmental Panel on Climate Change (IPCC)) [2].

1 Global Sustainability Report 2020 — Buro Happold. 2021. URL: https://www.burohappold.com/publications/global-sustainability-report-2020/

To achieve the target values of GHG emissions by 2050, it is necessary to introduce low-carbon principles of evaluation, monitoring and capital construction management into the practice of engineering design and economic analysis and offer effective, efficient and self-sustaining instruments for the economic evaluation of the carbon impact (CI) in respect of newly constructed and renovated buildings [3].

THE MAIN PART

According to EN 15643-4:2012 "Sustainability of construction works. Framework for the assessment of economic performance", sustainable development of industrial production and construction industries is a key management task at all stages of the life cycle (LCC) of a construction project. The implementation of this principle facilitates the development of optimal cost-effective low-carbon design solutions at initial stages of a project, including the feasibility study and selection of building materials, products and structures, machinery and construction technologies. However, an extensive methodological framework, currently used for quantifying GHGs, is still not adequately represented in the instruments for its economic evaluation [4, 5]. Currently, about 70–80 % of GHG emissions are associated with the operational phase of buildings (B 1-7), while embodied emissions are primarily associated with the production of building materials (A1-A3), transportation (A4) and construction procedures (A5), as well as emissions at the end of the life cycle (C1-C4) [6]. The World Green Building Council identifies emissions at stages A1-A5 as the "upfront carbon", which is becoming increasingly important in evaluating CI during the LCC (Fig.).

Building life cycle information												
A 1-3	A 4-5		B 1-7							C 1-4		
Product stage	Construction process stage		Use stage							End of life stage		
Raw material supply Transport Manufacturing	Transport	Construction installation process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction Demolition	Transport	Waste processing	Disposal
A1–A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4
The ability to influence the carbon Impact (CI) max ← min												
The variability of instruments of influence on CI			Energy-saving and energy-efficient technologies									

Carbon footprint throughout the life cycle of a building

The ratio of preliminary GHG emissions at stages A1-A5 varies depending on the type and purpose of a building, its special arrangement and structural solutions [7]. The main sources of upfront carbon include energy and resource-intensive building materials, products, structures and processes at the stages of procurement of raw materials and construction (supply of raw materials, production of materials, transportation, etc.) [8]. For the preliminary evaluation of GHG emissions for a designed building it is necessary and sufficient to determine the amounts of principal energy and resource-intensive building materials at the early stages of design. This will allow to carry out the economic analysis to identify the areas of optimization of structural and spatial solutions at the stage of design and project budget development. The building information modeling (BIM) technology is increasingly used in the design practice, also to perform the quantitative assessment of the resource intensity of design solutions, although it needs effective tools for their interpretation, including the carbon impact assessment. BIM principles, used to design efficiency evaluation instruments, have proven that the project resource intensity is highest at the pre-project stage, when the detailed amount of construction resources is unavailable. Hence, methods of analyzing the resource intensity of structural solutions at early stages of design gain in importance [9]. Therefore, further development of methods for the quantitative assessment of the resource intensity of construction and its carbon impact becomes an effective tool for the instant diagnostics of structural solutions used to assess building sustainability [10] and the implementation of its economic incentive mechanisms.

The monitoring of embodied carbon, or the total GHG emissions associated with the process of using construction resources throughout the building life cycle is a relatively new area of research, whose results have been implemented neither in any standards or regulations, nor in a preliminary carbon impact assessment of construction projects at early stages of design [11]. A variety of international developers use decarbonization methods in structural design and collect data on various types of facilities in different countries: Australian Sustainable Built Environment Council, Building Research Establishment (BRE), C40 Cities Climate Leadership Group, Danish Building Research Institute — Aalborg University, Nanyang Technological University, Saint-Gobain, Global Alliance for Building and Construction (GABC), Architecture 2030, etc.

In order to demonstrate the proposed construction principles, the co-authors developed an improved methodology for assessing the carbon intensity of a construction project at the preliminary stage of design, selected the key resources for the twenty projects of residential apartment buildings in the Belgorod agglomeration, belonging to the same group by the floorage, the functional purpose and equivalent design solutions, that represented a monolithic reinforced concrete (RC) frame (Table 1). This methodology is a basic construction management tool, that takes account of the building's carbon footprint.

The selection allowed the co-authors to analyze the relationship between the amount of key construction resources and indicators of space-planning solutions of buildings (area, number of storeys, structural density) using linear multiple regression, which demonstrated a stable, strong and qualitative regression relationship (Table 2).

These dependencies not only demonstrate a relationship between the key indicators of the resource intensity and SPS of residential buildings, but also provide an effective algorithm for the preliminary assessment of design solutions at the stage of their feasibility study, thus eliminating the most resource-intensive solutions and focusing the designer's attention on those of them that feature the highest carbon efficiency [12]. The methodology development by adding other structural and process patterns to the analyzed samples and analyzing an expanded list of construction resources (masonry, finishing, lumber, composites, plastics, etc.) will serve as the basis for a fast evaluation of the resource and carbon intensity of buildings and structures, thus, quantitatively formalizing

Table 1. Selective resource intensity of mid-rise residential apartment buildings having monolithic RC frames in the Belgorod region

Project No.	Space-planning solutions (SPS)			Construction resources		
	Total area (A), m²	Number of storeys (S), pcs.	Structural floor density (D), m³ walls/m² area	<CMa>CD: concrete, m³	<CPr>AJAA: Steel, t	<CPr>ACA: wall masonry materials, pcs.
1	1,223.5	3	0.11	331.0	13.0	290.5
2	1,395.0	3	0.13	280.7	15.6	434.1
3	1,448.1	3	0.15	359.5	13.1	274.9
4	1,475.5	3	0.13	370.6	15.6	174.0
5	1,492.2	3	0.10	331.3	14.9	336.3
6	1,984.2	3	0.10	289.8	14.3	382.5
7	3,512.0	3	0.11	711.0	47.0	620.2
8	1,876.8	5	0.13	290.7	13.7	250.1
9	2,776.0	5	0.11	759.9	21.1	481.9
10	3,257.0	5	0.15	612.8	74.6	647.6
11	3753.6	5	0.14	748.0	45.2	491.4
12	4,232.2	5	0.10	810.2	44.1	800.5
13	4,260.0	5	0.11	1,041.7	65.3	686.4
14	4,998.6	5	0.11	940.6	59.7	879.1
15	5,374.4	5	0.11	870.1	47.6	785.0
16	6,109.0	5	0.10	1,003.1	56.3	607.7
17	6,192.9	5	0.14	976.3	49.9	867.9
18	6,839.1	5	0.11	1,980.2	56.8	862.7
19	8,805.8	5	0.14	2,079.0	63.3	641.5
20	8,826.4	5	0.13	2,661.0	66.6	1,010.1

Table 2. Regression models of a number of construction resources: concrete, steel, wall masonry materials

<CMa>CD = – 514.3D + 0.27A – 31.59S	$R^2_{norm} = 0.889$, F(116.2) >$F_{nominal}$ (4.5×10-11)
<CPr>AJAA = – 65.17D + 0.005A – 6.1S	$R^2_{norm} = 0.863$, $F(75.0) > F_{nominal}$ (1.2×10^{-9})
<CPr>ACA = 300.75D + 0.07A + 61.57S	$R^2_{norm} = 0.892$, $F(122.6) > F_{nominal}$ (3.0×10^{-11})

the principle of low-carbon design. It will also enable methodology users to proceed to the design support, sustainable construction, and construction industry development [13].

Economic incentive mechanisms, that boost low-carbon development, include the preliminary evaluation (and full evaluation at further stages of design) of the resource intensity of design solutions and the cost assessment of the carbon impact of key construction resources in the form of a conditional ecological tax (EcoT) [14]. EcoT is a tool that objectively evaluates the environmental sustainability of the industry and represents an effective state regulation mechanism that allows for the additional assessment of the project, taking into account the degree of the project development, with regard for the regional market of green materials and solutions and the local specificity of the construction industry [15]:

$$EcoT = \frac{ECC_{max} - ECC_{min}}{CO_{2max} - CO_{2min}} K,$$

where ECC_{max} is the maximum estimated cost of the building construction; ECC_{min} is the minimum estimated cost of the building construction; CO_{2max} is the maximum carbon footprint of the building; CO_{2min} is the minimum carbon footprint of the building; K is the multiplier used to selectively assess and regulate the degree of economic interest of developers in the application of green technologies broken down by sectors and types of buildings. Buildings

are selected according to the construction projects of a similar focus implemented in the region.

In this case, the key factor of the green developers' efficiency is their active involvement in the implementation of state-funded construction projects. In this regard, given the initial less economically preferable bidding price offer coming from green developers, it is advisable to introduce the institution of green developer certification and using it as the basis for regulating bidding preferences and rising the competitiveness of green developers [16].

The rational use of bidding preference regulation tools will allow executive authorities to regulate the degree of involvement of the state in the green building development in the regions [17]. An example of the proposed concept of assigning bidding preferences to green developers, based on their green certification, is provided in Table 3.

Table 3. The concept of bidding preferences aimed at the effective functioning of the institution of green certification of developers

Green certificate for developers	% EcoT to the total cost of buildings completed by the developer	Bidding preferences
A	0…10	Priority right to obtain large contracts, maximum credibility in the course of evaluation of bidding documents
B	11…25	Preferences in obtaining large contracts, high credibility in the course of evaluation of bidding documents
C	26…99	General contract placement procedure, minimum credibility in the course of evaluation of bidding documents

CONCLUSIONS

Fundamental areas of improvement of the system of construction and industry sustainability support, presented in the article, employ the tools of economic stimulation of low-carbon development as an essential constituent of the building life cycle. The rapid assessment of the resource intensity of construction projects in respect of several types of construction resources and potential space-planning and structural solutions is proposed by the co-authors. The proposal has a set of initial data used for the quantitative assessment of a capitalized carbon impact of a building and generation of institutional instruments to motivate developers to use green technologies. For buildings designed using BIM, the proposed technology will enable the real-time management of estimated supplementary eco-costs by optimizing the design solutions in terms of the investment cost of construction projects. As a result, an effective tool will be implemented to assess the carbon impact of buildings throughout their life cycle in conjunction with measures aimed at reducing operational GHG emissions. It will contribute to the improvement of the instrumental support of conversion to the low-carbon sustainable development of the entire construction industry.

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Совершенствование механизмов устойчивого развития строительного комплекса путем сокращения углеродного воздействия зданий

Влияние строительной отрасли на окружающую среду неоспоримо: около 40 % общего мирового потребления энергии связано со строительной и промышленной деятельностью, что составляет около трети глобальных выбросов парниковых газов. Интенсивный рост строительства, в первую очередь в жилищном секторе, и возросшее внимание к глобальным изменениям климата делает вопросы сокращения выбросов парниковых газов и перехода к низкоуглеродному устойчивому развитию перспективным направлением исследования. Важность оценки углеродного воздействия в течение всего жизненного цикла зданий, которое становится основой эффективных инструментов экономического симулирования зеленого низкоуглеродного строительства, обусловлена перспективами оптимизации на его основе проектных и организационно-технических решений в строительстве. В статье выполнен анализ существующих методов эколого-экономической оценки углеродного воздействия жилых зданий на ранних этапах реализации инвестиционно-строительных проектов, выявлены ключевые строительные ресурсы, которые критически влияют на его экологическую эффективность с позиции минимизации углеродного воздействия, продемонстрирован механизм эколого-экономической оценки и ранжирования функционально и конструктивно эквивалентных проектных решений жилых многоквартирных домов средней этажности, запроектированных и реализуемых в Белгородской агломерации посредством сравнительного анализа их углеродного воздействия. Авторами показано, что внедрение низкоуглеродных принципов устойчивого развития в практику проектирования жилых зданий должно и может быть подкреплено совершенствованными методиками экономической оценки эффективности инвестиционно-строительных проектов с позиции декарбонизации строительства, которые монетизируют натуральное углеродное воздействие жилых зданий и становятся основой действенных инструментов рыночной мотивации участников инвестиционно-строительного процесса к переходу на зеленые низкоуглеродные технологии.

Ключевые слова: *устойчивое развитие, зеленое строительство, низкоуглеродное строительство, углеродное воздействие зданий, экономическая эффективность строительных проектов*

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Об авторах: **Суворова Мария Олеговна** — старший преподаватель кафедры экспертизы и управления недвижимостью; **Белгородский государственный технологический университет им. В.Г. Шухова (БГТУ им. В.Г. Шухова)**; 308012, г. Белгород, ул. Костюкова, д. 46; РИНЦ ID : 811292, Scopus: 57196246833, ResearcherID: AAC-4403-2019, ORCID: 0000-0001-7423-6866; marykrutilova@gmail.com;

Авилова Ирина Павловна — кандидат экономических наук, профессор кафедры экспертизы и управления недвижимостью; **Белгородский государственный технологический университет им. В.Г. Шухова (БГТУ им. В.Г. Шухова)**; 308012, г. Белгород, ул. Костюкова, д. 46; РИНЦ ID 646843, Scopus: 57164826800; kafeun@mail.ru;

Наумов Андрей Евгеньевич — кандидат технических наук, доцент, заведующий кафедрой экспертизы и управления недвижимостью; **Белгородский государственный технологический университет им. В.Г. Шухова (БГТУ им. В.Г. Шухова)**; 308012, г. Белгород, ул. Костюкова, д. 46; РИНЦ ID: 683551, Scopus: 56448117200, ResearcherID: K-1704-2018, ORCID: 0000-0002-8162-1946; andrena@mail.ru.

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