Methodology of ecooriented assessment of constructive schemes of cast in-situ RC framework in civil engineering

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Abstract. Economic growth is the main determinant of the trend to increased greenhouse gas (GHG) emission. Therefore, the reduction of emission and stabilization of GHG levels in the atmosphere become an urgent task to avoid the worst predicted consequences of climate change. GHG emissions in construction industry take a significant part of industrial GHG emission and are expected to consistently increase. The problem could be successfully solved with a help of both economical and organizational restrictions, based on enhanced algorithms of calculation and amercement of environmental harm in building industry. This study aims to quantify of GHG emission caused by different constructive schemes of RC framework in concrete casting. The result shows that proposed methodology allows to make a comparative analysis of alternative projects in residential housing, taking into account an environmental damage, caused by construction process.

1. Introduction

Russia has emerged as a major player in international climate politics due to its decisive role into force of the Kyoto Protocol, its position as a major global fossil-fuel supplier, and its significant rate of global emissions (fourth-largest, with a rate about 5%) [1]. The building sector should be prioritized in order to be able to reach a sustainable society because, as of 2010, the building sector constituted almost 30% of global CO₂ emission (IEA) [2]. In Russia, the emission rates are 7% of total emission in addition to the transport services sector accounts for about 10%, which allows estimating the total emission in construction industry, including related logistics in the range of 12-15%. It makes the task of reducing the environmental harm caused by construction industry quite significant. The 2013 Prognosis of Socio-economic Development until 2030 (developed by the Ministry of economic development of the Russian Federation) forecasts that greenhouse gas (GHG) emissions will reach 75% of the 1990 level by 2020, thereafter declining to 70% by 2030 as a result of energy-efficiency measures, increased labor productivity, and renewable energy policies [3]. In this context, the issues of enhancement of practical algorithms of calculation and penalization of environmental harm in building activities will be a part of basis for successful solution of the problem.

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2. The problem statement and methods
As environmental issues continue to become increasingly significant, the energy required for construction industry and for the material production is getting of greater importance. GHG emissions at the construction phase are not usually considered in life cycle assessment of GHG emission and which called indirect emission. It should be noted that building materials (including manufacturing), construction works (including building equipment) and transport – all of these processes consume energy and therefore emit GHG [4]. Despite the fact that during the life cycle of the building a number of studies on energy consumption and GHG emission was carried out, practical methods for GHG emission quantifying at the construction stage have not been still implemented in construction design.

The building’s total consumed energy depends on the amount of the material and installation work used in construction stage and their previously consumed energy [5]. In this case the environmental safety grade of used materials and the energy safety grade of used construction technology are important. Thus, it is necessary to consider environmental pollution and try to decrease emissions at the pre-project and project stages, thereby to mitigate the environmental consequences of the construction of buildings and structures. Firstly the problem deals with erecting of reinforced concrete (RC) structures as the most common and energy consumed constructions.

Constructive schemes active used in RC frameworks in Russian civil engineering in last 7 years presented in Figure 2. Average share of cast-in-situ frameworks sustainably increased by 14% per year, nowadays totally including more than 18% of newly constructed residential houses [6].

![Figure 1. Russia’s GHG emission rate according to economic sector, 2012 [1].](image1)

![Figure 2. Arrangement of residential houses according to constructive materials in the Russian Federation in 2009-2017.](image2)

At pre-project stage in civil RC constructions design, in most cases, several constructive schemes are allowable, but till nowadays comparative analysis of alternative schemes is carrying out according to such economic issues as construction cost, duration of construction and consumed manpower.
Meanwhile alternative schemes often drastically differ by energy and resource consumption. This important issue has almost no reflection in construction prices and could not be taken into account according actual construction code, because of lack of practical methods of environmental harm quantifying. Thus, improved algorithms of economic environmental analysis should be updated by the calculation and penalization (CP) method of GHG emission, caused by alternative constructive schemes. Proposed CP consists of four main stages [4]:

1. Estimating of basic expenditures of building the multistory RC frames by alternative constructive schemes.
2. Determination of GHG emission caused by building materials and construction works based on actual estimating codes.
3. Monetary penalization of revealed GHG emission
4. Comparative estimation of construction cost incl. eco- penal fines for alternative constructive schemes.

3. Results and discussion

Let’s take a closer look to the importance and significance of CP at pre-project stage in a comparative analysis of possible constructive schemes of RC frame forming residential house (MRH).

Stage 1. According to ABC analysis one can highlight the most significant and expensive structural materials and installation works. It allows to preliminary assess the effectiveness of “green” building technologies in various constructive schemes and select the safest one for project stage. Based on the authors’ data, the most costly and resource-intensive lines in estimates of MRH RC frames are: 1. Concrete mix’s materials. 2. Preparing of concrete mix. 3. Pouring of concrete mix. 4. Steel reinforcements. 5. Formwork construction. 6. Reinforcements and concrete mix transportation.

According to preliminary analysis three mostly preferred constructive scheme of MRH RC frame are (figure 3):

1. Frequently placed square-shaped columns and separate rigid walls (scheme 1);
2. Distantly placed rectangular-shaped pylons and rigid cores (scheme 2);
3. System of longitudinal and transverse walls (scheme 3).

Figure 3. Constructive schemes of MRH RC frame.
For estimating of basic expenditures in building of MRH RC frames by constructive schemes shown above the quantity and cost of necessary materials, machines and equipment should be determined, also 1m² of constructed framework. Table 1 shows list of quantities and estimated costs for three constructive schemes determined by using of Federal Unit Rates for construction works in Russia [8].

**Table 1.** Estimates of basic expenditures for constructive schemes of MRH RC frame.

| Material expenditures | Scheme 1 | Scheme 2 | Scheme #3 |
|-----------------------|----------|----------|-----------|
| Concrete, m³          | 1590     | 2031     | 2704      |
| Steel reinforcements, t | 215     | 155      | 180       |

| Machines expenditures | Cranes, hrs | Trucks, hrs | Mixers, hrs | Welding machines, hrs |
|-----------------------|-------------|-------------|-------------|----------------------|
|                       | 79          | 851         | 34          | 101                  |
|                       | 105         | 945         | 43          | 155                  |
|                       |             |             |             | 184                  |
|                       |             |             |             | 1227                 |
|                       |             |             |             | 71                   |
|                       |             |             |             | 218                  |
| Total construction cost before penalties, mlnRUR | 16.31 | 24.13 | 41.22 |

**Stage 2.** At this stage, GHG emission caused by main construction materials (concrete and steel) and works is quantified. For certain, all the embodied GHG emission, caused by producing and installation of constructions, using engines and equipment, wasting of energy to provide all kinds of necessary in-situ management need to be estimated separately. All the building materials during its producing, transportation and installation require energy consumption and cause GHG emission as well [9]. ABC analysis at previous stage allowed to highlight the basic construction materials and works, which GHG emission’s determination should be enough for comparative purposes. Based on [10, 11] GHG emission from the production of materials shown in tables 2-3.

**Table 2.** GHG emission from the production of 1m³ of typical concrete.

| GHG emission | Unit | Total |
|--------------|------|-------|
| CO₂          | kg   | 1.5   |
| CO           | g    | 0.86  |
| NOₓ          | g    | 2.3   |
| SOₓ          | g    | 3.3   |
| CH₄          | g    | 1.7   |
| HC           | g    | 0.32  |

Main equipment for RC frame’s construction (trucks, cranes, mixers) were selected by specific machines’ models. Each machine has its engine power and performance specifications, affecting the GHG emission. Based on [12] GHG emission from the specified machines shown in table 4.

**Table 4.** GHG emission from the specified machines

| Equipment type | Manufacturer | Engine power, kW | GHG emission |
|----------------|--------------|------------------|--------------|
| Trucks         | Kamaz 5501   | 176              | 69 g/s       |
| Cranes         | Potain MDT-180 | 120          | 46 g/s       |
| Mixer          | Putzmeister BSA 1407 D | 115 | 77 g/s |
| Welding machine | Stavr SAI-180 BTL | 6 | 33 g/kg |
According to list of quantities GHG emission were determined for construction materials and works (including machines and equipment) in table 5, 6.

**Table 5.** GHG emission calculator: construction processes(scheme1).

| Machines              | Volume  |
|-----------------------|---------|
| 1. Trucks             |         |
| Truck’s engine power, kW | 176     |
| Lifting capacity, t   | 10      |
| Estimated working time, hr | 1227    |
| Estimated GHG emission, g/sec | 24.5    |
| Estimated GHG emission total, t | 108     |
| 2. Cranes             |         |
| Crane’s engine power, kW | 120     |
| Lifting capacity, t   | 8       |
| Estimated working time, hr | 184     |
| Estimated GHG emission, g/sec | 46      |
| Estimated GHG emission total, t | 18.9    |
| 3. Mixer              |         |
| Mixer’s engine power, kW | 115     |
| Mixing capacity, m3/hr | 71      |
| Estimated working time, hr | 57      |
| Estimated GHG emission, g/sec | 77      |
| Estimated GHG emission total, t | 15.8    |
| 4. Welding machines   |         |
| WM’s power, kW        | 6       |
| Estimated working time, hr | 218     |
| Estimated GHG emission, g/kg | 33      |
| Estimated GHG emission total, t | 5.9     |

| Materials             | Volume  |
|-----------------------|---------|
| 1. Reinforced concrete (RC) |         |
| Estimated GHG for cement production, g/cub.m | 1508   |
| Estimated concrete volume, cub.m | 2704    |
| Estimated GHG emission total, t | 4.1     |
| 2. Construction Steel |         |
| Estimated GHG emission for steel production, t/t | 0.6    |
| Estimated GHG emission total, t | 108     |

**Table 6.** GHG emission calculator: results(scheme 1, 2, 3).

| Constructive schemes                  | Scheme 1 | Scheme 2 | Scheme 3 |
|---------------------------------------|----------|----------|----------|
| Total GHG emission caused by machines, t | 105      | 115      | 149      |
| Total GHG emission caused by materials, t | 134      | 99       | 116      |
| Total GHG emission caused by construction process, t | 238      | 214      | 265      |

**Stage 3.** At this stage the revealed GHG emission should be monetary penalized. All actual damage, determined in GHG-emission volume for compared constructive schemes at the previous stages should be expressed in monetary equivalent (penalties) according proposed method of estimating: eco-penalty is equal to the Cost Of Prevention (COP) before or Cost Of Sanitation (COS) after harm caused [13].

\[
\text{Eco-penalty} = \text{COS} + \text{COP} = \text{RCT} \times k5 + (\text{COP}_1 \times k_1 + \text{COP}_2 \times k_2 + \text{COP}_3 \times k_3) \times k_4 \quad (1),
\]

As the basis for the assignment of eco-penalties is GHG emissions per unit of material/work/services, COP is defined as:

\[
\text{COP} = (\text{COP}_1 \times k_1 + \text{COP}_2 \times k_2 + \text{COP}_3 \times k_3) \times k_4 \quad (2),
\]

\text{COP}_1—\text{cost of Research and Development (R&D), aimed to environmental sustainability of the material/technology over the past year divided by GHG emission in the country’s production;}
COP\textsubscript{2}—difference in cost of materials/services produced by the most eco-friendly technology for the current year to the cost of the same materials/services produced by the technology specified by manufacturer, which is penalized.

COP\textsubscript{3}—difference in amount of material/services, produced in the penultimate and preceding year multiplied by the average across the region the cost of material/services.

\(k_1...k_3\)— weight indexes, \(k_4\)— activity index.

COP\textsubscript{1} encourages research funding, COP\textsubscript{2}—implementation of green technologies, COP\textsubscript{3}— using of energy-efficient constructive schemes. Indexes \(k_1...k_3\) are set by the authorities, giving importance to a particular direction of greening construction, and, accordingly, using a certain management politics at the construction market. Index \(k_4\) allows to level the peaks and valleys of activity in the market, reducing and increasing financial responsibility for environmental project’s deficiencies, depending on whether authorities fosters or hinders the local construction industry according with the current trends of the regional’s ecology.

The Kyoto Protocol determines total number of permitted emissions of GHG on the planet establishing regional carbon taxes (RCT) at the market \cite{2}. Thus, cost of sanitation (COS) is defined as:

\[
\text{COS} = RCT \times k_5 \quad (3),
\]

\(k_5\) — accumulated cost of regional constructions divided by current year’s GDP.

\begin{figure}[h]
\centering
\includegraphics[width=0.7	extwidth]{figure4.png}
\caption{Construction cost of different types of RC frameworks before and after penalization (specimen of eco-oriented assessment).}
\end{figure}

4. Conclusion
Summarizing the above, we can say that conducted method of eco-oriented assessment of constructive schemes of monolithic RC frame in civil engineering allows to carry out comparative analysis of alternative designs in residential housing according to taking into account of embodied environmental harm, caused by construction process. This engineering technique based on selecting the number of basic construction materials, works, machines help to assess construction costs after eco-penalization and could be efficient additional tool at the pre-project eco-environmental analysis of civil structures. The same method could be implemented in comparative analysis and looking for environmentally safest possible design in widespread civil constructions. Observed penalty method is the effective way to decrease environmental harm caused by construction sector itself by means of enhancement of construction legislation.

Thus, according to the figure 4 alternative constructive schemes are ranked by economic efficiency as: 1, 2, 3 (before penalties). After implementing CP-procedure the alternative constructive schemes
are ranked by eco-oriented economic efficiency as: 2, 1, 3. That means constructive scheme #2 is environmentally fittest and should be considered in further at the project stage.

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