Research article
УДК 691.714:504.3.054
doi:10.18720/SPBPU/2/id21-39

Julia A. Lednova, senior lecturer, PhD,
Peter the Great St.Petersburg Polytechnic University,St.Petersburg, Russia,
lednovajulia@mail.ru

Konstantin O. Semenov, production and technical department engineer,
Capital Tver' Ltd., Tver', Russia,
semenov-k-o@yandex.ru

Vincenzo Bianco, professor, PhD,
University of Genoa, Genoa, Italy,
vincenzo.bianco@unige.it

Anatolii V. Lednov, associated professor, PhD,
Nosov Magnitogorsk State Technical University, Magnitogorsk, Russia,
alednov@mail.ru

GATE-TO-GATE APPROACH FOR OPTIMAL MANUFACTURING TECHNOLOGY OF STEEL MEMBERS

Abstract. Gate-to-gate life cycle assessment (LCA) approach was applied for comparing four variants of I-beam production, taking into account manufacturing, delivery, mounting stages, and load actions. Material and energy consumption, emissions into the atmosphere and economic costs were calculated. Additional manufacturing processes lead to the increase of energy consumption and emissions into the atmosphere during the manufacturing stage while determining a significant decrease on delivery stage.

Key words: I-beam, life cycle assessment, gate-to-gate approach, optimization, environmental impact.

Юлия Анатольевна Леднова, кандидат географических наук,
старший преподаватель, Санкт-Петербургский политехнический
университет Петра Великого, Санкт-Петербург, Россия,
lednovajulia@mail.ru

Константин Олегович Семенов, инженер ПТО,
ООО «Капитал Тверь», Тверь, Россия,
semenov-k-o@yandex.ru

Винченцо Бьянко, профессор, PhD,
Университет Генуи, г. Генуя, Италия,
vincenzo.bianco@unige.it

Анатолий Викторович Леднов, кандидат технических наук, доцент,
Магнитогорский государственный технический университет
им. Г. И. Носова, г. Магнитогорск, Россия,
alednov@mail.ru

КОМПЛЕКСНЫЙ ПОДХОД ДЛЯ ОПТИМАЛЬНОЙ ТЕХНОЛОГИИ ПРОИЗВОДСТВА МЕТАЛЛИЧЕСКИХ БАЛОК

Аннотация. Для сравнения четырех вариантов производства двутавровых профилей был использован подход «от двери к двери» оценки жизненного цикла с учетом стадий производства, доставки и установки, а также требуемых нагрузок. Были рассчитаны потребление материалов и энергии, выбросы в атмосферу и экономическая стоимость. Дополнительные производственные процессы приводят к увеличению потребления энергии и выбросов в атмосферу на стадии производства и значительно снижаются на стадии доставки.

Ключевые слова: двутавровый профиль, оценка жизненного цикла, подход «от двери к двери», оптимизация, воздействие на окружающую среду.

1. Introduction

The concept of "sustainable buildings" has been emerged to resources saving and environmental management during the whole cycle from planning to building demolish, in the last years [1]. The concept is determined by the balance between reduction of the environmental impact, material and energy consumption and increasing of economic efficiency. To realize the concept the tool of life cycle assessment (LCA) can be used. LCA helps to assess the level of sustainability of a building and reduction of the environmental impact of the building sector [2].

LCA technique can be applied for different purposes and different scales for the whole life cycle or partly, which is named as gate-to-gate studies [3]. It leads to apply environmental management approach and find "win-win" solution between resources saving, environmental protection and economic aspects.

LCA approach for the building sector all around the globe is used in different countries, type of buildings and/or constructions and various types of materials. Different research groups have studied various aspects and application of LCA approach for the building market, for example:

– the role of materials in building energy balance [4];

– production methodologies of building materials and an impact on the environmental footprint of buildings group [5];

– amount of energy consumption and emission of greenhouse gases on different phases of life cycle of buildings and type of buildings [6];

– application of the LCA tool to estimate the total carbon emissions as well as the connected costs, in order to minimize them [7];

– economic aspects of construction in the field of international market [8];

– energy and carbon pay-back period for different retrofitting strategies [9].

Other authors have focused on the detailed analysis of the materials and technologies, used in the construction process:

– the environmental footprint for cradle-to-grave approach for I-beam manufactured with stainless steel and glass reinforced plastics [10];

– LCA analysis focused on the welding processes of construction elements [11];

– technologies for metal cutting, taking into account technological and environmental considerations [12];

– optimization of cutting parameters to minimize direct energy consumption during the operation [13].

In this paper an analysis based on the gate-to-gate approach was done for assessment and comparison of I-beam production for four variants of manufacturing processes. Additionally the optimal manufacturing solution in terms of environmental and economic impact for the area of Yamal Region, located in the Northern part of Russia, is identified.

The aim of the present paper is to find the solution that minimizes the mass of the girder, material, energy consumption, transportation costs and the amount of pollutant emissions in the atmosphere taking into account specifics of the loads and comparison of the different manufacturing process to find a “win-win” solution.

It is necessary to take into account that any additional procedure can lead to extra energy and material consumption, increasing negative impact on the environment and total cost. Thus, a "win-win" solution can be achieved by finding the optimal ratio between all the mentioned above components.

2. Materials and Methods

2.1. General description of the case study

Yamal Peninsula is located in the Northern part of West Siberia, which is an important area on gas mining. Specific location of Peninsula includes extreme environmental condition for living and industry development, long distance from highly-developed industrial and economic centers, as well as high sensibility of the environment [14]. The area is under development and requires significant amount of construction works to support mining industry. Closest metallurgy facilities, where steel sections are produced, are located on the Middle and South Urals and West Siberia. The distance between South Urals to Yamal Peninsula is approximately 2200 km, whereas Surgut is located on the distance of 1000 km.

The case is focused on one of the main construction element of any kind of industrial building – I-beam, which can be produced by different technologies. For the assessment of gate-to-gate LCA approach 1,200 simple-jointed girders (I-beams) were assessed to produce, deliver to the construction site and mounting steel structures.

Four technologies of I-beam manufacturing were considered (fig. 1):

1) hot-rolled universal beam (HRN) with rectangular flanges characterized by unified parameters, which has been produced on iron and steel plant without any changes in shape structure (extra procedures are negligible);

2) hot-rolled universal beam with optimization (HRO) of flange geometry, characterized by extra cutting off metal to weight reduction due to special shape requirements;

3) welded beam with rectangular flanges (WN), which is produced of several sheets of metals and requires cutting and welding; and

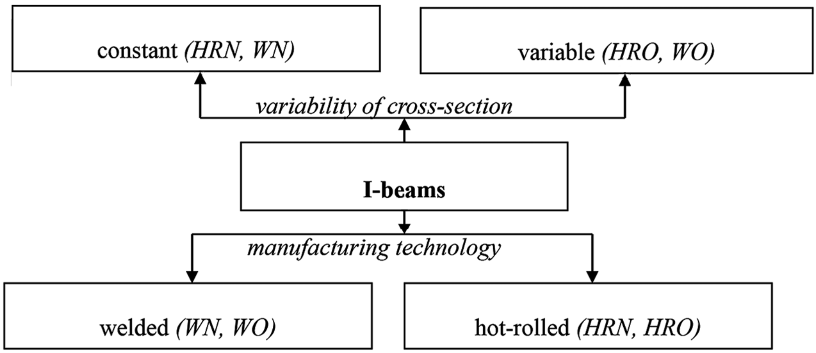


Figure 1. Technologies of I-beams manufacturing

4) welded beam with optimized (WO) flange geometry, which requires cutting and welding between wall and flanges.

The present study does not consider emissions into the atmosphere during manufacturing HRN beams; solely additional manufacturing processes were calculated.

Gate-to-gate LCA was applied for mentioned above types of I-beam manufacturing technologies and was included:

1) the design of I-beams, which should satisfy by strength, stability and stiffness conditions, a mass of beam and amount of work;

2) energy consumption;

3) emissions into the atmosphere;

4) cost assessment for manufacturing, environmental impact, delivering and mounting.

2.2. Data

The main parameters and characteristics of the beams were:

– total amount of simple-jointed girders (I-beams) – 1,200 units;

– length of single girder – 12 m;

– equivalent uniformly distributed design load – 16 kN/m.

All the loads are static and distributed. Beams are made of carbon steel S255 and considered without stiffness ribs.

Material consumptions for HRO, WO and WN were used from guideline [15]. Welds between wall and flats are assumed T-joint, full penetration fillet welded from both sides.

Original data on emissions into the atmosphere for cutting and welding were used from [16].

The rates of charges for emissions into the atmosphere were determined for pollutants, emitted during manufacturing procedure by [17].

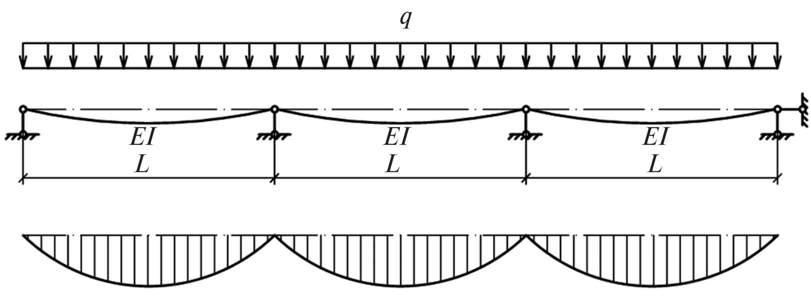
Delivering of manufactured I-beams was related to quantity of beams, loaded into the each truck. Assessment of fuel consumption was made for truck KAMAZ 6460 with trailer SZAP 9328, combustion engine works on diesel.

Overhead expenses for manufacturing and mounting equaled to 90 % of salary fund. Estimated profit was consisted from 85 % of salary fund.

2.3. Gate-to-gate LCA assessment

The beams were designed in according with SP 20.13330.2016 "Loads and Actions" [18] and SP 16.13330.2017 "Steel Structures" [19]. Calculation scheme and diagram of internal forces are shown in fig. 2.

Minimal height of the beam cross-section was determined taking into account strain tolerance. Local buckling of hot-rolled beams was



$M\text{max} = 0.5qL^2$

Figure 2. Calculation scheme and diagram of bending moment
Note: M – bending moment; I – second moment of cross-section area, cm^4; E – Yong's modulus, N/mm^2; q – uniformly distributed load, kN*m; L – length of the beam, m

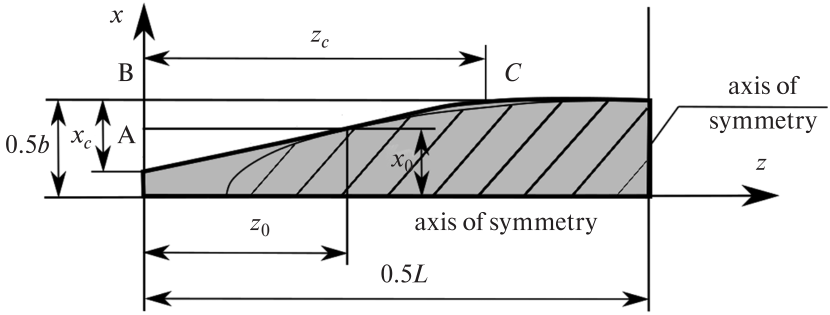


Figure 3. Geometry of beam flange Note: x_c – x coordinate of point C (start of cutting), mm; x_0 – coordinate of flange's edge across beam, mm; z_c – z coordinate of point C (start of cutting), mm

avoided a priori. The beams with ribs are related to optimization issue and are considered as a special case of welded beams.

The figure 3 a quarter of flange is represented. The hatching shows required flanges shape by condition of resistance, grey color is the shape of flange, provided minimal beam weight, associated with production convenience.

Tangent of the graph of "ideal" curve of flange in point (x_0; z_0) is made by equation (1), taking into account coefficient of simplification (2):

$$\mathrm{tg}\alpha_0 = x'(z) = \frac{0,5q(L-2z_0)}{R_y K_{cs}}, \qquad \text{(Eq. 1)}$$

$$K_{cs} = 2\, {}^{W_f}\!/_{b_f}, \qquad \text{(Eq. 2)}$$

where $\mathrm{tg}\alpha_0$ – tangent of the graph of "ideal" curve of flange in point (x_0; z_0), deg; $x'(z)$ – first-order derivative of $x(z)$, mm; z_0 – coordinate of flange's edge along the beam, mm; R_y – yield stress, N/mm^2; K_{cs} – coefficient for simplification, cm^2; W_f – section modulus of flanges (without wall), cm^3; b_f – maximal width of flange, mm.

The assessment of energy consumption, emissions into the atmosphere and economic issues the official standard Russian methodologies were used.

3. Results and Discussion

Calculation results for manufacturing, delivering and mounting stages are shown in tables from 1 to 5.

Table 1

Results of beam design

<table>
<tr><td rowspan="4">Type of beam</td><td rowspan="4">Flanges, cm</td><td colspan="6">Parameters</td></tr>
<tr><td colspan="2">cross-section</td><td colspan="4">beam</td></tr>
<tr><td rowspan="2">W_{max} cm^3</td><td rowspan="2">I_{max} cm^4</td><td rowspan="2">Mass, t</td><td rowspan="2">Weld length, m</td><td colspan="2">Cut length, m</td></tr>
<tr><td>flanges</td><td>wall</td></tr>
<tr><td>HRN</td><td>rectangular</td><td>1287.0</td><td>28699</td><td>0.794</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>HRO</td><td>optimized</td><td>1284.1</td><td>34865</td><td>0.683</td><td>0</td><td>48.1</td><td>0</td></tr>
<tr><td>WN</td><td>rectangular</td><td rowspan="2">1240.2</td><td rowspan="2">34727</td><td>0.642</td><td>24</td><td>48.3</td><td>25.1</td></tr>
<tr><td>WO</td><td>optimized</td><td>0.515</td><td>24</td><td>48.1</td><td>25.1</td></tr>
</table>

The highest mass of I-beam was assessed for HRO and the lowest for WO. Regarding to calculation all the considered I-beams were worked for required loads and actions.

Table 2

Results of energy estimation for manufacturing and delivering stages

<table>
<tr><td rowspan="2">Type of beam</td><td rowspan="2">Flanges</td><td colspan="4">Consumption, toe</td></tr>
<tr><td>Acetylene</td><td>Electricity</td><td>Diesel</td><td>Total</td></tr>
<tr><td>HRN</td><td>rectangular</td><td>0</td><td>0</td><td>83.457</td><td>8.457</td></tr>
<tr><td>HRO</td><td>optimized
(bmax = 22 cm)</td><td>1.939</td><td>0</td><td>7.279</td><td>72.218</td></tr>
<tr><td>WN</td><td>rectangular</td><td>2.235</td><td>2.774</td><td>65.886</td><td>70.895</td></tr>
<tr><td>WO</td><td>optimized</td><td>2.228</td><td>2.774</td><td>52.714</td><td>57.716</td></tr>
</table>

Energy consumption for HRN was assessed for delivering stage; manufacturing of this kind of I-beam was not considered. Solely additional energy consumption for optimization processes were calculates. Additional energy sources and materials were used for HRO, WN and WO manufacturing stages. Diesel was applied for delivery stage for all types of I-beams. The highest amount of diesel consumption for delivery stage was assessed for HRN. Acetylene for cutting and diesel for transportation and consumption of energy is equal to 1.939 and 70.279 toe for HRO, respectively. Acetylene, electricity and diesel for cutting and welding processes were used for WN and WO I-beams with the total. The total amount of energy consumption has shown significant differences up to 22 % between WN and WO manufacturing technology, which is equal to 70.895 toe and 57.716 toe respectively. Total amount of energy consumption for HRN and HRO was varied between lowest and biggest amount of energy consumption, presented by 83.457 toe and 72.218 toe, correspondingly.

Table 3

Gross emissions into the atmosphere during *I*-beam production for i component

	HRO	WN	WO
Pollutant	ton/period	ton/period	ton/period
Ferrum oxide	0.276	0.348	0.347
Manganese and compounds	0.004	0.014	0.014
SiO_2 dust (20 %–70 %)	0.000	0.002	0.002
CO_2	0.113	0.146	0.145
NO_2	0.105	0.136	0.135
Total sum	0.497	0.645	0.644

Ferrum oxide is emitted into the atmosphere during operations both cutting and welding and is shown the biggest amount of the pollutants on manufacturing stage. Manganese and compounds has significantly lower amount of emissions and the value varies from 0,004 to 0,014 for HRO and WO I-beams correspondingly. Emissions of CO_2 and NO_2 are presented during cutting and welding process. Total amount of emissions into the atmosphere is lowest for HRO and is approximately 1/3 higher for WN and WO and related to similarity of the processes of manufacturing.

Environmental payment was calculated for 2016 and 2017, where official rates on payment are varied, according to standards, which shows the differences between years for investigational purposes. The total payment for ferrum oxide emissions for I-beam is slightly varied and is achieved to 0,92 € for HRO and to 1,13 € per manufacturing period in 2017 for WN and WO. Significant differences were shown in payment for manganese and compounds, due to high standard rate on emission 1 tons of the component. It is varied more than three times for WN and WO, achieved 2.22 €, in comparison with HRO, where total payment equals to 0.60 €. Environmental payment on SiO_2 dust (20 %–70 %) and CO_2 is negligible. Payment for NO_2 is slightly varied for HRO and both WN and WO from 0.43 € to 0.55 € respectively.

Table 4

Results of calculation for delivering stage and emissions into the atmosphere

	Type of fuel	A number of trucks, unit	A number of beams in a truck, unit	Total fuel consumption, ton	Environmental payment*, €	
					2016	2017
HRN	Diesel	38	32	76.354	14.2	14.8
HRO	Diesel	32	38	64.298	11.9	12.4
WN	Diesel	30	40	60.279	11.2	11.7
WO	Diesel	24	50	48.228	8.9	9.3
* Environmental payment during delivering stage was made for assessment of the pressure on the environment for scientific purposes						

Table 5

Total costs on manufacturing, delivering and mounting stages for 1,200 I-beams

Stage	Cost, €			
	HRN	HRO	WN	WO
Steel	381120	466440	308160	247200
Manufacturing	0	27287	60777	60685
Delivering	222130	191077	179606	144077
Mounting	258518	222378	209029	167679
Total	861769	907181	757572	619641

A number of trucks are inversely proportional to number of I-sections, which is necessary to deliver to construction site. Diesel consumption for one round route is decreased from 76.354 ton for HRN to 48.228 ton for WO.

Environmental payment depends on quantity of trucks or route during delivering stage. Payment for emissions during transportation of WN is 11.7 €, that is 7 % less in comparison with HRO, which emissions is assessed on 12.4 €.

Steel and delivering has the main contribution into cost of I-beam and slightly vary in percentage relation between all types of possible manufacturing constructional members and in generally explains up to 72 % of the total sum. Total sum for manufacturing, delivering and mounting of I-section is significantly varied from the biggest costs of HRO, which is equaled to 907181 € to 619641 € for WO.

4. Conclusion

Gate-to-gate LCA approach can be applied for analysis and decision-making for stakeholders. It gives an opportunity to choose optimal solution for every single project. In this paper the case study for four variants of I-beam manufacturing, delivering and mounting were made.

Additional treatment operations for production lead to increase consumption different materials and related emissions into the atmosphere.

Environmental payment assessment was made to show and to compare changes in the emissions into the atmosphere. Current environmental legislation is not included environmental payment for vehicles.

Different manufacturing technologies of I-beams are related to assessment the balance between material and energy consumption, emissions into the atmosphere and economic issues. The optimal solution can be made after precise assessment of all the mentioned above parameters.

Assessment of WO technology of I-beam manufacturing was the most efficient on material and energy consumption, but emissions into the atmosphere was comparable with WN and the emissions into the atmosphere was assessed as relatively high. For the case study “win-win” solution is WO, but detailed assessments are necessary for each project.

5. References

1. Gong, X. Life Cycle Energy Consumption and Carbon Dioxide Emission of Residential Building Designs in Beijing A Comparative Study [Text] / X. Gong, Z. Nie, Z. Wang, S. Cui, F. Gao, T. Zuo // Journal of industrial ecology. – 2012. – N 16 (4). – P. 576–587. DOI: 10.1111/j.1530-9290.2011.00415.x.

2. Ortiz, O. Sustainability in the construction industry: A review of recent developments based on LCA [Text] / O. Ortiz, F. Castells, G. Sonnemann // Construction and Building Materials. – 2009. – N 23. – P. 28–39. DOI: 10.1016/j.conbuildmat.2007.11.012.

3. Finkbeiner, M. The new international standards for Life Cycle Assessment: ISO 14040 and ISO 14044 [Text] / M. Finkbeiner, A. Inaba, R. Tan, K. Christiansen, H.-J. Klüppel // Int. J. Life Cycle Assess. – 2006. – N 11 (2). – P. 80–85. DOI: 10.1065/lca2006.02.002.

4. Bribian, I.Z. Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification [Text] / I. Z. Bribian, A. A. Uson, S. Scarpellini // Building and Environment. – 2009. – N 44. – P. 2510–2520. DOI: 10.1016/j.buildenv.2009.05.001.

5. Bribian, I. Z. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential [Text] / I. Z. Bribian, A. V. Capilla, A. A. Uson // Building and Environment. – 2011. – N 46. – P. 1133–1140. DOI: 10.1016/j.buildenv.2010.12.002.

6. Sharma, A. Life cycle assessment of buildings: a review [Text] / A. Sharma, A. Saxena, M. Sethi, V. Shree // Renew Sust Energ Rev. – 2011. – N 15 (1). – P. 871–875. DOI: 10.1016/j.rser.2010.09.008.

7. Tsai, W.H. Incorporating life cycle assessments into building project decision-making: An energy consumption and CO2 emission perspective [Text] / W. H. Tsai, S. J. Lin, J. Y. Liu, W. R. Lin, K. C. Lee // Energy. – 2011. – N 36. – P. 3022–3029. DOI: 10.1016/j.energy.2011.02.046.

8. Tan, Y. An empirical study on the relationship between sustainability performance and business competitiveness of international construction contractors [Text] / Y. Tan, J. J. Ochoa, C. Langston, L. Shen // Journal of Cleaner Production. – 2015. – N 93. – P. 273–278. DOI: 10.1016/j.jclepro.2015.01.034.

9. Abd Alla, S. Life-cycle approach to the estimation of energy efficiency measures in the buildings sector [Text] / S. Abd Alla, V. Bianco, F. Scarpa, L.A. Tagliafico // Applied Energy. – 2020. – N 264. DOI: 10.1016/j.apenergy.2020.114745.

10. Ibbotson, S. LCA case study. Part 2: environmental footprint and carbon tax of cradle-to-gate for composite and stainless steel I-beams [Text] / S. Ibbotson, S. Kara // Int J Life Cycle Assess. – 2014. – N 19. – P. 272–284. DOI: 10.1007/s11367-013-0639-4.

11. Sproesser, G. Life Cycle Assessment of welding technologies for thick metal plate welds [Text] / G. Sproesser, Y. J. Chang, A. Pittner, M. Finkbeiner, M. Rethmeier // Journal of Cleaner Production. – 2015. – N 108. – P. 46–53. DOI: 10.1016/j.jclepro.2015.06.121.

12. Chetan. Application of sustainable techniques in metal cutting for enhanced machinability: a review [Text] / Chetan, S. Ghosh, P. V. Rao // Journal of Cleaner Production. – 2015. – Vol. 100. – P. 17–34. DOI: 10.1016/j.jclepro.2015.03.039.

13. Velchev, S. Empirical models for specific energy consumption and optimization of cutting parameters for minimizing energy consumption during turning [Text] / S. Velchev, I. Kolev, K. Ivanov, S. Gechevski // J. Clean. Prod. – 2014. – N 80. – P. 139–149. DOI: 10.1016/j.jclepro.2014.05.099.

14. Lednova, J. Concept of environmental monitoring in the Russian arctic coastal regions [Text] / J. Lednova, G. Gogoberidze, V. M. Abramov, L. N. Karlin, S. Berboushi // International Multidisciplinary Scientific Geoconference and EXPO, SGEM 2014; Albena; Bulgaria; 17 June 2014 through 26 June 2014. – 2014. – Vol. 1, Issue 5. – P. 161–168. – DOI:10.5593/SGEM2014/B51/S20.022.

15. ВСН 416-81 Общие производственные нормы расхода материалов в строительстве. Сборник 30. Сварочные работы [Текст] = VSN 416-81 Obshchie proizvodstvennye normy raskhoda materialov v stroitel'stve. Sbornik 30. Svarochnye raboty [Common standard material consumption in building construction. Volume 30. Welding]. – М. : Стройиздат, 1990. (in Russian).

16. ГОСТ Р 56164-2014. Выбросы загрязняющих веществ в атмосферу. Метод расчета выбросов при сварочных работах на основе удельных показателей [Текст] = Air pollution emissions. Method of calculating emissions during welding work on the basis of relative rates. – Введ. 2015-07-01. – М. : Стандартинформ, 2015. – 48 р. (in Russian).

17. Постановление Правительства от 13.09.2016 г. №913 "О ставках платы за негативное воздействие на окружающую среду и дополнительных коэффициентах" [Текст] = RUSSIAN FEDERATION: Government Decree No.913 of 2016 on the Rates of Payment for Negative Impact on the Environment and Aditional Factors. (in Russian).

18. СП 20.13330.2016. Свод правил. Нагрузки и воздействия. Актуализированная редакция СНиП 2.01.07-85* [Текст] = Loads&actions. – Введ. 2017-06-04. (in Russian).

19. СП 16.13330.2017. Свод правил. Стальные конструкции. Актуализированная редакция СНиП II-23-81* [Текст] = Steel structures. Revised edition of SNiP II 23 81*. – Введ. 2017-08-28. – М.: Стандартинформ, 2017. (in Russian).