

Application of the six sigma method for quality management of concrete works in construction

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ABSTRACT

Introduction. Focus of the review is the application of statistical methods of product quality management to the analysis of the quality of concrete structures. The relevance of the chosen topic is substantiated by the fact that, under conditions of dynamic construction, it is necessary to optimize the execution timelines of key construction processes while maintaining the quality of the constructed structures. The application of the Six sigma method in the production of concrete structures is considered, where there is a wide range of possible defects (cracks, braces, verticality deviation, etc.), which have a significant impact on the quality and safety of buildings and structures. **Methods and materials.** The Six sigma methodology optimizes processes to reduce the risk of defects and improve product quality. Quality management based on this method allows you to optimize the schedule of work, eliminate delays and downtimes and reduce labor costs. The tables of main defects have been compiled, values of Six sigma for various combinations of the volume of concrete structures and the corresponding number of defects are calculated. The main method of process improvement is the DMAIC cycle (definition, measurement, analysis, improvement, control). Considered each stage of the cycle for concrete works in construction. The implementation of the adapted Six sigma methodology has been carried out to monitor the quality level of the construction of a concrete framework with improvements in organizational and technological processes according to the DMAIC cycle. **Discussion and conclusion.** The method Six sigma obtained from the results of the study allows for quality assessment of the production of concrete structures at various objects. The reliability and objectivity of this method as a tool for monitoring the quality of concrete works has been confirmed. Based on the obtained quality assessment, the effectiveness of the application of improvements to the DMAIC cycle is justified. The implementation of the study confirms the conclusion that the quality management of concrete works has improved through a combination of monitoring quality according to the Six sigma method and improvement of construction production according to the DMAIC cycle.

KEYWORDS: 6 sigma, quality monitoring, quality management, concrete structures, concrete works, organization of construction

SOURCES OF FUNDING FOR THE SCIENTIFIC WORK THAT RESULTED IN THE PUBLICATION: This scientific work was carried out with the support of the Federal State Budget Higher Education Educational Institution "National Research Moscow State Construction University" and has a registration card number at NIOCTR ISU: 125070808055-3, St. Petersburg State University of Architecture and Civil Engineering.

FOR CITATION:

Makarov A.N., Malkova A.S., Bovteev S.V. Application of the Six sigma method for quality management of concrete works in construction. *Nanotechnologies in Construction*. 2026; 18(3):407–416. <https://doi.org/10.15828/2075-8545-2026-18-3-407-416>. EDN: VFAHEZ.

Применение метода «6 сигм» для управления качеством бетонных работ в строительстве

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АННОТАЦИЯ

Введение. Приведены сведения о применении статистических методов управления качеством продукции к анализу качества монолитных бетонных конструкций. Обоснована актуальность выбранной темы – в условиях динамичного строительства необходимо оптимизировать сроки реализации ключевых строительных процессов с сохранением качества изготавливаемых конструкций. Рассмотрено применение метода «Шесть сигм» в производстве монолитных бетонных конструкций, где существует широкий набор возможных дефектов (трещины, сколы, отклонение от соосности и т.д.), которые оказывают значительное влияние на качество и безопасность зданий и сооружений. **Методы и материалы.** Методология «Шесть сигм» позволяет оптимизировать технологические процессы с целью снижения риска возникновения дефектов и повышения качества продукции. Управление качеством работ на основе данного метода позволяет оптимизировать график работ, устранить задержки и простои и следственно снизить трудозатраты. Составлены таблицы основных дефектов, вычислены значения 6 сигм для различных сочетаний объема монолитных конструкций и соответствующего числа дефектов. Основным методом улучшения процессов – цикл DMAIC (определение, измерение, анализ, улучшение, контроль). Рассмотрен каждый этап цикла для монолитных работ в строительстве. Выполнено внедрение адаптированной методики «6 сигм» для мониторинга уровня качества возведения монолитного каркаса с выполнением улучшений организационно-технологических процессов по циклу DMAIC. **Обсуждение и заключение.** Полученная по результатам исследования методика «6 сигм» позволяет выполнять оценку качества производства монолитных конструкций на различных объектах. Подтверждены достоверность и объективность данной методики как инструмента мониторинга качества бетонных работ. На основе полученной оценки качества обоснована результативность применения улучшений по циклу DMAIC. Внедрение исследования подтверждает вывод о повышении эффективности управления качеством бетонных работ за счет сочетания мониторинга качества по методике «6 сигм» и улучшению строительного производства по циклу DMAIC.

КЛЮЧЕВЫЕ СЛОВА: шесть сигм, мониторинг качества, управление качеством, монолитные конструкции, бетонные работы

ИСТОЧНИКИ ФИНАНСИРОВАНИЯ НАУЧНОЙ РАБОТЫ, РЕЗУЛЬТАТОМ КОТОРОЙ СТАЛА ПУБЛИКАЦИЯ: Данная научная работа выполнена при поддержке Федерального государственного бюджетного образовательного учреждения высшего образования «Национальный исследовательский Московский государственный строительный университет» и имеет регистрационный номер карты в ЕГИСУ НИОКТР: 125070808055-3, ФГБОУ ВО «Санкт-Петербургский государственный архитектурно-строительный университет»

ДЛЯ ЦИТИРОВАНИЯ:

Макаров А.Н., Малькова А.С., Бовтеев С.В. Применение метода «6 сигм» для управления качеством бетонных работ в строительстве. *Нанотехнологии в строительстве*. 2026;18(3):407–416. <https://doi.org/10.15828/2075-8545-2026-18-3-407-416>. EDN: VFAHEZ.

INTRODUCTION

To manage product quality, companies in various areas are implementing the global Six sigma quality management methodology to improve organizational performance, identify errors and minimize them [1–3]. This approach is based on the static measurement of a process in the number of defects [4]. The aim of the methodology is to reduce variation in production and business processes to a level corresponding to six standard deviations from the mean [5]. The main tool of the Six sigma methodology is the DMAIC improvement cycle consisting of five

steps: determination, measurement, analysis, improvement, control [6–8]. If it is not possible to completely eliminate errors in the process, statistical monitoring will help. It involves the use of control schedules to monitor and analyze deviations within the limits allowed [9]. In construction, the Six sigma method can be used effectively to improve processes such as materials and works quality management, time management and budget [10]. By minimizing deviations from the project, high economic performance and labor costs can be achieved [11]. The methodology has been applied in practice in the fields of production and services – with a view to improving

the quality of products and services, reducing production costs, reducing waiting times [12, 13]. The method was successfully applied in production to improve the quality of galvanized iron treatment: the introduction of an automated zinc layer thickness control system using ultrasonic sensors allowed to reduce coating defects, Increase adhesion and increase line speed. This approach has not only made products more competitive in the market, but also ensured that they meet standards while minimizing corrosion in construction and engineering. The targeted optimization of key parameters in the towelling process has led to a significant increase in output performance – the material removal rate, which is a direct indication of the effectiveness of the approach used [14]. The DMAIC cycle was applied in the foundry industry at the plant to minimize defects and improve market competitiveness: analysis of six-month data revealed critical points, which reduced manufacturing marriage [15]. In Europe and South America, a leading private electricity distribution operator has been using the Six sigma methodology to identify electrical grid stability factors. It helped to distinguish resilience events from reliability events by helping to classify events (high impact, low probability) that threaten the energy system [16]. The DMAIC cycle is closely integrated with lean construction, reinforcing it through data and statistics. Lean Six Sigma’s comprehensive approach is based on the Six sigma methodology and focuses on loss elimination (overproduction, downtime, re-engineering). Low-cost construction tools have already been applied to coal mining. Optimizes processes, eliminates waste and improves product quality by reducing unnecessary operations, resource efficiency and productivity [17, 18]. The Russian construction industry faces development problems due to specificities – seasonality, dependence on weather, multiple subcontractors and difficulties in implementing new management methods – resistance to change, low digitalization, shortage of qualified specialists. The construction organization requires improvements, as domestic companies are losing out to foreign companies in terms of efficiency. Implementation of these approaches in the construction sector is limited so far (unlike mechanical engineering), but experience of domestic practice shows their effectiveness [19]. It is necessary to increase the competitiveness of construction companies through instruments of economical production: elimination of losses, growth of margin without compromising quality; identification of weak points and unnecessary processes. The main shortcoming of new management technologies is a lack of ready-made implementation [20]. The absence of a ready-made DMAIC implementation method is overcome with a step-by-step approach. The DMAIC standard cycle needs to be adapted as a basis for the construction sector. The implementation should start with a pilot project in one process (for example, concrete pouring), assemble a team consisting of the project

manager, the project manager and construction control engineers, and allocate resources for implementation. Engineers analyze key problems of the construction industry – high downtimes, overconsumption of materials and low productivity, and propose a set of measures to optimize concrete works based on principles of economical construction [21].

Concrete works make up a significant share of the volume of typical construction projects. At the same time, they have a wide and diverse range of possible defects that have a significant impact on the reliability and safety of buildings and structures. The appearance of defects in concrete construction increases its cost by 15–25% and contributes to a delay in the completion of projects. Therefore, the introduction of modern methods for monitoring and managing the quality of concrete works should increase their efficiency and contribute to sustainable development by minimizing costs and increasing productivity.

METHODS AND MATERIALS

The authors of the study propose the introduction of the Six sigma concept into the construction industry. The aim of the study is to improve the quality of production of concrete structures. Let’s identify the main defects that arise in concrete construction. Consider the main process of construction – concrete work. We will carry out static data collection on the basis of defective statements from a housing construction facility in Moscow.

Number of possible significant and critical defects (non-conformities) per unit for concrete work $n_{CTQC} = 20$. The following defects are critical – D2, D4, D5, D7, D16, D20, in which case an increasing factor is introduced to calculate by the Six sigma method $\gamma_{b,1} = 3$. For the remaining significant defects, the coefficient $\gamma_{b,2} = 1.0$.

As part of this study, an analysis was carried out of defective statements obtained during the author and technical supervision of concrete works on three large residential complexes at different stages of construction in Moscow. The aim of the analysis was to statistically identify and quantify the most common defects shown in Fig. 1.

Apply the method 6 sigma, which will allow to systematically analyze the variability of processes through statistical tools, establish strict control criteria, Identify root causes of discrepancies and implement targeted improvements to achieve the level of defects of the respective 5–6 sigma.

Number of defects (non-conformities) per million possible defects [22]. The value Y_{DPMO} is calculated by formula (1):

$$Y_{DPMO} = \frac{Nd}{n_{units} \times n_{CTQC}} \cdot 1000000, \quad (1)$$

where n_{units} – number of units of products checked (grab of concrete structures);

Table 1. Table of defects in concrete works

№	Name of defects
	Concrete work
1	Discrepancy between the frost resistance, strength, and water permeability parameters of the concrete and the project specifications
2	The minimum strength of concrete during the removal of formwork for unloaded structures is less than the specified normative value
3	Violation of project requirements and standards regarding the location and design of construction joints during concreting
4	Deviations in the thickness of the protective layer exceed the specified norms
5	Deviations from the design marks of supporting surfaces in concrete structures exceed the specified values
6	Concrete surfaces have voids, pores, and exposed reinforcement
7	Delamination of concrete on the surface of the structure
8	Bulges and chips on the concrete surface
9	Deviation of structural openings from the design position
10	Shift of column and support axes relative to layout axes in the support section exceeds the specified values
11	Deviation of column axes from vertical in the upper section, depending on the column length, exceeds the specified values
12	Discrepancy between the design of openings and holes in concrete structures and the working documentation
13	Deviation from straightness and flatness of the surface over a length of 1–3 m, and local unevenness of the concrete surface in concrete structures
14	Deviation of horizontal planes across the entire inspected area of the structure
15	Deviation of lengths or spans of elements, dimensions in clear openings from specified values
16	Deviation of the axes of frame building columns over the entire height of the building from the specified values
17	Deviation of the cross-sectional size of element h from the specified value
18	The arrangement of anchor bolts does not comply with the standards
19	Deviation from the coaxiality of vertical structures
20	The width of crack openings in concrete structures exceeds design and specified values

N_d – number of defects (discrepancies) detected;

n_{CTQC} – number of possible defects (non-conformities) per seizure.

The boundary values are defined in accordance with Annex A [22] and are given in Table 2.

Table 3 is based on the Six sigma methodology, where the number of sigmas reflects the variability of defects in concrete works.

Adapted the DMAIC cycle algorithm (definition, measurement, analysis, improvement, control) for the quality management process of concrete works as shown in Fig. 2.

Stage 1 (Define) involves identifying problem areas that prevent the construction of concrete structures. To improve the quality of manufactured structures, we propose to first identify defects in the packing – 30 concrete mixture. At the next stage, we conduct a defect analysis and perform calculations for the first floor of concrete structures, with subsequent scaling to tiers and the entire building. When

constructing a residential complex, scaling can be extended to all objects carried out by the general contractor within the framework of the complex construction.

Stage 2 (Measure) – measurement of deviations and counting of detected defects for each 30 m³ concrete structure.

Stage 3 (Analyze) – analysis of surveyed structures – determine the values “ σ ” by the number of detected defects. If, after pouring the first batch of concrete mixture, a significant number of damages was found, and the result is within the range 2–3, 1–2 sigmas make it necessary to change the production technology for the remaining attachments, applying crucial organizational and technological solutions (OR) to improve quality. If, according to the results of the analysis of sigma in boundaries 3–4, 4–5, then the use of point TRO is required, repair work. If the result is 5–6 sigma, the effect of defects is negligible, and the remaining structures can be constructed using the same technology.

SYSTEM SOLUTIONS FOR TECHNOLOGICAL PROBLEMS

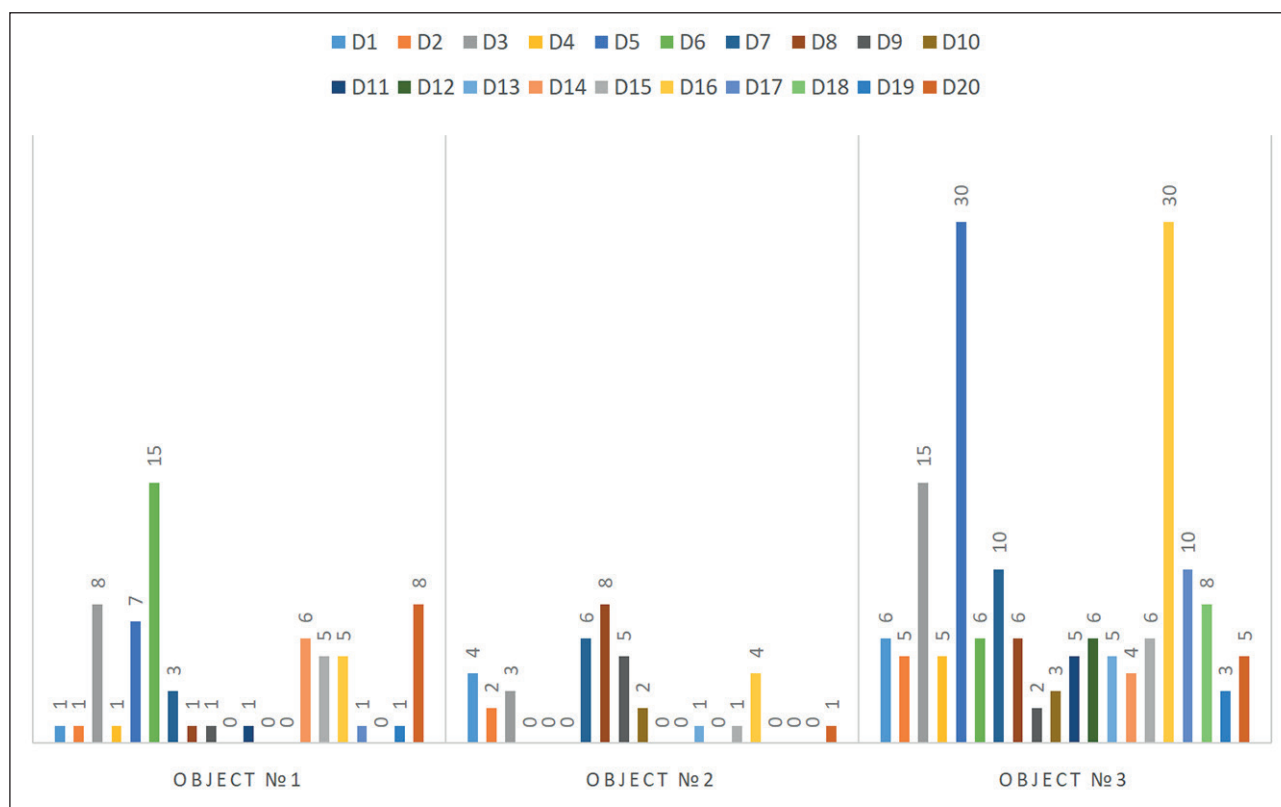


Fig. 1. Analysis of defective schedules of residential complexes in Moscow

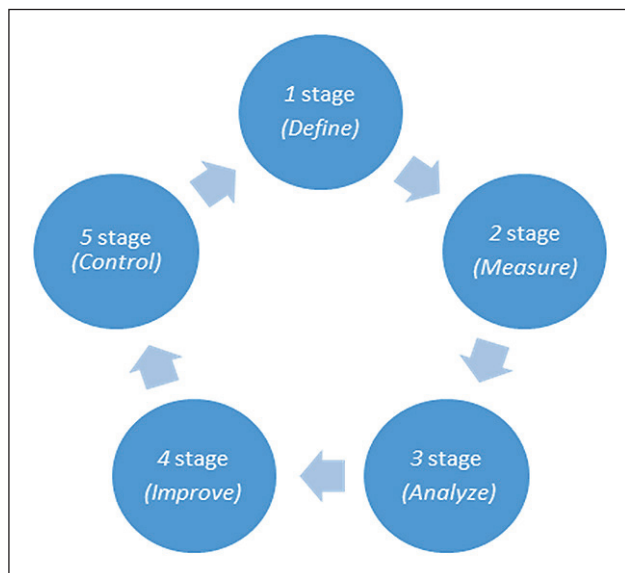


Fig. 2. Cycle DMAIC

Table 2. Number of sigma

Calculated value Y_{DPMO}	Number of sigma (standard deviations of random value) Z_{value}
308 538.0	2
66 807.0	3
6210.0	4
233.0	5
3.4	6

Table 3. Quality classification of concrete works by sigma

Number of sigma (standard deviations of random value) Z_{value}	Quality of concrete work
1–2	Defect. Complete process re-engineering
2–3	Low quality. Global improvements needed
3–4	Medium quality. Improvements needed
4–6	High quality. Does not require improvement

Stage 4 (Improve) – improvement. Applying this method, it is necessary to include in the project of EPR production in case of exceeding the permissible number of defects, for example, change of contractor organization, training of workers, replacement of equipment, adjustment of technological processes, increase of engineering-Technicians (IIT) and additional training.

Stage 5 – (Control) – monitoring the implementation of improvements and further quality control. The technical client must carry out monitoring and control both independently and with the involvement of copyright supervision. It is important to implement continuous monitoring of key parameters of work using modern measurement and control tools. Implementation of a feedback system is needed to quickly identify and address the causes of poor quality. For sustainable improvement, it is recommended to analyze the causes of defects and apply corrective actions aimed at preventing their recurrence. A system for documenting and analyzing deviations should be implemented. It is also important to create a design health monitoring system and a quality control organization monitoring system on the site.

RESULTS

Testing of the method was carried out during the construction of a 40-storey residential building with a concrete framework in Moscow. In total, the building was divided into 400 entries of 30–60 m³ ($n_{units} = 400$). In the Excel calculation package results Y_{DPMO} are shown in Table 4.

The results are highlighted in color according to Table 5.

The following defects were identified in Site 1 during Phase I, as reflected in Table 6.

Initially, the site was surveyed for 10 seizures, and 7 defects were found (2 critical, 5 significant). The calcu-

Table 5. Sigma value ranges notation

4–5 sigma	
3–4 sigma	
2–3 sigma	
1–2 sigma	

Table 4. Table of values Y_{DPMO} – number of defects per million possible defects

Concrete works		NUMBER OF CATCH						
		1	8	10	20	50	80	100
N U M B E R O F D E F E C T S	1	5×10^4	6250	5×10^3	2500	10^3	625	500
	2–6	$10^5 - 3 \times 10^5$	12 500–37 500	$10^4 - 3 \times 10^4$	$5 \times 10^3 - 15 \times 10^3$	2000–6000	1250–3750	$10^3 - 3 \times 10^3$
	7	35×10^4	5×10^4	35×10^3	17 500	7×10^3	4375	3500
	10	5×10^5	68 750	55 555	25×10^3	10^4	6250	5×10^3
	15	75×10^3	93 750	75×10^3	37 500	15×10^3	9375	7500
	20	10^6	125×10^3	10^5	5×10^4	2×10^4	12 500	10^4
	25	125×10^4	156 250	125×10^3	62 500	25×10^3	15 625	12 500
	30	15×10^5	187 500	15×10^4	75×10^3	3×10^4	18 750	15×10^3
	35	175×10^4	218 750	175×10^3	87 500	35×10^3	21 875	17 500
	40	2×10^6	25×10^4	2×10^5	10^5	4×10^4	25×10^3	2×10^4
	45	225×10^4	281 250	225×10^3	112 500	45×10^3	28 125	22 500
	50	25×10^5	312 500	25×10^4	125×10^3	5×10^4	31 250	25×10^3

SYSTEM SOLUTIONS FOR TECHNOLOGICAL PROBLEMS

lated value of the sigma refers to an interval of 3–4 sigma, which indicates problems with the quality of concrete works and requires improvement in production.

In Site 1, complex organizational and technical work was carried out to eliminate the identified defects in concrete structures, presented in Table 7.

Furthermore, at the end of the following month, the collection of quality indicators was carried out: number of defects per carried-out captures.

During the reporting period, 20 seizures were made. There were 2 significant defects. The calculation of quality assessment indicators according to formula (1) has been carried out, the corresponding value of the sigma has been determined, and the relative quality indicators have also been calculated: $N_{d,100}$ – Number of defects per 100 m³ concrete, $N_{d,z}$ – number of defects per unit. The values of indicators before and after organizational and technical work are presented in Table 8.

The result obtained on quality control of concrete works at Site 1 is in the range 4–5 sigma, which corresponds to high quality according to the method Six sigma, therefore does not require additional adjustments, but only maintenance through a control plan and statistical maps for stability of indicators.

For the testing of the Six sigma method as a monitoring and quality assessment tool, the authors collected data on defects at several concrete construction sites. The technical and economic indicators of the objects were analyzed, and the relative indicators of defects were calculated – number of defects per 100 m³ concrete ($N_{d,100}$), number of defects per seizure ($N_{d,z}$). The results are shown in Pivot Table 9.

The values of the sigma in objects 1, 2 are of high quality, and this is also shown by the relative values of $N_{d,100}$. In object 1, the relative value of $N_{d,100}$ With the relative value in object 1 $N_{d,z}$ is greater than 0.1, and the value of the sigma

Table 6. Defects of concrete structures, 1st stage of quality recording of completed works

Defect No.	Description of the defect	Type of defect
D1	Concrete strength parameter mismatch	Significant
D6	Concrete surfaces have washbasins	Significant
D7	Concrete delamination on the structure surface	Critical
D11	Column axis deviation from vertical in upper section exceeds normative values depending on column length	Significant
D12	Nonconformity of the device of openings, holes in concrete work documentation structures	Significant
D19	Verticality deviation of structural elements	Significant
D20	The width of crack opening in concrete structures exceeds standard values	Critical

Table 7. OTR complex for eliminating defects in concrete work

Defect code	Name of defect	Organizational and technological solutions to prevent defects
D1	Concrete strength settings are inconsistent with the project	<ul style="list-style-type: none"> Laboratory control of each batch with inspection of cement ratio, mobility, air circulation Monitoring the viability of the mixture Reducing the height of the mixture being dropped into the formwork
D6	Concrete surfaces have washbasins	<ul style="list-style-type: none"> Vibration compression optimization: 3–5 min/layer, step 40–60 cm Training with a master class for concrete workers on the sealing process Use of plasticizers Wizard Checksheet: checking layer evenness, step check and vibrating time
D11	Column axis deflection from vertical	<ul style="list-style-type: none"> Installation of axes and mirrors by laser mixer before filling (3 mm/3 m tolerance) Rigid paving of the formwork with anchor every 1.5 m Geodetic control of formwork geometry during mixture laying
D12	Nonconformity of the device of openings, holes	<ul style="list-style-type: none"> Preliminary marking of gaps by RD templates with double geodetic verification Use of removable inlays in formwork (plywood/plastic) Integration into BIM model for 3D control
D20	Crack clearance width is higher than normal	<ul style="list-style-type: none"> Solidification mode: cover with film + moisturizing 7 days, t = 5–25 °C Limit loads to 70% of the project (28 days) Additives to the concrete mixture against shrinkage (0.5–1% by mass)

Table 8. The result of calculating the value of a sigma before and after organizational and technical work

No.	Indicator name	Value of indicator before organizational and technical work	Value of indicator after organizational and technical work
1	Number of hikes	10	20
2	Volume of concrete	300	600
3	Number of defects	7	2
	critical	2	–
	significant	5	2
4	Y_{DPMO}	55 000	5000
5	Sigma	3.1	4.08
6	$N_{d,100}$	2.3	0.3
7	N_{dz}	0.7	0.1

Table 9. Pivot analysis of defects in concrete works on objects

Object	Total area, m ²	Volume of concrete	Number of hikes	Number of comments, N_d	Number of comment of hikes, N_{dz}	Number of comments per 100 m ³ , $N_{d,100}$	Y_{DPMO}	Sigma, Z_{value}
No. 1	92 208	42 680	711	90	0.13	0.21	6300	3.99
No. 2	112 776	33 009	550	37	0.07	0.11	3363	4.21
No. 3	31 305	16 177	270	84	0.31	0.52	15 555	3.66

has a borderline value. In turn, site 3's sigma is the lowest of the table and corresponds to an average level of quality, which requires significant changes in approach to concrete work. It is worth noting that relative quality indicators N_{dz} и $N_{d,100}$ for this object also has the worst values.

DISCUSSION

The authors of the study first applied the Six sigma method in construction quality control on concrete works. Assessment of the quality level according to the proposed method and comparison with classical indicators, such as number of defects, number of defects per 100 m³ of concrete ($N_{d,100}$) and for the hike (N_{dz}). Classical metrics do not set limits on the range of values to translate quantitative into qualitative, which is necessary for decision-making. It is possible to establish such boundaries in an expert way. The authors have established these boundaries using the corresponding sigma boundaries. The metric comparison is shown in Table 10.

When analyzing the table, it is found that the selected ranges of the peaks correspond to the relative ranges of the indicators determined by experts. The adapted 6-sigma assessment method has several advantages over known metrics:

- takes into account the influence of significant and critical defects through the introduction of a weighting factor;
- resistant to fluctuations in indirect characteristics such as concrete volume and number of packings;
- is more sensitive to fluctuations in the number of defects and gives more representative values compared to relative quality indicators.

Thus, the Six sigma method is more sensitive to types and number of defects, depending less on indirect characteristics (volume of concrete and quantity of material), than relative quality indicators N_{dz} и $N_{d,100}$. The ranges of sigma values are mathematically formalized, limited to representative values, and explicitly translated into qualitative indicators.

Table 10. Comparison of metrics for assessing the quality of concrete works

Z_{value}	$N_{d,100}$	N_{dz}	Qualitative indicator
1–2	20–46	6–14	Defect. A complete re-engineering of processes
2–3	4–20	1–6	Poor quality. Global improvements required
3–4	0.4–4	0.1–1	Medium quality. Improvements needed
4–6	0–0.4	0–0.1	High quality. No need for improvement

The use of the Six sigma method within the DMAIC cycle allows for its continuity and inclusiveness, which is important in the paradigm of low-cost construction, and enables continuous improvements to be achieved until an investor achieves a level of quality of final products.

CONCLUSION

The Six sigma methodology is a systematic approach to assessing and monitoring the quality of concrete structures, which has high reliability and representativeness compared with existing methods. The article demon-

strates the effectiveness of the application of the DMAIC cycle in a complex with an adapted evaluation method Six sigma. The integration of these methods allows for improving the efficiency of quality management in concrete works during the construction of buildings made of concrete reinforced concrete, and contributes to the refinement of traditional quality control methods. This monitoring and decision-making tool contributes to the continuous improvement of construction organization, effective quality management, minimization of defects and achieving a qualitatively new level of reliability of construction objects.

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ADDITIONAL INFORMATION

The authors declare that no generative artificial intelligence technologies or artificial intelligence-based technologies were used in the preparation of this article.

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A.N. Makarov – an idea, a scientific guide.

A.S. Malkova – collection of material, processing of material, conducting research, writing the source text.

S.V. Bovteev – research concept formulation and editing scientific text.

The authors declare no conflicts of interest.

The article was submitted 12.03.2026; approved after reviewing 05.06.2026; accepted for publication 09.06.2026.