Decision making with visualizations: a cognitive framework for quality management in construction

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Abstract. In conditions with unstable economy and a constantly increasing competition in the construction market, one of competitive advantages and factors of organization's sustainable development is the existence of an effective QMS based on a risk-oriented approach for decision-making. Risk management is a process that is very important for construction industry enterprises and organizations. Each organization decides for itself how this process should be implemented. But in any case, an integral part of the process is the decision-making stage, which is most often representing a mechanism for managing corrective and preventive actions (CAPA). Analysis of various sources dedicated to the theory and practice of CAPA showed that several stages of the CAPA process cause difficulties for employees of quality management services of construction organizations. This article presents the author's approach to a collecting and analyzing data stage implementation on detected inconsistencies and their root causes and as well as an implementation for stage of a list of corrective actions creation. The author proposes the concept of cognitive management of nonconformities based on visualization of data on nonconformities and their causes. The main result of the presented study is the nonconformity management technique aimed at improving the efficiency of the quality management system as a factor in sustainable development and increasing the competitiveness of Russian construction organizations.

1. Introduction
The most important task of managing any construction organization is ensuring that it functions effectively. The implementation of quality management systems (QMS) at Russian construction enterprises has become one of the solutions to this problem. Practice has shown that a successful implementation and functioning of the QMS is largely determined by a level of management of two groups of nonconformities. Let us start discussion about mentioned groups by looking at the ISO 9001 standard and see how the term ‘nonconformity’ is defined in the standard.

The current edition of ISO 9001 defines this term as a non-compliance with one or more of requirements described in the mandatory clauses [1].

As already mentioned, nonconformities are divided into two groups. The first group consists of inconsistencies in the organization’s management processes, the second group includes QMS non-conformities with the requirements of the current version of the ISO 9001 standard. In turn, the nonconformities of both groups can be divided into two categories: minor and significant. While discussing categories of non-conformities, Richard Keen [2] writes: «A minor nonconformance is an event or action that is outside of the ISO 9001 requirements. However, this type of violation does not have any dire consequences to the way the business operates nor does it cause any major effects. A
major nonconformance, on the other hand, is identified when there is a huge violation of the business’ QMS, preventing the entire company from meeting the requirements outlined in ISO 9011 guidelines».

The most important tasks of non-compliance management are an identification of possible causes of non-conformities and a development of necessary corrective actions to prevent them. The ISO 9001:2015 Standard gives an important place to corrective actions to eliminate identified non-conformities. As known, in the current version of the standard there is no section in which specific requirements for preventive actions are formulated. But this does not mean that preventive actions should be rejected. As noted in [3, 4], on the contrary, preventive actions become an integral part of a risk management system. They become part of “risk-based thinking,” where risk comes to the fore. Melicharova [5], Martins, and da Silva [6] noted this particular feature of the current version of the ISO 9001 standard in their studies.

2. Materials and Methods

2.1. Why CAPA?

Currently, a risk-based approach is recommended as the most suitable for taking into account a wide range of circumstances encountered in various areas of the economy [7, 8, 9]. The practical implementation of this approach assumes that it is based on reliable data obtained during the identification and analysis of emerging nonconformities [10, 11].

A review of studies related to non-conformity management shows that researchers consider the Corrective and Preventive Action Mechanism (CAPA) as the primary tool. In particular, Markens [12] states that «The CAPA system is the cornerstone for a Quality Management System … and the backbone and driver for Quality improvements».

2.2. The classic approach to the CAPA system implementation

An analysis of studies related to the CAPA system allows us to state that there is a clear idea of the composition and sequence of actions that must be performed for the effective implementation of CAPA [12, 13, 14]. The opinion of most researchers on this subject is well reflected in the phrase of Markens: «The most efficient way to implement a sustainable and robust CAPA system is by applying a closed loop system» [12]. The components and description of the stages of the CAPA system are presented in table 1.

| Step                  | Step description                                      |
|-----------------------|-------------------------------------------------------|
| Identification        | Identification and description of nonconformity.       |
| Evaluation            | Assessment of nonconformity’s impact on the organization. |
| Investigation         | Formation of a list of possible nonconformity causes and a search for root causes. |
| CAPA Implementation   | Preparation and implementation of a corrective action plan aimed at eliminating the causes of nonconformity. |
| Verification          | Assessment of the effectiveness and efficiency of measures taken. |
As a rule, while implementing the Investigation phase, one uses 7 basic quality tools (7BQT) [15], which provide the simplest means of visualizing the results of processing data on identified non-conformities and their causes.

2.3. Visualization as a way to increase the CAPA system effectiveness

Modern approaches to cognitive management of complex organizational systems require the use of tools such as cognitive analysis and cognitive modeling. Describing the features of these tools, Tsvetkov and Solov'ev [16] note that both of these tools, based on the concept of cognitive management about using of the information space as an environment for the integration of cognitive management, are actively used in the study of management problems and decision making.

Using histograms, Pareto diagrams, Ishikawa diagrams, we can obtain a set of sufficiently informative visual data representations on non-conformities. However, they practically do not reflect relationships between various inconsistencies, an influence of any reason on some inconsistencies that arose separately. These tools are of little use in finding the root cause of a particular non-conformity. Of course, there are other means to solve this problem, but they create new independent visual representations of the processed data. The same problem arises when forming a corrective action plan.

3. Results

Unfortunately, the author did not come across works which presented multi-purpose visualization’s tools applicable to information about non-conformities. As an own solution to the problem, the author proposes two non-standard ways of visualizing data under discussion. The first is a functional semantic network (FSS), the second is a three-dimensional diagram of the costs of eliminating non-conforming products, inconsistencies and reasons for their occurrence.

In contrast to the well-known simple quality tools, the FSS reflects a fact of one reason’s influence on occurrences of a number of nonconformities and a situation when one non-conformity causes another, forming a chain of nonconformities (Figure 1).

The main FSS components, the rules for its construction and algorithms for dynamic changes in FSS structure were considered in more sufficient details in previous author's publications [3, 4].

The three-dimensional diagram of the costs of eliminating low-quality products, non-conformities and the reasons for their occurrence is a visual display of information related to the identified non-conformities. This is data on the non-conformities occurrence frequency for one reason or another, on the costs of eliminating low-quality products and on the costs of eliminating the causes of non-conformities. The diagram is based on a graphical representation of the costs of eliminating inappropriate products proposed by the author and described in [17].

Below are the main points of the study [17].

Each detected non-conformity $j$, which is caused by the reason $i$, leaves the "spot" of a certain type. The cost of such "spot" removal will be considered equal to the value of the cost of removal of non-conforming products associated with the identified non-conformity - $z_{np}^{ij}$. The graphical representation of the term "spot" is illustrated in the form of a rectangle with sides, equal to $1$ and $n_{ij}$ (Figure 2a). If any nonconformity $j$, due to the reason $i$, is detected repeatedly, the total area of "spots" of one type ("area of contamination") will be equal to the sum of the areas of elementary rectangles (Figure 2b) or the area of a rectangle with sides $N_{ij}$ and $z_{np}^{ij}$ (Figure 2c). Value $N_{ij}$ is the number of times when non-conformity $j$ due to reason $i$ happened.

Value $z_{np}^{ij}$ is the average cost of the nonconforming products elimination, which is calculated according to the formula (1):

$$ z_{np}^{ij} = \frac{\sum_{k=1}^{N_{ij}} z_{np}^{ijk}}{N_{ij}} $$

A three-dimensional diagram is obtained by adding a third dimension to each of the “spots”, which we conventionally call the “degree of pollution” (Figure 3). PLi - “degree of pollution” by i-th cause of nonconformity.

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Figure 1. An example of FSS (fragment)

Figure 2. The cost of removal of nonconforming products ("area of contamination") which is a result of non-conformity \( j \) due to reason \( i \):
a) for a single detection of non-conformity; b) with repeated detection of non-conformity; c) model "average cost".

The value of this dimension \( PL_i \) is calculated as a ratio of the costs to eliminate the causes of the “spot’s” \( S_i \) appearance to the costs of eliminating the “spot” itself (2).

\[
PL_i = S_i / \sum_{k=1}^{N_{ij}} z_{np}^{ijk} \tag{2}
\]
Recall that costs of eliminating the “spot” are costs of eliminating inappropriate products. The costs of an action to eliminate a cause of the appearance of the “spot” $S_j$ are considered as the costs of the corrective actions aimed at eliminating $i$-th cause of the nonconformity $j$ [17].

This value is used as an indicator of the effectiveness of corrective actions when they are included in the risk management plan. The lower is a value of the indicator the more effective is a corrective action.

![Figure 3](image)

**Figure 3.** Example of a three-dimensional costs diagram of elimination low-quality products, nonconformities and their causes.

As an example, we consider the application of the above approach to the data described by the author in article [18].

An analysis of the nonconformities and causes of nonconformities (Table 2) and the chain of inconsistencies made it possible to identify 4 root causes.

**Table 2.** Identified nonconformities and causes of their occurrence

| Nonconformity | Cause |
|---------------|-------|
| Nonconformity 1. The laying was performed by a low-level bricklayer | Cause 1. Absence in the staff of the organization a mason of the required level |
| | Cause 2. Parallel maintenance of masonry on 2 objects |
| Nonconformity 2. In the masonry, more broken bricks were found than required | Cause 3. A batch of bricks contained a large amount of breakage |
| | Cause 4. The brick was pricked because of low qualification of the mason |
| Nonconformity 3. Over-run of cement mortar | Cause 5. Bad weather conditions prevented the finishing of the job |
| | Cause 6. Over-run due to low qualification of the mason |

Based on the acts of eliminating non-conforming products, the total additional costs associated with each cause of a particular nonconformity were determined (Table 3) and formed a list of possible measures aimed at eliminating the causes of each non-conformities (Table 4).

Let us to calculate the value of the “pollution level” for each of the causes (Table 5) and construct a three-dimensional diagram for nonconformity 2 and the reasons for its occurrence (Figure 4).

The figure shows that the lowest value corresponds to cause 3. Then comes cause 1, and finally cause 2.
Table 3. The costs of eliminating nonconforming products depending on the nonconformity and the reasons for its occurrence, thousand rubles

| Cause’s code | Cause’s description | Non-conformity 2 | Non-conformity 3 |
|--------------|---------------------|------------------|------------------|
| cause1       | Absence in the staff of the organization a mason of the required level | 80               | 40               |
| cause2       | Parallel maintenance of masonry on 2 objects | 40               | 20               |
| cause3       | A batch of bricks contained a large amount of breakage | 50               | 15               |
| cause5       | Bad weather conditions prevented the finishing of the job | 50               | 15               |

Table 4. The costs of the risk reduction measure

| Risk reduction measure | Implementation costs of the measure |
|------------------------|-------------------------------------|
| 1. Improvement of professional skills of the mason | 20                                   |
| 3. The acquisition of a program for more efficient allocation of labor resources | 12                                   |
| 4. Replacing the brick supplier | 5                                    |

Table 5. Result of calculation the value of the “pollution level” for each of the causes

| Cause’s code | Cause’s description | The costs of eliminating nonconforming products | Risk reduction measure | Implementation costs of the measure | Effectiveness of corrective action (PL) |
|--------------|---------------------|-----------------------------------------------|------------------------|------------------------------------|--------------------------------------|
|              |                     |                                               | Improvement of professional skills of the mason | Acquisition of a program for more efficient allocation of labor resources | Replacing the brick supplier |
|              |                     |                                               | 20                     | 12                                 | 5                                    |
| cause1       | Absence in the staff of the organization a mason of the required level | 80 | 0,25 |                          | 0,25                                 |
| cause2       | Parallel maintenance of masonry on 2 or more objects | 40 | 0,50 | 0,30 | 0,40                                 |
| cause3       | A batch of bricks contained a large amount of breakage | 50 | 0,10 | 0,10 |                                    |
4. Conclusions

In addition to the previously described features of data visualization related to nonconformities and the reasons for their occurrence, it is proposed to add to the FSS some cartography’s and coloristic’s elements.

In the initial version of the FSS, information about the costs of eliminating non-conforming products due to one or another reason is not displayed at all. It is proposed to introduce a stratification of inconsistencies and their causes on the basis of data on the indicated costs and display these objects in the FSS in different sizes, similar to the display of settlements depending on the population in them. The higher the total costs associated with the manifestation of one or another reason, the more noticeable should be the object of the FSS corresponding to this reason.

Also, to increase descriptiveness, it is proposed to introduce a color scheme for FSS objects using 7 rainbow colors. Red color will correspond to the most significant discrepancies and their reasons. A large red object is the subject of an immediate response! Violet color marks minor nonconformities. You can ignore small purple objects; a large purple object should make a quality specialist think: it is possible that attention should be paid to the nonconformity and the reasons for its occurrence and put them to the category of significant one. The numerical boundaries of the strata can be determined by the employees of each organization independently.

Thus, we can conclude that visualization is an important factor in cognitive quality-management. The proposed visualization tools can be widely used in various construction organizations while implementing a risk-based approach within the QMS. It seems that the integrated use of the proposed tools will ensure scientifically based decision-making on the management of non-compliances, cost reduction and, as a result, increase the efficiency of the organization.

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