SAFETY OF TECHNOLOGICAL PROJECTS USING MULTI-CRITERIA DECISION MAKING METHODS

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Abstract. The article analyzes a construction technology project as a safety standard document for a construction site and describes the application of mathematical methods at the stages of construction and design. Due to the fact that the construction project consists of (safety point of view) the site plan and technological cards (notably these documents indicate safety design solutions), the indicators making up a comparable set of indicators to evaluate the site plan, technological cards and the entire project may vary and be diverse. Practice shows that the construction technology project or its parts thereof are to be assessed using 5 to 7 parameters, as in case of a larger quantity of indicators, the significance of each indicator becomes relatively lower and has effect on the priorities of line formation. To ensure the safety of workers on construction sites, when preparing construction technology projects, the application of experimental design is proposed, thus starting the evaluation of the quality of technological solutions to construction projects in terms of safety employing multi-criteria mathematical methods.

Keywords: construction site, labour safety, dangerous factors, technology project, multi-criteria method.

1. Introduction

In the most general sense, construction is a human activity field particularly closely related to the environment where the whole humanity exists. Therefore, there is a natural desire to take care of the environment creating (construction and building design, construction stage) and actually using it (maintenance stage) while it is trying to manage such a way that its elements, including people would be mutually coherent and defined as harmonious construction development.

The business of construction is rather specific, and this partly determines the specificity of work safety in enterprises (Dėjus 2009a). Because of specific construction features as a business type, work safety in construction enterprises is more complex and complicated than that in other companies.

In general, accidents on construction sites can also be classified as the rejection of a safety control system of the company determined applying various criteria – technical, technological, organizational and other possible factors (Dėjus 2007, 2008); any of adverse events on a building site is associated with construction design in the broadest sense, particularly with designing construction technology, including safety in operation.

This article analyzes the construction technology project as a safety standard document in Lithuania as planning conditions and as a possibility of applying mathematical methods for safe work to prepare construction and design stages.

2. Workplace Safety Design in Building Construction

Scientists from various countries pay huge attention to researching work safety problems and reaching effective solutions.

The level of accidents in a certain sector of national economics is assessed using the following information: the number of the employees of the analyzed sector, the number of victims during accidents at work, the frequency and hardness of accidents (Hoła 2007, 2009, 2010).

Most accidents on construction sites occur when raising operations of a mobile and tower crane. The authors of the article made research and defined seven reasons for accidents (data of 1997–2003) (Beavers *et al.* 2006).

Balance loss, collapse and falling from height are the main reasons for injuries on residential construction sites in New Zealand (Bentley *et al.* 2006). The article of Choudhry and Fang (2007) discusses the reasons for unsafe work of constructors.

The main reason for all falls including falling from a roof is the loss of balance. The principle goal of research is to overview the present knowledge about activities connected with balance control when working on the roof (working on the roof: roof construction, repair, renovation, reinforcement). Many reasons for balance loss were defined while analyzing the acquired information (Hsiao and Simeonov 2001).

The major principle factors of employees' injuries include the collapse of construction where an employee

stands, various slips, the loss of balance etc. (Paine and McCann 2004; Husberg *et al.* 2005)

Peculiar dangers and prevention of them depend on a construction site, constructions types, employees themselves and other factors. The extension of practical solutions could help with decreasing the risk of injuries (Spielholz *et al.* 2006).

Construction business in Singapore has been using Safety Management System for 10 years (Teo and Ling 2006). However, the system does not give any results. Therefore, there was a decision to check the efficiency of the system. Safety Management System includes safety policy, safety work practice, safety trainings, group meetings, accident research and analysis, domestic rules of safety, analysis into a hazard and other similar elements. The article describes the performance and efficiency of each element.

The papers analyze automatization methods for safety systems (Giretti *et al.* 2009), define the peculiarities of a safety system in Nigeria (Idoro 2008) and road building in Shri-Lanka (Perera *et al.* 2009). Lithuanian scientists suggest assessing solution, to safety at work (Liaudanskienė *et al.* 2009).

The articles by Zavadskas and Vaidogas (2008; 2009), Vaidogas and Juocevičius (2008, 2009) analyze the peculiarities of industrial accidents and suggest methods for forecasting accidents; these methods could be used to conducting investigations into accidents at work and to preparing project documentation.

Safety problems on construction sites also are studied in other works by (Abudayyeh *et al.* 2003; Fredericks *et al.* 2005; Fung *et al.* 2008; Hinze *et al.* 2006; Mohan and Zech 2005).The performed researches clearly shows that the problems of employee's safety at work are typical in most countries.

However, the author failed to find the sources that would be offered specifically for designing construction works; those include construction planning and preparation of technological cards (TC – is the main document of a technological project; works on a certain construction site are performed in accordance with TC; labour safety decisions are also provided) and the application and use of mathematical methods to solve safety problems in other range.

To design building construction technology using traditional methods, it seems to be normal to consider the following tasks: one or more promising construction technologies and organization options are selected according to the designer's view; technical and economic criteria are determined one of which, as a rule, is project cost and another is the duration of implementation that is always important for the developer of the project while implementing a "rational" technological-organizational version of the project; the specification of the selected "rational" version is either performed or not.

The earlier presented algorithm design is acceptable to prepare a construction technology project as the main and single safe work in a particular regulatory document on the construction site and could be applied if drawing attention to several features of project preparation.

The appendixes of Regulation (STR 1.08.02:2002) provide that the contractor prepares the technology project of construction before construction work begins. Project preparation, as mentioned in Regulation (STR 1.08.02:2002), must be guided by design solutions to a technical project; also, specific safety assurance solutions must be submitted, but links or excerpts of occupational safety and health regulation cannot be used as solutions kinds.

In general, the project of construction technology consists of notes, a construction scheme of the situation, a site plan, a vertical cross-section of construction with a crane, a timetable of construction and technological cards (TC).

Annex 5 of the Rules (DT 5-00) states that specific design solutions, determining technical means and work methods that ensure safety and health, must be made in the technology project of construction. These solutions cannot be replaced by references or excerpts from safety and health legislation, regulation and technical documentation referring only to an appropriate design solution.

To prepare design solutions, it is necessary to clarify dangerous and harmful factors associated with work technology and conditions for constructions, to specify their operational areas and to identify hazard.

Changes in building conditions that affect safety and health as well as the technology project of construction should be modified and / or adjusted.

From the given information it can be concluded that the safety of technology solutions to a construction project is very clearly and unambiguously defined, and all attention on safety at work preparation is concentrated on five risk factors – a fall from height, falls of structures and products, injury of mechanisms and prevention from electrocution and falling soil. These points are completely connected to concluding (Dėjus 2009a) hazard factors.

3. Evaluation Factors of Suggested Safety Solutions on Construction Sites

As the construction technology project consists of a site plan and technological cards (these documents indicate safety design solutions), the criteria making up a comparable set of indicators to evaluate the site plan, technological cards and the entire project may vary and be diverse. Therefore, it is clear that project preparation can be performed successfully only by the salvation of multi-criteria assignments.

Šarka *et al.* (2008) claims that multi-criteria mathematical methods in various areas were begun to be regarded in the middle of the 20th century, when the first works were published (Churchman and Ackoff 1954; Churchman *et al.* 1957; MacCrimmon 1968; Paelinck 1976; Hwang and Yoon 1981).

The chosen topic by Zavadskas (2008) was developed later (Kapliński 2008a,b 2009; Peldschus 2008, 2009, 2010).

Next, the known multi-criteria methods were developed and the new ones were created. The methodology of comparing variants was based on the known and new multi-criteria methods (Kaklauskas *et al.* 2010; Ustinovi-

chius *et al*. 2007; Zavadskas *et al*. 2009a, 2009b, 2010; Zavadskas and Turskis 2010; Brauers and Zavadskas 2010).

The created methods and methodologies in the analyzed articles were used for engineering solutions to tasks (Zavadskas *et al*. 2009b; Antuchevičiene *et al*. 2010). Also, they were applied in various fields of economy and business such as improving the process of work by contract arrangement and contractor selection (Ustinovichius *et al*. 2009; Banaitiene *et al*. 2008), assessing construction technological effectiveness or solving efficiency enlargement tasks using technological and legal aspects (Podvezko *et al*. 2010; Turskis and Zavadskas 2010).

The design of a technological project is completed at two stages: designing a plan of a construction site and designing technological cards.

When designing the plan of the construction site, danger zones are determined (in accordance to Regulation (STR 1.08.02:2002), Section 1.1.3 p.) and the areas of hazardous zones are calculated.

Really dangerous areas on the construction site are as follows (Dėjus 2009a):

1. When *difference in height* is more than 1.3 m, there is the risk of workers falling from high ceilings (on the whole perimeter), roof structure around the periphery of stairs on all floors of building structures (flight and landings around the periphery), openings in overlays (holes in each floor all around the perimeter) and near openings in vertical structures (such as doors to a balcony) – horizontal projection of the length of a dangerous area.

2. There is risk that falling materials and construction can injure the workers as such zones are about 5–10 meters width (depending on building height) all around the building and near the openings of laps. A danger zone consists of opening width and an additional 3 meters wide zone of the entire perimeter of opening. The above-mentioned risk can be controlled by collective security means – roofs, protective overlays or decks. Therefore, options can be compared both by hazardous areas as well as by how the area should cover the above-mentioned collective security means.

3. Working (or moving) *construction machinery* is the risk of damage to employees. In this case, an employee can be injured by a directly moving construction of a mechanism (for example, by a dozer blade or crane counterweight) or when an employee is injured by a mechanism affecting the object – lifting load, pushing soil etc.

4. There are variants of the construction plan when there is *risk to injure people working close to a construction site rather than inside it*. In that case, a fence around a construction site is used which means not only minimal price but also a lower risk of injuries to people who are near to the construction site.

5. The matter of the offered model (Dėjus and Viteikienė 2003) is that risk is estimated employing only one attribute in the construction company – finding a dangerous factor in a particular workplace or a means of how to be protected from it. A comparison of regulations

and real situations is done establishing if means meets safety requirements. If one requirement is not appropriate, risk is accepted as unacceptably large, however, there is a way of risk reduction – it is necessary to perform requirements for the standard mentioned above. In general, the estimation of any object by one index is not comprehensive, and the results of this estimation could distort realistically existing setting. However, if attribute content was completed, the mentioned problems would be avoided. Thus, professional risk that appears in a construction company could be estimated by the performance of requirements for safety standards, i.e. only by one attribute which is the answer to the question if *Law comply with requirements regulating the organization of safety and its performance on a construction site* (further – *rate of standard requirement performance* – SRPR). The complexity of the attribute is hidden in the set of safety standard acts, which involves the absolute majority of activity directions to construction workers.

The *application of SRPR* also has a disadvantage – it is relatively difficult to select "the most important" requirements for standard acts and to do work essentially for an appropriate quality of both construction and safety.

When explaining the concept of "the most important" standard law requirements, it is possible to use the scheme of safe work security on the construction site (Dėjus 2009a).

6. While evaluating a construction plan from the point of view of safety, other attributes can be applied (hardness of a construction site is a quite subjective index because it is evaluated considering points and can depend on such special factors as the number of working mechanisms on the construction site, maximum height of means used at one time, a vertical or horizontal projection of such means, cargo lifting using two cranes, the used power of electrical tools and equipment, technological width of cellar floor, the number of different collective means of safety from falling, movement roads and the length of roads of construction mechanisms, etc.)

Designing technological cards for construction work takes place along with the projection of a construction site or follows it and safety at work problems are considerably solved in the technological card rather than making a plan for a construction site. At the same time, there is certainty about technological cards. There should not be alternative solutions to safety at work. The above mentioned circumstances mean that for assessing the quality of the technological card, other attributes of comparison are also available.

In addition, TC are prepared for performing separate works as construction works are different in their technology and difficulty and, certainly, in safety at work factors that influence employees at their work places and workplace preparation peculiarities. Therefore, TC solutions are made for a certain work place or work area.

The following solutions to safety at work are suggested:

1. The number of safety belts fastening places in one work area should be as less as possible because while choosing technical safety equipment, the priority is given

for collective means of safety. Safety belts are kept as an individual means of safety used for defending a worker from falling from height and are irrational to make a collective safety means at the place. Safety belts are personal protection measures to protect a worker from falling from high places where installing collective protection measures are not rational, the use of security measures is single or takes only short-term, the risk of being affected by hazardous agents has only one employee, the installation of collective protection from a technological point of view is rather complicated or impossible etc.

2. Technical accuracy of using platforms (ladders, planked floors etc.) is a complex index because while finding out its significance, it is necessary to evaluate the maximal number of factors connected with technical accuracy of equipment – from manufacturer documentation to the workers instructed at the work place about individual safety means and work on platforms.

The above mentioned index of technical accuracy is closely related to the spoilage of the used platform means (including individual and collective safety means) that should be marked in TC. It is important to mark certain activities of workers even when there is suspect that the used equipment is not technically in a good working order.

3. A comparative attribute is expressed by dangerous factors acted in a certain work area with a number of used technical safety means that defend from the above mentioned factors. The introduced attribute should not be less than 1 and should be looked at while choosing a scale of attribute meanings.

4. The number of electrical and simple tools used at a work area is an index that could be minimized having in mind that each tool generates even one dangerous factor. There should be certain safety means for each of the factors. Thus, in this case, we also use a reasoned principle of minimization.

5. The evaluation of the safety of a construction plan and prepared TC quality SRPR are used to finding out TC compliance with legislative regulations and foreseeing the probability of accidents.

The presentation of prepared TC solutions influences TC realization on a real construction site. In that case, we should use regulations (Dėjus 2009a) on using a 3D principle representing safety solutions to a construction work project. 3D should be used when the suggested solutions are presented on the work place plan where the same work place layer, the third sketch showing the installation of technical safety measures, the used element or knot, the image from the other side or technical documentation (TC) *transparency* could be one of subjective TC quality assessment indicators.

The quality of a construction technology project can be evaluated according to the relationship of TC with the quantity of construction work in a construction object calendar. Every work must be designed and done in an appropriate way only after preparing appropriate TC.

Practice shows that a construction technology project or parts of it are evaluated according to attributes 5–7 as in case there is a bigger number of attributes. The

meaning of each attribute becomes less (Zavadskas *et al.* 2007) and influences the formation of a priority line.

The mathematical meanings of the above-mentioned attributes could be used for making a solution matrix, which would let find out a rational variant of a construction technology project or parts of it.

4. The Evaluation of the SAW Method for Safety Solutions to Construction Sites

It is not important what kind of a multi-purpose mathematical method is used for preparing a construction technology project. Thus, a mathematical method, which is the most appropriate way for a counter, is usually used. It means that counting formulas is not difficult as this process does not require much time; a physical meaning of counting is easily understandable and the obtained results are quiet reliable.

One of the reliable factors of multi-purpose mathematical methods is method sensitivity (Zavadskas *et al.* 2007). Therefore, it is recommended to use multi-purpose mathematical methods of low sensitivity.

One of the applied methods is Simple Additive Weighting (SAW) method (MacCrimmon 1968; Dėjus 1992, 2009b) that is quite simple and easily understandable.

$$A = \{ A_i \Big| \max_i \sum_{j=1}^{n} q_j \ \overline{X}_{ij} \Big| \sum_{j=1}^{n} q_j \}, \qquad (1)$$

where $\overline{X}_{ij}$ – a normalised value of criteria; q_j – the weight of each criteria; $i = 1, n$ – the number of alternative; $j = 1, m$ – the number of criteria.

$$\overline{X}_{ij} = \frac{\min\limits_i}{X_{ij}} \qquad \text{if optimal is min;} \qquad (2)$$

$$\overline{X}_{ij} = \frac{X_{ij}}{\max\limits_i} \qquad \text{if optimal is max.} \qquad (3)$$

The following condition (4) should be fulfilled:

$$\sum_{j=1}^{n} q_j = 1. \qquad (4)$$

Three technological cards prescribed for one storey, one hole building reinforced with concrete ceiling constructions (beams and ceiling slabs) were prepared and compared.

In TC, work safety solutions including employees' fall from height were produced.

Different schemes for three technological cards are designed. The schemes are different not only because of work organization factors (constructions are installed considering one, two and four positions of a crane) but also due to employees' safety factors – the length of barriers, the efficiency of raising equipment (from the work safety point of view), sizes of hazardous zones, etc.

The evaluated criteria along with their numbers and meanings are usually chosen by a decision maker; in this case, it is the author of the article, though it is possible to apply experts' assessments.

Solution matrix X is made while dealing with the example presented in Table 1.

Table 1. Solution matrix X

	X_1	X_2	X_3	X_4	X_5
A_1	1	7	2	346	97
A_2	2	6	3	227	92
A_3	2	3	3	207	86
q	0.1	0.25	0.2	0.15	0.3
Optimization direction	min	max	min	min	max

X_1 – the number of fitting places for safety belts;

X_2 – an evaluative coefficient of technical accuracy for elevation means;

X_3 – the number of used equipment;

X_4 – the width of the danger zone of a crane, m^2;

X_5 – SRPR, marks until 100;

A_1, A_2, A_3 – alternatives/variant numbers;

q – weights of criteria.

The matrix of solutions is normalized according to appropriate formulas and normalized matrix $\overline{X}$ is made and presented in Table 2.

Table 2. Normalized matrix $\overline{X}$

	$\overline{X}_1$	$\overline{X}_2$	$\overline{X}_3$	$\overline{X}_4$	$\overline{X}_5$
A_1	1	1	1	0.598	1
A_2	0.5	0.875	0.66	0.912	0.948
A_3	0.5	0.43	0.66	1	0.886

For the rationality of the variant, the members of normalized matrixes are multiplied by their meanings and summed up:

$A_1 = 1 \cdot 0.1 + 1 \cdot 0.25 + 1 \cdot 0.2 + 0.598 \cdot 0.15 + 1 \cdot 0.3 = 0.9397$.

$A_2 = 0.5 \cdot 0.1 + 0.875 \cdot 0.25 + 0.66 \cdot 0.2 + 0.912 \cdot 0.15 + 0.948 \cdot 0.3 = 0.822$.

$A_3 = 0.5 \cdot 0.1 + 0.43 \cdot 0.25 + 0.66 \cdot 0.2 + 1 \cdot 0.15 + 0.886 \cdot 0.3 = 0.7055$.

Counting discloses that the priority line is as follows: A_1, A_2, A_3. A rational variant is A_1.

5. Conclusions

In order to secure the safety of workers on a construction site it is suggested:

1. To use different construction technology projects, start evaluating the quality of safety in construction technology projects and apply multi-criteria decision making methods.

2. When applying multi-criteria methods, use the suggested efficiency attributes of solutions to work safety, including regulations on acting norms (SRPR), the length of dangerous zones, the width of zones where risk to be injured by several operating mechanisms may occur and the width of zones that should be covered with collective security measures protecting workers from the injuries caused by falling substances or small structures.

3. When assessing the quality of a construction site plan considering safety position, the indicators such as the area of the building or construction that involve workers simultaneously working in one vertical separated by a single ceiling slab and the number of self-propelled machinery concurrently working on the construction site are applied.

4. For the evaluation of solutions to work safety projected in TC, the following attributes are used: the number of places along with fitting safety belts in one work area, technical accuracy of platforms (complex attribute) and the number of electrical and simple tools used in a work area.

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DARBUOTOJŲ SAUGOS STATYBVIETĖSE SPRENDINIŲ DAUGIATIKSLIS VERTINIMAS

T. Dėjus

S a n t r a u k a

Šiame straipsnyje analizuojamos statybos darbų technologijos projekto, kaip darbuotojų saugos norminio dokumento, rengimo sąlygos ir aplinkybės bei matematinių metodų taikymo galimybės rengiant saugos darbe sprendinius statybos paruošimo ir projektavimo etape.

Kadangi statybos darbų technologijos projektas susideda (saugos darbe požiūriu) iš statybvietės plano ir technologinių kortelių (būtent šiuose dokumentuose užfiksuojami saugos darbe projektiniai sprendiniai), tai ir rodikliai, sudarantys lyginamų rodiklių aibę ir vertinantys statybvietės planą, technologines korteles ir visą projektą, gali būti labai įvairūs ir skirtingi.

Praktika rodo, kad statybos darbų technologijos projektas ar jo dalys vertintini pagal 5–7 rodiklius, nes, esant didesniam rodiklių skaičiui, kiekvieno rodiklio reikšmingumas santykinai mažėja ir tai turi įtakos prioritetų eilutės formavimui.

Siekiant užtikrinti darbuotojų saugą statybvietėse siūloma rengiant statybos darbų technologijos projektus taikyti variantinį projektavimą, pradėti vertinti statybos darbų technologinių projektų sprendinių kokybę saugos darbe požiūriu ir tam taikyti daugiatikslius matematinius metodus.

Reikšminiai žodžiai: pavojingi veiksniai statybvietėse, saugaus darbo statybvietėse projektavimas, statybos darbų technologijos projekto rengimas, daugiatiksliai matematiniai metodai, techniniai ekonominiai rodikliai, prioritetų eilutė.

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