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Analysis and prevention of construction site accidents

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Preliminary report

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Analysis and prevention of construction site accidents

The analysis of reports on construction site accidents suggests that most accidents involve work at high elevations and the lack or inappropriate use of personal protection devices. Therefore, the paper provides several alternatives of personal protection devices intended for the prevention of falls from elevations. It is suggested to select the most appropriate protection device using the new multiple criteria decision making (MCDM) method of the weighted aggregated sum product assessment with grey numbers (WASPAS-G) to help prevent accidents when working at elevations.

Key words:
construction site accidents, prevention of accidents, personal protection devices, MCDM, WASPAS-G

Prethodno priopćenje

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Analiza i prevencija nesreća na gradilištima

Iz analiza izvještaja o gradilišnim nesrećama može se zaključiti da do nesreća najčešće dolazi tijekom rada na visini i zbog nekorištenja ili neodgovarajućeg korištenja osobnih zaštitnih sredstava. Zbog toga se u ovom radu daje nekoliko mogućnosti osobnih zaštitnih sredstava koja se koriste za prevenciju pada s visine. Predlaže se odabir najprikladnijeg zaštitnog sredstva primjenom nove metode za višekriterijsko odlučivanje (engl. multiple criteria decision making - MCDM) s ocjenjivanjem ponderiranih skupnih proizvoda i sivim brojevima (engl. weighted aggregated sum product assessment with grey numbers - WASPAS-G) kako bi se pridonijelo naporima za sprečavanje nesreća tijekom rada na visini.

Ključne riječi:
gradilišne nesreće, sprečavanje nesreća, osobna zaštitna sredstva, MCDM, WASPAS-G

Vorherige Mitteilung

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Analyse und Prävention von Baustellenunfällen

Aus Analysen von Berichten über Baustellenunfälle geht hervor, dass die meisten Unfälle bei Arbeiten in der Höhe geschehen, sowie durch mangelnden oder nicht fachgerechten Gebrauch persönlicher Schutzausrüstung verursacht werden. Daher werden in dieser Arbeit Möglichkeiten zur Verwendung persönlicher Schutzausrüstung gegeben, die als Absturzsicherung gebraucht wird. Es wird empfohlen, aufgrund der neuen auf mehreren Kriterien beruhenden Entscheidungsmethode (engl. multiple criteria decision making - MCDM) zur Beurteilung gewichteter Produktsummen mit grauen Zahlen (engl. weighted aggregated sum product assessment with grey numbers - WASPAS-G), die passende Schutzausrüstung zu wählen, um der Prävention von Umfällen bei Arbeiten in der Höhe beizutragen.

Schlüsselwörter:
Baustellenunfälle, Unfallprävention, persönliche Schutzausrüstung, MCDM, WASPAS-G

1. Introduction

A substantial number of construction site accidents can be avoided by appropriate planning of works and assessment of the potential risk of falling or contracting an injury. Workplaces, scaffolding or other elevated structures should be properly installed and secured. Special attention should be paid to employee training and providing instruction on various occupational health and safety issues.

The objective of this paper is to analyse safety measures that could prevent accidents at construction sites. The greatest attention is paid to the prevention of falls from an elevation since accidents are the most frequent among workers operating at elevations. The analysis of accident reports revealed many cases of failure to provide workers with personal protection devices or inability of workers to use them correctly. Hence, the two rope system or a system with an anchor secured to the ceiling and an attached belt should be used to protect workers from falls during roof installation works or when working close to an unfenced floor edge.

The use of a multiple criteria decision making (MCDM) methodology to select the most appropriate protection device is suggested in the paper. The analysis of the factors pertaining to falls from elevations resulted in alternative versions of safety measures, involving products currently available on the market. The alternatives were described using technological and economic criteria, the relative significance of which was defined based on an expert survey results which were processed using mathematical statistical methods. It is suggested in the paper that the best alternative should be determined using the new MCDM method of the weighted aggregated sum product assessment with grey numbers (WASPAS-G). The method is capable of processing ambiguous information, where initial data are expressed as grey numbers, and it provides a reliable and a sufficiently accurate solution. The information can be updated if the situation changes either on the market or at construction site. Consequently, the suggested approach could help in selecting the most effective devices, while it can also contribute to some extent to the prevention of construction site accidents, particularly when work is conducted at an elevation.

2. Literature review: construction site accidents and prevention measures

2.1. Statistics of construction site accidents

Construction site accidents commonly occur among workers operating at an elevation, i.e. repairing or installing a roof, performing finishing works, or climbing a ladder to a workplace. The key causes of construction site accidents are: inappropriately organised or undertaken dangerous works, absence of collective protection devices, work performed by a worker who is not properly trained and/or certified and instructed on issues of occupational health and safety, and insufficient internal control of occupational health and safety. Such accidents can be avoided by appropriately planning works in advance, by assessment of the potential risk of falling or injury, and by the use of personal and collective protection devices.

Although the construction sector employs about 7 % of the total global working population, it is responsible for approx. 30-40 % of all accidents [1]. Over the last two decades, the US construction sector claimed more than 26 000 lives, or five workers per day. 40 % of all deaths were due to falls from an elevation, with one-third of workers falling off a roof. 30 % of workers that fell from a height either did not use any personal protection devices, or used inappropriate devices [2]. For construction companies, accidents related to falls from a height also entail financial obligations and so, in the US alone, annual compensations for workers who fell from a height amounted to US$ 54 million, which is US$ 106 thousand per person [3].

According to 2012 data of the Building Safety Group (BSG), which is responsible for health and safety at work in the Great Britain, the number of falls from a height grew by 140 % and accounted for 23 % of all accidents. Despite the growth in the number of falls from a height, the total number of construction site accidents decreased by 21 % [4].

Over one and a half years, Lithuanian construction companies accounted for 73 serious injuries and fatal accidents. This number makes up 28 % of the accidents registered in all sectors of national economy. 86 % of occupational accidents occurred due to a fall from a height. Among key causes of accidents are the perception of health and safety instructions as a formality, inappropriate set-up of workplaces, and failure to use personal and collective protection devices. However, continuous prevention campaigns cut down the number of falls from an elevation, and so the total number of accidents was reduced [5].

2.2. Analysis of measures for prevention of construction site accidents

Over the past 20 years, all technical and organisational efforts have been engaged to improve occupational safety (reduce the number of occupational injuries) in many sectors; however, the construction sector failed to achieve this goal [6]. Construction projects are dynamic. They are impacted by many factors, such as turnover of workers, weather conditions, and a large percentage of unqualified and temporary workers. A different attitude towards construction is required to identify hazards and risks, and to ensure safety and prevent accidents.

Frequently, inadequate assessment of hazardous factors and risks is due to limited or overestimated knowledge used in planning and implementing occupational safety measures, as well as to insufficiently trained workers. Occupational safety can only be ensured if appropriate measures are taken during the entire life-cycle of the project. Planning of occupational safety starts with the identification of hazardous factors and selection of appropriate protection measures [2] (Zhang 2013). It is also important to observe all requirements while designing the technological work card, which should point to hazardous work sites [7].

Construction managers find it difficult to identify hazardous factors at a construction site. According to data provided in a British study, only 6.7 % of construction managers are capable of identifying all hazardous factors related to a construction site. Human errors are among the key causes of accidents. Errors may occur due to negligence, carelessness or the lack of knowledge/experience. Many studies demonstrated that skills required to identify hazardous factors and risks can be improved through training [8].

Training of workers at a construction site is usually perceived as a formality. A more serious attention is given only in case of a serious potential hazard or an accident. Just as in any other branch of economy, construction site workers can only gain experience through continuous and appropriate training. Researchers [9] studied the hypothesis that the worker training at a virtual reality site is more effective compared to traditional forms of training. The study involved 66 workers. Half of the group participants were instructed using traditional methods and the instruction of the other half involved 3D virtual reality technologies, i.e. a virtual image of a construction site. Results of the study revealed that workers who took part in the virtual training on the safety of concrete works passed occupational safety tests with better results compared to those who participated in the traditional training. When attending the training involving a virtual construction site, workers can focus better on the issues studied, get more engaged in the learning process, and find it easier to understand the training materials [9]. The use of a virtual construction site allows instructors to discuss relevant issues, e.g. the order of works to be performed, and appropriate ways to perform individual work tasks. Besides, more attention can be given to hazardous factors (workplaces).

Workers are greatly influenced by the attitude of construction managers or foremen toward occupational health and safety [10]. Although construction managers have more knowledge about occupational safety than workers, they rarely make observations regarding unsafe work [11].

The implementation of construction projects is focused on timely completion, quality, and staying within budget. The risk of a hazard increases as the workers focus on the amount of work to be performed, i.e. as attempts are made to work faster without paying proper attention to safety [12]. Therefore, it is especially important to maintain continuous communication among managers, foremen, and crews. It was established that daily communication between foremen and workers on issues of occupational safety, or even simple reminders (e.g. to wear safety goggles), increased the level of safety by 70 % [13].

To avoid construction site accidents, they must be considered at the early design stage. Works that demand greater safety should be defined as critical and marked as such in the construction timetable [14]. The design of buildings with the help of 3D models may help in assessing the most hazardous spots on the construction site [15]. The use of real blueprints can eliminate misunderstandings, help prepare for works, and comprise a safety plan. 3D models make it easier for construction coordinators and contractors to assess hazardous workplaces [16].

New technologies, such as the Building Information Modelling (BIM), can aid in planning of occupational safety measures. Hazardous factors affecting construction can automatically be identified and eliminated through the use of BIM. The situation on a construction site changes on a daily basis, and new safety issues come up as soon as the previous ones are resolved. An open application programming interface can be used to install an automatic rule-based checking system into an appropriate BIM software [2, 17].

3. Analysis of data on falls from elevations

Most accidents involve work at elevations; therefore, the following part of the paper will focus on falls from elevations in construction industry.

The analysis covers data on 90 accidents at building sites involving construction of residential and public buildings. The analysed cases are from Lithuania. The analysis period is 2007-2012, when pre-trial investigation was carried out.

The first aim was to use the available data and identify the most dangerous height, i.e. the height from which workers fell most frequently. Results of the analysis on the link between the number of accidents and the height of fall are presented in Figure 1.

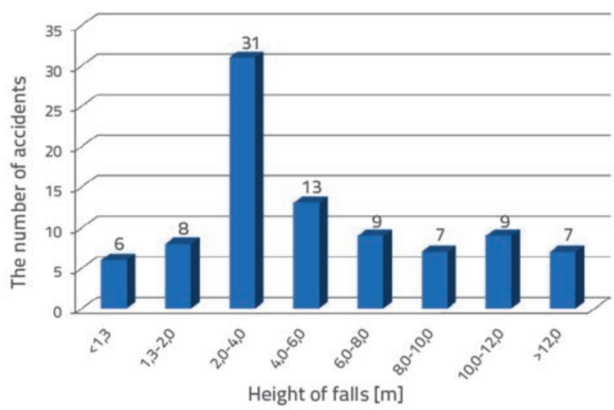

Figure 1. Diagram of falls from a height

The use of personal protection devices while performing construction works remains a significant and sensitive issue. The analysis of 90 accidents revealed that personal protection devices (PPD), such as body harnesses and belts, were used in ten cases only. However, even in these ten cases, five of accidents were fatal, and five resulted in serious bodily injuries. It can therefore be concluded that workers failed to use personal protection devices appropriately, i.e. they had body harnesses but they failed to attach them to lifelines.

Although 90 cases were investigated in the study, a total of 98 workers were injured, i.e. in some cases more than one worker suffered from injuries. 58 cases ended up with serious bodily injuries, 27 accidents were fatal, and 12 workers sustained minor injuries (Figure 2).

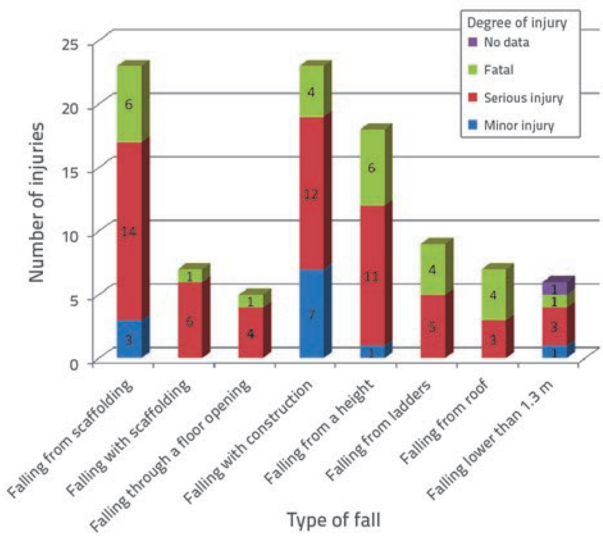

Figure 2. Level of injury depending on type of fall

The available data were used to ascertain the main causes of falls from elevations. Out of 90 cases, 24 workers fell from scaffolding. Out of these 24 cases, as many as 17 occurred due to absence or inadequacy of supports, fencing with railing, platforms, or safety nets.

In six cases, workers fell together with scaffolding. These accidents occurred due to uneven surface, unfit and unstable scaffolding, failure to observe instructions, scaffolding mounted on excessively steep ramps and, definitely, because of inadequacy or absence of supports and fencing. In five cases, workers fell through an unprotected floor opening, i.e. because of inadequacy or absence of fencing with railing, platforms, or safety nets.

In 16 cases, workers fell together with construction elements. Such cases mostly occurred due to inadequacy or absence of supports, fencing with railing, platforms, and safety nets; also, no measures were taken to monitor temporal instability of structures. In three out of sixteen cases, platforms as well as decking and scaffolding ladders were inappropriately designed. Besides, workers failed to observe technological requirements, or workplaces were loaded with weights greater than permissible.

Eight workers fell from ladders because they lost balance. These cases could have been avoided if safety belts were used. One case was registered in excavation, and is due to failure to take safety measures. Demolition works were supervised by an incompetent individual, no safety measures were taken, and no platforms or safety nets were set-up. Two cases occurred because of inadequacy or absence of support, fencing with railing, platforms or safety nets.

Causes of falls from elevations were as follows. Three cases occurred due to failure to set-up collective protection devices, and failure to provide workers with personal protection devices. Works on a roof may have been undertaken without stairs or required safety measures. Two cases involved failure to appropriately set-up supports, fencing with railing, platforms or safety nets. In one case, raised structures could have been non-compliant with requirements, or the worker failure to use safety belts for work on a ladder at a height greater than 1.3 m.

Accidents may depend on working hours or a season. The available data were used to try to determine the riskiest hour of a working day and the most dangerous month.

At most construction sites, the first shift starts at approx. 6:00 a.m., and ends at 3:00 p.m. An analysis demonstrated that as many as 18.9 per cent of accidents occurred between 14:00 and 15:00. It can therefore be concluded that workers are less cautious toward the end of a working day. Other accidents occurred around lunchtime, i.e. at 11:00-12:00 and 12:00-13:00, with eleven and ten accidents, respectively. The smallest number of accidents occurred during morning hours.

Out of 90 cases, twelve, eleven and ten accidents occurred in June, May and August, respectively, i.e. in months when construction activities are at their peak. However, in October, November and December, the monthly number of accidents varied from eight to nine. The most probable reasons for these accidents were adverse weather conditions.

4. Use of WASPAS-G for selection of most rational protective measures preventing falls from elevations

Collective protection measures (fencing, nets, etc.) are the best choice for protection of workers against falls from elevations. In cases when collective protection measures are impossible to set-up (e.g. mounting of facades), personal protection devices, such as belts and body harnesses, must be used.

The presented analysis revealed circumstances under which falls from elevations occurred due to inappropriate use or absence of safety devices. Therefore, safety solutions were formulated for the following cases: falling from scaffolding, falling through an opening, falling with a structure, and falling from a roof. In each case, five alternatives were formulated and defined using various criteria, so as to provide assistance in selecting the most appropriate personal safety device.

Multiple criteria decision making (MCDM) methods are suggested for the selection of an optimum alternative. MCDM has grown out of operations research, and is concerned with designing mathematical and computational tools for supporting evaluation of performance criteria by decision makers. The name MCDM was used for the first time in a paper by Zeleny in 1975 [18]. The evolution and application of the methods is comprehensively analysed in a number of review articles [19-21]. A special issue on multiple criteria decision making and operations research was published in [22]. A special issue on applications for engineering was presented in [23]. Applications in civil engineering were published in [24, 25]. Zavadskas et al. [26] summarized reviews (review papers and books) on the MCDM topic in 2014. The latest vital issue of using hybrid multiple criteria decision making approaches for engineering applications was analyzed in a paper by Zavadskas et al. in 2016 [27].

Selecting an appropriate method is a continuous challenge in every situation that requires a decision. No single method can be considered the best, either with regard to a general or a particular problem [28]. Different MCDM methods can sometimes yield different rankings of alternatives. Therefore, this paper uses WASPAS method that is able to integrate two different traditional methods with the help of an originally derived aggregation coefficient, enabling attainment of the highest accuracy when estimating a multiple attribute problem. Moreover, based on literature review that involves development and applications mostly of a crisp method under consideration, the authors suggest that grey extension of the WASPAS method is feasible for most real world applications.

4.1. Formulation of protective measures preventing falls from elevations

Appropriate protection measures must be selected to protect workers from falls from elevations. This research formulates protection-device alternatives for different types of falls as presented in Figure 2.

However, certain situations do not require the use of personal protection devices. According to health and safety regulations, no works performed at a height lower than 1.3 m are regarded as hazardous; therefore, no collective or personal protection devices have to be used.

Also, no protection-device alternatives are formulated for climbing a ladder, as health and safety regulations require the use of leaning ladders with devices that prevent slippage or falling.

Prior to works on scaffolding, it is important to check its stability, and to make sure that the work surface is even and has no gaps larger than 5 mm, and fenced to prevent workers from falling. Therefore, no personal protection measures are offered for cases of workers falling from scaffolding or together with scaffolding as such accidents occur due to inappropriately installed elevated structures.

Alternatives are formulated for cases of workers operating close to an edge of an unfenced floor or opening, installing a roof, or mounting a façade.

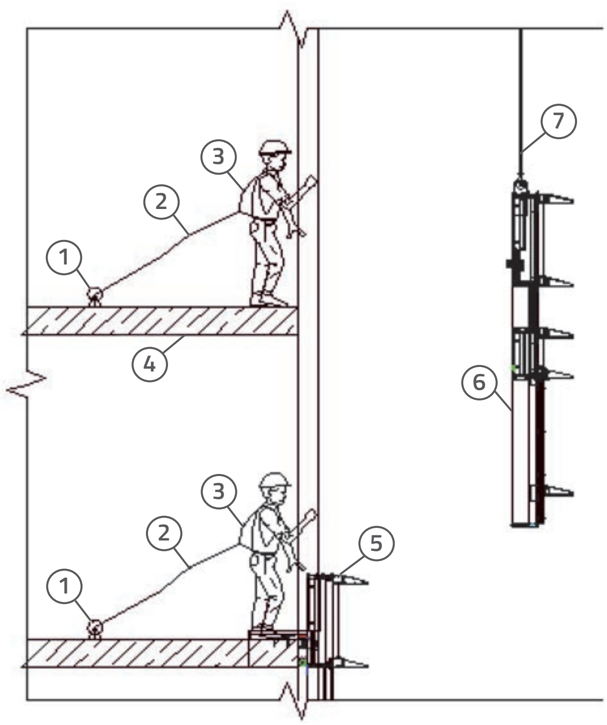

Figure 3. Two-rope system: 1 - anchor, 2 - lifeline; 3 - harness, 4 - floor, 5 - a mounted façade element, 6 - a façade element to be mounted, 7 - sling

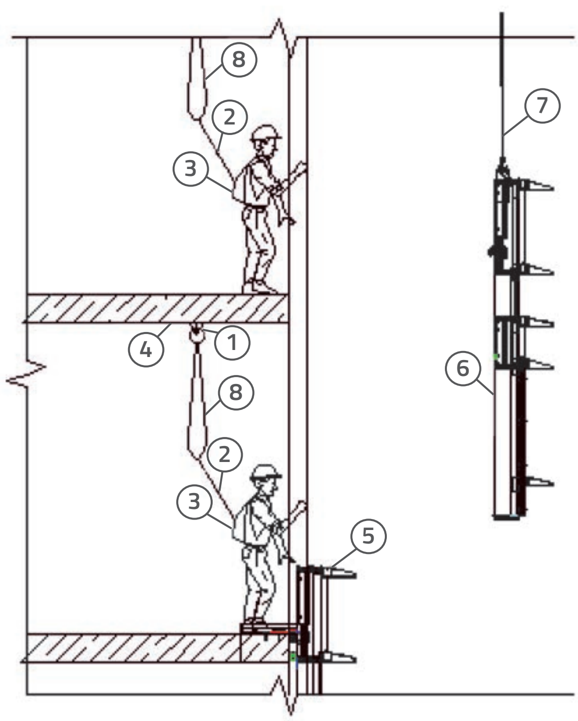

Figure 4. Anchor attached to the ceiling: 1 - anchor, 2 - lifeline; 3 - body harness, 4 - ceiling, 5 - a mounted façade element, 6 - a façade element to be mounted, 7 - sling, 8 - belt/loop attached to a lifeline

The two rope system (Figure 3) or a system with an anchor secured to the ceiling and an attached belt (Figure 4) should be used to protect workers from falls during roof installation or operation close to an unfenced floor edge (façade installation).

A two rope system is made of anchors secured to the floor, a rope stretched through the anchors, and a lifeline with one end attached to the rope and the other to the body harness worn by a worker. Five alternative combinations for the two rope system are evaluated with the help of six actual criteria. Initial data are presented in Table 2.

The second system also consists of anchors secured to the ceiling. The anchor is used to attach a belt/loop, which is attached to a lifeline. Five alternative combinations are evaluated with the help of five actual criteria. The initial decision-making is presented in Table 3.

The alternatives are described using technological and economic criteria. Price is an important criterion because of its decisive role in public procurement. However, for safe use and convenient operation, other relevant technical characteristics should simultaneously be considered, including the weight of harness, weight of fall arrester, length of rope on fall arrester, and number of anchors.

Relative significance of criteria is determined using expert evaluations, i.e. experts evaluate criteria based on their personal experience and knowledge. According to the Kendall concordance theory, the number of experts must be no less than seven and no less than the number of criteria [29, 30]. Accordingly, 11 experts, including 3 technical directors of construction companies and 8 construction work supervisors, having not less than 5 years of construction-site experience, were asked to evaluate the importance of criteria when selecting a protective measure. As opinions and attitudes of experts to assessed criteria may differ, this method of evaluation is regarded reliable only once expert opinions are in concordance, i.e. once the significance of the Kendall Coefficient of Concordance has been verified. It has been proven that the statistical hypothesis about expert agreement of ranks can be accepted [31] when the calculated value of the significance of the Coefficient of Concordance is higher than the critical value taken from distribution table, with the corresponding degree of freedom and the selected significance level close to null.

4.2. WASPAS-G method

The weighted aggregated sum product assessment method WASPAS was suggested in 2012 [32]. This method was designed on the basis of two methods (Weighted Sum Model (WSM) and Weighted Product Model (WPM)), and an originally determined aggregation coefficient was used. Table 1 provides examples of the use of the WASPAS [32] method for civil engineering problems with crisp information.

Table 1. Use of WASPAS in civil engineering

References	Investigated problem
Bagočius et al., 2013 [33]	Expanding State Seaport
Dėjus, Antuchevičienė, 2013 [34]	Assessing occupational health and safety at a construction site
Hashemkhani Zolfani et al., 2013 [35]	Determining a potential location for a supermarket
Šiožinytė, Antuchevičienė, 2013 [36]	Improving natural lighting in old buildings
Staniūnas et al., 2013 [37]	Ecological and economic assessment of renovation of multi-apartment buildings
Zavadskas et al., 2013 [38]	Assessing facades
Vafaeipour et al., 2014 [39]	Selecting the most suitable location for a solar power plant

The WASPAS-G method was suggested for problems in an uncertain environment with primary data expressed in intervals using the grey numbers theory [40]. The method was adjusted for selection of construction contractors [40]. The authors of the paper suggest the use of the new WASPAS-G method for assessing safety measures on the basis of multiple criteria and for determining the order of priorities.

Suppose, A_i are alternatives, x_j are criteria, $i = 1,..., m$; $j = 1,..., n$; where:

m - number of alternatives

n - number of criteria

$\otimes x_{ij}$ - grey evaluations of the i-th alternative with respect to the j-th attribute.

$\otimes x_{ij}$ consists of two real numbers: α is the lower limit and β is the upper limit, $\otimes x_{ij} = [\alpha, \beta]$.

<u>WASPAS-G stages [40]:</u>

1. 1. The initial decision making matrix is composed (Tables 2 and 6). $\otimes x_{ij}$ - initial grey value of criterion.
2. Initial values of decision making criteria are normalised (Tables 3 and 7). $\otimes \bar{x}_{ij}$ s grey normalized value of criterion. Eqn (1) is used if a criterion is maximised, and eqn (2) if a criterion is minimised:

$$\otimes \bar{x}_{ij} = \frac{\otimes x_{ij}}{\max_i \otimes x_{ij}}; \quad \bar{x}_{ij\alpha} = \frac{x_{ij\alpha}}{\max_i x_{ij\beta}}; \quad \bar{x}_{ij\beta} = \frac{x_{ij\beta}}{\max_i x_{ij\beta}} \tag{1}$$

$$\otimes \bar{x}_{ij} = \frac{\min_i \otimes x_{ij}}{\otimes x_{ij}}; \quad \bar{x}_{ij\alpha} = \frac{\min_i x_{ij\alpha}}{x_{ij\beta}}; \quad \bar{x}_{ij\beta} = \frac{\min_i x_{ij\alpha}}{x_{ij\alpha}} \tag{2}$$

3. A weighted normalised decision making matrix is composed (Tables 4 and 8), i.e. the value of each normalised criterion is multiplied by the significance of a respective criterion. $\otimes \hat{x}_{ij}$ is the grey weighted normalised value of criterion, $\otimes w_j$ - the weight of the criterion:

$$\otimes\hat{x}_{ij} = \otimes\bar{x}_{ij} \times \otimes w_j \quad (3)$$

4. Values of optimality criteria are determined:

$$S_i = \sum_{j=1}^{n} \otimes\hat{x}_{ij},\ j = 1,\dots,m, \quad \text{or} \quad S_i = 0.5\sum_{j=1}^{n}\left(\hat{x}_{ij\alpha} + \hat{x}_{ij\beta}\right) \quad (4)$$

$$P_i = \prod_{j=1}^{n} \otimes\bar{x}^{\otimes w_j},\ j = 1,\dots,m, \quad \text{or} \quad P_i = \prod_{j=1}^{n} 0.5\left(\otimes\bar{x}_{j\alpha}^{\otimes w_j} + \otimes\bar{x}_{j\beta}^{\otimes w_j}\right) \quad (5)$$

where:
S_i - optimality criterion for WSM
P_i - optimality criterion for WPM.

5. To improve accuracy and efficiency of calculations, λ coefficient is also used:

$$\lambda = 0.5\frac{\sum_{i=1}^{m} P_i}{\sum_{i=1}^{m} S_i} \quad (6)$$

6. Relative values of alternatives Q_i are determined, and the order of priorities is defined (Tables 5 and 10):

$$Q_i = \lambda\sum_{j=1}^{n} \otimes\hat{x}_{ij} + (1-\lambda)\prod_{j=1}^{n} \otimes\bar{x}^{\otimes w_j}, \quad \lambda = 0,\dots,1 \quad (7)$$

Table 2. Initial decision making matrix (prevention of falls from a roof, two rope system)

No.	Criterion x_j / Alternative A_i	Number of activity types, for which the belt is suitable* [units]	Weight of harness [g]	Weight of fall arrester [g]	Length of rope on fall arrester [m]	No. of anchors (installed system 50 m in length) [units]	Price per kit [EUR]
1	A_1: body harness P02, fall arrester CR 200, anchors, rope	9	1080	(4700–6000)	(6–12)	(4–6)	(336.17–343.06)
2	A_2: body harness P20, fall arrester CR 200, anchors, rope	9	1350	(5300–6100)	(10–15)	(5–7)	(359.59-344.49)
3	A_3: body harness P50, fall arrester CR 200, anchors, rope	8	1460	(6000–7500)	(15–20)	(6–8)	(364.12-477.06)
4	A_4: body harness P60, fall arrester CR 200, anchors, rope	8	1540	(4700–5300)	(6–10)	(7–9)	(368.99-375.38)
5	A_5: body harness P70, fall arrester CR 200, anchors, rope	8	1660	(5300–6000)	(10–12)	(8–10)	(416.9–417.40)
Optimization direction		max	min	min	max	min	min
Relative significance w_i		0.0719	0.2026	0.1961	0.1699	0.0850	0.2745

*Number of activity types, for which the belt is suitable - as indicated by the producer (construction and installation works for reinforced concrete. masonry, steel or timber structures, roofing, concreting, scaffolding installation works. tower crane installation works, rescue works, climbing works)

Table 3. Normalized grey decision making matrix and the second criterion of optimality

Criterion / Alternatives	x_1	x_2	x_3	x_4	x_5	x_6	P_i	Ranking order
A_1	1	1	1	0.3000	1	1	0.8290	1
	1	1	0.7833	0.6000	0.6667	0.9799		
A_2	0.8889	0.8000	0.8868	0.5000	0.8000	0.9349	0.8050	2
	0.8889	0.8000	0.7705	0.7500	0.5714	0.9321		
A_3	0.8889	0.7397	0.7833	0.6000	0.6667	0.9232	0.7510	3
	0.8889	0.7397	0.6267	1	0.5000	0.7047		
A_4	0.8889	0.7013	1	0.3000	0.5714	0.9111	0.7130	4
	0.8889	0.7013	0.8868	0.5000	0.4444	0.8955		
A_5	0.8889	0.6506	0.8868	0.5000	0.5000	0.8064	0.6970	5
	0.8889	0.6506	0.7833	0.6000	0.4000	0.8054		

Table 4. Weighted normalized grey decision making matrix and the first criterion of optimality

Criterion / Alternatives	x_1	x_2	x_3	x_4	x_5	x_6	S_i	Ranking order
A_1	0.0719	0.2030	0.1960	0.0510	0.0850	0.2750	0.8690	1
	0.0719	0.2030	0.1540	0.1020	0.0570	0.2690		
A_2	0.0719	0.1620	0.1740	0.0850	0.0680	0.2570	0.8180	2
	0.0719	0.1620	0.1510	0.1275	0.0490	0.2560		
A_3	0.0640	0.1500	0.1540	0.1020	0.0570	0.2540	0.7620	3
	0.0640	0.1500	0.1230	0.1700	0.0430	0.1940		
A_4	0.0640	0.1420	0.1960	0.0510	0.0490	0.2510	0.7510	4
	0.0640	0.1420	0.1740	0.0850	0.0380	0.2460		
A_5	0.0640	0.1320	0.1740	0.0850	0.0430	0.2220	0.7130	5
	0.0640	0.1320	0.1540	0.1020	0.0340	0.2210		

4.3. Search for optimum solution: prevention from fall using two rope system

The initial decision making matrix for preventing falls from a roof using a two rope system is presented in Table 2.

Five alternatives (A_1 to A_5) are formulated based on products currently available on the market, combining different body harnesses, fall arrester with various lengths of rope, and various number of anchors.

Calculations applying eqns. (1-7) and the ranking order of alternative decisions for preventing falls from a roof using the two rope system are presented in Tables 3-5.

Table 5. Final results for preventing falls from a roof (the two rope system)

Alternatives	P_i	S_i	Q_i	Ranking order
A_1	0.8290	0.8690	0.7740	1
A_2	0.8050	0.8180	0.7297	2
A_3	0.7510	0.7620	0.6587	3
A_4	0.7130	0.7510	0.6253	4
A_5	0.6920	0.7130	0.5959	5
	Σ 3.794	Σ 3.913	λ = 0.4848	

Table 6. Initial decision making matrix (for the protection against fall through an opening)

No,	Criterion x_j / Alternative A_i	Number of activity types. for which the belt is suitable * [units]	Weight of harness [g]	Weight of fall arrester [g]	Length of rope on fall arrester [m]	Price per kit [EUR]
1	A_1: body harness P02, fall arrester CR 200	9	1080	(4700–6000)	(6–12)	(271.14-278.03)
2	A_2: body harness P20, fall arrester CR 200	9	1350	(5300–6100)	(10–15)	(289.94-291.01)
3	A_3: body harness P50, fall arrester CR 200	8	1460	(6000–7500)	(15–20)	(289.85-402.79)
4	A_4: body harness P60, fall arrester CR 200	8	1540	(4700–5300)	(6–10)	(290.1-296.49)
5	A_5: body harness P70, fall arrester CR 200	8	1660	(5300–6000)	(10–12)	(333.39-333.89)
	Optimization direction	maks.	min.	min.	maks.	min.
	Relative significance w_i	0.0760	0.2000	0.2190	0.1710	0.3330

*Number of activity types, for which the belt is suitable - as indicated by the producer (construction and installation works for reinforced concrete, masonry, steel or timber structures, roofing, concreting, scaffolding installation works, tower crane installation works, rescue works, climbing works)

Table 7. Normalized grey decision making matrix and second criterion of optimality

Criterion / Alternatives	x_1	x_2	x_3	x_4	x_5	P_i	Ranking order
A_1	1	1	1	0.3000	1	0.8391	1
	1	1	0.7833	0.6000	0.9752		
A_2	1	0.8000	0.8868	0.5000	0.9352	0.8249	2
	1	0.8000	0.7705	0.7500	0.9317		
A_3	0.8890	0.7397	0.7833	0.6000	0.9354	0.7671	3
	0.8890	0.7397	0.6267	1	0.6732		
A_4	0.8890	0.7013	1	0.3000	0.9346	0.7555	4
	0.8890	0.7013	0.8868	0.5000	0.9145		
A_5	0.8890	0.6506	0.8868	0.5000	0.8133	0.7359	5
	0.8890	0.6506	0.7833	0.6000	0.8121		

Table 8. Weighted normalized grey decision making matrix and the first criterion of optimality

Criterion / Alternatives	x_1	x_2	x_3	x_4	x_5	S_i	Ranking order
A_1	0.0760	0.2000	0.2190	0.0513	0.3330	0.8770	1
	0.0760	0.2000	0.1716	0.1026	0.3247		
A_2	0.0760	0.1600	0.1942	0.0855	0.3114	0.8350	2
	0.0760	0.1600	0.1687	0.1283	0.3103		
A_3	0.0676	0.1479	0.1716	0.1026	0.3115	0.7750	4
	0.0676	0.1479	0.1372	0.1710	0.2242		
A_4	0.0676	0.1403	0.2190	0.0513	0.3112	0.7910	3
	0.0676	0.1403	0.1942	0.0855	0.3045		
A_5	0.0676	0.1301	0.1942	0.0855	0.2708	0.7450	5
	0.0676	0.1301	0.1716	0.1026	0.2704		

The obtained results suggest that the fist alternative (A_1) with the two rope system is the best while the fifth (A_5) is the least suitable.

4.4. Search for optimal solution: protection against fall through an opening

An initial decision making matrix for protection against fall through an opening is presented in Table 6.

Five alternatives (A_1 to A_5) were formulated based on products currently available on the market, combining different body harnesses and fall arrester with different length of rope. Important criteria for selecting the best alternative included the weight of harness, weight of fall arrester, length of rope on fall arrester, price, and suitability of a device for different activities. In accordance with expert evaluations, it was found that the selection of safety device was mostly impacted by the price and weight of a device, i.e. their relative significances were larger (Table 6).

Calculations applying eqns. (1-7) and the ranking order of alternative decisions for the protection against falls through an opening are presented. The normalized grey decision making matrix, and the ranking according to the second criterion of optimality, are presented in Table 7. The weighted normalized grey decision making matrix, and the ranking of alternatives according to the first criterion of optimality, are presented in Table 8. The final ranking of alternative devices for the protection against falls through an opening is presented in Table 9.

Table 9. Final results for protection against fall through an opening

Alternatives	P_i	S_i	Q_i	Ranking order
A_1	0.8391	0.8771	0.7869	1
A_2	0.8249	0.8352	0.7554	2
A_3	0.7671	0.7745	0.6775	3
A_4	0.7555	0.7907	0.6774	4
A_5	0.7359	0.7452	0.6407	5
	Σ 4.023	Σ 3.923	λ = 0.4877	

Advantages of the selected MCDM method are revealed in the current case. The priority order of analysed alternatives differs when applying the first and the second criteria of optimality.

The third (A_3) and the fourth (A_4) alternatives are interchanged, as can be seen in Tables 7-8. Then the aggregation coefficient should be used, enabling the highest accuracy of estimation. The use of WASPAS-G for the selection of the best alternative for the protection against falls through an opening revealed that the best alternative is the first one (A_1) with the second one (A_2) lagging behind just by a little bit, while the fifth alternative (A_5) is the worst one. By applying a weighted aggregation of two criteria of optimality, it was found that the third (A_3) and the fourth (A_4) alternatives are equal, and that they present the same rationality values (Table 9).

5. Discussion

Vincke [41] believes that the main difficulty in solving multiple criteria decision making problems lies in the fact that, usually, there is no optimal solution to such a problem, which could dominate other solutions in all the criteria. As a response to this dilemma, various methods have been proposed for solving the MCDM problems. The selection of the most appropriate, most robust and effectively most useable method has been a continuous subject of scientific discussions for decades [28, 42, 43]. This means that the experts usually look for the Pareto optimal solution. Therefore, while an optimal solution is obtained by several methods, this emphasizes that proposed method will achieve the near to optimum answer. In this regard, WASPAS-G method has a strong advantage over the other methods as it summarizes three approaches: two methods as well as the grey system theory.

As it is not easy to prove that the proposed method is actually applicable, it proved necessary to solve several multiple criteria problems. Accordingly, two problems, i.e. selecting alternatives protection devices for two different types of falls, were presented. It is encouraging that the results have shown the applicability of the suggested approach for evaluating protection devices, having the ultimate goal of better preventing accidents at construction sites.

6. Conclusion

Occupational accidents are a particularly acute issue. Human errors are among the key causes of accidents as usually workers lack knowledge regarding occupational safety and are incapable of correctly identifying hazardous factors. Therefore, more attention should be paid to the briefing and training of workers with the help of a virtual construction site. Construction managers should continuously cooperate with workers on safety issues and prevent dangerous situations.

The analysis was limited to 90 accidents at construction sites of residential and public buildings in Lithuania, for which the pre-trial investigation was carried out in 2007-2012. The analysed accidents revealed the failure to use or inappropriate use of personal protection devices (PPD), which is due to the lack of effective safety measures and inappropriate training of workers. In ten cases out of 90, PPD were used, yet five accidents were fatal and five resulted in serious bodily injuries. In addition, the most dangerous height was identified, as well as the riskiest working hours and months. According to the results, more attention should be given to occupational safety in cases when works are performed at a relatively low height (2-4 m) and toward the end of a shift. This could be achieved through continuous cooperation between construction managers and workers on safety issues, which also involves providing and encouraging the use of personal protection devices.

To prevent fall from elevations or falling off an edge of a floor (e.g. while mounting a façade), alternatives were offered for the two rope system consisting of anchors secured to the floor and a rope stretched through them. The rope is attached to the rope of the fall arrester, with the other end attached to the body harness on a worker.

To prevent falls from structures, body harnesses and lifelines were offered. These are to be used with one end attached to the body harness, and the other secured to an appropriately set-up structure.

Alternative versions were formulated based on products currently available on the market. The versions may be adjusted in case of change of needs or change in market situation.

Alternatives were described using several criteria, the significance of which was determined using the expert survey. It was established that the selection of safety kits was mostly impacted by the price and weight of a harness and fall arrester. The WASPAS-G method was used to determine the best alternative. The method was suggested because it is capable of processing somewhat uncertain information and providing a reliable and sufficiently accurate solution that could contribute to enhancing safety at a construction site by selecting the best measures for preventing accidents when working at elevations.

An analogous methodology may be used by examining other dangerous factors relevant to particular construction site conditions. Typical protective measures preventing falling of soil, falling of materials, machinery injury, and electric discharge, can be suggested, and alternative solutions can be compared in order to select the most rational measure.

The proposed approach seeks to demonstrate how formal decision making methods can be applied to manage risks related to various engineering projects and the use of existing structures. The ultimate goal of such decision making should be creation of a more sustainable work environment in terms of economic effectiveness and safety.

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