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Indicator on the performance of barriers against fatal accidents in construction

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ABSTRACT: The paper presents work to develop a safety performance indicator suitable for real-time management of major accident hazards in construction. Data on 60 fatal accidents in the period 2011–2016, resulting in 63 fatalities, have been analysed. About 70% of the accidents belonged to three main categories: fall from height, driver or person outside the cabin killed by moving construction machine/vehicle, and person killed by load or equipment during material handling. The three main categories have been further divided into subcategories (seven in all) and analysed to identify barriers to prevent adverse consequences. This analysis has resulted in checklists, one for each subcategory. They list observable conditions at a construction site that, if found substandard, will indicate that one or more of the important barriers are seriously deteriorated. The paper highlights the results of the accident concentration and barrier analyses. It also reviews remaining work to develop and test the performance indicator.

1 INTRODUCTION

Construction activities are characterized by the management of large amounts of energy such as in transportation, excavation, assembly, work at height etc. Loss of control of the energy flow may have major consequences. Natural hazards (rock fall, land slide etc.) represent significant additional risks. The statistics on severe accidents in construction reflect these conditions. According to ILO estimates, the fatal accident risk in construction is five times the average among workers worldwide (Murie 2007). Statistics from Norway for 2009–2014 show a fatal accident frequency rate of three times the general average for workers (Norwegian Labour Inspection Authority 2015).

Construction work is organised in projects with a limited duration. A project goes through different phases from site establishment and excavation to installation and completion, and the conditions at site and the activities change accordingly. Traditional safety management using performance measurements (such as the TRI rate) and feedback control is inadequate, due to lagging characteristics of most current safety performance indicators (Kjellén 2009, Lingard et al. 2017). There is a need for indicators that provide real-time data on safety performance to ensure timely feedback for control of safety performance (Kjellén 2018).

Behavioural sampling was developed in the 1950s to meet this requirement (Rockwell 1959). The method uses observations on deviations from safe work practices and conditions as data input. The "TR safety monitoring method" represents an application of behavioural sampling to the construction industry (Laitinen et al. 1999, Laitinen & Päivärinta 2010). Experiences show that the method produces reliable and valid results related to the prevention of ordinary occupational accidents.

There is a general lack of 'real-time' performance indicators suitable for the control of hazards in construction with fatal accident potential. The principles behind the "barrier performance indicators" developed by the process and oil and gas industries for the prevention of fires and explosions offer such as opportunity (Health and Safety Executive 2006, OGP 2011). The indicators measure the compliance of safety barriers to a standard.

Accident statistics indicate that this approach may be valid for the construction industry, despite the high variety of activities in the industry. A relatively small number of types of central events according to the bow-tie accident model, each representing the loss-of-control of significant amounts of energy, account for a substantial share of the fatal accidents in construction (Visser 1998, Swuste et al. 2012). By identifying barriers to prevent these central events and/or reduce their consequences, input may be provided to performance indicators on the risk of fatal accidents in construction projects.

Experiences from two case studies support the validity of this approach. An Indian hydropower project reported eight fatalities due to road departures and falling rocks in tunnels during 2,5 years after start-up (Kjellén 2012). The project implemented improved safety routines directed at barriers to prevent these types of accidents. It was completed three years later with one additional fatality not related to these types of events.

A large international construction contractor identified six dominating concentrations of fatal accidents in their operations world-wide (A. Berglund, personal communication, Nov. 17, 2017). These included falls from height, conflict between human and machine, structural failure, lifting operations (falling objects), fire/explosions, and electric arcs. The contractor implemented lifesaving rules directed at barriers to prevent these types of accidents. They experienced a reduction in the frequency of the affected types of fatal accidents by 60% in a five-year period after the intervention, compared to the previous five-year period. The number of construction workers was about the same in the two periods.

1.1 *This paper*

The paper presents research that is part of an ongoing project for the construction industry. Its aim is to develop safety performance indicators that are better suited for the management of safety by client and contractor companies than the lagging safety performance indicators in use today.

The research presented here focuses on developing a performance indicator of the availability of barriers against hazards with fatal accident potential. The intention is to provide data in 'real time' and thereby allow the involved companies to accomplish effective feedback control of the fatal accident risk at construction sites.

The paper highlights the first part of the research, aiming at identifying dominating fatal accident concentrations in the Norwegian construction industry and critical barriers that will prevent the relevant types of accidents from occurring. In the subsequent steps, these results will be used as input to the development of indicators for barrier availability for use by safety practitioners in the industry. These indicators will be tested and evaluated in intervention studies in construction projects.

2 MATERIAL AND METHOD

2.1 *Sources of data*

The analysis consists of two parts, an accident concentration analysis and a barrier analysis. A set of 60 fatal accidents resulting in 63 fatalities in the Norwegian construction industry between 2011 and 2016 represents the source data for the accident concentration analysis. The Norwegian Labour Inspection Authority (NLIA) provided the data from their general register of fatal occupational accidents in Norway.

The accident data was documented in a spreadsheet with the following information on each accident: date of the accident, registration number, type of construction business (classification), type of activity (classification), number of people killed, type of injury (classification), accident type (classification), free text resumé of the sequence of events.

In the subsequent barrier analysis, data from NLIA was supplemented with data from other sources:

- Observations at three construction sites and interviews with senior construction managers
- The author's library of in-depth investigations into fatal accidents and high potential incidents that fall within any of the accident concentrations selected for further analysis
- Lifesaving rules developed by major construction contractors
- Relevant regulatory requirements in Norway

The results were reviewed in workshops by high-level safety experts from construction client companies, contractors and an organisation of regional safety representatives.

2.2 *Methods*

2.2.1 *Accident concentration analysis*

An accident concentration analysis aims at identifying clusters of 'accident repeaters' with common characteristics (Kjellén & Albrechtsen 2017). By directing preventive measures at a selection of dominating accident concentrations, a significant risk reduction is expected.

The analysis is carried out stepwise in several dimensions to identify accidents with common characteristics. A natural starting point for the analysis of fatal accidents was to group the accidents according to the main type of energy involved.

In the current study, the dataset was first analysed by accident type according to NLIA's classification. For each accident type, the free-text descriptions of the accidents were reviewed to identify common patterns. A new, composite classification of the accidents was developed, where each 'accident concentration' was made-up of at least three fatal accidents with common characteristics.

2.2.2 *Barrier analysis*

The barrier analysis is rooted in the principles of defence in depth and the energy model of loss causation (Rasmussen 1993, Haddon 1980).

A model of the accident sequence encompassing three successive phases is shown in Figure 1

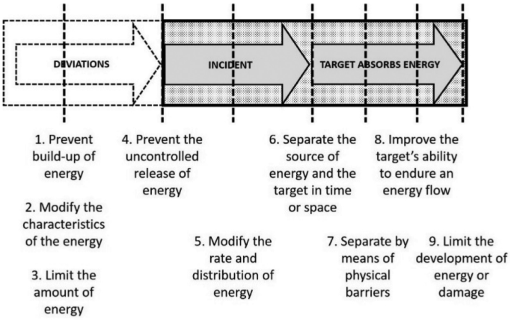

Figure 1. Barrier intervention in the accident sequence to eliminate or reduce loss (Kjellén & Albrechtsen 2017).

(Kjellén & Larsson 1981). Nine of Haddon's ten accident prevention strategies are introduced in the model as barrier functions. Each of these may, dependent on the type of accident, have the capacity to change the sequence of events and thereby eliminate or reduce loss.

The function of a barrier is realised through a barrier system. Whereas passive barriers consist of a physical element, active barriers are more complex with several elements including a control system. One or more human operators may be part of the control loop.

Input data to the barrier analysis consisted of the results of an analysis of accident concentrations among fatal accidents in construction in Norway between 2011 and 2016. For each accident concentration, barriers that are critical in preventing accidents in the accident concentration in question were identified. Next, the required performance of the elements that make up the barrier were identified for each identified barrier.

3 RESULTS

3.1 *Accident concentration analysis*

The distribution of the 60 fatal accidents in NLIA's database by accident type is shown in Table 1. This analysis represents the starting point for the identification of accident concentrations.

Falls represents the most common accident type in NLIA's database, followed by squeezed/caught and hit by object.

The analysis revealed some inconsistencies in the accident type classification by NLIA. A2 and A3 include accidents involving vehicles, but similar vehicle related accidents were classified as category A4.

The accident concentration analysis identified 12 categories of 'accident concentrations', covering 93% of the fatal accidents in the material,

Table 1. Distribution of accidents in NLIA's database on fatal accidents in construction in the period 2011–2016 (N = 60). The table also shows a summary description of accidents with common characteristics for each accident type.

Accident type (NLIA)	# of events	Coarse description of accidents
A1 Hit by object	9	Hit by load or machinery part during material handling, structural collapse, falling rock, flying object (bolt from pistol)
A2 Collision, hit by vehicle	11	Road/work area departure by vehicle (incl. mobile machine), collision, hit by vehicle
A3 Roll-over	3	Roll-over of vehicle
A4 Squeezed or caught	13	Hit by vehicle, road/work area departure by vehicle, roll-over of mobile machine, squeezed by lifting/transportation equipment during operation, rock fall, collapsing trench, structural collapse
A5 Fall	19*	Electric current through body (resulting in fall), fall from height (roof, deck, scaffold, ladder, machinery/equipment)
A7 Electric voltage	2	Electric current through the body from electric installation or hand tool
A10 Explosion, fire	3**	Accidental blast, explosion

* Two persons killed in one fall accident, ** Three persons killed in one blast accident.

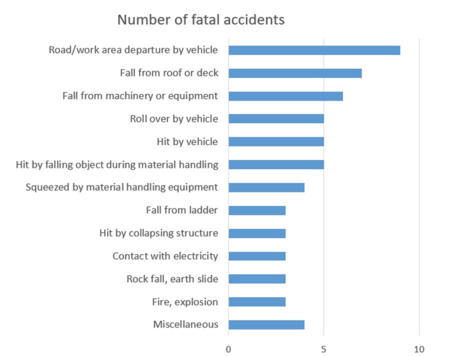

Figure 2. Distribution of fatal accidents by 'accident concentration' (N = 60).

Figure 2. The category 'miscellaneous' made up the remaining 7%.

28% of the accidents were related to fall from height. Similarly, 23% involved vehicles (including mobile construction machinery). If we add material handling by crane, conveyor belt, truck etc., we cover in all two thirds of the fatal accidents.

Accident concentrations with four or more fatalities were selected for further analysis. These included:

- Road or work area departure by vehicle: The driver was killed due to loss-of-control of the vehicle followed by departure from a road or construction area.
- Fall from or through roof or deck: The person being killed fell either outside the edge of a roof or deck or through and opening or weak point of the roof/deck.
- Fall from machinery or equipment: The person being killed fell when moving or working on machinery or equipment. Falls from ladder was introduced as a special case.
- Roll over of vehicle (or machine during transfer): The driver/operator has been killed due to roll-over during unloading, during transfer (when a machine behaved as a vehicle), or when a parked vehicle has accidently started to move.
- Hit by vehicle: The person being killed was present in the danger zone of a vehicle in motion and the driver was either not aware of the person or lost control of the vehicle.
- Hit by falling object during material handling: The fatalities occurred during crane handling or unloading of truck or trailer. The accidents involved loss of control of load or sudden, uncontrolled movements of equipment.
- Squeezed by movements of personnel lifts or material handling equipment: The person being killed was either squeezed by uncontrolled machinery movements, missing machine guarding or because the operator was not aware of the person being in the danger zone.

3.2 *Barrier analysis*

A basic assumption in this research project is the considerations of barriers as an additional measure implemented in a production system to achieve a tolerable level of risk. It means that the basic design of the work system, where the fatal accidents occurred, has not been questioned. Surface transportation, for example, was not considered as a barrier function to avoid being hit by falling objects during material handling. In Table 2, barrier types 1 and 2 have been excluded for this reason.

The barrier analysis has been based on some additional assumptions:

3. Limit the amount of energy: Has been included in barrier function no. 8 for falls from height (use of fall arrest system).

Table 2. Results of the barrier analysis. A barrier type marked "X has a function that is considered essential to prevent fatalities in the accident concentration in question.

	Type of barrier (see Figure 1):						
Accident concentration	3	4	5	6	7	8	9
Road/work area departure by vehicle		X	X		X	X	X
Fall from or through roof or deck	X	X	X		X		
Fall from machinery or equipment	X	X	X		X		
Fall from ladder	X	X	X				
Roll over of vehicle (or machine during transfer)		X	X		X		
Hit by vehicle		X		X			
Hit by falling object during material handling		X		X			
Squeezed by movements of lifting and material handling equipment		X		X	X		

4. Prevent uncontrolled release of energy: This barrier function is relevant to all analysed main types of accident concentrations. The barrier function is not relevant to subsets of accidents, where a machine operator has not been aware of personnel being present in the danger zone.
5. Modify the rate and distribution of energy: This applies to the use of safety belt in case of road/work area departure or roll-over and use of fall arrest system.
6. Separate the source of energy and the target in time or space: This barrier function is relevant to vehicle and material handling related accidents. A possible exception is sudden machinery movements due to mechanical failure, which could not reasonably have been foreseen.
7. Separate by means of physical barriers: This barrier function is relevant to all types of accident concentrations. In practice, the implementing this type of barrier is restrained by feasibility considerations.
8. Improve the target's ability to endure an energy flow: This barrier function is implemented through personal protective equipment. It is especially relevant to falls, when collective measures (physical barriers) are not applied. Use of helmet has limited effect in case of falling objects with high energy.
9. Limit the development of energy or damage: The general organisation of emergency response at site falls outside the scope of this analysis. Preparedness directed at specific types of hazards has been included such as use of mobile machine close to water way. In this case, the barrier relates to preparedness to safe the driver from drowning in case of departure from road or work area.

Table 3. Requirements related to barrier elements for each of three barriers essential to prevent fall from ladder.

Limit the amount of energy	Prevent uncontrolled release of energy	Modify the rate and distribution of the energy transfer
• Ladder used as an exception in lack of feasible alternative?	• Ladder checked and found in adequate condition?	• Use of safety harness and life line hooked to a solid attachment point
• Ladder used for a height difference to solid ground <6 m?	• Ladder positioned on solid ground and secured from tilting? • Ladder raises > 1 m above roof or landing?	

Table 4. Requirements related to barrier elements for each of two barriers essential to prevent personnel being hit by vehicle.

Prevent uncontrolled release of energy	Separate the source of energy and the target in time or space
• Vehicle is certified and regularly checked and maintained?	• Areas for transportation and loading/unloading separated from work areas and pedestrian traffic?
• Driver instructions regarding controlled operation of the vehicle available?	• Driver has full overview from the cabin of the operating zone?
• Adequate training and certification of driver?	• Driver instructions to have control of the operating zone for other personnel? Adequate operator training and certification?
• Foundation of the operating area of the vehicle adequately stable, inclination and friction satisfactory to ensure full operator control?	• Site instructions and training regulating avoidance of the operating zone of mobile machines? Adequately supervised and respected? • Use of highly visible uniforms by all personnel at the site? • Adequately illuminated work areas and roads?

The next step in the analysis has aimed at identifying performance requirements of barrier elements necessary for the applicable barrier function to be effective. These requirements provide the basis for the barrier performance indicator, which will measure average percent compliance with the requirements. The results of this analysis are illustrated by two examples in Table 3 and Table 4.

4 FURTHER WORK

Work is under way to develop and operationalise the identified performance requirements in cooperation with Client and Contractor personnel of a large infrastructure construction site. The requirements for successful performance of the different barrier elements will be scrutinized by site personnel in cooperation with the researchers and further developed to meet certain quality criteria (Kjellén & Albrechtsen 2017, Laitinen et al. 1999):

– Flexible for use at different types of construction sites,
– Transparent and easily understood by site personnel,
– Address site conditions that are observable and quantifiable,
– Sensitive to changes in the safety standard at construction sites,
– Produce reliable results when applied by different observers,
– Robust against manipulation.

The task of the observers will be to identify work at the construction site involving any of the seven identified major accident hazards. Next, the observers will use the relevant checklist to review the status of the different barrier elements and classify them as either correct or incorrect or not relevant. Incorrect barrier elements will be qualified through a short description. The results will be summarized, showing% of the checked barrier elements that are correct. This can be shown in total and for each type of major accident hazard.

To produce reliable results, characteristics of the various barrier elements that separate correct from incorrect must be defined in the checklists to the extent needed when used by experienced personnel. In addition to physical observations of the work, the observers will have to consult available documentation and make interviews to check items such as operator training and qualifications and maintenance standard of vehicle. This makes the use of the method to resemble a system audit more than an inspection, but not fulfilling the requirement to independence.

The next step of the research project will include testing and evaluation of the barrier performance indicator and underlying requirements to barrier elements in routine safety practice. A systematic approach will be applied in assessing the operational experience of the intervention itself, and various stages of outcome, including degree of implementation and immediate, intermediate and end results (Shannon et al. 1999). It will not be possible to monitor any effects on the fatal accident rate by this trial.

5 CONCLUSIONS

The work presented in this paper represents the first phase in developing a real-time performance indicator aiming at managing the risk of fatal accidents.

An important prerequisite has been the existence of dominating fatal accident concentrations in construction that may be prevented through a few well-defined barriers. This will allow the development of an indicator based on requirements for barrier availability that is adequately comprehensive still practicable. Results of the accident concentration analysis shows that this prerequisite generally is satisfied. There exists variation between individual accidents in the concentrations that are more complex. It is necessary in the further development and operationalisation of the requirements to check for these variations to ensure that the prerequisite is satisfied.

Another critical issue is the representativeness of the data used in this analysis for the fatal accident risk in construction in Norway. The period and number of events covered by the analysis, and the consistence of the results with findings in international research and safety practice referred to in this paper, call for a positive answer to this question.

The ultimate test of the viability of the proposed performance indicator will take place through integration is safety practice at selected construction sites. Here it will be possible to evaluate the indicator against predefined criteria. Only extensive and long-term use will validate the performance indicator as an efficient tool in preventing fatal accidents.

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