May 2014, Volume 8, No. 5 (Serial No. 78), pp. 517-528
Journal of Civil Engineering and Architecture, ISSN 1934-7359, USA

Development of an Expert Model to Assess Falls from Height Hazards in Construction Sites

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Abstract: This paper reports on the current state of an ongoing research project which is aimed at implementing intelligent models for hardly predictable hazard scenarios identification in construction sites. As any programmatic actions cannot deal with the unpredictable nature of many risk dynamics, an attempt to improve the current approach for safety management in the construction industry will be presented in this paper. To this aim, the features offered by Bayesian networks have been exploited. The present research has led to the definition of a probabilistic model using elicitation techniques from subjective knowledge. This model, which might be meant as a reliable knowledge map about accident dynamics, showed that a relevant part of occurrences fall in the "hardly predictable hazards" category, which cannot be warded off by programmatic safety measures. Hence, more effort turned out to be needed in order to manage those hardly predictable hazardous scenarios. Consequently, further developments of this research project will focus on a real time monitoring system for the identification of unpredictable hazardous events in construction.

Key words: Health and safety management, risk assessment, Bayesian networks, job sites.

1. Introduction

This paper reports the current state of an ongoing research project which is aimed at developing novel approaches for assessing hardly predictable hazard scenarios in job sites. In fact, available statistics report on the number of deaths caused by on-the-job accidents in construction, but they do not supply information on their elementary causes. Thus, the research step in this paper will suggest an analytical method to enhance the (partial) knowledge, already included in statistics, by means of expert knowledge from multiple sources. It will help to assess the main causes leading to accidents, as shown by the selected test-bed pertaining to falls from height.

Nowadays, the approach to H&S (health and safety) management in construction industry is a standard practice in EU countries. It starts off with the identification of task sequences at the design phase [1]. Then, elementary working activities and preventive or protective actions are defined to safeguard workers. During the execution phase, an appointed H&S coordinator is in charge of assuring the planned safety level [2]. In recent years, in the USA, the NIOSH (National Institute for Occupational Safety and Health) promoted the PtD (prevention through design) strategy [3, 4] as a standard that provides guidance on including prevention through design concepts within an occupational H&S management system. According to this approach, prescriptions can be incorporated into the process of design and redesign of work premises, tools, equipment, machinery, substances and work processes. Both approaches are based on the analysis of risk scenarios for each task and interfering activities expected in job sites [5]. Indeed, they follow the PCDA (plan check do act) cycle [6]: (1) hazard and risk identification; (2) classification of risks in order of priority; (3) definition of preventive and protective measures for all risks; (4) taking actions to mitigate and reduce risks; (5) checking and reviewing of drawn-up safety plan.

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The main weakness of that approach lies in the high costs tied to monitoring and control, because they ask for the enduring presence of an H&S coordinator on several job sites in order to preserve the planned level of safety.

Statistical data clearly show that the present programmatic approach is not adequate to the construction industry. Job sites are still among the most dangerous workplaces and the number of accidents reaches up to 10%-11% of the overall manufacturing sectors. Although the average of fatal accidents in the EU are decreasing (less than three fatalities per 100,000 employees), the construction industry figure exceeds 10 fatal accidents per 100,000 employees, the most frequent cause being falls from height [7].

This result is also confirmed by the US and Israeli surveys: they represent one third of the total in the first case, and 60% in the second one [8], which is further split into: 41% by falls from slabs and roofs, 19% by falls from scaffolding and working decks, 11% by falls from ladders.

The main purpose of this contribution is to provide models capable of simulating the underlying accident dynamics. The main outcomes will be as follows:

- A systematic methodology to develop risk assessment models in the H&S field, based on the adoption of Bayesian networks and capable of combining several sources of knowledge so as to unveil real risk triggers;
- A definition of the difference between two types of risk causes: on one hand the predictable ones, which can be assessed and mitigated at the planning phase; on the other hand "hidden" risks, so-called because they can be identified through the models but whose accurate preventive assessment is hampered by the variability of their likelihood due to the context evolution and the degree of occurrence of several external factors.

2. Methodology for the Development of Expert Models in Support of Safety Management in Job Sites

As well as in the field of health and safety management, in construction a great limit is represented by the poor statistics available about accidents. Accordingly, this paper shows how the few available data have been integrated with expert knowledge, in order to map in detail the main accident dynamics occurring in construction sites. The suggested procedure consists of four steps:

- selection of domain experts with different experience and knowledge in the field of safety management in construction sites;
- interviews with all experts to gather relevant knowledge about accident dynamics and triggers occurred in the past;
- representation of the gathered information and knowledge through Bayesian nets, because their qualitative structure successfully represents "cause and effect" relationships among all variables;
- translation of the gathered knowledge and information into probability distributions, which are aimed at formalizing links between variables in the model.

As the most frequent cause of accidents in construction sites is represented by falls from height (with almost 50% of fatalities), the first category considered in this research is "falls from height hazards". In particular, the following session reports an example regarding "falls from scaffolding" scenarios.

2.1 Selecting Experts

In the first step of our model development, six domain experts with different knowledge about health and safety have been selected, in order to set up a team with a large and complete expertise in this field. Table 1 shows the list of experts involved and the contribution they gave.

Table 1 List of the experts involved.

No.	Expert	Contribution
1	Professor in the field of construction management	Theoretical aspects
1	Occupational medicine phisycian	Aspects related to the protection of workers in their employment from risks resulting from factors adverse to health
1	Manager of a building company	All the aspects related to production can affect their contributions
1	Occupational safety and health inspector	Wide experience about safety and health in construction
1	Health and safety coordinators with over 10 years of experience	Established and detailed knowledge about safety management in construction sites
1	Scaffolding fitters	

2.2 Problem Analysis: De-structuring the Building Process

In order to facilitate the experts' analysis, the complexity of the problem was modeled as a multi-layered tree structure (corresponding to the work breakdown structure hierarchy), which is based on the top-down technique [9]. The built hierarchical tree allowed the expert to easily weigh the causal relationships involved and also to define the qualitative structure of the net.

Following a detailed analysis of the construction process and its de-structuring into elementary components, both procedures and purpose of experts involvement were defined.

Once all the documents had been analyzed, the experts were asked to specify all the activities which led to the creation of each defined elementary component (WP) and, for each activity, they listed the resources: materials, equipment and labor required to carry out each task. On the basis of these parameters, the related potential hazard scenarios were identified.

2.3 Defining Causal Model

By means of a first general questionnaire, the experts were asked to think individually about: hazardous scenarios, accident dynamics and triggers. In this way, each expert was given the time to develop his opinion before brainstorming with the others.

In this phase, a form, which was aimed at gathering information from all the experts, had been developed and successfully used. The form provided the experts with a guidance in the eliciting process and, at the same time, it allowed the analysts to gather homogeneous information.

On the basis of the information written in the forms filled in by the experts, information and knowledge about each "fall from height" scenario was successfully summarized. Then, it was represented through "cause and effect" diagrams (Fig. 1), which clearly show accident triggers.

These diagrams were proposed during the next brainstorming phase as the basis for a structured discussion.

In order to define in detail each hazard scenario and its main causes and dynamics, a first brainstorming session was conducted. By means of a specific questionnaire created "in itinere" (Fig. 2), the experts were led to translate "cause and effect" diagrams into a Bayesian network: a probabilistic graphical model whose nodes and links represent respectively a set of random variables and their conditional dependencies (Fig. 3).

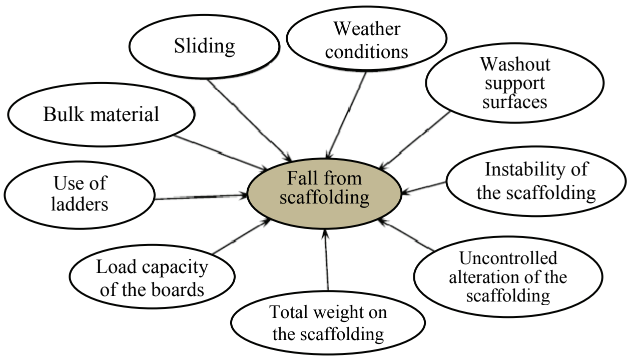

Fig. 1 The main causes elicited for "falls from scaffolding".

Q1	Which are the main causes of instability of the scaffolding?			
	R1.1	Washout support surfaces		
		Q1.1.1	Which are the main causes of washout support surfaces of the scaffolding?	
			R1.1.1.1	Rain
			R1.1.1.2	Snow and/or ice
	R1.2	Uncontrolled alteration of fasteners		
		Q1.2.1	Why fasteners could be altered?	
			R1.2.1.1	In order to make materials or equipments easier to move
			R1.2.1.2	In order to make some activities easier to carry out (improving workspace)
	R1.3	Wind		
		Q1.3.1	How the wind can cause instability of the scaffolding?	
			R1.3.1.1	Origin and intensity
	R1.4	Uncontrolled alteration of the base plates		
		Q1.4.1	Which are the main causes of uncontrolled alteration of the base plates of the scaffolding?	
			R1.4.1.1	In order to make materials or equipments easier to move
			R1.4.1.2	The presence of big machines or equipments
	R1.5	Extreme pressure on the supports of the scaffolding		
Q2	Which weather conditions can cause an heat stroke?			
	R2.1	High temperature and relative humidity (no wind)		
Q3	Which weather conditions can cause the sliding of the operators?			
	R3.1	Rain		
	R3.2	Snow and/or ice		
	R3.3	High relative humidity		
Q4	How the improper use of the scaffolding can cause fall from height of the operators?			
	R4.1	Bulky material		
	R4.2	Use of ladders, stands, etc.		
	R4.3	Overload on the boards (overcrowding and/or bulky material)		
Q5	Which parts of the scaffolding are altered frequently?			
	R5.1	Guar-rails		
	R5.2	Walk planks		

(grey)	The question is developed by the analysts before the brainstorming session on the basis of "cause-effect" diagrams
(blue)	The question is developed "in itinere" by the analysts during the brainstorming session

Fig. 2 An excerpt from the questionnaire for the logical structuring of the problem.

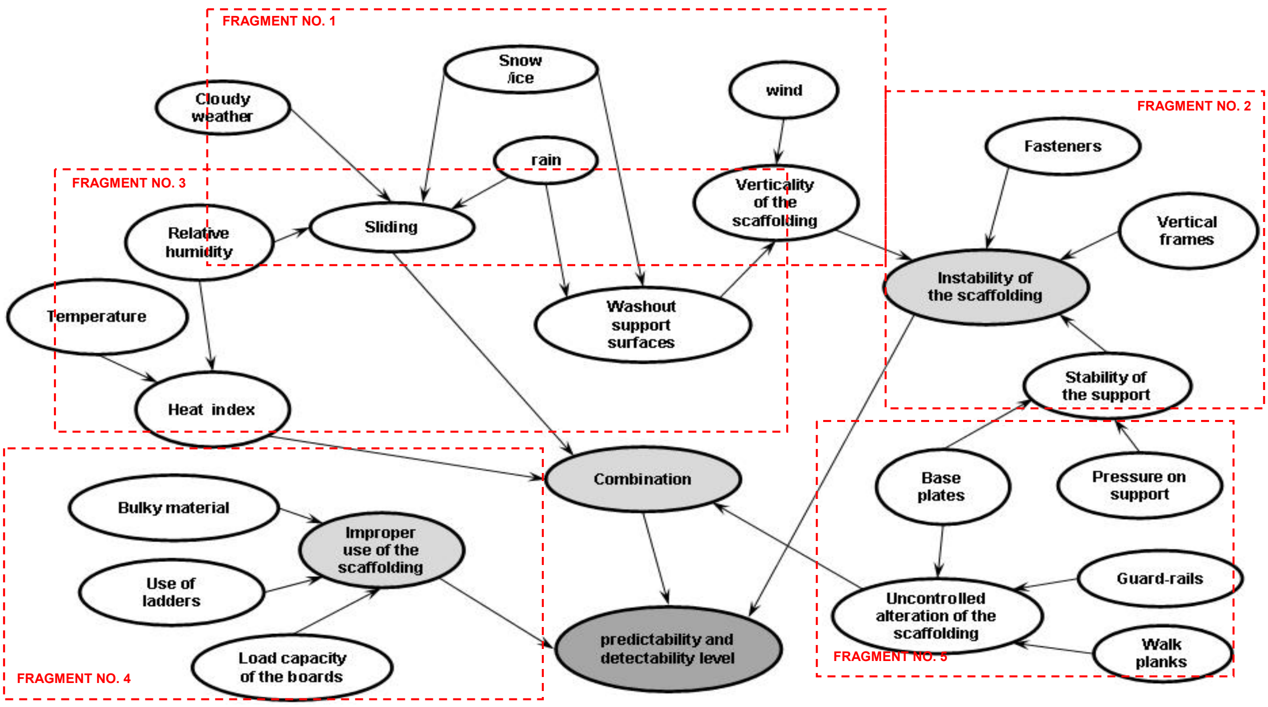

Fig. 3 Falls from scaffolding: the qualitative BN structure.

Bayesian networks exploit the concept of "Bayes conditionalization" [10], whose notation is $P(A|K)$, which combines the notions of knowledge and belief by attributing to "A" a degree of belief p, given the equation:

$$P(A \mid K) = \frac{P(A, K)}{P(K)}$$

where, K is also called the context of the belief in A. According to the Bayes theorem: it has become a definition of conditional probabilities. Besides the inversion rule, adopting Bayesian formalism and working with conditional probabilities provides several advantages in terms of computational power and makes the definition of input probabilities easier.

The tools used for facilitating computations are: the chain rule formula, the odds and likelihoods ratio, and conditional independence. The chain rule is used to perform inference via a flow of information which propagates probability estimations across the network step by step, that is to say passing through consecutive nodes. As a consequence, just conditional probabilities between parents and child nodes are necessary as input, in order to compute the joint state of any set of nodes in a network. Likelihoods ratio is the theory which allows to update inferences, once new knowledge is available: this process is usually called recursive Bayesian updating [11]. Conditional independence states that the state of any variable can be determined by the knowledge of the state of just its parents. Then a number of algorithms for inference propagation were developed for each network's structure, e.g., belief propagation in chains and causal trees [10]. In the software tool, we used for our purposes (i.e., Hugin^{TM} Expert), the conditional probabilities are represented by Dirichelet distributions, whose multinomial parameters can be learnt by the use of both datasets and quantitative expert judgments or a combination of both [12]. In particular, expert judgments may be used to define the initial experience, then subsequent data might be added and overall conditional probabilities redirected. Besides this tool, we also learnt conditional probabilities through the use of mathematical relationships [13].

The qualitative structure is focused on different clusters of variables, taking into account weather conditions, effective layout of the scaffolding and its components (e.g., fasteners, vertical frames, base plates, guard-rails and walk planks), the static aspects of the scaffolding (e.g., pressure on supports and walk

VARIABLE	STATE 1	STATE 2	STATE 3	STATE 4	STATE 5
PREDICTABILITY AND DETECTABILITY LEVEL	NO HAZARD	DETECTABLE HAZARD	HIDDEN HAZARD		
IMPROPER USE OF THE SCAFFOLDING	NOT SERIOUS	SERIOUS	EXTREMELY SERIOUS		
COMBINATION	NOT SERIOUS	SERIOUS	EXTREMELY SERIOUS		
INSTABILITY OF THE SCAFFOLDING	LOW	MEDIUM	HIGH		
LOAD CAPACITY OF THE BOARD	FALSE	TRUE			
USE OF LADDERS	FALSE	TRUE			
BULKY MATERIAL	0%<PO< 30%	30%<PO<60%	60%<PO<100%		
HEAT INDEX	(-INF-80)°F	(80-89)°F	(89-105)°F	(105-129)°F	(129-INF)°F
SLIDING	FALSE	TRUE			
UNCONTROLLED ALTERATION OF THE SCAFFOLDING	CAUTION	EXTREME CAUTION	DANGER		
VERTICALITY OF THE SCAFFOLDING	FALSE	TRUE			
FASTENERS	FALSE	TRUE			
VERTICAL FRAMES	FALSE	TRUE			
STABILITY OF THE SUPPORT	LOW	MEDIUM	HIGH		
TEMPERATURE	(0-80)°F	(80-89)°F	(89-104)°F	(104-129)°F	(129-275)°F
RELATIVE HUMIDITY	0-0.6	0.6-1			
CLOUDY WEATHER	FALSE	TRUE			
SNOW/ICE	FALSE	TRUE			
RAIN	FALSE	TRUE			
WASHOUT SUPPORT SURFACES	FALSE	TRUE			
WIND	CALM-GENTLE BREEZE	MODERATE BREEZE-STRONG BREEZE	HIGH WIND		
BASE PLATES	FALSE	TRUE			
PRESSURE ON SUPPORT	FALSE	TRUE			
GUARD RAILS	FALSE	TRUE			
WALK PLANKS	FALSE	TRUE			

Fig. 4 List of network variables and their states.

planks), and finally, workers' behaviors on the scaffolding. The net models show the relationships between each cluster of variables and fall from scaffolding scenario, and also highlight the predictability level of accident occurrence.

Fig. 4 shows all variables of the net and their possible states. The outcome was a comprehensive representation of the knowledge and information generated by different sources, which appears as a combination of several elementary fragments, each relative to an accident category.

2.4 Learning Probability Distribution

In the third phase of the elicitation process, the non-linear parameters of multivariate Dirichlet distributions, which express the strength of conditional independence among variables in Bayesian networks [12], were estimated through face-to-face interviews. Individual interviews with all the experts were carried out to determine their opinions about the qualitative structure of the model, and to design uncertainty in each variable. In this way, each expert was given the time to develop his opinion after debating with the other experts. Beginning from the qualitative structure of the net, the experts were asked to define, individually, a first information set related to:

- the state of all network nodes;
- the equations which allow to formalize links between variables in the model, when available.

An example pertaining to the second case is the "HI (heat index)" variable, which is linked to "Ta (temperature)" and "UR (relative humidity)" variables through the equation:

$$HI = -42.379 + 2.04901523\, Ta + 10.1433127\, UR + 0.22475541\, Ta\, UR - 6.83783 \times 10^{-3} (Ta^2) + 5.481717 \times 10^{-2} (UR^2) + 1.22874 \times 10^{-3} (Ta^2)\, UR + 8.5282 \times 10^{-4}\, Ta\, (UR^2) - 1.99 \times 10^{-6} (Ta^2)(UR^2)$$

Subjective estimations were then used to model the links among variables which cannot be defined by literature. The information gathered in this phase allowed us to create conditional probability tables for each fragment of the Bayesian network.

In Fig. 5, the network fragment related to "improper use of the scaffolding" is shown. To this aim, the experts were asked to define the states "yes" and "no" for both variables "use of ladders" and "load capacity of the board". Then, the experts estimated the states of the variable "bulky material". In this last variable, it was necessary to report the level of obstruction (PO) due to the presence of bulky material on the scaffolding walk planks. In this case, the expert opinions led to define the following three states for the variable "bulky material": State 1: 0% < PO < 30% low obstacle: Caution; State 2: 30% < PO < 60% medium obstacle: hazard; State 3: 60% < PO < 100% high obstacle: likely hazard.

As soon as the table related to this fragment of network had been structured, expert opinions were gathered by means of another questionnaire, where the probability distributions of the variable "improper use of the scaffolding" were estimated (Fig. 6).

Following the same procedure, all the other fragments of the network were analyzed, until defining a preliminary Bayesian model.

In those cases, where different estimates by the experts occurred, due to their different opinions and expertise they were combined into a discrete (x_i, f_i) distribution. In particular, x_i represents expert opinions and f_i stands for the weights associated to each expert [14]. Fig. 7 shows an example where three differing opinions are combined, provided that expert A is given twice the emphasis of each of the others owing to the wider experience of expert A in that field.

Once the tables of conditional probabilities for a specific variable had been gathered (Fig. 8), dissimilar

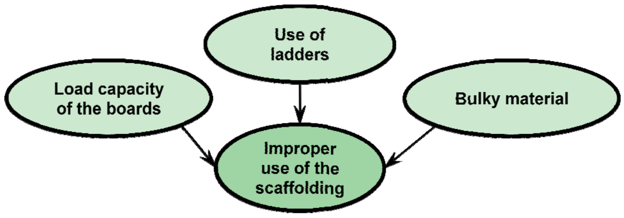

Fig. 5 One of the fragments of the Bayesian network.

Q1	When in the scaffolding there isn't the using of ladders and there isn't the overcoming of the admissible threshold of load bearing capacity, how much serious is the variable "improper use of the scaffolding" if there is the presence of bulky materials which covers, between 0% and 30%, the width of the scaffolding walk planks?
Q2	When in the scaffolding there isn't the using of ladders, how much serious is the variable "improper use of the scaffolding" if there is the overcoming of the admissible threshold of load bearing capacity and the presence of bulky materials which covers, between 0% and 30%, the width of the scaffolding walk planks ?
Q3	When in the scaffolding there isn't the overcoming of the admissible threshold of load bearing capacity, how much serious is the variable "improper use of the scaffolding" if there is the using of ladders and the presence of bulky materials which covers, between 0% and 30%, the width of the scaffolding walk planks ?
Q4	How much serious is the variable "improper use of the scaffolding" if there are, at the same time, the using of ladders, the overcoming of the admissible threshold of load bearing capacity and the presence of bulky materials which covers, between 0% and 30%, the width of the scaffolding walk planks ?
Q5	When in the scaffolding there isn't the using of ladders and there isn't the overcoming of the admissible threshold of load bearing capacity, how much serious is the variable "improper use of the scaffolding" if there is the presence of bulky materials which covers, between 30% and 60%, the width of the scaffolding walk planks?
Q6	When in the scaffolding there isn't the using of ladders, how much serious is the variable "improper use of the scaffolding" if there is the overcoming of the admissible threshold of load bearing capacity and the presence of bulky materials which covers, between 30% and 60%, the width of the scaffolding walk planks ?
Q7	When in the scaffolding there isn't the overcoming of the admissible threshold of load bearing capacity, how much serious is the variable "improper use of the scaffolding" if there is the using of ladders and the presence of bulky materials which covers, between 30% and 60%, the width of the scaffolding walk planks ?
Q8	How much serious is the variable "improper use of the scaffolding" if there are, at the same time, the using of ladders, the overcoming of the admissible threshold of load bearing capacity and the presence of bulky materials which covers, between 30% and 60%, the width of the scaffolding walk planks ?
Q9	When in the scaffolding there isn't the using of ladders and there isn't the overcoming of the admissible threshold of load bearing capacity, how much serious is the variable "improper use of the scaffolding" if there is the presence of bulky materials which covers, between 60% and 100%, the width of the scaffolding walk planks?
Q10	When in the scaffolding there isn't the using of ladders, how much serious is the variable "improper use of the scaffolding" if there is the overcoming of the admissible threshold of load bearing capacity and the presence of bulky materials which covers, between 60% and 100%, the width of the scaffolding walk planks ?
Q11	When in the scaffolding there isn't the overcoming of the admissible threshold of load bearing capacity, how much serious is the variable "improper use of the scaffolding" if there is the using of ladders and the presence of bulky materials which covers, between 60% and 100%, the width of the scaffolding walk planks ?
Q12	How much serious is the variable "improper use of the scaffolding" if there are, at the same time, the using of ladders, the overcoming of the admissible threshold of load bearing capacity and the presence of bulky materials which covers, between 60% and 100%, the width of the scaffolding walk planks ?

Fig. 6 An excerpt from the questionnaire about probability distributions.

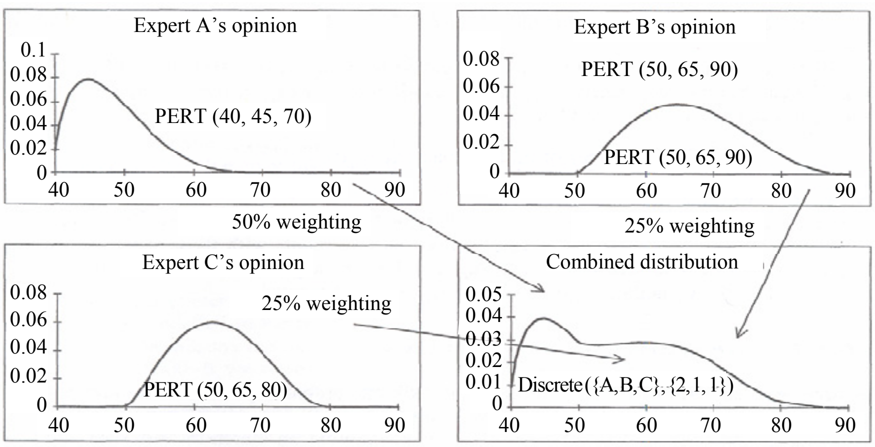

Fig. 7 Combining three dissimilar expert opinions.

Table 2 Table of the experts' weights related to "improper use of the scaffolding" fragment.

Experts	Improper use of the scaffolding
Professor	Weight = 0.25
Manager	Weight = 0.25
H&S inspector	Weight = 1
H&S coordinator	Weight = 0.75
Scaffolding fitters	Weight = 0.75
Occupational medicine physician	Weight = 0.10

Improper use of the scaffolding

Professor													WEIGHT: 0.25
	Bulky material	0-30	0-30	0-30	0-30	30-60	30-60	30-60	30-60	60-100	60-100	60-100	60-100
	Ladders	NO	NO	YES	YES	NO	NO	YES	YES	NO	NO	YES	YES
	Load capacity of the boards	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES
	EXTREMELY SERIOUS	0	40	50	70	15	85	55	100	80	100	85	100
	SERIOUS	20	50	30	30	50	15	35	0	20	0	15	0
	NOT SERIOUS	80	10	20	0	35	0	10	0	0	0	0	0

Improper use of the scaffolding

Manager													WEIGHT: 0.25
	Bulky material	0-30	0-30	0-30	0-30	30-60	30-60	30-60	30-60	60-100	60-100	60-100	60-100
	Ladders	NO	NO	YES	YES	NO	NO	YES	YES	NO	NO	YES	YES
	Load capacity of the boards	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES
	EXTREMELY SERIOUS	0	25	20	40	15	60	35	100	50	100	70	100
	SERIOUS	5	45	30	35	20	40	40	0	25	0	30	0
	NOT SERIOUS	95	30	50	25	65	0	25	0	25	0	0	0

Improper use of the scaffolding

H&S Inspector													WEIGHT: 1
	Bulky material	0-30	0-30	0-30	0-30	30-60	30-60	30-60	30-60	60-100	60-100	60-100	60-100
	Ladders	NO	NO	YES	YES	NO	NO	YES	YES	NO	NO	YES	YES
	Load capacity of the boards	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES
	EXTREMELY SERIOUS	20	70	70	90	50	100	80	100	95	100	100	100
	SERIOUS	40	30	30	10	35	0	20	0	5	0	0	0
	NOT SERIOUS	40	0	0	0	15	0	0	0	0	0	0	0

Improper use of the scaffolding

H&S Coordinator													WEIGHT: 0.75
	Bulky material	0-30	0-30	0-30	0-30	30-60	30-60	30-60	30-60	60-100	60-100	60-100	60-100
	Ladders	NO	NO	YES	YES	NO	NO	YES	YES	NO	NO	YES	YES
	Load capacity of the boards	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES
	EXTREMELY SERIOUS	20	68	68	85	50	100	75	100	95	100	100	100
	SERIOUS	40	28	32	15	35	0	25	0	5	0	0	0
	NOT SERIOUS	40	4	0	0	15	0	0	0	0	0	0	0

Improper use of the scaffolding

Scaffolding fitters													WEIGHT: 0.75
	Bulky material	0-30	0-30	0-30	0-30	30-60	30-60	30-60	30-60	60-100	60-100	60-100	60-100
	Ladders	NO	NO	YES	YES	NO	NO	YES	YES	NO	NO	YES	YES
	Load capacity of the boards	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES
	EXTREMELY SERIOUS	0	25	20	40	15	60	35	100	50	100	70	100
	SERIOUS	5	45	30	35	20	40	40	0	25	0	30	0
	NOT SERIOUS	95	30	50	25	65	0	25	0	25	0	0	0

Improper use of the scaffolding

Occupational medicine physician													WEIGHT: 0.10
	Bulky material	0-30	0-30	0-30	0-30	30-60	30-60	30-60	30-60	60-100	60-100	60-100	60-100
	Ladders	NO	NO	YES	YES	NO	NO	YES	YES	NO	NO	YES	YES
	Load capacity of the boards	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES
	EXTREMELY SERIOUS	0	40	50	65	10	80	60	100	90	100	80	100
	SERIOUS	15	50	25	25	55	20	30	0	10	0	20	0
	NOT SERIOUS	85	10	25	0	35	0	10	0	0	0	0	0

Fig. 8 Dissimilar expert opinions.

opinions were combined according to this procedure. The result was a weighted table (Fig. 9). The weights have been changed in relation to the specific part of the network and to the specific professional experience of each expert. For that reason, any expert, although judged as modestly influential on some aspects of the problem, might become the most significant on some other aspects (Table 2), their weight being dependent on the particular aspect analyzed.

According to the weighted mean formula, we have combined dissimilar expert opinions:

$$Ma, pond = \frac{\sum_{i=1}^{n} x_{ifi}}{\sum_{i=1}^{n} f_i}$$

where, x_i are the expert opinions and f_i are the weights given to each expert. The result was shown in Fig. 9.

Applying the same procedure all the other fragments of the network have been analyzed, until defining the preliminary Bayesian model depicted in Fig. 10.

3. Assessment on Network Utilization

The model described in Section 2 was intended as a knowledge map of accident dynamics and triggers relative to "falls from scaffolding" in construction sites. Such tool has been developed to interpret accident dynamics, instead of merely acknowledging potential hazards, and to support the decision process on the types of action to be taken to mitigate the possible detected accidents.

To this purpose, the proposed procedure allowed the inclusion of experienced experts with different backgrounds and knowledge, which managed to guarantee complementary contributions.

Weighted values	Improper use of the scaffolding											
Bulky material	0-30	0-30	0-30	0-30	30-60	30-60	30-60	30-60	60-100	60-100	60-100	60-100
Ladders	NO	NO	YES	YES	NO	NO	YES	YES	NO	NO	YES	YES
Load capacity of the boards	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES	NO	YES
Extremely serious	11.67	52.00	51.17	70.42	35.42	85.42	61.67	100.00	78.75	100.00	88.75	100.00
Serious	26.67	36.17	30.50	21.25	31.25	14.58	29.17	0.00	12.92	0.00	11.25	0.00
Not serious	61.67	11.83	18.33	8.33	33.33	0.00	9.17	0.00	8.33	0.00	0.00	0.00

Fig. 9 Weighted figure.

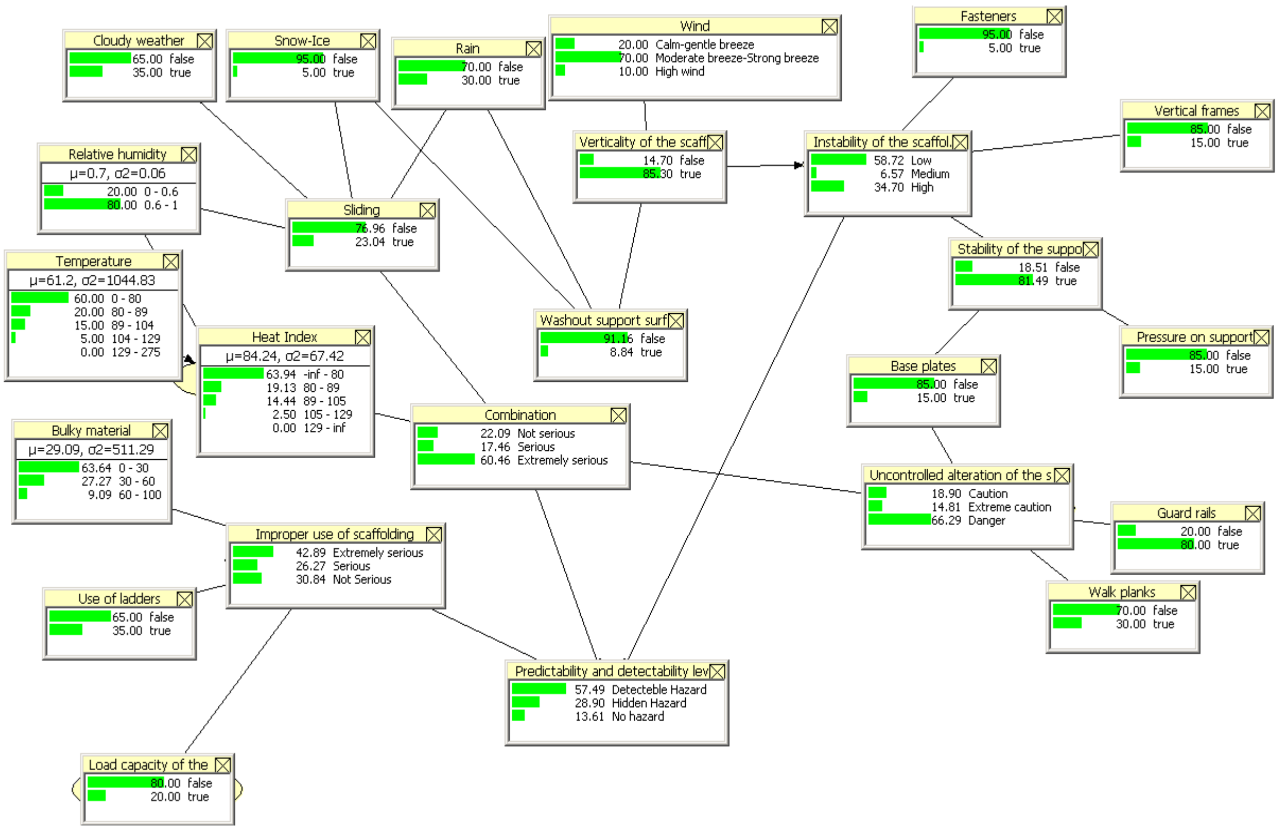

Fig. 10 The final Bayesian model.

The Bayesian networks allowed a synthesis of such dissimilar experiences within a tool of uniform representation, which also included an event estimate of the various variables states (Fig. 10).

The types of potential hazards which the probabilistic instrument is able to observe are the following:

- those linked to a complete or partial non-compliance with the relevant norms (about 75% of the dynamics under scrutiny);
- those linked to hardly predictable factors, despite a correct planning and the regular compliance with the safety rules and regulations (between 20% and 30% of the dynamics under scrutiny).

This suggested that applying the present system of safety management is not always enough, as it aims to minimize the probability of occurrence of risky situations by means of mere programmatic actions.

Such approach can be considered to be efficient only with regards to the first class of dynamics, linked to predictable dangers where the application of the relevant norms is enough to guarantee good safety standards or the total elimination of the hazard.

However, there are situations belonging to the second class, where the programmatic application of standard safety measures appears not to be enough.

Hence the usefulness of the Bayesian network, which was structured to return, besides the detail of possible accident dynamics, the probability that a well-known context might generate second-type, or "hidden" hazards.

To this aim, the end node of the net is an output meaning the predictability and detectability level of the hazardous events.

Fig. 11 shows the states of the end node of the network. The meaning of the states of the last nodes are differentiated: "detectable hazard" are those events already recognizable at the design phase, and which can be minimized by means of the application of safety legislation and regulations.

"Hidden hazards" are those combinations of hazardous events which cannot be prevented by means of compliance with technical safety regulations and legislation, because they occur as a consequence of unpredictable chains of events, most of the times triggered by external factors or by a weird combination of interferences among different teams. Hence they can be minimized just by means of on-site control during the execution phase.

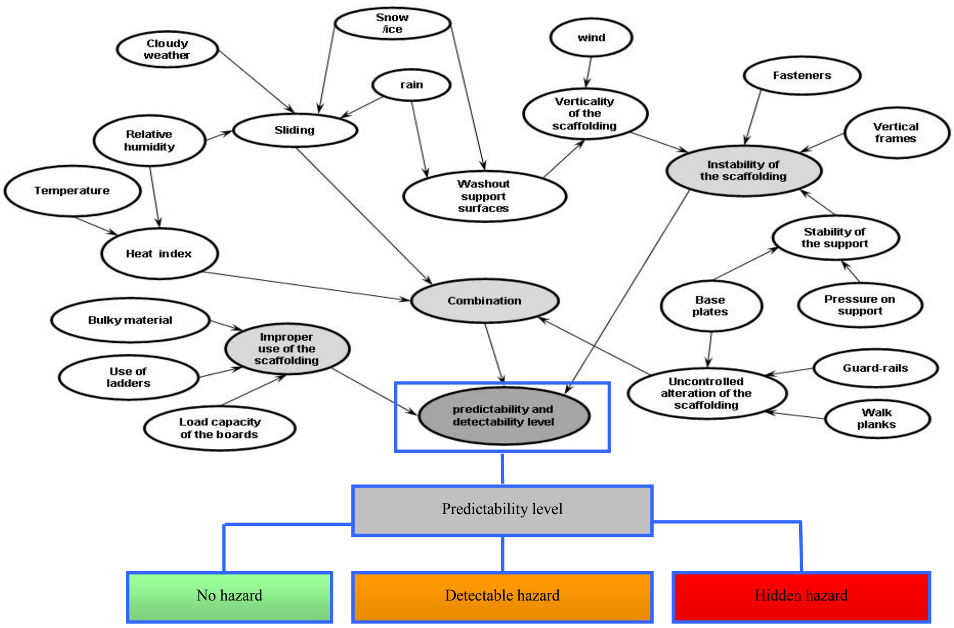

Fig. 11 The end node of the net.

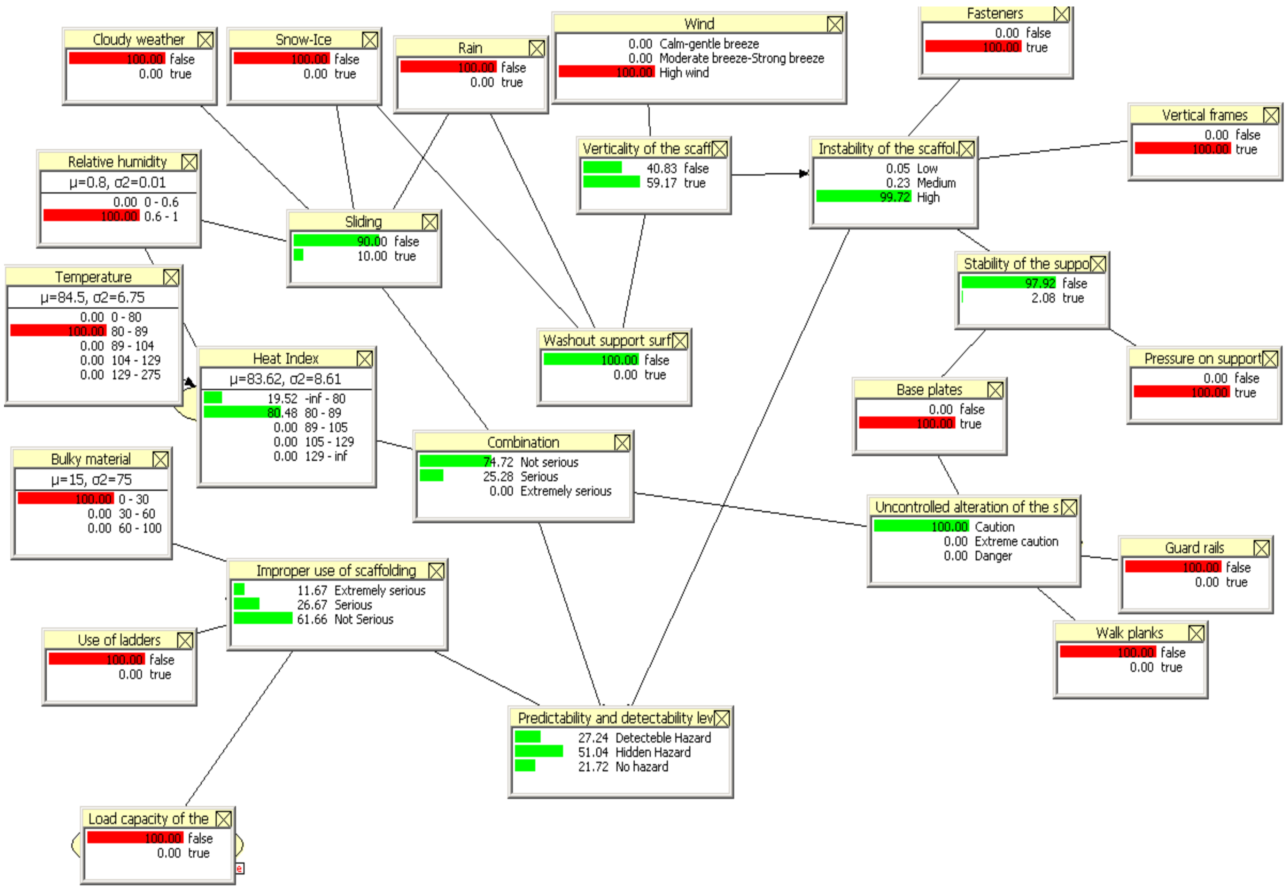

Fig. 12 A network's prediction.

To clarify this concept, Fig. 12 shows the network estimate, relatively to a peculiar situation of the construction site and under well-known weather conditions.

The states of some variables (relative humidity, temperature, bulky material, use of ladders, load capacity, cloudy weather, snow-ice, rain, wind, fasteners, vertical frames, base plates, pressure on support, guard rails and walk planks) show the evidences, show the evidences, that is the instantiated nodes meaning that the situation pertaining to such variable in the context description is well-known. The assignment of these inputs could be carried out by a safety coordinator, who would be noticed by the network about the occurrence probability of a "hidden hazard".

In fact, the final node of the network in this case takes on some probability values (< detectable hazard ≥ 27.24%; < hidden hazard ≥ 51.04%; < no hazard ≥ 21.72% >) which are quite different from those shown in Fig. 10 (that is, from the case of "a priori" knowledge). One can notice that the scaffolding configuration is correct (presence of stiffening and of base plates), but the combined increase of the wind intensity can lead to fall scenarios due to loss of stability of the scaffolding.

By analyzing the expert interviews once again, we have inferred that such a hazardous situation occurred in the past because of workers' incorrect behavior. They might consider it right to eliminate temporarily one or two scaffolding elements to solve interferences between work stages, which were both undetected and unpredicted during the planning phase, or factors external to the construction site. Such non authorized alteration could cause the scaffolding destabilization due to the wind, and the determination of risk of falls from height. In other words, the network indicates we must expect a non-predictable risk, and therefore it is necessary to integrate the current approach to H&S management with new solutions to mitigate the occurrence of these "hidden hazards", e.g., through automatic supervision which can replace expensive human supervisors [15].

4. Conclusions and Further Developments

The paper showed that in some cases programmatic safety mitigating measure could not be enough to prevent the occurrence of accidents in construction sites. This happens when "hidden hazards" can be potentially triggered by the specific site context. Thus, the built network constitutes the right tool capable of supporting health and safety coordinators in the assessment of those situations which should be monitored during the execution phase. This means that supervision is needed, which could be performed by means of automatic approaches. Consequently, the proposed network would be the kernel of a probabilistic model, to which new fragments could be added, each relative to the automatic supervision of every "hidden" hazard.

To this purpose, further research and information collection is necessary, in order to evaluate the factors involved in the occurrence of those unpredictable hazards. This step is mandatory prior to the design of an automatic system to be used as an intelligent support in the field of health and safety management.

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