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Multi-hazard multi-person quantitative occupational risk model and risk management

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ABSTRACT

A model for the quantification of occupational risk and a corresponding software tool are presented. The model quantifies occupational risk of one worker or several workers by taking into account their various tasks, activities and the associated hazards. Risk is evaluated for three types of consequences: recoverable injury, permanent injury and death. The occupational risk model is based on a set of 63 single-hazard models each assessing risk owing to a different hazard such as fall from a ladder, scaffold, roof etc. Data for quantifying these models come from the analysis of 9000 occupational accidents in the Netherlands in the period 1998–2004, and of the corresponding exposure data of activities and working conditions of the Dutch working population. Risk reducing measures are introduced, influencing the frequency of the more basic events of the model. A number of risk reducing measures forms a risk reducing policy. Each policy results in risk reduction, but it entails an economic cost. A multi-attribute evolutionary algorithm is used to develop the efficient frontier of the available solutions. The models and the software tool are demonstrated through a case study.

1. Introduction

Occupational Health and Safety constitutes one of the most important factors of the wellbeing of modern society. Occupational accidents in particular represent one of the major sources of risk today. According to Eurostat in 2014 in EU-15 the death toll was approximately 2.248 every year out of 2.26 million reported accidents that resulted in at least 4 days of absence. The number of fatalities at work has risen in the EU-28 to 3203 a year. In 2014 in the Netherlands there were 56,447 occupational accidents resulting in injuries and absence from work at least 4 days from which 39 people died [1]. Understandably occupational risk has received substantial and ever-increasing interest from the scientific community. The goal has always been to improve safety and decrease the number of accidents.

Attention has been focused on the individual (worker), behaviour, and the organization. Accident statistics, personal behaviour, risk perception and safety management systems have been extensively analysed in the hope of identifying causes of accidents and then formulating prevention policies. Methods used to manage accident prevention in companies include accident analysis, accident investigations and safety inspections which provide information on causes of accidents amongst particular groups of employees. A number of studies describe the distribution of injuries in terms of person, place and workplace characteristics [2–7]. Accident data have been analysed using descriptive statistics [8], factorial analysis [9], variance analysis [10] and multiple regression [11].

More recently a new tendency has emerged of trying to quantify occupational risk and by doing so to strengthen the basis for occupational risk management. In addition to the identification of causes of accidents in the work place, this new approach is striving to quantify the extent to which various working environment shaping factors are present in the work places and combine them with workers' exposure to hazards to arrive at quantified assessments of risk. Two semi-quantitative risk assessment methods for occupational risk assessment consist of [12–14]: a) risk matrices with two dimensions, the frequency of occurrence and the severity of consequences with semi quantified scales; b) the proportional risk – assessment technique or the so called "RSPE" method based on the function R=SPE, where R is the risk, S is the severity of accident occurrence, P the frequency of the accident and its consequences and E the frequency of employee exposure to hazard. The scales of the RSPE method are arbitrarily chosen and formed on a qualitative basis.

Recently a number of attempts at a more systematic and consistent approach to quantitative occupational risk assessment have appeared

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Nomenclature and definitions

J_n: nth job position

N: Number of Job positions (job types) in the entity under analysis

n: Index over the N job positions $(n=1,2,\ldots,N)$

E_n: Number of persons holding the nth position

M_n: Number of activities of J_n. The same symbol provides the non-overlapping sub-periods to which the overall period T_n for job-position n is divided.

m: Index over the M_n periods ($m=1,2,\ldots,M_n$)

$A_{n,m}$ Activity m for job position n

$T_{n,m}$: Duration of the mth activity for job-position n

T_n: Overall time period over which risk is calculated for

$$J_n.T_n = \sum_{m=1}^{M_n} T_{n,m} \qquad (1)$$

$I_{n,m}$: Number of single hazards present during the mth activity for job-position n

$h_{n,m,i}$: Index mapping the ith single hazard of the mth activity of the nth job type to the list of the 63 single hazards ($n=1,\ldots,N$ $m=1,\ldots,M_n$ $i=1,\ldots,63$)

λ_{ji}: Consequence specific accident rate for hazard i

$$\lambda_{ji} = \begin{cases} \lambda_{2i}\text{riskrateforarecoverableinjury}(j=2) \\ \lambda_{3i}\text{riskrateforapermanentinjury}(j=3) \\ \lambda_{4i}\text{riskrateforafatalinjury}(j=4) \end{cases} \qquad (2)$$

$\delta(i,m)$: Function mapping the ith hazard to the mth activity

$$\delta(i,m) = \begin{cases} 1\text{ifhazard}i\text{ispresentduringactivity}m \\ 0\text{ifhazard}i\text{isnotpresentduringactivity}m \end{cases} \qquad (3)$$

Λ_{jm}: Consequence specific accident rate for period m ($j=2$ for recoverable injury, $j=3$ for permanent injury, $j=4$ for fatal injury) $\Lambda_{jm} = \sum_{i=1}^{63} \lambda_{ji}\delta(i,m)\text{for} j = 2,3,4$ (4)

Λ_m Overall Accident rate for period m $\Lambda_m = \Lambda_{2m} + \Lambda_{3m} + \Lambda_{4m}$ (5)

P_{jm} Probability of consequence j during activity A_m, j=1, No accident, j=2, Recoverable Injury (RI), j=3 Permanent Injury (PI), j=4 Fatal Injury (FI)

R_{jn} Probability of consequence j over period T_n (j=2,3,4)

$R_{j,o}$ Expected number of workers with consequence j (j=2,3,4), The symbols "≻" and "≺" are used to indicate preferences as follows:, "≻" means "more preferred than ", "∼" means "indifferent between", "≺" means "less preferred than"

in the literature. A model has been developed to predict the frequency of occupational accidents in the offshore oil and gas industry, based on direct, corporate and external factors [15]. Quantified risk for various occupational groups in Sweden, based on the number of accidents and relevant exposure, has been calculated [4]. A Bayesian network analysis of workplace accidents caused by falls from height has been proposed [16] for identifying causes of accidents such as experience, task duration, and training, knowledge of regulations, hazard perception, safety harness and incorrect posture. Similarly a Bayesian network analysis has been applied to model offshore occupational risk in harsh environments. [17] Fuzzy methods have been used for risk assessment of occupational accidents in a steel company [18], at construction sites [19–21] and workplaces [22] . Artificial neural networks and a fuzzy inference system have been proposed to assess occupational risk indexes in the shipbuilding industry [23,24] and predict number of injuries [25]. Finally an exposure – damage approach for occupational risk quantification in workplaces involving dangerous substances is proposed in [12].

In 2003, the Ministry of Social Affairs and Employment in The Netherlands launched the policy program 'Improving Occupational Safety' which had two strands:

1. Sector-related improvement programs aimed at behaviour change of workers were carried out by companies.
2. A project was initiated to provide a way of prioritising occupational accident hazards and to provide individuals and organisations with a way to identify the most cost-effective set of measures to improve their safety performance.

With regards to the latter, a quantitative occupational accident risk model was required to provide probabilities of accident occurrence, together with the consequences, given a particular activity and working conditions. A research project to develop such a model, the Occupational Risk Model (ORM), was started. This project aimed to produce a software tool for policy makers, companies and workers to assess occupational accident risk and to reduce it by being able to choose the most cost-effective set of measures.

In the framework of the ORM project a methodology to quantify occupational risk from accidents has been developed and is presented in this paper. Risk is quantified by measuring the level of severity of potential health damage together with the relative likelihood of occurrence. The methodology and the associated model links the probability of a health damage following an accident with specific workplace-factors that can be changed through concrete and simple actions. Thus the model offers itself not only for the assessment of risk but also for evaluating alternative risk reducing sets of measures.

The Occupational Risk Model (ORM) addresses risk of damage to health as a result of accidents at work. Detrimental effects to health owing to chronic exposure to various hazardous agents are not included. The model calculates occupational risk in a group of people (e.g. a company) that perform a variety of jobs in similar or different environments and are exposed to any combination out of list of sixty three hazards [26–28]. These hazards are ranging from "fall from a height" to "human aggression" or "small explosions" .

Two sources of data have been used in the development and quantification of the model: (i) Detailed descriptions of accident that occurred in the Netherlands over a certain period of time and investigated by the Dutch Labour Inspectorate of the Ministry of Social Affairs and Employment. Serious accidents reportable under Dutch Law are covered; (ii) Exposure assessment that is, time during which the Dutch working population that generated the number of accidents in (i) were exposed to the various hazards. In addition the frequency with which several working conditions, linked to the onset of accidents, were present in the workplace was assessed. This second source of data was generated through surveys of the Dutch working population at a national level. Although the quantification of the model is based on Dutch data the methodology and the structure of the model has a wider application. The paper is organised as follows.

Section 2 summarises the single-hazard model (SHM) that links the probability of an accident with a reportable consequence from a single hazard with a number of broadly defined factors and conditions of the workplace. Section 3 describes the multi-hazard, multi-person model that calculates the risk in a group of persons performing different types of jobs and exposed to different sets of multiple hazards. Section 4 outlines an approach to occupational risk management using a multi-criteria optimisation technique. Section 5 demonstrates the use of the model and the associated computer tool through an example. Details of the risk calculations are given in the Appendix. Finally Section 6 discusses the main characteristics of the models and Section 7 presents the conclusions.

2. Single hazard model

The cornerstone to the development of a multiple-hazard, multiple-person model is the development of a single-hazard, single-person model. The objective of the single- hazard model is to logically link the composite event of an accident of a specific type (e.g. falling from a placement ladder) of a single person with the simpler events or under-