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Review

Risk-based management of occupational safety and health in the construction industry – Part 1: Background knowledge

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ABSTRACT

During the last decades, there has been a growing awareness about occupational safety and health risks by the various interested parties in the construction industry. However, despite the substantial improvements achieved, the rate of accidents is still significantly higher than in most of the other industries. Two major reasons have been used to explain this high rate of accidents in the construction industry: (i) the intrinsic riskiness due to the nature of the activities and the particular characteristics of constructions projects and organizations and (ii) the financial and economic issues regarding the implementation of additional safety measures in a growing competitive market.

This companion paper is presented in two parts. The present document refers to Part 1 and reviews the major lines of research and main contributions in the field of occupational safety and health in the construction industry. The review covers occupational safety and health research, organized in accident understanding studies, accident analysis studies and accident modeling studies, and occupational safety and health risk management, in particular risk criteria and limits. The review reveals the need for a methodology to quantify occupational safety and health risk in construction projects following the guidelines set by the international standard ISO 31000:2009. Part 2 proposes and details the Occupational Safety and Health Potential Risk Model (OSH-PRM) that was designed to allow estimating the statistical cost of occupational safety and health risk.

Contents

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1. Introduction

Occupational safety and health has been and still is a topic of intense research and practical developments. Globally, there has been a substantial improvement on occupational safety and health in the construction industry, at large motivated by the publication and ongoing implementation of the two most relevant standards in the field, the ILO-OSH 2001 and the BS OHSAS 18001, and increasingly stringent regulations. Nevertheless, accidents still occur in the construction industry at a substantial higher rate than in most of the other industries and with severe consequences, both for the workers and the public. According to the *European Agency for Safety and Health at Work* (EASHW, 2003), the construction is the most dangerous industry in terms of occupational safety and health. At a worldwide level, the construction workers are three times more likely to die and two times more likely to suffer injuries at work than the average of the workers in all other activities. Additionally, construction workers are more exposed to biological agents, chemical substances, ergonomic deficiencies, as well as noise, vibration and temperature. Thus, in addition to accidents (fatal and non-fatal), construction workers have also higher incidence rates of several health problems (Drever, 1995). Musculoskeletal disorders (Schneider, 2001; Welch et al., 2009; EASHW, 2010), asbestoses, mesotheliomas and other health problems ensuing from exposure to asbestos (EASHW, 2004a; Engholm and Englund, 2005), dermatitis, in particular by reaction to cement (EASHW, 2008b), hand arm vibration syndrome (EASHW, 2008a) and hearing loss (EASHW, 2004b) are identified as some of the main occupational diseases in the construction industry (NAO, 2004). The consequences resulting from the exposure to other potentially harmful substances have also been reported (e.g., silica – Linch, 2002; Flanagan et al., 2003, 2006; Beaudry et al., 2013; manganese – Meeker et al., 2007; various – Woskie et al., 2002) as well as whole-body vibration (Cann et al., 2003), among other health related issues in construction (e.g., Hartmann and Fleischer, 2005; Burström et al., 2010).

This scenario of occupational safety and health in the construction industry is motivated by several interrelated and complex factors that can be related to the industry in general and to the construction projects in particular. There are several characteristics inherent to the construction industry contributing to this scenario. Although the relationship is not supported by empirical evidence, their identification is based on solid theories and several years of observations (Hallowell, 2008). Some of the inherent characteristics are (Fredericks et al., 2005): (i) industry fragmentation; (ii) dynamic work environments (multiple teams performing multiple tasks simultaneously and in proximity); and (iii) industry culture. Probably, one of the most particular aspects of the construction industry is the fragmentation of the involved parties throughout the various phases of construction projects. Considering the traditional design-bid-build contractual arrangement, the design phase is carried out by architects, engineers and other professionals, followed by the request of proposals and the execution by the winning contractors. The operation stage is, in many cases, the responsibility of another party, which may be the promoter of the project or an end-user client. Normally, this is a linear process, with each step properly compartmentalized and performed by separate entities, loosely tied and with different, sometimes conflicting, objectives (Tatum and Korman, 2000). Gambatese (2006) reports that integrated contracting methods, such as design-build, are associated with lower accident rates. Unlike what happens in other industries, the work environment in construction projects is often unique, transient and dynamic. Construction sites are workplaces in constant change, exposed to stochastic elements (e.g., weather conditions; soil characteristics; road accidents) and may be significantly different from previous projects. Additionally, it is common the coexistence of work teams with different tasks working in common areas of the construction sites. Also, the work teams are in constant rotation throughout the project and their members may also change along the way. All these factors contribute to increase the possibility of accidents occurring and distract workers from completing their tasks safely, even if they are familiar with and the tasks are simple (e.g., see Hinze, 1997; Hinze and Wilson, 2000; Carter and Smith, 2006; Yi and Langford, 2006). Finally, the culture of many of the workers contributes to explain the high incidence rates in the construction industry. Factors such as machismo, substance abuse, language barriers and low level of education are some of the most relevant worker culture related aspects (Hallowell, 2008). According to Hinze (1997), the attitude of construction workers increase the risk tolerance and, therefore, the frequency and severity of accidents. For instance, the consumption of alcoholic beverages or drugs by construction workers in the U.S. is roughly twice the average recorded across all industries, which is a serious aggravating factor when associated with the type of tasks performed (Gerber and Yacoubian, 2001). The low level of education and the coexistence of workers of different nationalities originate communication barriers, not only among workers, but also between the management and the workers. Cultural differences and communication deficiencies hinder the prevention of accidents and may contribute for their occurrence.

The remaining of the first part of this companion paper reviews some of the most important occupational safety and health risk research (Section 2) and occupational safety and health risk management practices (Section 3), setting the background knowledge supporting and motivating the Occupational Safety and Health Potential Risk Model (OSH-PRM) presented in Part 2.

2. Occupational safety and health research

Peláez (2008) organizes occupational safety and health research into three main groups: (i) accident analysis studies; (ii) accident prevention studies; and (iii) risk evaluation studies. The accident analysis studies are rooted in the works of Heinrich (1930a), Leplat (1978) and Kjellen and Larsson (1981), including accident causation models (e.g., DeJoy, 1990; Abdelhamid and Everett, 2000; Suraji et al., 2001), statistical analysis of accidents (Hinze, 1996; Huang and Hinze, 2003) and studies on the economic cost of accidents (e.g., Leopold and Leonard, 1987; Everett and Frank, 1996; Waehrer et al., 2007). The accident prevention studies, rooted also in the works of Heinrich (1930b) and Helander (1980), are divided according to the level or stage of focus. Jaselskis et al. (1996) researched the prevention of occupational accidents at an organizational/institutional level, with Baxendale and Jones (2000) studying the application of laws and standards and Teo et al. (2005a) investigating the importance of occupational safety and health policies and manuals. Hinze and Francis (1992) and Gambatese and Hinze (1999) analyzed the relevance of occupational safety and health prevention in the design stage. The construction stage has been the focus of several prevention related studies, including: (i) the measurement of the efficiency of prevention (e.g., Laufer and Ledbetter, 1986); (ii) the influence of human behavior (e.g., Hinze, 1981); (iii) the contribution of safety and health plans (e.g., Burkart, 2002); (iv) the influence of financial incentives (e.g., Hinze, 2002); and (v) the responsibility of involved parties (e.g., Toole and Gambatese, 2002).

In the present paper, a different organization is adopted, considering only two major categories: (i) accident causation models and (ii) accident assessment studies. The accident causations models are mostly generic organizational constructs representing the underlying causes of accidents, providing a means of understand-

Table 1
Accident causation models main contribution and critique.

Models	Contribution	Critique
Generic accident process models		
Sequential models	Accident can be avoided by removing any factor in the sequence leading to it	Simplistic and omits data/interactions
Epidemiological models	A framework for analyzing existing accidents	Entirely descriptive and fails to directly evaluate causation
Energy transfer models	A set of generic countermeasures strategies	Neglects categories of accidents
System models	Performance evaluation and insight into accident causation	Accidents considered as a control problem
Human error and dangerous behavior models		
Behavioral models	Individual human characteristics may contribute for accidents	Discredited
Human decision process models	Understanding and predicting human decisions in accidents	No complete explanation of accidents
Human information processing models	Describing basic error mechanisms and document the knowledge required to perform tasks safely	No complete explanation of accidents
Error taxonomy models	Relation of multiple factors which must be considered for analyzing human error	No complete explanation of accidents
Human lesions mechanism models		
Cumulative stress models	Relates physical stressors with cumulative damage to people	Fails to directly evaluate causation
Immediate lesions modes models	Relates physical stressors with immediate damage to people	Fails to directly evaluate causation

ing and categorizing accidents causes and evaluating several issues related to safety in general and occupational safety and health in particular (Section 2.1). The accident assessment studies group the research that can be used to provide information to the risk assessment activities defined by the ISO 31000:2009, namely risk identification, risk analysis and risk evaluation. Within this research category, the focus of the literature review is limited to research primarily related to the execution stage of construction projects (Section 2.2).

2.1. Accident causation models

The various existing accident causation models show some fundamental differences. They can be distinguished depending on the area of application, the purpose and the focus. Significant differences can also be found in terms of their general structure, input data and results. Lehto and Salvendy (1991) identified three main classes of accident causation models: (i) generic accident process models; (ii) human error and dangerous behavior models; and (iii) human lesions mechanism models. An overview of the main categories of models in each class of accident causation models is presented in Table 1.

The generic accident process models can be grouped into four main categories (Lehto and Salvendy, 1991): (i) sequential models; (ii) epidemiological models; (iii) energy transfer models; and (iv) system models. Heinrich (1931) defines the reasoning of sequential models through the domino theory, in which an accident is the culmination of a series of events and circumstances. The greatest contribution of this theory is to recognize that an accident can be avoided by removing any factor in the sequence leading to it. Later models in this category were developed considering accidents as result from the convergence of multiple sequences of events. The epidemiological models guide the analysis of accidents by providing a structure to organize the multiple factors influencing their occurrence. According to Gordon (1949), these factors can be divided depending if they concern the bearer (victim), the agent (aggression) or the environment (local and surrounding). Epidemiological models are useful to organize and prioritize the efforts in safety and health. In their simplest form, the energy transfer models consider accidents to be caused by a transfer of various forms of unwanted energy between the source and a susceptible structure (Gibson, 1961). By allowing to list strategies to prevent damages, in particular, preventing the accumulation of energy, reducing the energy potential, preventing the release of energy, reducing the rate of energy release, separating or putting a barrier between the source of energy and the receptor, absorbing energy, strengthening the receptor or detecting and responding to the release of energy, Haddon (1973) converted these models for practical use. Energy transfer models are particularly useful for identifying hazards and defining measures in safety and health management. System models consider man–machine systems behavior to be similar to open or closed systems, establishing an analogy with electrical control systems. Accidents are considered disturbances in the system, helping to understand how the systems that use information from previous accidents to plan responses to future disturbances are more efficient.

Human errors and intentional dangerous behaviors are often referenced as predominant sources of accidents (e.g., Heinrich, 1931; Cooper, 1961). The accident causation models focused on human errors and dangerous behaviors can be organized into four main categories (Lehto and Salvendy, 1991): (i) behavioral models; (ii) human decision process models; (iii) human information processing models; and (iv) error taxonomy models. Behavioral models focus on inherent (e.g., personality; attitude) and/or situational (e.g., tension; anxiety) aspects of human behavior that may be in the origin of accidents. Studies have evidenced that the situational aspects are preponderant in the explanation of human errors (Surry, 1968; Hoyos and Zimolong, 1988). Focusing in aspects related to specific situations that explain accidents, the human decision process models emphasize that the specific goals and objectives in a given situation are crucial to explain dangerous behaviors (Taylor, 1976). This group of models helps to explain risk perception. Human information processing models can be seen as variants of the system models focusing in the information flux through the individuals while performing a task. The basic notion is that the information flows through several stages, including sensation, perception, memory, decision taking and response, and errors are a result from perturbations in any of them (Welford, 1968). These models allow the evaluation of aspects such as the experience or the resources in accident prevention. Human errors can be addressed from several perspectives. From a systems perspective, errors are deviations in performance, which may result from disturbances in the system where the work is being carried out. Lawrence (1974) classified the errors associated with fatal accidents in failure to percept, recognize or respond to warnings. The error taxonomy models are useful for relating different factors that explain human error.

Accidents resulting in injuries or fatalities of workers while performing their tasks are best analyzed using models of human lesions mechanism. These models are essentially based on ergonomic principles and can be grouped into two main categories (Lehto and Salvendy, 1991): (i) cumulative stress models and (ii) immediate lesions modes models. The cumulative stress models are the basis of several standards that establish exposure limits for different aggressive agents. They are closely related to issues of ergonomic workplaces and tools (Armstrong et al., 1986). A wide range of approaches aimed at modeling accidents with the intention of identifying modes of immediate injury, especially those designed to analyze the dangers in handling hazardous materials (Herrin et al., 1974) and those designed to analyze the causes of falls (Lehto and Salvendy, 1991; Lombardi et al., 2011). This group of models also appears associated with biometrics, psychophysiology and ergonomics, providing the basis supporting the setting of limits on aspects like the maximum loads that can be handled by individuals of different genders or the design of ladders and scaffolding.

Descriptive models of work behavior may be classified as a different type of accident causation models that attempt to understand accidents without reference to normative concepts of errors or violations. An important descriptive model is the one proposed by Rasmussen et al. (1994). The model assumes that workers operate within a work system shaped by objectives and constraints (e.g., economic, functional, safety related) and guide their behavior based on criteria such as workload, cost effectiveness, risk of failure or joy of exploration, among others.

The different categories of the models reviewed are not mutually exclusive. In practice, various models have been developed which comprise elements pertaining to the different categories. In the field of occupational safety and health, Hallowell (2008) highlights the following: (i) the two factors model and (ii) the trajectory model. The majority of the authors agree that incidents are the direct result of uncontrolled exposure to hazards and performing tasks in unsafe conditions (e.g., Hinze, 1997; Gibb et al., 2004). In this regard, the two factors model introduced by Heinrich (1931) suggests that incidents result from the combination of uncontrolled exposures to hazards with performing tasks in unsafe conditions. Although the relative importance of each factor may vary in each case, both are always present. The trajectory or "Swiss cheese" model (Reason, 1990), assumes that accidents take place when a failure occurs simultaneously in all lines of defense in the trajectory of the accident. The defense lines are made-up of technical, organizational, individual and cultural aspects, in addition to the existing protections.

More recently, some accident causation models have been developed specifically for the construction industry. Most of them combine elements of the generic accident process and human error and dangerous behavior models. Abdelhamid and Everett (2000) developed the Accident Root Causes Tracing Model (ARCTM), aimed at supporting the investigation of the causes of accidents considering three classes of sources: (i) failure to identify unsafe conditions previous to the task starting; (ii) decision to proceed with the task despite identifying unsafe conditions; and (iii) decision to perform a dangerous action, independently of the initial occupational safety and health conditions in the workplace. Suraji et al. (2001) developed a model centered on inappropriate behavior of individuals. This model, which can be called as "constraints-response" model, considers that the factors explaining accidents can be classified as proximal or distal. Proximal factors are those directly related to accidents, namely situation or condition in the area where the event or accident occurred, while the distal factors are the underlying reasons for the proximal factors and may also represent aggravating parameters, such as time and cost constrains or emergency responses. Based on the descriptive model proposed by Rasmussen et al. (1994), Mitropoulos et al. (2005) developed a model considering the following main factors in the origin of accidents: (i) dangerous working conditions and behavior controlling the exposure of workers to hazards and (ii) errors and surrounding conditions changes controlling the occurrence of incidents.

2.2. Accident assessment studies

Within the accident assessment studies, there are three main lines of research for the construction industry, namely: (i) accident understanding (Section 2.2.1); (ii) accident analysis (Section 2.2.2); and (iii) accident modeling (Section 2.2.3). Most of the studies fall into the accident understanding category, focusing in passive (e.g., underlying or aggravating factors of accidents, the causes and origins of accidents, the accidents consequences) and active (e.g., mitigation options and strategies and their efficiency and efficacy) aspects of occupation safety and health in varying contexts and both qualitatively and quantitatively. The accident analysis category concerns studies aimed at developing indicators, metrics or tools to quantify occupational safety and health risks. The last category is also the most recent and includes models or frameworks to assist the risk assessment of occupational safety and health in construction projects.

2.2.1. Accident understanding

Several authors have been dedicated to research the causes, origins and patterns of construction accidents, to study the effect of safety measures and to analyze occupational safety and health conditions in different countries or regions (Fullman, 1984; Goldsmith, 1987; Culver et al., 1990, 1992; Davies and Tomasin, 1990; La Bette, 1990; MacCollum, 1990; Rietze, 1990; Helander, 1991; Peyton and Rubio, 1991).

Based on the records of 1082 construction accidents occurred in the U.S. between 1994 and 1995, Hinze et al. (1998) organized their causes in 20 categories. These authors argued that this procedure allows greater understanding of the accidents and facilitates the selection of the most appropriate safety measures. Complementarily, they identified the most frequent causes of accidents for different types of construction workers occupations. Toole (2002) identified 8 categories for the causes of construction accidents and emphasized the need to assign responsibilities to various actors based on their ability to influence the respective causes. Reese and Eidson (2006) organized the causes of construction accidents in basic, direct and indirect.

Huang and Hinze (2003) identified patterns in accidents involving falls from height in the U.S. and compared the influence of several factors, including the type of task, the location and age of the workers, the time (hour and month) of the occurrence and the human error component. In addition, Derr et al. (2001) analyzed the temporal evolution of the number of fatalities caused by falls in different sub-sectors of the construction industry and in specific activities. Kartam and Bouz (1998) and Kartam et al. (2000) analyzed the incidence and causes of accidents in the construction industry in Kuwait, having identified falls from height as the main cause of fatal accidents and emphasizing that the deficiency of accident records prevents the correct assessment of the actual occupational safety and health conditions of the construction industry in the country.

Teo et al. (2005b) explored the factors that, according to the contractors, contribute to the occupational safety and health conditions in Singapore. They concluded that the most relevant where the safety policies of the companies, the construction processes, the staff management regarding occupational safety and health, and the incentives policies. Sawacha et al. (1999) analyzed 7 classes of factors influencing the occupational safety and health in the construction sector in the UK and found that the organizational and operational factors where the most relevant. Langford et al. (2000) identified 5 main factors influencing the workers attitude towards occupational safety and health management, highlighting the need to establish strong relations between all those involved to ensure good conditions for the workers in the construction industry. Suraji et al. (2001) concluded that conducting operations and activities in an inadequate manner is the most relevant reason underlying accidents occurring in construction sites in the UK. Choudhry and Fang (2008) evaluated the reasons motivating workers in the construction industry in Hong Kong to put themselves in dangerous situations, having identified the lack of knowledge regarding safety issues, the pressures and financial incentives to maximize the productivity and the lack of training and nonuse of safety equipment as some of the most important.

Duff et al. (1994) studied alternative measures to promote changes on the behavior of the construction workers in the UK as a way to improve occupational safety and health, having found that training influenced the outcome slightly and pointing out the establishment of objectives in combination with the dissemination of results as the most promising option. Barber (2003) found that the size of the company and the level of education of the trainers were the most relevant factors influencing the rate of accidents, while the number of training hours and the experience of the workers were not found to be statistically relevant.

Tam et al. (2004) identified elements of poor management of occupational safety and health in the Chinese construction industry, highlighting the lack of awareness to the problem by both the companies' top management and construction managers, the reluctance to allocate resources, and the lack of training as the most relevant. Fang et al. (2004) identified 5 main factors for establishing the allocation of limited resources in safety and health in construction sites in China, being the involvement of the occupational safety and health coordinators the most important. Aksorn and Hadikusumo (2008) identified 16 critical factors for the success of safety and health plans in construction projects in Thailand and the most important where the management support and workers education and training. Hassanein and Hanna (2008) identified the importance of implementing formal safety and health plans while comparing the performance of construction companies operating in Egypt and in the US in terms of occupational safety and health. Lai et al. (2011) compared the use of human resources in occupational safety and health management in the construction industry in Singapore and in the US, identifying differences particularly in the hiring and selection practices (e.g., taking gender, age or experience into account during the workers selection process).

While most studies in this category relate to accidents, some also take occupational diseases into account. Analyzing the causes of death, including accidents and diseases, in a group of 20,000 construction workers in Germany for a 10 years period, Arndt et al. (2004) observed lower incidence of fatalities associated with cancer or cardiovascular diseases comparing with mean values of the population, but higher rates of fatalities resulting from work-related injuries.

Several authors have developed lists of main factors influencing occupational safety and health in the construction industry, mostly based on questionnaires or interviews (e.g., Sawacha et al., 1999; Langford et al., 2000; Suraji et al., 2001; Toole, 2002; Fang et al., 2004; Teo et al., 2005b; Reese and Eidson, 2006; Aksorn and Hadikusumo, 2008; Choudhry and Fang, 2008). Despite the differences between the lists of the various studies, the factors can be generally grouped into workers-related, management-related and activity-related.

2.2.2. Accident analysis

Over the past decades, several methods for the quantification of occupational safety and health risks have been developed (Hallowell and Gambatese, 2009a), although with varying levels of sophistication and different fields of application. Brauer (1994) quantified occupational safety and health risks by applying a qualitative scale to the frequency of occurrence. Everett (1999) investigated ergonomic risks associated with 65 construction processes using a 3 level qualitative scale. Sun et al. (2008) multiplied the frequency of occurrence by the severity of the consequences to quantify 25 risk factors. Jannadi and Almishari (2003) added exposure on their method to quantify safety and health risks. Cuny and Lejeune (1999, 2003) developed risk curves to determine the probabilities associated with the consequences of work accidents (e.g., estimate the number of lost days).

In addition to the quantification of risk, the sources of information and the data analysis vary from simple mathematical comparisons of risk levels, obtained through expert elicitation, up to complex models, based on statistical information (Hallowell and Gambatese, 2009a). Jannadi and Almishari (2003) established semi-qualitative scales to measure the probability of occurrence, the severity of the consequences and the exposure, using expert opinion as the source of information. Sun et al. (2008) used the Analytic Hierarchy Process to investigate the safety conditions in construction sites and Lee and Halpin (2003) developed a software tool for dealing with expert data on occupational safety and health using a fuzzy logic approach.

2.2.3. Accident modeling

Most models developed for managing the risks of occupational safety and health focus on risk assessment (mainly risk identification) or in the comparison between relative risk levels relating occupations or industries. For example, considering only the cost of lost working time based on the average earnings of each professional class and on the days of absence, Baradan and Usmen (2006) analyzed the relative level of risk of various professional classes involved in the construction of buildings, using statistical data from the Bureau of Labor Statistics (BLS). In addition, several models were developed for the integration of risk and occupational safety and health management within the management of the organizations, in particular within the planning and scheduling tasks of construction projects. Kartam (1997) addressed the consideration of safety measures in the planning stage using techniques such as the critical path method (CPM). Cagno et al. (2001) developed an algorithm for scheduling the measures to implement in the framework of a program to improve occupational safety and health. Tam et al. (2002) presented a method for allocating resources to occupational safety and health based on established priorities, after comparing the performance of safety measures developed for the construction industry. Hadikusumo and Rowlinson (2002) developed a tool to visualize the construction process in order to assist in the identification of occupational safety and health hazards in the design stage. Saurin et al. (2004) devised a model integrating occupational safety and health management (in the design stage) and control (in the execution stage). Yi and Langford (2006) proposed a method for assessing the occupational safety and health risk coupled to the construction planning and scheduling, allowing the identification of risk concentration periods. More recently, Hallowell (2008) used the parallelism with structural design to develop the "Safety Equilibrium Model". This model is composed of two parallel modules, designated by demand (the actions) and response (the resistance), and connects directly with the planning and scheduling tasks through the analysis of occupational safety and health hazards of each construction operation or activity individually. Hallowell and Gambatese (2009a, 2009b, 2010) applied this model to formwork execution, quantifying the risk associated with the tasks involved in the activity and the effectiveness of usual measures implemented towards risk reduction. This proposal assesses the severity of the consequences and the probability of occurrence in semi-quantitative terms (Hallowell and Gambatese, 2008), but the balance between the cost and the benefit associated with the implementation of safety measures is not directly taken into consideration by the model. Mitropoulos et al. (2009) developed a model with a similar structure, but taking a distinct conceptual approach and a greater emphasis on factors originating the accidents. Mitropoulos and Namboodiri (2011) applied the model to the activities of roofs coating and road paving.

3. Occupational safety and health risk management

Haslam et al. (2005) analyzed 100 accidents in the construction industry and identified the lack of appropriate risk management as one of the most relevant underlying factors. In fact, according to these authors, 84% of the accidents could have been predicted and avoided if risk management had been properly carried out. It should also be noted that a significant portion of the accidents involved workers moving within the construction site or during preparatory activities. Therefore, since they were not involved in any construction activity, there were no risk analysis and no safety measures implemented in most cases. The extrapolation of these conclusions must take into consideration the specific context of the study, both in time and space, and its scope. In fact, there are studies reporting contradictory conclusions (e.g., Gürcanli and Müngen, 2013) and in overall terms there are similar distributions of the most relevant causes of fatal accidents in the construction industry in various countries, with falls coming in first place invariably. Still, the study of Haslam et al. (2005) has the merit of reinforcing the need for risk analysis not only for the tasks performed by the workers but for the construction site as a whole and taking into consideration possible interactions between tasks due to spatial and time conflicts.

Various reasons and explanations can be pointed out for the absence of adequate risk management, but the financial issues are often prevalent in comparison to the technical, given the plethora of tools, information and documentation available, accompanied by increasingly demanding legislation and regulations. Wilson and Koehn (2000) claim that, in the majority of the companies, occupational safety and health management is implemented in order to limit the responsibilities and costs associated with accidents and health problems.

Regarding risk management, the approaches used in the evaluation of hazards to the environment and to workers occupational safety and health present several similarities, especially concerning the way human life value is considered. Consequently, it is usual to find references (e.g., HSE, 2001; Ale, 2002) defining common criteria and limits for fatalities associated with environmental (e.g., release of toxic substances) or occupational safety and health hazards (e.g., falls). Despite the major focus of the present paper on occupational safety and health issues, there are also some brief references to environmental issues in the following sub-sections.

3.1. Criteria

Delimiting the scope of occupational safety and health (and environmental) risks to the analysis of hazards that may endanger the human life, the use of the concept of risk can be traced back to the 1950s (NAC, 1960). Within this scope, risk management was defined at a regulatory level as a "*process that entails consideration of political, social, economic, and engineering information with risk-related information to develop, analyze, and compare regulatory options and to select the appropriate regulatory response to a potential chronic health hazard*" (NRC, 1983).

The point of view adopted for managing safety and health risks is relevant for defining criteria. Assuming as a basis for comparison not to develop any project or perform any activity, the management of safety and health risks deals almost exclusively with hazards and not with opportunities. This is the traditional standpoint, implying the assumption that any commercial/professional/leisure activity involves an aggravated safety and health situation to the individuals in comparison with the alternative of not performing the activity. Adopting as reference the standard conditions in a given industry, type of project or activity at a specific moment in time, the risk management of safety and health should consider simultaneously both the hazards and the opportunities. At a regulatory level, these perspectives distinguish between setting as a goal a zero accident level or a non-zero accident level.

In general terms, when physical integrity and human lives (environment, safety and health) or ecological values (environment) are at stake, it is common to distinguish between individual and societal risks (Cox and Tait, 1998). Individual risks are "*the frequency with which an individual can be expected to bear a certain level of aggression resulting from the materialization of a specific hazard*" (IchemE, 1985). These risks affect each individual alone in clearly defined situations and generally correspond to events that are internal to the organizations. This type of risk is within the scope of individual concerns, which translate the way individual's percept the consequences arising from a particular hazard, regarding themselves and their values (HSE, 2001). Societal risks are defined as "*the relationship between the frequency and the number of individuals subject to certain level of aggression resulting from the materialization of a specific hazard*" (IchemE, 1985). These risks involve situations in which a significant hazard is shared by a large number of individuals for a short period of time. Although they could be addressed under the prospect of individual risks, given the low level of risk for each individual in isolation, it would lead to a wrong perception of the risk relevance. The concept of societal risks allows the explicit consideration of the number of individuals potentially affected. This concept arises from social concerns reflecting the perception of the society regarding the consequences of a particular hazard to their elements and their values as a whole (HSE, 2001).

There are several common aspects between individual and societal risks, but, usually, the former tend to be more easily estimated and often assumed by each individual in the pursuit of benefits, while for the later it tends to be more difficult for the individuals to estimate the hazard intuitively, since they affect a group or the whole society and not just a single individual (HSE, 2001). The relative importance of individual and societal risks and its justification from a cost-benefit analysis viewpoint can prove to be contradictory (e.g., Smith (2004) presents an example of the imbalance that may occur in a cost-benefit analysis when comparing individual with societal risks).

Due to the highly subjective values at stake, the limits to the levels of safety and health (and environmental) risk are usually set at a regulatory level. Three basic classes of criteria used in the field of safety and health (and environment), including occupational safety and health, are (HSE, 2001): (i) equity-based criteria; (ii) utility-base criteria; and (iii) technology-based criteria. Equity-based criteria are grounded on the premise that all individuals (or ecosystems) have an unconditional right to a certain level of protection. This leads to the definition of absolute rules applicable in general or exceptional conditions, resulting in the establishment of limits to the maximum level of risk that an individual (or ecosystem) may be exposed. These criteria imply that if the risk level is higher than the defined threshold the associated project or activity is considered unacceptable, regardless of the potential benefit arising from it. In practice, decision making using criteria based on equity may involve the use of pessimistic scenarios, with little resemblance to reality. Consequently, decisions tend to be made based on procedures that systematically overestimate the risks, which may cause unwarranted alarm and concern among the public or a disproportionate expenditure of resources in comparison to the benefits obtained. Utility-based criteria compare the additional benefit resulting from the implementation of measures to address the risk with the corresponding cost. These criteria imply a weighting, usually in monetary terms, of the benefits and resources associated with the risk treatment measures. It is common to deliberately shift this balance in favor of the cost, by imposing a disparity between benefits and costs, to ensure that the costs are much greater than the benefits. This is a conservative approach since it promotes the implementation of costly measures. However, decision making using criteria based on utility tends to ignore that, in fields such as occupational safety and health, there are issues of different nature, such as ethical, cultural or social, which are beyond the purely economic domain and more in the Human side. In practice, there are projects or activities with risks whose likelihood of occurrence is too high or the consequences are too severe to be considered acceptable, regardless of the potential benefits. Technology-based criteria reflect the belief that the use of the most advanced control mechanisms (e.g., technology – equipment, devices; management – models, systems; organizational – procedures, protocols) ensures an appropriate level of risk, regardless of the circumstances. This approach ignores the balance between costs and benefits, which can lead to situations where costs are largely disproportionate to the benefits obtained. As with the utility-criteria, criteria based on technology fail to identify risks whose likelihood of occurrence is too high or the consequences are too severe to be considered acceptable, regardless of having the most advanced technologies available for its control.

Each of these classes of criteria has been used separately, but given the limitations of each, the most accepted models use them in combination. In the UK, the model adopted by the Health and Safety Executive (HSE), called Tolerability of Risk (TOR), accommodates the three classes of criteria, giving more importance to the first two (equity and utility based criteria). This model is one of the tools most used to tackle the inherent subjectivity of risk management in the domains of safety and health (and environment) and considers that the risk level may fall into one of three categories: (i) acceptable; (ii) tolerable; and (iii) unacceptable. The equity-based criteria dominate in the region of unacceptable risk and the utility-based criteria in the remaining, where the technology criteria is also possible to be used as a complement (Bowles, 2007).

In the tolerable risk region, it is current to use principles such as SFAIRP (So Far Is the Reasonably practicable), ALARA (As Low As Reasonably Achievable) or ALARP (As Low As Reasonably Practicable) to assess the implementation of additional measures to reduce the risk. These principles are, in essence, identical, being used preferentially in different domains. In the references on risk management in general, the ALARP principle is more commonly used and it will be adopted in the present study. It should be noticed that there have been several critics on these principles (e.g., Kuo, 2001; Melchers, 2001; Bedford, 2008). The criticism tends to concentrate on the relative nature of the words – low, reasonably, practicable – and the difficulty/subjectivity in converting all values at risk to monetary terms. According to these authors, the application of the ALARP principle raises questions on terms of consistency (evaluation using ALARP is somewhat subjective and changes with time and framework), morality and economics (reasonable and practical changes depending on the context, for instance, for different countries), public participation (provides a means of validating choices in situations where little experience exists) and political reality (reasonable changes with the occurrence of a major accident depending on the political consequences), among others. Still, most critics do not present alternatives or the alternatives presented are not necessarily better. Furthermore, the concept has been discussed (e.g., Jones-Lee and Aven, 2011), improved (e.g., Kletz, 2005) and adopted even in countries that do not have a legal system similar to the "Common Law" of the Commonwealth countries and the USA (e.g., Norway), as well as its inclusion in international standards (e.g., ISO 14971:2007).

The model TOR is also compatible with other concepts, such as the Fatal Accident Frequency Rate (FAFR) (Gibson, 1976). A note must be made to the implications of the ALARP principle depending on the legal framework where it is to be applied (see Hartford, 2009). For the purpose of quantitative risk-based safety and health management discussed in the present study, it is assumed a common law legal framework context.

3.2. Limits

The selection and definition of quantitative boundaries between the different risk regions is not an easy or simple task. The indicators and their limiting values must represent the problem under consideration accurately enough and ensure that consistent decisions can be made (Holden, 1984). According to Fischhoff et al. (1981) the concept of acceptable safety and health (and environmental) risk is affected by uncertainties related to: (i) the definition of the problem; (ii) ascertaining the facts; (iii) assessing values; (iv) the human element; and (v) the difficulties in assessing the quality of the decision.

The most widely used form to quantify individual risks is through the concept of individual risk (IR – Individual Risk), which can be expressed mathematically as (Jonkman et al., 2003):

$$\mathrm{IR} = p_o p_{f|o} \quad (1)$$

where p_o is the probability of occurrence of an accident (–); and $p_{f|o}$ is the probability of an individual dying or being exposed to a hazard in the case of accident, assuming the permanent unprotected presence of the individual (–). Usually, the IR is used to evaluate fatalities, but the concept can be generalized in the line adopted by the HSE. A probability of one fatality of 10^{-3}/year, for workers, and of 10^{-4}/year, for the general public, are limits commonly used by the HSE to set the boundary between the unacceptable and the tolerable regions. For the region of acceptable risk level, the HSE requires an IR below 10^{-6}/year and that all measures under the ALARP principle have been implemented (HSE, 2001). In the Netherlands the IR limit is expressed as (VROM, 1988):

$$\mathrm{IR} < \beta\ 10^{-4} \quad (2)$$

where β is the political factor (–). This political factor takes into account the degree of control and the benefit of the activity from which the risk emanates to the individual. It is a correction that takes into consideration aspects related to the perception of risk. Table 2 presents the values proposed for the political factor in the Netherlands. Also in the Netherlands, the acceptability limit is 10^{-6}/year, for new hazardous installations, and 10^{-5}/year, for existing facilities (Ale, 2002).

Other ways to quantify individual risks include the reduction in life expectancy, measured in terms of the average number of days of life lost compared to the standard life expectancy in each country, or the variation of annual probability of death, comparing the annual probability of death in an activity/industry with a default value (Bedford and Cooke, 2001). The problem with these methods is the fact that the default value is neither easily defined nor constant. For example, the live expectancy has increased constantly

Table 2
Values proposed for the political factor (adapted from Vrijling et al. (1998)).

Political factor (β)	Degree of control	Benefit
100	Completely voluntary	Direct benefit
10	Voluntary	Direct benefit
1	Neutral	Direct benefit
0.1	Involuntary	Some benefit
0.01	Involuntary	No benefit

over the last decade in most developed countries and it is different for each gender.

One approach currently adopted for the measurement of societal risks is through the expected value of fatalities (EV – Expectation Value), determined from the spatial integration of the IR of all individuals exposed (Ale et al., 1996; Laheij et al., 2000):

$$E(N) = \int_A \mathrm{IR}(A)M(A)dA \tag{3}$$

where $E(N)$ is the expected number of fatalities in a year (number of individuals); IR(A) is the individual risk of each individual in the area (–); $M(A)$ is the population density in the area (number of individuals/m^2); and A is the area affected by the hazard. Since the societal risk does not relate to any particular individual, it is common to convert the IR into a probability density function and the expected value of fatalities, often referred to as the Potential Loss of Life (PLL) in the literature, is determined as (Carter and Hirst, 2000):

$$E(N) = \int_0^\infty x f_N(x)dx \tag{4}$$

where x is the number of individuals; and $f_N(x)$ is the probability density function (pdf) of the number of fatalities per year (–). Jonkman (2007) demonstrates that the expressions (3) and (4) are equivalent, which is also equivalent to the area under frequency–fatality curves (FN-curves), usually designated as the Risk Integral (Vrijling and van Gelder, 1997). The HSE (HSE, 2009a,b) proposes a slightly different indicator, called Weighted Risk Integral $\mathrm{RI}_{\mathrm{COMAH}}$, which includes a weighting to represent the aversion to accidents involving large numbers of victims, expressed by:

$$\mathrm{RI}_{\mathrm{COMAH}} = \int_0^\infty x^\alpha f_N(x)dx \tag{5}$$

where α is the aversion coefficient, which is $\geqslant 1$ (–). Hirst and Carter (2002) proposed a value of 1.4 for the aversion factor, which is referenced in various HSE publications (e.g., HSE, 2009a,b). For hazardous industrial facilities in the Netherlands, Ale (2005) reports several debates about the aversion coefficient to adopt, discussing values between 1.2 and 2, before the latter being adopted at a regulatory level.

It is still possible to find a diversity of approaches in the literature, which are basically extensions of the presented above (e.g., Bohnenblust, 1998; Hoej and Kroon, 2001). Usually, most of those approaches introduce an additional parameter that also quantifies the aversion to the size of the accidents. Jonkman et al. (2003) present the following generic expression for the societal risk:

$$E(N) = \int_0^\infty x^\alpha C(x) f_N(x)dx \tag{6}$$

where $C(x)$ is the aversion factor (–). The difference between the various approaches to societal risk that follow this general structure tends be limited to the values adopted for the aversion coefficient (α) and the aversion factor ($C(x)$).

The expressions presented here in the integral form are often applied, in practice, in summation form because information about groups of individuals and their respective IR is frequently discontinuous. A graphical form, usually used to set limits on the social risk is through FN-curves. The limits shown in FN-curves can be translated mathematically by the following expression (Vrijling et al., 1998):

$$1 - F_N(x) < \frac{C}{x^n} \text{ when } x > 10 \tag{7}$$

where F_N is the probability distribution function of the number of fatalities per year (–); C is a constant determining the position of the curve; and n is the curve slope (–). Table 3 presents some values used to define FN-curves in the boundaries between acceptable and tolerable regions.

An important aspect of the limiting FN-curves is the value chosen for the slope, which grows with the aversion to large accidents. The expected number of fatalities (equivalent to the area under the FN-curves) is also used to set limits on the societal risk. In dam safety, the British Colombia Hydro (Bowles et al., 1999) and the United States Bureau of Reclamation (USBR, 2003) defined limits of 10^{-3} and 10^{-2} for the annual probability of one fatality, respectively. The Australian National Committee on Large Dams (ANCOLD, 2003) sets a limit of 10^{-3}, for existing dams, and 10^{-4}, for new dams or in the case of interventions in existing dams resulting in a significant capacity increase. The United States Bureau of Reclamation (USBR, 2003) further establishes that the boundary between acceptable and tolerable region corresponds to an expected value of 10^{-3} lives per year and limits the probability of failure to 10^{-4}, regardless of the number of lives potentially affected.

Laheij et al. (2000) present several other ways to set boundaries for societal risk, both of generic nature (e.g., Potential Loss of Life – PLL) or specific to particular sectors or hazardous activities (e.g., Distance Density Figures – DDF). Griffiths (1994) discusses the applicability of the number of immediate and non-immediate fatalities as measures of societal risk and Holden (1984) argues that accidents involving multiple fatalities cannot be conveniently measured using a single parameter, much less a single value. The latter also state that some approaches, such as the use of Average Individual Risk proposed by Kletz (1982), lead to illogical results.

Societal risk criteria in general have a limited applicability to occupational risks, which are mostly individual. However, there are several examples of construction accidents resulting in multiple fatalities (e.g., structural collapse of temporary structures; explosions) where societal criteria may be more adequate. For instance the use of the FN-curves, in particular with slopes higher than one, provides a way of differentiating the tolerance to accidents with a single fatality from accidents with multiple fatalities. A more common example of such situation is the risk of cave-in in trenching operations. Since in many cases, this type of accidents involves more than one fatality, different limits could be established for the tolerable and acceptable regions by using the FN-curves.

Although it is more common to deal with the value of human life indirectly, some approaches seek to quantify it directly in monetary terms, namely: (i) based on compensations decided in courts; (ii) based on insurance estimates; and/or (iii) based on the will of the society to pay for additional safety. Several government agen-

Table 3
Limit FN-curves (adapted from Stallen et al. (1996), Bottelberghs (2000), Floyd and Ball (2000), HSE (2001), Jonkman et al. (2003), and Ale (2002)).

Country	n	C	Maximum number of fatalities	Application
United Kingdom (HSE)	1	10^{-2}	–	Hazardous facilities
Hong-Kong[a]	1	10^{-3}	1000	Hazardous facilities
Netherlands (VROM)	2	10^{-3}	–	Hazardous facilities
Netherlands	2	10^{-4}	–	Transportations
Denmark	2	10^{-2}	–	Hazardous facilities

[a] FN-curve with a maximum limit.

cies and researchers have established distinct values for human life over the past decades. This amount is usually referred to as the Value of a Statistical Life (VSL) and, very simply, is determined from the hourly cost associated with additional compensation to accept an increase in the level of risk. In the US, the EPA (Environmental Protection Agency) points to central VSL values of $ 6.3 million in 2002 and $ 7.4 million in 2006. However, depending on the purpose of the study in question, these values ranged from $ 4.6 million to $ 12.9 million in 2001 (USEPA, 2010). Viscusi and Aldy (2002, 2003) carried out a survey of VSL values in several studies in the United States, noting a range from $ 0.5 million to $ 20.8 million, for work related accidents, and between $ 0.77 million and $ 5.13 million, for non-work related accidents (2000 values). Internationally, these authors obtained VSL ranging from $ 0.7 to $ 74 million, for work related accidents (2000 values). Viscusi (2003) also examined the VSL from different sectors of activity and for different individual characteristics (e.g., gender, race). The concept of VSL is shrouded in controversy, as discussed by Viscusi (2010), starting from the fact that it depends on the age of the individuals.

Risk management in general, and applied to occupational safety and health in particular, can be an highly subjective task as a result of several factors, including: (i) the level of knowledge and information; (ii) the individual, cultural and social contexts; and (iii) the type of risk, in particular the familiarity and the potential consequences, which imparts in the definition of limits, among other aspects. Being out of the scope of the present discussion, the concept of risk perception approaches the subjectivity of the risk management and it may play an important role in establishing limits (or valuing risks). For the interested readers the work of Paul Slovic and partners will provide more details in this topic (e.g., Fischhoff et al. (1981); Slovic, 1987; Kasperson et al., 1988).

4. Concluding remarks

Construction sites are workplaces that enclose a diversity of hazards to the safety and health of workers and many of the activities developed within the course of the execution stage of construction projects are potentially dangerous. Despite focusing the present study in the execution stage, in practice, the design stage also presents important opportunities to manage occupational safety and health risks (Hinze and Wiegand, 1992; Whittington et al., 1992; Smallwood, 1996; Gambatese and Hinze, 1999; Suraji et al., 2001; Gibb et al., 2004; NAO, 2004; Behm, 2005; Gambatese et al., 2008). Jaselskis et al. (1996) obtained statistically significant results pertaining to design factors relevant to the occupational safety and health during the execution stage and Weinstein et al. (2005) demonstrated that occupational accidents prevention should begin in the design stage involving designers and contractors. According to Dias (2009), in the European Union (EU), 60% of the fatal occupational accidents in construction could be prevented through the correct definition of adequate measures during the design stage and the planning and organization of construction sites. Gambatese et al. (1997) developed a tool to assist safety and health issues to be taken into consideration during the design stage and Gambatese et al. (2005) debate its practical implementation. The European Agency for Safety and Health at Work goes even further and recommends the management of safety and health in construction projects following an integrated approach involving all stages of the project life cycle – design, execution and operation (EASHW, 2004c). Additionally, the designers and contractors are not the only interested parties in the issues related to occupational safety and health in construction projects. Huang (2003) and Huang and Hinze (2006) found that the owner also influences significantly the safety and health in construction, in particular through the establishment of objectives and by participating in the management of occupational safety and health. In line with the EU Directive 92/57/EEC, of 24 June 1992, Dias (2009) highlights the importance of the owner as a participant in the overall project management in most of the common contractual models and the consideration of the end-users as actors during the operation stage.

From the review presented herein the following main conclusions can be dawn: (i) there are several tools and methods to investigate and comprehend accidents in general and occupational accidents in the construction industry in particular; (ii) the main hazards in construction projects and their underlying factors have been identified for various contexts; (iii) the frequency and consequences of the accidents have been quantified; (iv) models to estimate the risk level associated with construction activities have been developed; (v) the tools and strategies to mitigate safety and health risks are known and their efficiency and efficacy has been quantified; and (vi) indicators to quantify occupational safety and health performance exist and measurable objectives have been established. Therefore, to apply the ALARP principle the missing link identified by the authors is a tool to quantify the risk in each construction activity and by groups of workers in monetary terms to assist in the evaluation of the cost-benefit relation of possible risk mitigation options available. The Part 2 of this companion paper proposes the Occupational Safety and Health Potential Risk Model (OSH-PRM), developed with the intention of suppressing that gap.

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