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Mitigating construction safety risks using prevention through design

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ABSTRACT

Research and practice have demonstrated that decisions made prior to work at construction sites can influence construction worker safety. However, it has also been argued that most architects and design engineers possess neither the knowledge of construction safety nor the knowledge of construction processes necessary to effectively perform Construction Hazards Prevention through Design (CHPtD). This paper introduces a quantitative methodology that supports designers by providing a way to evaluate the safety-related performance of residential construction designs using a risk analysis–based approach. The methodology compares the overall safety risk level of various construction designs and ranks the significance of the various safety risks of each of these designs. The methodology also compares the absolute importance of a particular safety risk in various construction designs. Because the methodology identifies the relevance of each safety risk at a particular site prior to the construction stage, significant risks are highlighted in advance. Thus, a range of measures for mitigating safety risks can then be implemented during on-site construction.

Keywords:
Construction Hazards Prevention through Design, risk assessment, health and safety management, building, construction process.

1. INTRODUCTION

The construction industry is statistically one of the most hazardous industries in many countries (Carter and Smith, 2006; Wang et al., 2006; Camino et al., 2008). For example, in Spain, approximately 30% of fatal accidents in all industries between 2000 and 2006 occurred in the construction industry, killing approximately 350 employees per year (Ministerio de Trabajo e Inmigración, Subsecretaría de Trabajo y Asuntos Sociales, 2006). Besides causing human tragedy, construction accidents also delay project progress, increase costs and damage the reputation of the contractors (Wang et al., 2006).

Formal identification of hazards in the workplace is one of the foundations of successful safety management (Trethewy et al., 2003; Carter and Smith, 2006) and an essential component of occupational health and safety (OHS) legislation (Trethewy et al., 2003). However, the findings of Carter and Smith (2006) indicate that current hazard identification levels in construction projects are far from ideal. These authors identified several significant barriers to improving hazard identification: knowledge and information barriers (i.e. failure to share information across projects, lack of resources in smaller projects, subjective hazard identification and risk assessment, and reliance upon tacit knowledge) and process and procedure barriers (i.e. lack of a standardized approach, and undefined structures for tasks and hazards).

Most contractors see their health and safety plans, which must include full risk assessment, as merely a burdensome requirement that they must fulfil in order to avoid government fines. As a result, they often neglect the proper implementation of these plans (Wang et al., 2006; Saurin et al., 2008). Since to the adoption of Royal Decree 1627/1997 (transposition of Directive 92/57/EEC), Spanish building designers are legally required to consider working conditions in their designs. However, studies have shown that designers in general—not just in the construction industry—fall short of satisfying this obligation (Behm, 2005; Fadier and De la Garza, 2006; Frijters and Swuste, 2008). Some earlier studies have indicated that safety planning and control methods need to be improved even beyond what is required by regulations and standards (Saurin et al. 2004).

Not only contractors, but also designers, architects and structural engineers have an influence on the health and safety of building site employees (Gambatese and Hinze, 1999; Behm, 2005; Frijters and Swuste, 2008; Gambatese et al., 2008; Toole and Gambatese, 2008). Research conducted by Behm (2005) and Gambatese et al. (2008) demonstrated that 42.0% of construction fatalities were linked to the design of the construction safety concept.

In recent years, academics and professionals have focused on the concept of Construction Hazards Prevention through Design (CHPtD), in which engineers and architects explicitly consider, during the design process, the safety of construction workers (Toole and Gambatese, 2008). As noted by Toole and Gambatese (2008), even though articles on CHPtD have appeared in top construction journals, the literature has not yet addressed the technical principles underlying CHPtD in order to help designers better perform CHPtD and to facilitate the development of additional CHPtD tools. Additional tools and processes are needed in order to assist architects and design engineers with hazard recognition and design optimization (Gambatese, 2008).

Up until now, most publications on this subject have offered solutions that can be directly implemented and checklists for the subsequent monitoring of the design. Precise advice of this sort inhibits the designer's creative process and hampers the usual design process (Frijters and Swuste, 2008). Other authors, such as Gambatese and Hinze

(1999), have developed a repository with design suggestions for improving construction worker safety while in the design phase.

Even so, there has been little research on how health and safety aspects can be interactively integrated during the design and preparation phase. Of the papers that have provided such methods, the approaches of Carter and Smith (2006), Cheung et al. (2004a), Cheung et al. (2004b), Imriyas (2009) and Seo and Choi (2008) are among the most noteworthy; however, subjective judgements often influence their accuracy. Especially worthwhile is the method developed by Frijters and Swuste (2008), which has proved to be an objective, albeit labour-intensive, way of integrating safety aspects into the design process.

This study aims to establish the necessary basis and criteria to quantitatively measure the safety performance of construction projects. Its objectives are, first, to provide designers with a risk-analysis-based way of evaluating the safety-related performance of their residential construction designs, and second, to help construction companies improve their on-site safety performance.

Therefore, we have developed a quantitative methodology for dealing with potential safety risks at the pre-construction stage (in the design, planning and preparation phases), thereby contributing to the customization of the Safety Decision Hierarchy proposed by Manuele (2006) for construction projects. This hierarchy supports the idea that it is better to eliminate safety hazards through design than to later try to protect workers from hazards. In short, proactive hazard identification and elimination is safer and more cost-effective than reactive hazard management (Toole and Gambatese, 2008). This proactive elimination of hazards must be done by designers during the conceptual and detailed design of a facility (Toole and Gambatese, 2008). Hazards remaining after successive redesigns must be addressed by the contractor during the execution phase.

2. METHODS

This paper presents a systematic approach for dealing with potential safety risks at the pre-construction stage (in the design, planning and preparation stages). The proposed methodology serves as an assessment tool for measuring the safety risk level of construction projects. It also provides a consistent basis for comparisons, future labelling and CHPtD benchmarking between different construction companies and construction sites.

Figure 1 summarizes the methodology for predicting and assessing the safety risks related to the construction of residential buildings.

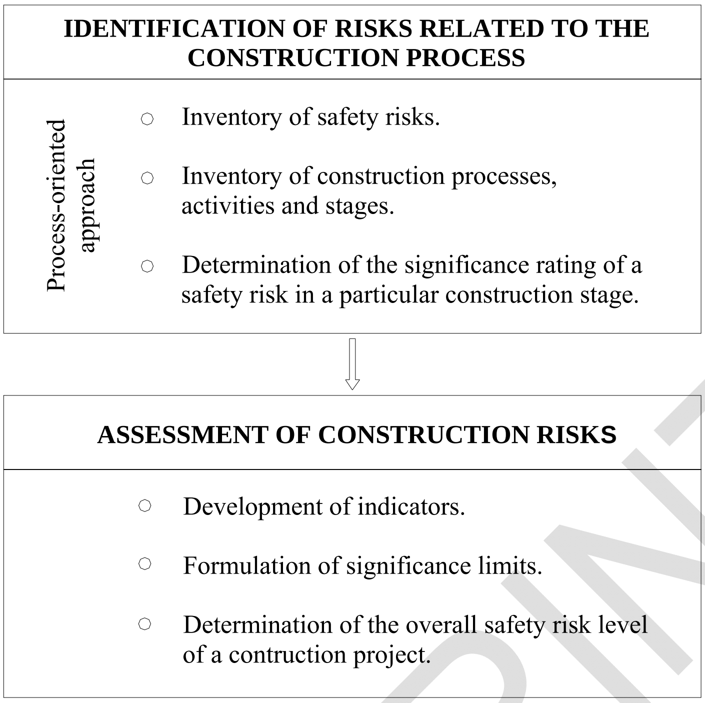

Fig. 1. Research methodology.

The first step is to identify specific safety risks related to the construction process. The process-oriented approach requires an inventory of construction processes, activities and stages, as well as common safety risks. Decisions regarding significant risks in each construction process must be made based on the establishment of a significance rating. The second step is to assess construction safety risks. This involves developing corresponding indicators, formulating significance limits and determining the overall safety risk level of a construction project.

2.1. IDENTIFICATION OF SAFETY RISKS RELATED TO THE CONSTRUCTION PROCESS

The first step of this methodology is to identify construction risks. For this purpose, an exhaustive, process-oriented preliminary analysis, similar to that of Gangolells et al. (2009), is carried out (Fig. 2).

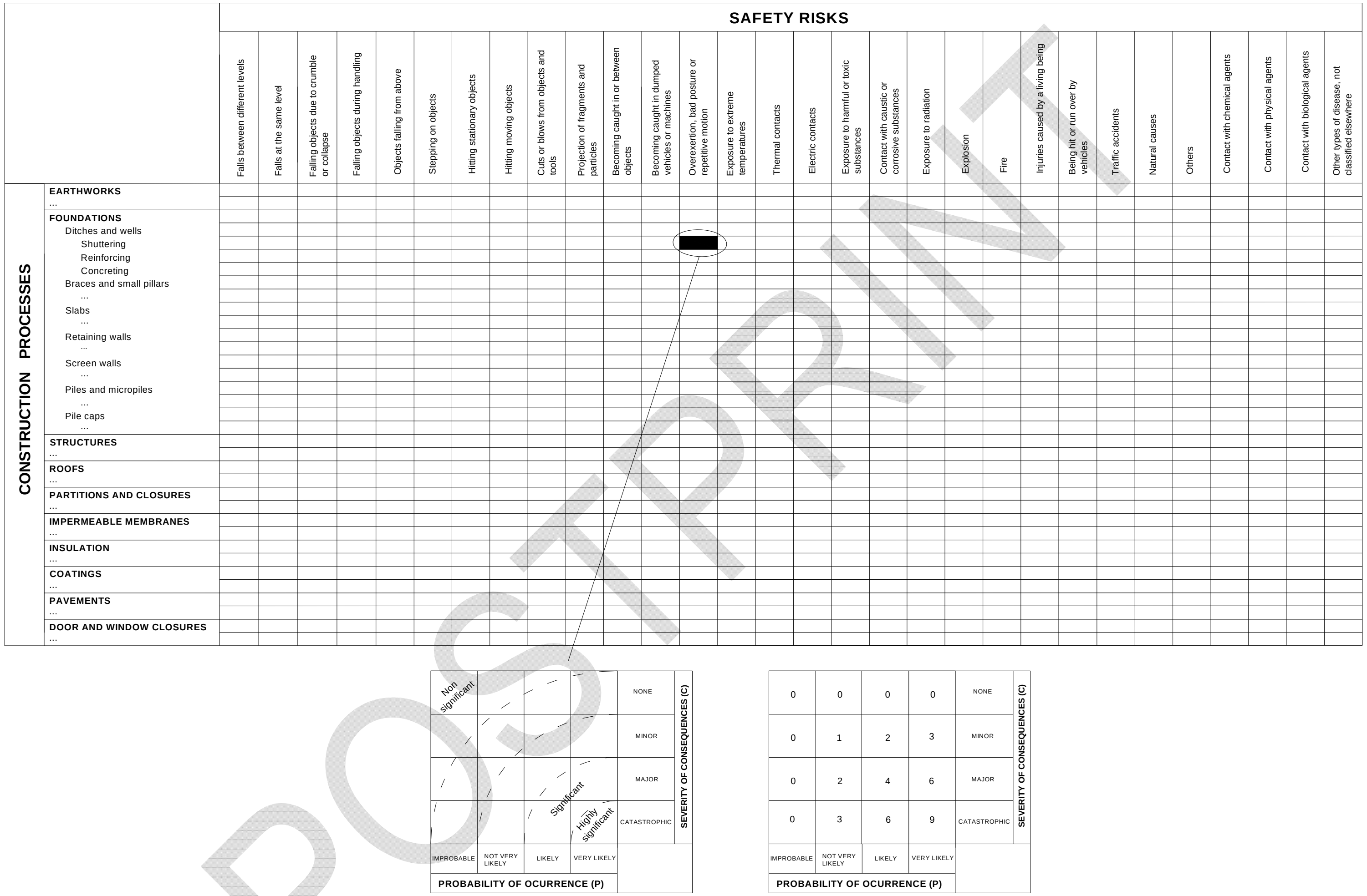

Fig. 2. Identification of construction risks in a process-oriented approach and numerical scales for the two evaluation components: probability of occurrence (P) and severity of consequences (C). Source: Partially adapted from Gangolells et al. (2009).

2.1.1. Inventory of construction processes, activities and stages

In any process-oriented approach, the first step is to identify the main processes. As in Gangolells et al. (2009), the construction processes considered as main processes were (1) earthworks, (2) foundations, (3) structures, (4) roofs, (5) partitions and closures, (6) impermeable membranes, (7) insulations, (8) coatings, (9) pavements and (10) door and window closures. Each of these main processes was separated into smaller process steps. A total of 219 stages and activities were ultimately considered in this initial safety review (Fig. 2).

2.1.2. Inventory of safety risks

As suggested by OHSAS 18001:2007 and OHSAS 18002:2000, this initial review uses reports of incidents (including ill health) and accidents that have occurred in other organizations (Fig. 2). We used the Occupational Accident Report Form of the Spanish National Institute of Safety and Hygiene at Work as a guide in order to initially identify general safety risks (Fig.2).

2.1.3. Determination of the significance rating of a safety risk in a particular construction stage

OHSAS 18001:2007 defines a risk as the combination of the likelihood of occurrence of a hazardous event and the severity of the injury or ill health that can be caused by the event. Consideration of risks in terms of the probability of their occurrence and the severity of their consequences provides the general rationale behind safety risk assessments (Carter and Smith, 2006). Probability (P) is defined as the likelihood of a hazard's potential being realized and initiating an incident or series of incidents that could result in harm or damage. Severity of consequences (C) is defined as the extent of harm or damage that could result from a hazard-related incident (Manuele, 2006).

Neither the probability nor the severity of consequences depend on the construction project, so they can be used in this early stage to determine significant risks that are common to every construction process (Fig. 2).

A panel of academic and professional experts in the construction field was asked to rate construction risks in terms of probability and severity of consequences. The consultation panel was composed of three architects with more than 15 years of experience as building designers and two engineers with active experience of making safety risk inventories at design companies as they were in charge of developing health and safety studies to satisfy current legal requirements stated in Royal Decree 1627/1997. Three construction project managers working in construction SMEs and two internal advisers on working conditions at construction companies were also selected to be part of the panel of experts. Finally, the consultation panel was composed of four associate professors at the Technical University of Catalonia. The basic considerations for selecting them included a background in construction management as well as familiarity with safety issues.

Firstly, the research team mailed to all participants a personalized letter outlining the nature of the research and indicating that they would be called to arrange a meeting. During the meeting, discussions focussed on a survey prepared to facilitate data collection, represented as a matrix whose columns were general construction risks and whose rows where construction stages. To reduce the intrusion of subjectivity during the identification of construction risks, a four-interval scale was developed for each of these evaluation components. The probability of occurrence ranges from low probability (improbable) to relatively high probability (very likely or frequent). The scale of probability was thus defined as a progression through the various levels of likelihood. The severity of consequences was rated by taking into account the extent of the damage that could result from an incident.

Probability of occurrence and severity of consequences can be cross-referenced. For example, during the placement of in-situ concrete, stepping on objects has a high probability of occurrence but entails minor consequences, whereas becoming caught in a dumped vehicle or machine is improbable, but would result in fatal injuries if it were to happen. These two evaluation components can therefore be represented graphically with the probability of occurrence as the x-axis and the severity of consequences as the y-axis. A risk is highly significant if it is plotted in the lower right part of the graph (Fig. 2).

In order to calculate the significance of a risk in a specific construction stage, the four-grade scales for the two evaluation components are converted into numerical scales (Fig. 2). Unfortunately, the literature provides no suitable models on which to base such a scoring system, so we established the system shown in Table 1.

Probability of occurrence (P_i)	**Severity of consequences (S_i)**	**Score**
Improbable	None	0
Not very likely	Minor	1
Likely	Major	2
Very likely	Catastrophic	3

Table 1. Scoring system for probability of occurrence (P_i) and severity of consequences (S_i).

The significance rating of a risk in a particular construction stage was defined as follows:

$$SG_i = P_i \cdot C_i \qquad (1)$$

where SG_i denotes the significance rating of a risk in a specific construction stage i, P_i represents its probability of occurrence and C_i corresponds to its severity of consequences.

During this initial review, a risk was considered significant in a specific construction stage when its significance rating was equal to or greater than 3. The resulting matrix allowed us to distinguish potential safety risks for each construction stage. In order to make future assessments controllable and effective, most of the construction risks were aggregated with the help of the experts.

As a result of this process, 90 significant safety risks for construction activities were obtained in 22 different categories. Table 2 lists these specific construction risks.

2.2. ASSESSMENT OF CONSTRUCTION SAFETY RISKS

The immediate causes of accidents include factors that can cause an accident physically and directly, whether the accident happens or not. These causes include unsafe conditions and unsafe acts (Jannadi and Assaf, 1998; Fang et al., 2004). Unsafe conditions are physical conditions which, if left uncorrected, are likely to cause an accident. To improve safety at the work site, such conditions must be detected before an accident occurs (Jannadi and Assaf, 1998). Unsafe acts are not considered in this paper because they cannot be assessed during the study, design, planning or preparation stages of the construction project. In order to assess unsafe conditions, we considered *exposure*, a variable understood as the frequency of occurrence of the hazard-event (Fine and Kinney, 1971) or the quantitative or semi-quantitative estimation of potentially hazardous situations to which workers are exposed during the construction process. In contrast to the evaluation components mentioned above (probability of occurrence and severity of consequences), this component depends on the characteristics of each construction project.

2.2.1. Assessment of risk exposure

Together with a panel of experts, we developed specific indicators to assess construction risk exposure. These indicators were based on particular observable or measurable characteristics of a construction project and represented, in all cases, the variable that was being measured (risk exposure). Because this methodology is intended to assess construction safety risks in advance, the indicators were always based on the information contained in the construction project documents (e.g. building specifications, drawings, bill of quantities, health and safety plan, and budget).

In developing the indicators, we took into account the traits highlighted by Manuele (2003). Therefore, most of the developed indicators are objectively quantifiable, which helps make the outcome of the process independent of the people who conduct the assessment. From an administrative point of view, they are practical and do not involve a great deal of time. They are sufficiently sensitive to detect changes in a process, but stable if there is no change, i.e. they produce the same results in successive applications to a single situation. Table 2 shows the indicators.

CONSTRUCTION SAFETY RISK		INDICATOR [P]	SOURCE	EX[1] = 0	EX = 1	EX = 3	EX = 5
FALLS BETWEEN DIFFERENT LEVELS							
FH-1	During small demolition operations, earthworks and foundation work.	Total perimeter with a difference in floor level of more than 20 cm during the demolition, earthworks or foundation phases per m^2 of site occupation [m/m^2].	Drawings	-	P[2] < 0.4279	0.4279 ≤ P < 1.5269	P ≥ 1.5269
FH-2	During structural work.	Total perimeter of floors more than 20 cm high (from zero level) plus roof perimeter without boundary walls plus perimeter of holes measuring more than 0.40 m^2 per m^2 of floor area [m/m^2].	Drawings	-	P < 0.0161	0.0161 ≤ P < 1.1715	P ≥ 1.1715
FH-3	During roof work.	Roof perimeter without boundary walls plus perimeter of holes measuring more than 0.40 m^2 per m^2 of roof area [m/m^2].	Drawings	P = 0.0000	0.0000 < P < 0.2551	0.2551 ≤ P < 0.5809	P ≥ 0.5809
FH-4	During work on facades, partition walls and vertical coatings.	Total area of partition walls plus total area of cladding on them (parging, plastering, tiling, painting, etc.) [m^2].	Drawings / bill of quantities / budget	-	P < 3 363.8	3 363.8 ≤ P < 25 216.7	P ≥ 25 216.7
		Total area of facades plus total area of cladding on them (parging, coating, painting, etc.) [m^2].	Drawings / bill of quantities / budget	-	P < 480.39	480.39 ≤ P < 5 273.84	P ≥ 5 273.84

CONSTRUCTION SAFETY RISK		INDICATOR [P]	SOURCE	EX[1] = 0	EX = 1	EX = 3	EX = 5
FH-5	During floor work.	Total perimeter of holes measuring more than 0.40 m^2 plus total perimeter of balconies without boundary walls per m^2 of floor area [m/m^2].	Bill of quantities / budget	P = 0.0000	0.0000 < P < 0.0708	0.0708 ≤ P < 0.1906	P ≥ 0.1906
FH-6	During work on door and window closures.	Number of balconies without boundary walls and windows in the building [units].	Bill of quantities / budget	-	P < 11.00	11.00 ≤ P < 149.00	P ≥ 149.00
FH-7	During work on false ceilings and ceiling coatings.	Total area of cladding of structural floors plus total area of false ceilings plus total area of cladding on them (parging, plastering, painting, etc.) [m^2].	Bill of quantities / budget	-	P < 462.0	462.0 ≤ P < 6 411.3	P ≥ 6 411.3
FALLS AT THE SAME LEVEL							
FS-1	During small demolition operations and earthworks.	Site occupation [m^2].	Building specifications / drawings	-	P < 114.5	114.5 ≤ P < 1 604.5	P ≥ 1 604.5
FS-2	During reinforcement work.	Weight of reinforcing bars [kg].	Bill of quantities / budget	-	Prefabricated structures	In-situ concrete structures: P < 149 268.9	In-situ concrete structures: P ≥ 149 268.9
		Site occupation [m^2].	Building specifications / drawings	-	P < 114.5	114.5 ≤ P < 1 604.5	P ≥ 1 604.5
FS-3	During roof work.	Total area of roof [m^2].	Drawings	-	P < 70.064	70.064 ≤ P < 628.140	P ≥ 628.140
FS-4	During work on partition walls and vertical coatings.	Total area of partition walls plus total area of cladding on them (parging, plastering, tiling, painting, etc.) [m^2].	Drawings / bill of quantities / budget	-	P < 3 363.8	3 363.8 ≤ P < 25 216.7	P ≥ 25 216.7

CONSTRUCTION SAFETY RISK		**INDICATOR [P]**	**SOURCE**	**EX[1] = 0**	**EX = 1**	**EX = 3**	**EX = 5**
INJURIES FROM FALLING OBJECTS DUE TO CRUMBLE OR COLLAPSE							
FOC-1	During earthworks.	Volume of excavated and/or filled material [m^3].	Bill of quantities / budget	P = 0.00	0.00 < P < 203.56	203.56 ≤ P < 12 361.65	P ≥ 12 361.65
FOC-2	Due to the use of in-situ concrete.	Volume of in-situ concrete [m^3].	Bill of quantities / budget	P = 0.00	0.00 < P < 154.16	154.16 ≤ P < 2 267.75	P ≥ 2 267.75
FOC-3	During cladding work on facades.	Area of discontinuous cladding in facades [m^2].	Drawings / bill of quantities / budget	P = 0.000	0.000 < P < 22.743	22.743 ≤ P < 320.055	P ≥ 320.055
FOC-4	During cladding work on partition walls.	Area of discontinuous cladding in partition walls [m^2].	Drawings / bill of quantities / budget	P = 0.00	0.00 < P < 212.79	212.79 ≤ P < 2 050.08	P ≥ 2 050.08
FOC-5	During false ceiling work.	False ceiling area [m^2].	Drawings / bill of quantities / budget	P = 0.000	0.000 < P < 64.482	64.482 ≤ P < 1 620.336	P ≥ 1 620.336
INJURIES FROM FALLING OBJECTS DURING HANDLING							
FOH-1	In materials and waste management operations.	Weight[3] of structural floors, foundations, facades, partition walls, floors and roofs [kg].	Bill of quantities / budget	-	P < 762 380	762 380 ≤ P < 8 134 735	P ≥ 8 134 735
FOH-2	In prefabricated structure assembly.	In case of prefabricated structures: floor area [m^2].	Bill of quantities / budget	-	P < 690.72	690.72 ≤ P < 5 504.27	P ≥ 5 504.27
FOH-3	In cladding work.	Presence of heavy claddings.[4]	Bill of quantities / budget	No heavy claddings.	-	Heavy claddings.	-

CONSTRUCTION SAFETY RISK		INDICATOR [P]	SOURCE	EX[1] = 0	EX = 1	EX = 3	EX = 5
FOH-4	In work on door and window closures.	Size of window closures [m].	Bill of quantities / budget	-	-	Windows are less than 1 m wide per 1 m of height.	Windows are more than 1 m wide per 1 m of height.
INJURIES FROM OBJECTS FALLING FROM ABOVE							
OF-1	During materials and waste management operations.	Weight[3] of structural floors, foundations, facades, partition walls, floors and roofs per m^2 of floor area [kg/m^2].	Bill of quantities / budget	-	$P < 1\,095.5$	$1\,095.5 \leq P < 1\,642.3$	$P \geq 1\,642.3$
OF-2	During earthworks.	Volume of excavated and/or filled material per m^2 of site occupation [m^3/m^2].	Bill of quantities / budget	$P = 0.0000$	$0.0000 < P < 0.6215$	$0.6215 \leq P < 7.1199$	$P \geq 7.1199$
OF-3	During structural work.	Volume of in-situ concrete structures per m^2 of floor area [m^3/m^2].	Bill of quantities / budget	-	Prefabricated structures	In-situ concrete structures: $P < 0.7284$	In-situ concrete structures: $P \geq 0.7284$
OF-4	During roof work.	Total roof perimeter without boundary walls plus total perimeter of holes in the roof measuring more than 0.40 m^2 per m^2 of roof area [m/m^2].	Drawings	$P = 0.0000$	$0.0000 < P < 0.2551$	$0.2551 \leq P < 0.5809$	$P \geq 0.5809$
OF-5	During work on facades and vertical coatings.	Total area of facades plus total area of cladding on them (parging, coating, painting, etc.) [m^2].	Drawings / bill of quantities / budget	-	$P < 480.39$	$480.39 \leq P < 5\,273.84$	$P \geq 5\,273.84$
OF-6	During work on partition walls and vertical coatings.	Total area of partition walls plus total area of cladding on them (parging, plastering, tiling, painting, etc.) [m^2].	Drawings / bill of quantities / budget	-	$P < 3\,363.8$	$3\,363.8 \leq P < 25\,216.7$	$P \geq 25\,216.7$

CONSTRUCTION SAFETY RISK		INDICATOR [P]	SOURCE	EX[1] = 0	EX = 1	EX = 3	EX = 5
OF-7	During false ceiling work.	False ceiling area [m^2].	Drawings / bill of quantities / budget	P = 0.000	0.000 < P < 64.482	64.482 ≤ P < 1 620.336	P ≥ 1 620.336
INJURIES FROM STEPPING ON OBJECTS							
SO-1	During small demolition operations.	Presence of foundations, retaining walls or evacuation elements from previous buildings to be demolished.	Building specifications / bill of quantities / budget	No elements to be demolished.	-	Elements to be demolished.	-
SO-2	During removal of garden elements.	Type of garden elements to be removed.	Building specifications / bill of quantities / budget	No garden elements to be removed.	-	Bushes or short trees (less than 3.5 m tall) to be removed.	Trees (more than 3.5 m tall) to be removed.
SO-3	Such as reinforcing bars, screws or nails.	In case of wood formwork or unknown type of formwork: volume of in-situ concrete in structures [m^3].	Bill of quantities / budget	P = 0.000	0.000 < P < 73.655	73.655 ≤ P < 1 360.652	P ≥ 1 360.652
		Weight of reinforcing bars [kg].	Bill of quantities / budget	-	Prefabricated structures or in-situ concrete structures: P < 8 668.7	In-situ concrete structures: 8 668.7 ≤ P < 149 268.9	In-situ concrete structures: P ≥ 149 268.9
INJURIES FROM HITTING STATIONARY OBJECTS							
HS-1	In provisional on-site facilities and storage areas.	Site occupation [m^2].	Building specifications / drawings	-	P < 114.5	114.5 ≤ P < 1 604.5	P ≥ 1 604.5

CONSTRUCTION SAFETY RISK		INDICATOR [P]	SOURCE	EX[1] = 0	EX = 1	EX = 3	EX = 5
HS-2	During small demolition operations.	Presence of foundations, retaining walls or evacuation elements from previous buildings to be demolished.	Building specifications / bill of quantities / budget	No elements to be demolished.	-	Elements to be demolished.	-
HS-3	During removal of garden elements.	Type of garden elements to be removed.	Building specifications / bill of quantities / budget	No garden elements to be removed.	-	Bushes or short trees (less than 3.5 m tall) to be removed.	Trees (more than 3.5 m tall) to be removed.
HS-4	During structural work.	Volume of in-situ concrete structures per m^2 of floor area [m^3/m^2].	Bill of quantities / budget	-	Prefabricated structures	In-situ concrete structures: $P < 0.7284$	In-situ concrete structures: $P \geq 0.7284$
INJURIES FROM HITTING MOVING PARTS OF MACHINERY							
HM-1	During materials and waste management operations.	Weight[3] of structural floors, foundations, facades, partition walls, floors and roofs per m^2 of floor area [kg/m^2].	Bill of quantities / budget	-	$P < 1\,095.5$	$1\,095.5 \leq P < 1\,642.3$	$P \geq 1\,642.3$
HM-2	During earthworks.	Volume of excavated and/or filled material per m^2 of site occupation [m^3/m^2].	Bill of quantities / budget	$P = 0.0000$	$0.0000 < P < 0.6215$	$0.6215 \leq P < 7.1119$	$P \geq 7.1119$
HM-3	During foundation work.	Volume of in-situ concrete in foundations per m^2 of site occupation [m^3/m^2].	Bill of quantities / budget	-	$P < 0.2151$	$0.2151 \leq P < 1.2226$	$P \geq 1.2226$

CONSTRUCTION SAFETY RISK		INDICATOR [P]	SOURCE	EX[1] = 0	EX = 1	EX = 3	EX = 5
HM-4	During structural work.	Volume of in-situ concrete structures per m^2 of floor area [m^3/m^2].	Bill of quantities / budget	-	Prefabricated structures	In-situ concrete structures: $P < 0.7284$	In-situ concrete structures: $P \geq 0.7284$
HM-5	During work on concrete foundations and floors.	Volume of in-situ concrete in concrete foundations and floors per m^2 of floor area [m^3/m^2].	Bill of quantities / budget	-	$P < 0.0502$	$0.0502 \leq P < 0.1730$	$P \geq 0.1730$
INJURIES FROM CUTS OR BLOWS FROM OBJECTS AND TOOLS							
CS-1	During removal of garden elements.	Type of garden elements to be removed.	Building specifications / bill of quantities / budget	No garden elements to be removed.	-	Bushes or short trees (less than 3.5 m tall) to be removed.	Trees (more than 3.5 m tall) to be removed.
CS-2	During work on foundation and structure.	Volume of in-situ concrete in foundations and structures [m^3].	Bill of quantities / budget	-	Prefabricated structures	In-situ concrete structures: $P < 2\ 283.95$	In-situ concrete structures: $P \geq 2\ 283.95$
CS-3	During finishing work on roofs.	Total area of roof [m^2].	Drawings	$P = 0.000$	$0.000 < P < 70.064$	$70.064 \leq P < 628.140$	$P \geq 628.140$
CS-4	During work on facades and partition walls.	Total area of facades and partition walls [m^2].	Drawings / bill of quantities / budget	-	$P < 874.43$	$874.43 \leq P < 10\ 187.10$	$P \geq 10\ 187.10$
CS-5	During work on coatings or floors.	% of facing brick closure.	Bill of quantities / budget	$P = 0.00\%$	$0.00\% < P < 14.85\%$	$14.85\% \leq P < 76.51\%$	$P \geq 76.51\%$
		% of area with discontinuous ceramic and/or stone surfaces.	Bill of quantities / budget	$P = 0.00\%$	$0.00\% < P < 30.33\%$	$30.33\% \leq P < 60.71\%$	$P \geq 60.71\%$

CONSTRUCTION SAFETY RISK		INDICATOR [P]	SOURCE	EX[1] = 0	EX = 1	EX = 3	EX = 5
CS-6	During work on false ceilings.	False ceiling area [m^2].	Drawings / bill of quantities / budget	P = 0.000	P < 64.482	64.482 ≤ P < 1 620.336	P ≥ 1 620.336
INJURIES FROM PROJECTION OF FRAGMENTS AND PARTICLES							
FF-1	In cutting operations.	% of facing brick closure.	Bill of quantities / budget	P = 0.00%	0.00% < P < 14.85%	14.85% ≤ P < 76.51%	P ≥ 76.51%
		Total area of ceramic partition walls [m^2].	Bill of quantities / budget	P = 0.0000	0.0000 < P < 238.5944	238.5944 ≤ P < 5 201.9861	P ≥ 5 201.9861
		% of area with discontinuous ceramic and/or stone surfaces.	Bill of quantities / budget	P = 0.00%	0.00% < P < 30.33%	30.33% ≤ P < 60.71%	P ≥ 60.71%
FF-2	In concrete operations.	Volume of in-situ concrete in concrete foundations and floors [m^3].	Bill of quantities / budget	-	P < 41.207	41.207 ≤ P < 574.129	P ≥ 574.129
FF-3	In spray-gun painting operations.	% of facade painted with spray gun.	Bill of quantities / budget	P = 0.00%	0.00% < P < 21.64%	21.64% ≤ P < 83.18%	P ≥ 83.18%
INJURIES FROM BECOMING CAUGHT IN OR BETWEEN OBJECTS							
CO-1	During materials and waste management operations.	Weight[3] of structural floors, foundations, facades, partition walls, floors and roofs [kg].	Bill of quantities / budget	-	P < 762 380	762 380 ≤ P < 8 134 735	P ≥ 8 134 735

CONSTRUCTION SAFETY RISK		INDICATOR [P]	SOURCE	EX[1] = 0	EX = 1	EX = 3	EX = 5
CO-2	During small demolition operations.	Presence of foundations, retaining walls or evacuation elements from previous buildings to be demolished.	Building specifications / bill of quantities / budget	No elements to be demolished.	-	Elements to be demolished.	-
CO-3	During removal of garden elements.	Type of garden elements to be removed.	Building specifications / bill of quantities / budget	No garden elements to be removed.	-	Bushes or short trees (less than 3.5 m tall) to be removed.	Trees (more than 3.5 m tall) to be removed.
CO-4	During earthworks.	Volume of excavated and/or filled material [m^3].	Bill of quantities / budget	P = 0.00	0.00 < P < 203.56	203.56 ≤ P < 12 361.65	P ≥ 12 361.65
CO-5	During work on piles, micro-piles and screen walls.	Presence of piles, micro-piles or screen walls.	Bill of quantities / budget	No piles, micro-piles or screen walls.	-	Piles, micro-piles or screen walls.	-
CO-6	In forming and shoring operations.	Volume of in-situ concrete in structure [m^3].	Bill of quantities / budget	P = 0.000	0.000 < P < 73.655	73.655 ≤ P < 1 360.652	P ≥ 1 360.652
CO-7	In operations with scaffoldings or working platforms.	Floor area [m^2].	Building specifications / drawings	-	P < 690.72	690.72 ≤ P < 5 504.27	P ≥ 5 504.27
INJURIES FROM BECOMING CAUGHT IN DUMPED VEHICLES OR MACHINES							
CV-1	During materials and waste management operations.	Weight[3] of structural floors, foundations, facades, partition walls, floors and roofs per m^2 of floor area [kg/m^2].	Bill of quantities / budget	-	P < 1 095.5	1 095.5 ≤ P < 1 642.3	P ≥ 1 642.3

CONSTRUCTION SAFETY RISK		INDICATOR [P]	SOURCE	EX[1] = 0	EX = 1	EX = 3	EX = 5
CV-2	During earthworks.	Volume of excavated and/or filled material per m^2 of site occupation [m^3/m^2].	Bill of quantities / budget	$P = 0.0000$	$0.0000 < P < 0.6215$	$0.6215 \leq P < 7.1199$	$P \geq 7.1199$
CV-3	During foundation work.	Volume of in-situ concrete in foundations per m^2 of site occupation [m^3/m^2].	Bill of quantities / budget	-	$P < 0.2151$	$0.2151 \leq P < 1.2226$	$P \geq 1.2226$
CV-4	During structural work.	Type of auxiliary machinery used to assemble the structure.	Health and safety plan	-	-	Fixed crane	Mobile crane
CV-5	During structural work.	Volume of in-situ concrete in concrete foundations and floors per m^2 of floor area [m^3/m^2].	Bill of quantities / budget	-	$P < 0.0502$	$0.0502 \leq P < 0.1730$	$P \geq 0.1730$
INJURIES FROM OVEREXERTION, BAD POSTURE OR REPETITIVE MOTION							
OX-1	Injuries form overexertion, bad posture or repetitive motion.	All cases.	-	-	-	All cases	-
INJURIES FROM EXPOSURE TO EXTREME TEMPERATURES							
ET-1	Injuries from exposure to extreme temperatures.	Climate situation of the construction site.	Building specifications	The construction site is not located in an extremely hot or cold climate area.	-	The construction site is located in an extremely hot or cold climate area.	-
INJURIES FROM THERMAL CONTACTS							
TC-1	Due to specific welding operations.	Type of structure.	Building specifications	The structure of the building is not metallic.	-	The structure of the building is metallic.	-

CONSTRUCTION SAFETY RISK		INDICATOR [P]	SOURCE	EX[1] = 0	EX = 1	EX = 3	EX = 5
TC-2	Due to joining waterproof membranes.	Type of joints used with waterproof membranes.	Building specifications	Waterproof layer joints are sealed off by mechanical or adhesive means.	-	Waterproof layer joints are sealed off by applying heat.	-
INJURIES FROM ELECTRIC CONTACTS							
EC-1	With active elements.	All cases.	-	-	-	All cases.	-
EC-2	Due to breakage of underground electric power cables.	Presence of underground electric power cables.	Building specifications	No underground electric power cables.	-	Underground electric power cables.	-
EC-3	Due to contact with balling pumps.	Excavation level.	Building specifications	The excavation level does not exceed the ground-water level.	-	The excavation level exceeds the ground-water level.	-
EC-4	Due to contacts with overhead electric power lines.	Presence of overhead electric power lines.	Building specifications	No overhead electric power lines.	-	Overhead electric power lines.	-
INJURIES FROM EXPOSURE TO HARMFUL OR TOXIC SUBSTANCES							
EH-1	During materials and waste management operations.	All cases.	-	-	-	All cases.	-
EH-2	During specific welding operations.	Type of structure.	Building specifications	The structure of the building is not metallic.	-	The structure of the building is metallic.	-

CONSTRUCTION SAFETY RISK		INDICATOR [P]	SOURCE	EX[1] = 0	EX = 1	EX = 3	EX = 5
EH-3	Due to the use of concrete release agents at the construction site.	Use of concrete.	Building specifications / drawings	-	Neither the structure of the building nor its facades are made on in-situ concrete.	The structure of the building (or most of its facades) is made of in-situ concrete.	The structure of the building and most of its facades are made of in-situ concrete.
EH-4	Due to joining waterproof membranes.	Type of joints used with waterproof membranes.	Building specifications	Waterproof layer joints are sealed off by mechanical means.	-	Waterproof layer joints are sealed off by adhesive means or by applying heat.	-
EH-5	Due to the use of synthetic paints and varnishes.	% paints and varnishes that are synthetic.	Bill of quantities / budget	P = 0.000%	0.000% < P < 5.151%	5.151% ≤ P < 43.063%	P ≥ 43.063%
EH-6	In surface-polishing operations.	Presence of floor area made from natural wood or other materials that require polishing.	Bill of quantities / budget	No floor area made from natural wood or other materials that require polishing.	-	Floor area made from natural wood or other materials that require polishing.	-
INJURIES FROM CONTACT WITH CAUSTIC OR CORROSIVE SUBSTANCES							
CC-1	During work on foundations and in-situ concrete structures.	Volume of in-situ concrete in foundations and structures [m^3].	Bill of quantities / budget	-	Prefabricated structures	In-situ concrete structures: P < 2 283.95	In-situ concrete structures: P ≥ 2 283.95
CC-2	During work on brick closures and coatings.	Volume of mortar [m^3].	Bill of quantities / budget	P = 0.000	0.000 < P < 71.248	71.248 ≤ P < 541.495	P ≥ 541.495

CONSTRUCTION SAFETY RISK		INDICATOR [P]	SOURCE	EX[1] = 0	EX = 1	EX = 3	EX = 5
CC-3	During work on concrete foundations and floors.	Volume of in-situ concrete in concrete foundations and floors [m^3].	Bill of quantities / budget	-	P < 41.207	41.207 ≤ P < 574.129	P ≥ 574.129
INJURIES FROM EXPOSURE TO RADIATION							
ER-1	Due to specific welds.	Type of structure.	Building specifications	The structure of the building is not metallic.	-	The structure of the building is metallic.	-
INJURIES FROM FIRES AND EXPLOSIONS							
AC-1	Injuries from fires in areas for storing flammable and combustible substances.	Floor area [m^2].	Building specifications / drawings	-	P < 690.72	690.72 ≤ P < 5 504.27	P ≥ 5 504.27
AC-2	Injuries from breakage of underground pipes (electric power cables, telephone lines, water pipes, or liquid or gaseous hydrocarbon pipes).	Site occupation per m^2 of floor area [m^2/m^2].	Building specifications / drawings	-	P < 0.1684	0.1684 ≤ P < 0.3376	P ≥ 0.3376
AC-3	Injuries from breakage of receptacles containing harmful substances, such as storage tanks for dangerous products.	Floor area [m^2].	Building specifications / drawings	-	P < 690.72	690.72 ≤ P < 5 504.27	P ≥ 5 504.27

CONSTRUCTION SAFETY RISK		INDICATOR [P]	SOURCE	EX[1] = 0	EX = 1	EX = 3	EX = 5
AC-4	Injuries from fires due to specific welds.	Type of structure.	Building specifications	The structure of the building is not metallic.	-	The structure of the building is metallic.	-
INJURIES FROM BEING HIT OR RUN OVER BY VEHICLES							
HV-1	During material transport operations.	Weight[3] of structural floors, foundations, facades, partition walls, floors and roofs per m^2 of site occupation [kg/m^2].	Bill of quantities / budget	-	$P < 2\,878.33$	$2\,878.33 \leq P < 9\,545.00$	$P \geq 9\,545.00$
HV-2	During earthworks.	Volume of excavated and/or filled material per m^2 of site occupation [m^3/m^2].	Bill of quantities / budget	$P = 0.0000$	$0.0000 < P < 0.6215$	$0.6215 \leq P < 7.1199$	$P \geq 7.1199$
HV-3	During foundation work.	Volume of in-situ concrete in foundations per m^2 of site occupation [m^3/m^2].	Bill of quantities / budget	-	$P < 0.2151$	$0.2151 \leq P < 1.2226$	$P \geq 1.2226$
HV-4	In prefabricated structure assembly.	In case of prefabricated structure: floor area [m^2].	Bill of quantities / budget	-	$P < 690.72$	$690.72 \leq P < 5\,504.27$	$P \geq 5\,504.27$
INJURIES FROM TRAFFIC ACCIDENTS							
TA-1	Injuries from external or internal traffic accidents.	Volume of excavated and/or filled material per m^2 of site occupation [m^3/m^2].	Bill of quantities / budget	$P = 0.0000$	$0.0000 < P < 0.6215$	$0.6215 \leq P < 7.1199$	$P \geq 7.1199$
		Weight[3] of structural floors, foundations, facades, partition walls, floors and roofs per m^2 of site occupation [kg/m^2].	Bill of quantities / budget	-	$P < 2\,878.33$	$2\,878.33 \leq P < 9\,545.00$	$P \geq 9\,545.00$

CONSTRUCTION SAFETY RISK		INDICATOR [P]	SOURCE	EX[1] = 0	EX = 1	EX = 3	EX = 5
INJURIES FROM CONTACT WITH CHEMICAL AGENTS							
L-1	Dust generation in activities involving construction machinery or transport.	Volume of excavated material per m^2 of floor area $[m^3/m^2]$.	Bill of quantities / budget	P = 0.0000	0.0000 < P < 0.5554	0.5554 ≤ P < 1.1686	P ≥ 1.1686
L-2	Dust generation in earthworks and stockpiles.	Volume of excavated material per m^2 of floor area $[m^3/m^2]$.	Bill of quantities / budget	P = 0.0000	0.0000 < P < 0.5554	0.5554 ≤ P < 1.1686	P ≥ 1.1686
L-3	Dust generation in activities with cutting operations.	% of facing brick closure.	Bill of quantities / budget	P = 0.00%	0.00% < P < 14.85%	14.85% ≤ P < 76.51%	P ≥ 76.51%
		% of area with discontinuous ceramic and/or stone surfaces.	Bill of quantities / budget	P = 0.00%	0.00% < P < 30.33%	30.33% ≤ P < 60.71%	P ≥ 60.71%
INJURIES FROM CONTACT WITH PHYSICAL AGENTS							
L-5	Generation of noise and vibrations due to site activities.	Time of activity, use of special machinery (road roller, graders and compactors, etc.)	Health and safety plan/geotechnical study/budget	-	Normal activity during daytime hours (8:00-20:00) and no use of special machinery).	Normal activity during daytime hours (8:00-20:00) and use of special machinery).	Normal activity during nighttime hours (20:00-8:00).

[1] EX: risk exposure.
[2] P: indicator. P values can be extracted from the quantitative data available in the project documents.
[3] Weight [kg]: 2 500·Co + 150·Af + 225·Aw; where Co = amount of concrete $[m^3]$, Af = floor area $[m^2]$ and Aw = wall area $[m^2]$.
[4] Heavy claddings include ceramic and cement mortar tiles, stoneware, limestone, artificial stones and fibrocement sheets.

Table 2. Evaluation of health and safety risks related to residential construction designs.

Some health and safety indicators are expressed in absolute terms, assuming that exposure to a particular health or safety risk is directly related to the volume of work. This is the case for the risk ‘Falls between different levels during work on door and window closures’, which is measured by the absolute indicator ‘Number of balconies without boundary walls and windows in the building’. Other indicators are expressed in relative terms in order to measure the ‘density of hazards’ (depending on the case, input figures are referenced to m^2 of floor area, m^2 of roof area or m^2 of site occupation). The indicator for the health and safety risk ‘Falls between different levels during floor work’ is a relative one: ‘Total perimeter of holes measuring more than 0.40 m^2 plus total perimeter of balconies without boundary walls per m^2 of floor area’. For the same reason, other health and safety indicators are expressed as a percentage of a total amount.

So as to include detailed criteria to help decision-makers determine whether exposure to a particular construction risk is significant, a four-interval scale was developed (Table 3).

Risk exposure (EX_i)	**Score**
No exposure	0
Low exposure	1
Significant exposure	3
High exposure	5

Table 3. Scoring system for risk exposure (EX_i).

To help achieve a homogeneous outcome, numerical limits were established between the four categories. These numerical limits were obtained by means of a statistical analysis of 25 new-start construction projects. They ranged in size from a small block of two dwellings with a total floor area of 371 m^2 to a property development of 93 dwellings and a floor area of 12 681 m^2. They also ranged from three to seven levels above ground and from zero to two levels below ground.

Because a large proportion of construction projects have significant exposure to safety risks, a 68% confidence interval $[\mu-\sigma, \mu+\sigma]$ was calculated for each indicator. Thus, if an indicator was lower than $\mu-\sigma$ for a particular construction project, the exposure to the corresponding construction safety risk was considered low. However, if the indicator was higher than $\mu+\sigma$, the exposure to the corresponding risk was considered high. Indicators within $[\mu-\sigma, \mu+\sigma]$ show significant exposure.

Table 4 shows the estimated distribution for each of the quantitative indicators considered in this analysis, as well as the means and standard deviations of the corresponding distributions. Also included are the upper and lower limits of the 68% confidence interval.

HEALTH AND SAFETY RISKS	Estimated distribution	Mean	Standard deviation	R^2	Lower limit	Upper limit
Total perimeter with a difference in floor level of more than 20 cm during the demolition, earthworks or foundation phases per m^2 of site occupation area [m/m^2].	Log-normal	-0.0924	0.2763	0.9793	0.4279	1.5269
Total perimeter of floors more than 20 cm high (from zero level) plus roof perimeter withour boundary walls plus perimeter of holes measuring more than 0.40 m^2 per m^2 of floor area [m/m^2].	Log-normal	-0.8616	0.9304	0.9749	0.0161	1.1715
Roof perimeter without boundary walls plus perimeter of holes measuring more than 0.40 m^2 per m^2 of roof area [m/m^2].	Gaussian	0.4180	0.1629	0.9545	0.2551	0.5809
Total area of partition walls plus total area of cladding on them (parging, plastering, tiling, painting, etc.) [m^2].	Log-normal	3.9643	0.4374	0.9543	3 363.8	25 216.7
Total area of facades plus total area of cladding on them (parging, coating, painting, etc.) [m^2].	Log-normal	3.2019	0.5203	0.9792	480.39	5 273.84
Total perimeter of holes measuring more than 0.40 m^2 plus total perimeter of balconies without boundary walls per m^2 of floor area [m/m^2].	Log-normal	-0.9348	0.2150	0.9706	0.0708	0.1906
Number of balconies and windows in the building [units].	Log-normal	1.5978	0.5744	0.9804	10.55	148.69
Total area of cladding of structural floors plus total area of false ceilings plus total area of cladding on them (parging, plastering, tiling, painting, etc.) [m^2].	Log-normal	3.2358	0.5712	0.9436	462.0	6 411.3
Site occupation [m^2].	Log-normal	2.6321	0.5732	0.9414	114.5	1 604.5
Weight of reinforcing bars [kg].	Log-normal	4.5560	0.6180	0.9501	8 668.7	149 268.9
Total area of roof [m^2].	Log-normal	2.3218	0.4763	0.9736	70.064	628.140
Volume of excavated and/or filled material [m^3].	Log-normal	3.2004	0.8917	0.9430	203.56	12 361.65
Volume of in-situ concrete [m^3].	Log-normal	2.7718	0.5838	0.9517	154.16	2 267.75

HEALTH AND SAFETY RISKS	Estimated distribution	Mean	Standard deviation	R^2	Lower limit	Upper limit
Area of discontinuous cladding in facades [m^2].	Log-normal	1.9310	0.5742	0.9521	22.743	320.055
Area of discontinuous cladding in partition walls [m^2].	Log-normal	2.8199	0.4919	0.9332	212.79	2 050.08
False ceiling area [m^2].	Log-normal	2.5095	0.7001	0.9652	64.482	1 620.336
Weight of structural floors, foundations, facades, partition walls, floors and roofs [kg].	Log-normal	6.3963	0.5141	0.9659	762 380	8 134 735
Floor area [m^2].	Log-normal	3.2900	0.4507	0.9658	690.72	5 504.27
Weight of structural floors, foundations, facades, partition walls, floors and roofs per m^2 of floor area [kg/m^2].	Gaussian	1 368.9	273.4	0.9696	1095.5	1 642.3
Volume of excavated and/or filled material per m^2 of site occupation [m^3/m^2].	Log-normal	0.3230	0.5295	0.9306	0.6215	7.1199
Volume of in-situ concrete structures per m^2 of floor area [m^3/m^2].	Gaussian	-0.5175	0.3798	0.9610	0.1267	0.7284
Volume of in-situ concrete structures [m^3].	Log-normal	2.5005	0.6333	0.9645	73.655	1 360.652
Volume of in-situ concrete in foundations per m^2 of site occupation [m^3/m^2].	Log-normal	-0.2900	0.3773	0.9876	0.2151	1.2226
Volume of in-situ concrete in concrete foundations and floors per m^2 of floor area [m^3/m^2].	Gaussian	0.1116	0.0614	0.9006	0.0502	0.1730
Volume of in-situ concrete in foundations and structures [m^3].	Log-normal	2.7758	0.5829	0.9711	155.95	2283.95
Total area of facades and partition walls [m^2].	Log-normal	3.4749	0.5332	0.9080	874.43	10 187.10
% of facing brick closure.	Gaussian	0.4568	0.3083	0.9389	14.85%	76.51%
% of area with discontinuous ceramic and/or stone surfaces.	Log-normal	-0.3674	0.1507	0.9546	30.33%	60.71%
Total area of ceramic partition walls [m^2].	Log-normal	3.0469	0.6693	0.9229	238.5944	5 201.9861
Volume of in-situ concrete in concrete foundations and floors [m^3].	Log-normal	2.187	0.572	0.958	41.207	574.129

HEALTH AND SAFETY RISKS	Estimated distribution	Mean	Standard deviation	R^2	Lower limit	Upper limit
% of facade painted with spray gun.	Gaussian	52.4062	30.7692	0.9642	21.64%	83.18%
% of paints and varnishes that are synthetic.	Log-normal	-0.2871	0.4611	0.9843	5.15%	43.06%
Volume of mortar [m^3].	Log-normal	2.2932	0.4404	0.9582	71.248	541.495
Weight[3] of structural floors, foundations, facades, partition walls, floors and roofs per m^2 of site occupation [kg/m^2].	Log-normal	6 211.67	3 333.33	0.9731	2 878.33	9 545.00

Table 4. Statistical analysis for quantitative indicators.

However, we were unable to obtain a quantitative indicator for each health and safety risk based on the information contained in the project documents. Therefore, we had to include 11 qualitative health and safety indicators, such as the indicator 'Climate situation of the construction site' for the health and safety risk 'Injuries from exposure to extreme temperatures' or the indicator 'Presence of foundations, retaining walls or evacuation elements from previous buildings to be demolished' for the risk 'Injuries from becoming caught in or between objects during small demolition operations'. The significance limits for indicators expressed in qualitative terms were derived with the help of the panel of experts.

2.2.3. Determining the overall safety level of a construction project

Numerical scores for risk exposure were assigned as shown in Table 3. If the documents of a construction project lacked the information needed to make a satisfactory appraisal, high exposure was automatically assumed (EX_j=5).

If, after conducting the assessment, any construction safety risk is found to be unacceptable (EX_j>9), actions to eliminate or reduce that risk must be planned.

The methodology assesses the overall safety level of a construction project as shown in (2).

$$R = \sum_{j=1}^{n} EX_j \qquad (2)$$

where R is the overall safety risk level of a construction project and EX_j is the exposure corresponding to a specific construction safety risk j.

The construction project with the highest sum is considered to have the lowest safety level.

3. ALTERNATIVE DESIGN OPTIONS

The developed methodology is able to highlight how changing design decisions may affect the significance of a particular safety risk and consequently how this may affect the overall safety risk level of the construction project. However, the methodology does not provide a pre-defined list of design improvements as this could be seen by designers as an intrusion into their creative process. In this sense, Frijters and Swuste (2008) state that the designer's main concerns when using CHPtD tools are that the design process should not be seriously disrupted and that their freedom in designing should not be impaired.

The proposed methodology is a useful tool for backing up or making a particular design decision. In case of senior designers, previous acquired experiences in building's design can be helpful in proposing design modifications. In case of less-experienced designers, the methodology provides a way to facilitate a well-grounded choice between different design alternatives.

4. RESULTS AND DISCUSSION

To demonstrate the benefits of the methodology, this section applies the model to the design process of a specific construction project. In this case, client's requirements include designing an isolated four-storey building with one underground car park floor. Due to urban constraints, the building's floor area cannot exceed 2 241.18 m^2, and it can contain a maximum of 19 dwellings.

The large range of current available alternative building materials and techniques significantly increases the freedom of the design and consequently the difficulty in finding the most suitable solution. Judgement of the adequacy of a particular building design is frequently related to its appearance, to the way it functions, to its cost or to its execution time. The proposed methodology adds the on-site safety performance axis to the design decision making.

One of the first choices might lie between designing an in-situ concrete structure or a precast concrete structure. The safety risk level of designing an in-situ concrete structure was found to be 36 whereas the safety risk level of designing a precast structure was found to be 18. Appendix A shows detailed results of the safety evaluation of both design alternatives. Designing a precast structure instead of an in-situ concrete structure significantly reduces risks FS-2 (falls at the same level during reinforcement work), FOC-2 (injuries from falling objects due to crumble or collapse due to the use of in-situ concrete), OF-3 (injuries from objects falling from above during structural work), SO-3 (injuries from stepping on reinforcing bars, screws or nails), HS-4 (injuries from hitting stationary objects during structural work), HM-4 (injuries from hitting moving parts of machinery during structural work), CS-2 (injuries from cuts or blows from objects and tools during work on foundation and structure), CO-6 (injuries from becoming caught in or between objects in forming and shoring operations), EH-3 (injuries from exposure to harmful or toxic substances due to the use of concrete release agents at the construction site) and CC-1 (injuries from contact with caustic or corrosive substances during work on foundations and in-situ concrete structures). However, designing a precast concrete structure instead of an in-situ concrete structure causes two other safety risks: FOH-2 (injuries from falling objects during handling in prefabricated structure assembly) and HV-4 (injuries from being hit or run over by vehicles in prefabricated structure assembly).

The choice of roof type may also have safety implications. According to the results shown in Appendix B, executing a trafficable roof with boundary walls involves nearly half the safety risk level related to the execution of a slate gable roof with a slope of 45% and windows for ventilation. Actually, the execution of a trafficable roof with boundary walls reduces the construction safety risks FH-3 (falls between different levels during roof work) and FS-3 (falls at the same level during roof work). Safety risks OF-4 (injuries from objects falling from above during roof work), and CS-3 (injuries from cuts or blows from objects and tools during finishing work on roofs) are also reduced as a result of this design alternative.

Four of a number of alternative designs for the external facades of the building are taken into account. In the first three design alternatives, the external facades are primarily three-layer masonry walls. The first design alternative includes facing brick wall, the second one has natural stone cladding, and the third one has a single-layer mortar coating. The fourth alternative includes designing precast concrete panels (without in-situ claddings). According to Appendix C, the highest safety risk level corresponds to the facing brick facade (37), followed by the masonry wall with natural stone cladding (36) and the masonry wall with single-layer mortar coating (25). Finally, the safety risk level of designing precast concrete panels (without in-situ claddings) is 19. Designing precast concrete panels (without in-situ claddings) reduces some safety risks, such as FOC-3 (injuries from falling objects due to crumble or collapse during cladding work on facades), FOH-3 (injuries from falling objects during handling in cladding work), CS-5 (injuries from cuts or blows from objects and tools during work on coatings or floors), FF-1 (injuries from projection of fragments and particles in cutting operations), CC-2 (injuries from contact with caustic or corrosive substance during work on brick closures and coatings) and L-3 (dust generation in activities with cutting operations).

Suppose a choice is to be made between designing balconies with wood railings and designing balconies with boundary walls (Appendix D). The second alternative would clearly reduce risk FH-5 (falls between different levels during floor work) and FH-6 (falls between different levels during work on door and window closures), although in this case the exposure rating would not change.

Other minor design decisions may also have different safety implications. For example, designing an artificial wood floor that does not require polishing instead of a natural one reduces risk EH-6 (injuries from exposure to harmful or toxic substances in surface-polishing operations) from 3 to 0 (Appendix E). Sealing the waterproof layer joints mechanically instead of by applying heat reduces two other safety risks: TC-2 (injuries from thermal contacts due to joining waterproof membranes) and EH-4 (injuries from exposure to harmful or toxic substances due to joining waterproof membranes) both from 3 to 0 (Appendix F).

Likewise, reducing the size of the windows could reduce risk FOH-4 (injuries from falling objects during handling in work on door and window closures) from 5 to 3 (Appendix G).

Appendix H includes detailed results corresponding to the assessment of those construction safety risks not dependant on the abovementioned design alternatives.

Obviously each design alternative tends to provide different benefits and to have different safety implications. The overall safety risk level of this construction project may range from 143 in the safest design (precast concrete structure, trafficable roof with boundary walls, precast concrete facades, balconies with boundary walls, artificial wood floors, waterproof layer joints sealed off by mechanical means and reduced size of windows closures -0.80 m per 0.80 m-) to 198 in the lowest safety design (in-situ concrete structure, slate gable roof with slope of 45% and windows for ventilation, facing brick facades, balconies with wood railings, natural wood floors, waterproof layer joints sealed off by applying heat and windows more than 1 m wide per 1 m of height). Designers may assume different safety risk levels in the final design as the methodology highlights the significant remaining health and safety risks and measures can then be implemented at the construction site in order to eliminate these risks or reduce them to an acceptable level.

5. CONCLUSIONS

This study is a step forward in the current efforts to encourage smaller construction and design firms to adopt the CHPtD concept. We presented a quantitative methodology that supports designers by providing a way to evaluate the safety-related performance of residential construction designs using a risk-analysis-based approach. The methodology ranks the significance of the safety risks involved in a construction design and compares the overall safety risk level of designs. It also compares the absolute importance of a particular safety risk in the various construction designs being assessed.

The methodology does not start from a standard set of health and safety risks. Instead, the first step is a process-oriented analysis. This exhaustive preliminary study examines specific health and safety aspects related to the construction process and tailored to regional specificities. In order to objectively assess the health and safety risks related to the construction of residential buildings, the second stage includes the development of 45 performance indicators based on quantitative data available in the project documents. Significance limits for quantitative indicators are established on the basis of a statistical analysis of 25 new-start construction projects. The outcome of the process therefore does not depend on the people who conduct it.

The strength of this methodology lies in the fact that it helps designers to explicitly consider construction worker safety during the design process. Designers can compare construction techniques and systems during the design phase and determine the corresponding level of safety risk without their creative talents being restricted. The methodology is especially worthwhile for those less-experienced designers who lack the skills and knowledge required to recognize hazards and develop optimal designs.

Another key feature of this methodology is the assessment of health and safety risks prior to the construction stage. Proactive hazard identification and elimination is always safer and more cost-effective than reactive hazard management.

Moreover, once a final design is reached, the methodology highlights the significant remaining health and safety risks. A range of measures can then be implemented at the construction site to eliminate the remaining risks or reduce them to an acceptable level. Improved levels of hazard identification lead to successful on-site safety management.

6. FURTHER RESEARCH

Further research needs to be done so that contributing causes of accidents can be considered in the methodology. Manageable factors for promoting workplace safety performance through reasonable project-safety efforts may also be important when predicting and assessing potential safety risks at the pre-construction stage. Future studies should explore the possibility of introducing a weighting system in order to better estimate the overall safety risk level of a construction design.
Further research is also needed in order to implement the methodology in a web-based information- and knowledge-management system with databases. By doing this, the time devoted to the assessment of each design could be reduced by re-using indicator calculations, and data collected in previous assessments could be reused in order to refine the methodology, in particular with regard to the significance limits of the health and safety risks.

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APPENDICES

Appendix A. Assessment of the safety-related performance of designing an in-situ concrete structure or a precast structure.

CONSTRUCTION SAFETY RISK		IN-SITU CONCRETE STRUCTURE		PRECAST CONCRETE STRUCTURE	
		P	**EX**	**P**	**EX**
FS-2	Falls at the same level during reinforcement work.	10 725.6	3	Prefabricated structure.	1
		647.2	3	647.2	3
FOC-2	Injuries from falling objects due to crumble or collapse due to the use of in-situ concrete.	319.74	3	93.74	1
FOH-2	Injuries from falling objects during handling in prefabricated structure assembly.	No prefabricated structures.	0	2 241.18	3
OF-3	Injuries from objects falling from above during structural work.	0.1008	3	Prefabricated structure.	1
SO-3	Injuries from stepping on reinforcing bars, screws or nails.	Unknown formwork: 226.000	3	0.000	0
		10 725.6	3	Prefabricated structure.	1
HS-4	Injuries from hitting stationary objects during structural work.	0.1008	3	Prefabricated structure.	1
HM-4	Injuries from hitting moving parts of machinery during structural work.	0.1008	3	Prefabricated structure.	1
CS-2	Injuries from cuts or blows from objects and tools during work on foundation and structure.	319.74	3	Prefabricated structure.	1

CONSTRUCTION SAFETY RISK		IN-SITU CONCRETE STRUCTURE		PRECAST CONCRETE STRUCTURE	
		P	**EX**	**P**	**EX**
CO-6	Injuries from becoming caught in or between objects in forming and shoring operations.	226.000	3	0.000	0
EH-3	Injuries from exposure to harmful or toxic substances due to the use of concrete release agents at the construction site.	The structure of the building (or most of its facades) is made of in-situ concrete.	3	Neither the structure of the building nor its facades are made on in-situ concrete.	1
CC-1	Injuries from contact with caustic or corrosive substances during work on foundations and in-situ concrete structures.	319.74	3	Prefabricated structure.	1
HV-4	Injuries from being hit or run over by vehicles in prefabricated structure assembly.	No prefabricated structures.	0	2 241.18	3
SAFETY RISK LEVEL			**36**		**18**

Appendix B. Assessment of the safety-related performance of designing a slate gable roof with a slope of 45% and windows for ventilation or a trafficable roof with boundary walls.

CONSTRUCTION SAFETY RISK		SLATE GABLE ROOF WITH SLOPE OF 45% AND WINDOWS FOR VENTILATION		TRAFFICABLE ROOF WITH BOUNDARY WALLS	
		P	**EX**	**P**	**EX**
FH-2	Falls between different levels during structural work.	0.3318	3	0.2313	3
FH-3	Falls between different levels during roof work.	0.1787	1	0.0000	0
FS-3	Falls at the same level during roof work.	630.000	5	541.920	3
OF-4	Injuries from objects falling from above during roof work.	0.1787	1	0.0000	0
CS-3	Injuries from cuts or blows from objects and tools during finishing work on roofs.	630.000	5	541.920	3
SAFETY RISK LEVEL			**15**		**9**

Appendix C. Assessment of the safety-related performance of designing in-situ facades (facing brick, masonry walls with natural stone cladding and masonry walls with single-layer mortar coating) or precast facades (precast concrete panels without in-situ claddings).

CONSTRUCTION SAFETY RISK		FACING BRICK*		MASONRY WALLS WITH NATURAL STONE CLADDING*		MASONRY WALLS WITH SINGLE-LAYER MORTAR COATING*		PRECAST CONCRETE FACADES*	
		P	**EX**	**P**	**EX**	**P**	**EX**	**P**	**EX**
FH-4	Falls between different levels during work on facades, partition walls and vertical coatings.	9 383.5	3	9 383.5	3	9 383.5	3	9 383.5	3
		972.87	3	2 918,61	3	3 891,48	3	972,87	3
FOC-3	Injuries from falling objects due to crumble or collapse during cladding work on facades.	0.000	0	972.87	5	0.000	0	0.000	0
FOH-3	Injuries from falling objects during handling in cladding work.	No heavy cladding.	0	Heavy claddings.	3	No heavy cladding.	0	No heavy cladding.	0

CONSTRUCTION SAFETY RISK		FACING BRICK*		MASONRY WALLS WITH NATURAL STONE CLADDING*		MASONRY WALLS WITH SINGLE-LAYER MORTAR COATING*		PRECAST CONCRETE FACADES*	
		P	**EX**	**P**	**EX**	**P**	**EX**	**P**	**EX**
OF-5	Injuries from objects falling from above during work on facades and vertical coatings.	972.87	3	2918.61	3	3891.48	3	972.87	3
CS-5	Injuries from cuts or blows from objects and tools during work on coatings or floors.	100.00%	5	0.00%	0	0.00%	0	0.00%	0
		25.13%	1	40.75%	3	25.13%	1	25.13%	1
FF-1	Injuries from projection of fragments and particles in cutting operations.	100.00%	5	0.00%	0	0.00%	0	0.00%	0
		1 020.42	3	1 020.42	3	1 020.42	3	1 020.42	3
		25.13%	1	40.75%	3	25.13%	1	25.13%	1

CONSTRUCTION SAFETY RISK		FACING BRICK*		MASONRY WALLS WITH NATURAL STONE CLADDING*		MASONRY WALLS WITH SINGLE-LAYER MORTAR COATING*		PRECAST CONCRETE FACADES*	
		P	**EX**	**P**	**EX**	**P**	**EX**	**P**	**EX**
FF-3	Injuries from projection of fragments and particles in spray-gun painting operations.	0.00%	0	0.00%	0	100.00%	5	0.00%	0
CC-2	Injuries from contact with caustic or corrosive substances during work on brick closures and coatings.	81.90	3	107.73	3	68.67	1	0.00	0
TA-1	Injuries from external or internal traffic accidents.	2.1509	3	2.1509	3	2.1509	3	2.1509	3
		2 447.5	1	2 447.5	1	2 447.5	1	2 447.5	1
L-3	Dust generation in activities with cutting operations.	100.00%	5	0.00%	0	0.00%	0	0.00%	0
		25.13%	1	40.75%	3	25.13%	1	25.13%	1

CONSTRUCTION SAFETY RISK	**FACING BRICK***		**MASONRY WALLS WITH NATURAL STONE CLADDING***		**MASONRY WALLS WITH SINGLE-LAYER MORTAR COATING***		**PRECAST CONCRETE FACADES***	
	P	**EX**	**P**	**EX**	**P**	**EX**	**P**	**EX**
SAFETY RISK LEVEL	**37**		**36**		**25**		**19**	

* In case of dry partition walls.

Appendix D. Assessment of the safety-related performance of designing balconies with wood railings or balconies with boundary walls.

CONSTRUCTION SAFETY RISK		**BALCONIES WITH WOOD RAILINGS**		**BALCONIES WITH BOUNDARY WALLS**	
		P	**EX**	**P**	**EX**
FH-5	Falls between different levels during floor work.	0.1950	5	0.1031	3
FH-6	Falls between different levels during work on door and window closures.	42.00	3	30.00	3
SAFETY RISK LEVEL			**8**		**6**

Appendix E. Assessment of the safety-related performance of designing natural or artificial wood floors.

CONSTRUCTION SAFETY RISK		**NATURAL WOOD FLOORS**		**ARTICIAL WOOD FLOORS**	
		P	**EX**	**P**	**EX**
EH-6	Injuries from exposure to harmful or toxic substances in surface-polishing operations.	Floor are made from natural wood or other materials that require polishing.	3	No floor are made from natural wood or other materials that require polishing.	0
SAFETY RISK LEVEL			**3**		**0**

Appendix F. Assessment of the safety-related performance of designing waterproof layer joints sealed off by applying heat or by mechanical means.

CONSTRUCTION SAFETY RISK		WATERPROOF LAYER JOINTS SEALED OFF BY APPLYING HEAT		WATERPROOF LAYER JOINTS SEALED OFF BY MECHANICAL MEANS	
		P	**EX**	**P**	**EX**
TC-2	Injuries from thermal contacts due to joining waterproof membranes.	Waterproof layer joints are sealed off by applying heat.	3	Waterproof layer joints are sealed off by mechanical or adhesive means.	0
EH-4	Injuries from exposure to harmful or toxic substances due to joining waterproof membranes.	Waterproof layer joints are sealed off by applying heat.	3	Waterproof layer joints are sealed off by mechanical or adhesive means.	0
SAFETY RISK LEVEL			**6**		**0**

Appendix G. Assessment of the safety-related performance of designing the size of the windows.

CONSTRUCTION SAFETY RISK		WINDOW CLOSURES: 2 m wide per 2 m of height.		WINDOW CLOSURES: 0.80 m wide per 0.80 m of height.	
		P	**EX**	**P**	**EX**
FOH-4	Injuries from falling objects during handling in work on door and window closures.	Windows are more than 1 m wide per 1 m of height.	5	Windows are less than 1 m wide per 1 m of height.	3
SAFETY RISK LEVEL			**5**		**3**

Appendix H. Assessment of construction safety risks not dependant on the abovementioned design alternatives.

CONSTRUCTION SAFETY RISK		P	EX
FH-1	Falls between different levels during small demolition operations, earthworks and foundation work.	0.3634	1
FH-7	Falls between different levels during work on false ceilings and ceiling coatings.	1 720.3	3
FS-1	Falls at the same level during small demolition operations and earthworks.	647.2	3
FOC-1	Injuries from falling objects due to crumble or collapse during earthworks.	1 392.06	3
FOC-4	Injuries from falling objects due to crumble or collapse during cladding work on partition walls.	971.96	3
FOC-5	Injuries from falling objects due to crumble or collapse during false ceiling work.	194.271	3
OF-2	Injuries from objects falling from above during earthworks.	2.1509	3
OF-7	Injuries from objects falling from above during false ceiling work.	194.271	3
SO-1	Injuries from stepping on objects during small demolition operations.	No elements to be demolished.	0
SO-2	Injuries from stepping on objects during removal of garden elements.	No garden elements to be removed.	0
HS-1	Injuries from hitting stationary objects in provisional on-site facilities and storage areas.	647.2	3
HS-2	Injuries from hitting stationary objects during small demolition operations.	No elements to be demolished.	0
HS-3	Injuries from hitting stationary objects during removal of garden elements.	No garden elements to be removed.	0

CONSTRUCTION SAFETY RISK		P	EX
HM-2	Injuries from hitting moving parts of machinery during earthworks.	2.1509	3
HM-3	Injuries from hitting moving parts of machinery during foundation work.	0.1448	1
HM-5	Injuries from hitting moving parts of machinery during work on concrete foundations and floors.	0.0553	3
CS-1	Injuries from cuts or blows from objects and tools during removal of garden elements.	No garden elements to be removed.	0
CS-4	Injuries from cuts or blows from objects and tools during work on facades and partition walls.	1 993.29	3
CS-6	Injuries from cuts or blows from objects and tools during work on false ceilings.	194.271	3
FF-2	Injuries from projection of fragments and particles in concrete operations.	123.9390	3
CO-2	Injuries from becoming caught in or between objects during small demolition operations.	No elements to be demolished.	0
CO-3	Injuries from becoming caught in or between objects during removal of garden elements.	No garden elements to be removed.	0
CO-4	Injuries from becoming caught in or between objects during earthworks.	1 392.06	3
CO-5	Injuries from becoming caught in or between objects during work on piles, micro-piles and screen walls.	No piles, micro-piles or screen walls.	0
CO-7	Injuries from becoming caught in or between objects in operations with scaffoldings or working platforms.	2 241.18	3
CV-2	Injuries from becoming caught in dumped vehicles or machines during earthworks.	2.1509	3
CV-3	Injuries from becoming caught in dumped vehicles or machines during foundation work.	0.1448	1

CONSTRUCTION SAFETY RISK		P	EX
CV-5	Injuries from becoming caught in dumped vehicles or machines during structural work.	0.0553	3
OX-1	Injuries form overexertion, bad posture or repetitive motion.	All cases.	3
ET-1	Injuries from exposure to extreme temperatures.	The construction site is not located in an extremely hot or cold climate area.	0
TC-1	Injuries from thermal contacts due to specific welding operations.	The structure of the building is not metallic.	0
EC-1	Injuries from electrical contacts with active elements.	All cases.	3
EC-2	Injuries from electrical contacts due to breakage of underground electric power cables.	No underground electric power cables.	0
EC-3	Injuries from electrical contacts due to contact with balling pumps.	The excavation level does not exceed the ground-water level.	0
EC-4	Injuries from electrical contacts due to contacts with overhead electric power lines.	No overhead power cables.	0
EH-1	Injuries from exposure to harmful or toxic substances during materials and waste management operations.	All cases.	3
EH-2	Injuries from exposure to harmful or toxic substances during specific welding operations.	The structure of the building is not metallic.	0
EH-5	Injuries from exposure to harmful or toxic substances due to the use of synthetic paints and varnishes.	0.000%	0

CONSTRUCTION SAFETY RISK		**P**	**EX**
CC-3	Injuries from contact with caustic or corrosive substances during work on concrete foundations and floors.	123.9390	3
ER-1	Injuries from exposure to radiation due to specific welds.	The structure of the building is not metallic.	0
AC-1	Injuries from fires in areas for storing flammable and combustible substances.	2 241.18	3
AC-2	Injuries from breakage of underground pipes (electric power cables, telephone lines, water pipes, or liquid or gaseous hydrocarbon pipes).	0.2888	3
AC-3	Injuries from breakage of receptacles containing harmful substances, such as storage tanks for dangerous products.	2 241.18	3
AC-4	Injuries from fires due to specific welds.	The structure of the building is not metallic.	0
HV-2	Injuries from being hit or run over by vehicles during earthworks.	2.1509	3
HV-3	Injuries from being hit or run over by vehicles during foundation work.	0.1448	1
L-1	Dust generation in activities involving construction machinery or transport.	0.6211	3
L-2	Dust generation in earthworks and stockpiles.	0.6211	3
L-5	Generation of noise and vibrations due to site activities.	Normal activity.	3
SAFETY RISK LEVEL			**88**

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