Hazard Function Deployment: a QFD based tool for the assessment of working tasks – A practical study in the construction industry

Despite the efforts made, the number of accidents has not significantly decreased in the construction industry. The main reasons can be found in the peculiarities of working activities in this sector, where hazard analysis and safety management result in being more difficult than in other industries. To deal with these problems, a comprehensive approach for hazard analysis is needed, focusing on the activities in which a working task is articulated since they are characterized by different types of hazards and thus risk levels. The study proposes a methodology that integrates the Quality Function Deployment (QFD) and Analytic Network Process (ANP) methods to correlate working activities, hazardous events and possible consequences. This provides a more effective decision making, while reducing the ambiguity of the qualitative assessment criteria. The results achieved can augment the knowledge on the usability of QFD in safety research, providing a basis for its application for further studies.

Keywords: occupational health and safety; Quality Function Deployment; Analytic Network Process; occupational risk assessment; hazards prioritization; safety management; construction industry.

List of abbreviations

HoQ	= House of Quality	Rs	= Risks' types
ECs	= Engineering Characteristics	P	= Probability
CRs	= Customer Requirements	S	= Severity
W_i	= i-th matrix/eigenvector	As	= Activities
RI	= Random Index	Hs	= Hazards' types
CI	= Consistency Index	Cs	= Consequences
HFD	= Hazard Function Deployment	QFD	= Quality Function Deployment
R_{HFD}	= risks calculated using the HFD approach	ANP	= Analytic Network Process
R_T	= risks calculated using the traditional approach	PHA	= Preliminary Hazard Analysis
JSA	= Job Safety Analysis	ORA	= Occupational Risk Assessment

1. Introduction

In recent years, standards and regulations concerning occupational safety have become more and more rigorous. Despite such an effort, the number of accidents and victims is still significant and the construction sector is certainly one of the most affected by this situation [1-6]. For example, in the European Union (EU), the statistics and reports related to construction accidents show that, although a reduction of the overall number of accidents was registered in recent years, the average number of fatalities is still significant at about 1.000 cases per year and over 800.000 workers are injured [7].

The main reasons for this situation are due to the specific characteristics of the sector [8-10]. As a matter of fact, the large variety of activities usually carried out by companies, the use of obsolete machinery and equipment, the continuous change of workplaces, and the simultaneous use of the working site by different companies, are all factors that make the management of safety issues a difficult task to deal with [11-15]. To achieve effective results, safety managers should adopt a proactive hazard identification and elimination approach [16]. In addition, Underwood and Waterson [17] underlined the need of a holistic approach for risk assessment in order to better understand and evaluate the interactions among the operator, the technical systems, and the working environment. In such a context, Mitropoulos et al. [18] emphasized the role of the analysis of the working task characteristics in construction accidents, as the normative approaches do not consider the characteristics of the working processes properly. Working tasks should be considered with more attention, since ensuring the safety of the various tasks performed in a construction site can be the precondition for ensuring a higher level of safety at both project and company levels [10, 19]. Parise et al. [20] argued that an extensive effort is required to develop a hazard assessment approach based on the analysis of the specific tasks executed in a construction site. Accordingly, Zhou et al. [21] remarked the lack of construction safety research on the specific working tasks. Furthermore, the relevance of accidents related to the use of machinery and work equipment in a construction site was pointed out in numerous studies (e.g. in [22-27]). Accordingly, Jaafar et al. [28] remarked that the leading causes of this situation are mainly due to the operators' unsafe behavior, as well as to the lack of the proper management of the work equipment. Hence, when performing risk assessment of a working task such as the use of a work equipment, all of the specific activities related to its use and management (e.g. setting, operating, maintaining, cleaning, etc.) should be considered, since they can present different levels of risk [29]. To address these concerns, a more user-centred approach is needed to investigate the different phases that characterize the use of a machinery or an equipment in practice [30].

On these considerations, it is clear that safety managers /professionals need to implement a risk assessment approach in order to provide companies with information concerning potential hazards as well as prevention and improvement measures (i.e. a safety plan) based on the specific working activities carried out. To deal with such an issue, several studies suggested the use of the Quality Function Deployment (QFD) method [31] as a means of performing hazard analysis and risk assessment of the working tasks in a holistic manner [32, 33]. In particular, both Liu and Tsai [34] and Bas [35] focused on the use of QFD to perform risk assessment concerning the working tasks in the construction industry. These two studies propose effective procedures for safety management at a general level. However, at a practical level, a more specific and hands-on approach should be adopted, in order to make its use easier also in the case of Small and Medium-sized Enterprises (SMEs), which often rely on external professional services to carry out the activities related to the protection and prevention of occupational risks, due to the lack of internal resources [11, 36-39]. To address these issues, the paper presents a procedure for the hazard analysis of the working activities related to the use of a work equipment, which takes into account all of the foreseeable phases of its usage. In other words, this study is an attempt to answer the following research question: How to correlate the activities concerning a working task (e.g. the use of a work equipment), the related hazardous situations and events, and their corresponding prevention and improvement measures in an effective and thorough manner?

With this goal in mind, we propose a risk assessment methodology based on the use of QFD, augmented by the integration of the Analytic Network Process (ANP) approach [40]. Its validity was verified by means of a practical case study concerning the use of an in-transit concrete mixer, which was carried out in collaboration with two companies operating in the construction industry. In such a context, the working task is the use and management of the machinery which consist of a set of working activities (e.g. preparation of the concrete mixer, concrete discharge, maintenance and cleaning, etc.).

The remainder of the paper is articulated as follows. In Section 2, the background and research motivations are introduced. Section 3 presents our research approach, while its application to the case study is described in section 4. Then, Section 5 discusses the results achieved and Section 6 concludes the article addressing further work.

2. Background and motivations

The need to focus on the relationships between the operator, the working system and the working environment when performing risk assessment activities has been largely discussed in the literature, as notably remarked by Karwowski [41]. Dealing with these issues requires a holistic approach [42-45], which should take into account the feedback from the system's (i.e. the equipment) users [46, 47]. In such a context, several studies proposed the use QFD as a means of carrying out hazard analysis and risk assessment activities in a holistic manner, through the analysis of the inter-relationships and interactions among hazards, causes, effects and their consequences [30, 33-35, 48].

The core of the method is certainly the so-called "House of Quality" (HoQ), whose innermost part is represented by the relationship matrix, which links customer needs and expectations (i.e. the so-called Customer Requirements (CRs), also called the "whats") to appropriate technical attributes (i.e. the Engineering Characteristics (ECs), also called the "hows"), providing their weight and thus their prioritization (Figure 1).

Figure 1. Scheme of the traditional House of Quality (HoQ) (adapted from [31]).

[Figure 1 near here]

In particular, focusing the attention on occupational safety in the construction industry, two main approaches were presented. Firstly, Liu and Tsai [34] introduced a two-phase approach (by means the development of two Houses of Quality (HoQs)) that provides a correlation among construction items (i.e. working tasks), hazard types and hazard causes (Figure 2), following a top-down approach for hazard analysis [49].

[Figure 2 near here]

Figure 2. Scheme of the approach proposed by Liu and Tsai [34].

To augment the effectiveness of the QFD, both the Analytic Network Process (ANP) and the Fuzzy-Failure Modes and Effect Analysis (FMEA) approaches were implemented. More in detail, the ANP approach was used to address the inner-relationships and inter-relationships among the HoQ's components. In addition, the Fuzzy Logic approach was applied to allow a more accurate analysis. Hence, the study included the use of a fuzzy-FMEA method to complete the risk assessment activities (i.e. the estimation of the risk level of each hazard cause to determine the relative preventive and protective measures).

A more comprehensive approach based on the QFD method is the one presented by Bas [35]. In this study, a three-phase approach is represented (Figure 3), where three HoQs were used to consider the relationships between tasks and hazards, hazards and events, and events compared with preventive and protective measures.

[Figure 3 near here]

Figure 3. Scheme of the approach proposed by Bas [35].

Compared with the former study, this framework presents a more complete risk assessment approach, since:

- the hazard analysis follows a bottom-up approach [49];
- it enables the analysis of the relationships between the hazards and the possible preventive/protective measures;
- the final priority weight of the events (in the third phase) considers the probability of occurrence, the expected economic cost of each event, and the expected consequences of the events.

Nevertheless, some drawbacks can be underlined: the validation of the procedure by means of an empirical application was not performed. Second, the availability of statistical data on the occurrence of accidents was used to complete the third phase of the procedure, while the correlation relationships were not considered, limiting the benefits of the HoQ in assessing mutual relationships among its parameters. In addition, both the above-mentioned approaches are aimed at supporting engineers at a project level and thus they take into account macro-activities, while the specific activities that characterize a working task are not addressed sufficiently. Moreover, focusing on the operator and the activities carried out when performing a specific task, the use of a structured risk management approach can allow the achievement of safer solutions [50]. Merging these considerations, we can observe that, when carrying out occupational risk assessment (ORA) activities, four main issues need to be addressed:

1. a bottom-up approach should be preferred to provide engineers with a thorough procedure for hazard analysis and prioritization;
2. in order to meet the practical needs of companies that operate in a construction site, the specific activities in which a working task is articulated need to be analyzed;
3. involving operators in the risk assessment process allows engineers to better define the specific tasks, the identification of hazards and the determination of risks [51];

4. the evaluation of the inner relationships among the different parameters analyzed (e.g. working activities, hazardous events and consequences) is significant in order to make their assessment more consistent.

In the literature, numerous ORA approaches can be found: as remarked by Pinto et al. [52], in the construction industry one of the most commonly used ORA methods is the Preliminary Hazard Analysis (PHA). Accordingly, with the goal of accident prevention through planning, more specific tools were proposed to properly address the above mentioned issues. In particular, the approaches based on the Job Safety Analysis (JSA) (or Task Hazard Analysis (THA)) [53] stress on the importance of identifying hazards and the potential accidents starting from the analysis of the specific activities in which each job can be split, while the assessment criteria are similar to the ones used in the traditional PHA-based methods [54]. Despite the unquestioned benefits that can be achieved by the JSA approach, which allows engineers to address the first three ORA issues mentioned above, some limitations can be found [55-56], especially when considering its capability to deal with the mutual influences of the different factors analyzed.

To tackle these issues, a QFD-based methodology was developed for the risk assessment of a working task concerning the use of a machinery in a construction site.

3. Research approach

The proposed safety assessment tool consists of three main phases, each based on the HoQ augmented by the ANP approach to assess the inner and outer relationships [57].

3.1. The HoQ augmented by the ANP

The ANP approach uses pairwise comparisons to allow the evaluation and ranking of alternatives while deciding on the optimal solutions to a complex problem [40, 58-59]. Hence, the use of the ANP can support engineers in reducing the limitations of the traditional QFD in differentiating the relative importance of different attributes effectively [60]. In Figure 4 a scheme of such an integration is reported, where the CRs (i.e. the "whats") correspond to the HoQ's inputs, while the ECs (i.e. the "hows") represent the outputs [61].

[Figure 4 near here]

Figure 4. Scheme of the integration of the ANP approach in the HoQ.

Accordingly, the augmented HoQ can be represented as in Figure 5, where:

- W_1 is an eigenvector representing the weight (i.e. the importance level) of each EC.
- W_2 is the correlation matrix representing the inner dependency matrix of CRs.
- W_3 is the relationship matrix, where the pairwise comparison of each CR with respect to each EC is determined.
- W_4 is the correlation matrix among representing the inner dependency matrix of ECs.
- W_5 is an eigenvector representing the weight of each EC.

[Figure 5 near here]

Figure 5. Scheme of the HoQ augmented by the ANP.

In practice, the integration of the ANP within the HoQ is carried out by means of the following procedure:

1. Definition of the list of CRs and ECs.

2. Definition of the eigenvector W_1: pairwise comparisons of CRs with respect to each CR are carried out taking into account that there is no dependence among the CRs. The output (W_1) is represented by the importance degrees of each CR.

3. Definition of the correlation matrix W_2: pairwise comparisons of CRs with respect to each CR are performed. The output (W_2) is represented by the importance degrees of each CR (inner dependencies).

4. Definition of the eigenvector W_3: pairwise comparisons of ECs with respect to each CR are carried out taking into account that there is no dependence among the ECs. The output is represented by the relationship matrix W_3 that provides the importance degrees of each EC.

5. Definition of the correlation matrix W_4: pairwise comparisons of ECs with respect to each EC are performed. The output (W_4) is represented by the importance degrees of each EC (inner dependencies).

6. Definition of the inter-dependent priorities of CRs: the interdependent weight of CRs is calculated by means of the following equation:

$$W_{CRs} = (W_2 \times W_1) \quad (1)$$

7. Definition of the inter-dependent priorities of ECs: the interdependent weight of ECs is calculated by means of the following equation:

$$W_{ECs} = (W_4 \times W_3) \quad (2)$$

8. Definition of the overall priorities (W_5): the overall priorities of the ECs are calculated by multiplying the four resulting weight vectors/matrices as in the following equation:

$$W_5 = (W_4 \times W_3) \times (W_2 \times W_1) = W_{ECs} \times W_{CRs} \quad (3)$$

As per the criteria used in the pairwise comparisons, the judgment scores reported in Table 1 can be used [34].

[Table 1 near here]

Accordingly, to verify the consistency of each pairwise comparison matrix for *m* elements, the values reported in Table 2 for the computation of the Random Index (RI) [40] can be used following equations:

$$Consistency\ Index\ (CI) = \frac{\lambda_{max} - m}{m-1} \quad (4)$$

$$Consistency\ Ratio = \frac{CI}{RI} \quad (5)$$

where λ_{max} represents the largest eigenvalue of the pairwise comparison matrix, while CI is the consistency index. It has to be noted that the consistency ratio of a pairwise comparison matrix has to be lower than 0.1 to guarantee the consistency in human judgement [34].

[Table 2 near here]

3.2. The Hazard Function Deployment (HFD) methodology

Following such a scheme, the proposed methodology provides a bottom-up approach for hazards identification and assessment, i.e. when focusing on a specific task, the analysis starts from the identification of the working activities related to such a task, followed by examining the hazards and the possible hazardous situations and how they can lead to harms [49]. The general scheme of the proposed approach, called Hazard Function Deployment (HFD), is shown in Figure 6, where the main phases are the followings:

Phase I. Hazard types' assessment: from the activities that characterize a certain working task (e.g. the use of a machinery), hazard types are defined and assessed.

Phase II. Hazardous events' assessment: starting from the type of hazards, hazardous situations and events are defined and assessed.

Phase III. Hazards effects' assessment: starting from the hazardous situations and events, effects and consequences are defined and assessed.

With reference to the scheme proposed in Figure 6, in the name of each matrix and vector the number of the phase was added. For example, the equation (3) for Phase I becomes:

$$W_{5I} = (W_{4I} \times W_{3I}) \times (W_{2I} \times W_{1I}) \quad (6)$$

[Figure 6 near here]

Figure 6. Scheme of the HFD approach.

The definition of the various parameters of the three HoQs should be carried out with the support of experts and experienced operators. In fact, on the one hand, the experts' consultation concerning the importance of both hazardous situations/events and their possible consequences can facilitate the risk assessment activities, since the ranking provided already takes into account the probability factors based on the experts' know-how. It order to prevent any bias in the assessment activities carried out by the group of experts, the Delphi technique can be used. Such a tool is a well-known means of gathering experts' opinions through several rounds of consultation and controlled feedback of results [62]. In particular, it is a suitable approach when the analysis carried out is based on a subjective assessment (e.g. the definition of the weights or importance levels) [63].

On the other hand, also the feedback from experienced operators can help the safety managers in better addressing the implementation of the HoQs, especially for what concern the definition of the specific activities carried out when performing a task [47]. It has to be noted that in the present study a working task is the general assignment the operator carries out (e.g. use of the in-transit concrete mixer). A working task consists of several specific activities (e.g. setting the machinery, discharge the concrete, cleaning). Moreover, in our model the output of the analysis of the hazardous situations (i.e. the specific working situation during a working activity that exposes the operator to the hazard) and hazardous events (i.e. how the hazard can cause harm) is synthetized in the category "hazardous situations and events". In order to verify the validity of this approach, it was applied to an empirical case study concerning the use of a truck mixer in a construction site. On these considerations, in order to define and assess the various parameters of the three HoQs, the company's operators are interviewed in order to define the activities related to the use of the work equipment, including all foreseeable operations, as well as experienced accidents, near misses, and operative troubles.

The list of the CRs and ECs for each phase, as well as their mutual assessment, can be defined in collaboration with a group of experts in the field of occupational safety in the construction industry.

4. Case Study

The validity of the HFD approach was tested in collaboration with a company that operates in the construction industry where the use of an in-transit concrete mixer was considered. As far as accidents related to this type of machinery is concerned, official statistics cannot be considered exhaustive. In fact, on the one hand data provided by the Italian Workers' Compensation Authority (INAIL) provide a detailed information concerning the fatal accidents occurred in recent years while operating a truck mixer: in Table 3 the number and the type of causalities of fatal accidents that occurred in the period 2008-2015 are reported [64].

[Table 3 near here]

On the other hand, information concerning non-fatal accidents, especially when minor injuries incurred, is often treated with a low amount of detail, while data concerning these injuries are provided at a macro level (i.e. accidents involving any heavy machinery in construction sites).

The study was carried out in collaboration with two small sized companies operating in such a sector. More in detail, 15 operators were interviewed to gather practical information concerning the working activities that accomplish the task “use of the in-transit mixer” and the safety problems they have experienced while performing them. On this, a group of experts was defined, consisting of 2 company managers (1 per each company) who have experience both as safety managers and supervisors, and 3 experts belonging to the Italian Workers’ Compensation Authority, who have experience in machinery safety and ORA in the construction industry. The group was asked to define the list of activities, the related hazard types, the hazardous events and situations and events, as well as the potential consequences/possible harms in order to fill the three HoQs (Table 4).

[Table 4 near here]

It has to be noted that in Table 4 the various elements are summarized due to space limits, since a more formal definition of each of them would have required longer sentences (e.g. instead of “Direct/indirect contact with electrical parts” a more appropriate sentence to indicate this hazardous situation should be “The operator is close to a conductive metallic body of the machinery or to an unprotected/worn out cable”). Then, following the procedure exposed in the previous section, the ANP-QFD approach was applied. To reduce the potential bias and to respect the privacy concerns of the companies, the Delphi technique was used in the assessment activities carried out by the group of experts. More precisely, once collected the information from the operators, two rounds of consultations were organized by means of questionnaires. While the first round concerned the definition of the elements of each phase of the procedure (i.e. the list of activities, hazard types, hazardous events, etc.), the second round concerned the pairwise comparisons. In detail, data used as input in the meetings were provided by means of structured (in the case of the first round) and semi-structured (in the case of the pairwise comparisons) questionnaires. It has to be noted that, although the participants knew each other, individual responses to questions were asked separately and kept anonymous in the further discussion to determine the final results of each round.

4.1 Phase I

In collaboration with the group of experts, the pairwise comparisons among activities and hazard types were carried out based on the criteria exposed in section 3:

- Eigenvector W_{1I}: the group of experts was asked to respond to a questionnaire, where each question inquired the relative importance between pairs of activities concerning the goal (determine important hazard types). calculated as shown in Table 5.

- Matrix W_{3I}: the comparison among hazard types was carried out considering the impact level of activities on each of the hazard types. The responses were provided using the criteria exposed in Table 1. It is worth nothing that when comparing an element of the matrix to itself (e.g. H1 compared to H1) a score of 1 is given (hence the values of the diagonal are equal to 1); while the values below the diagonal are the inverse of the corresponding values above the diagonal. This means that if a_{ij} represents the relative importance of the *i*-th element compared to the *j*-th element, then the relative importance of the *j*-th element compared to the *i*-th element is represented by $a_{ji} = 1/a_{ij}$. To better clarify the calculation mechanism, all the matrices used to derive the values for the matrix W_{3I} are reported in Annex I.

- Matrix W_{2I}: the comparison among the activities was performed using as criterion the occurrence of accidents (without considering their effects). In other words, the judgement score of 1 was given when the occurrence of accidents during an activity A was considered equal to the one of an activity B. Hence, following the same computational process reported in Annex I, the type of questions used in this case was: "With respect to A1 (arrival, departure, transit), what is the relative importance of: A1 compared to A2; A1 compared to A3; A1 compared to A4; etc.?" (Table 6).

- Matrix W_{4I}: the comparison among the hazards was performed using as criterion the relevance of hazard types [34]. Following the same computational process reported in Annex I, the type of questions used in this case was: “With respect to H1 (mobility), what is the relative importance of: H11 compared to H2; H1 compared to H3; etc.?”.

[Tables 5-6 near here]

In detail, the final results obtained in the first phase are shown in Table 7, where:

- $W_{4I} \times W_{3I}$ provides the interdependent weight of hazard types when compared with reference to working activities;
- $W_{2I} \times W_{1I}$ represents the interdependent weight of working activities when compared with reference to hazard types; and
- W_{5I} provides the importance weights of hazard types, i.e. their overall priorities.

[Table 7 near here]

4.2 Phase II

Following the same approach as in Phase I, at this stage the overall priorities of the possible hazardous events were calculated, as shown in Table 8, where:

- $W_{4II} \times W_{3II}$ provides the interdependent weight of hazardous events when compared with reference to hazardous events;
- $W_{2II} \times W_{1II} = W_{2I} \times W_{1I}$ represents the interdependent weight of hazard types derived from Phase I; and
- W_{5II} provides the weights of hazardous events, i.e. their overall priorities.

[Table 8 near here]

The numerical values of each matrix of Phase II are reported in Annex II.

4.3 Phase III

Similarly, in the last phase of the procedure the overall priorities of the possible consequences were calculated, as shown in Table 9 and Table 10, where:

- $W_{2II} \times W_{1II}$ represents the interdependent weight of hazardous events derived from Phase II (Table 9);
- $W_{4III} \times W_{3III}$ provides the interdependent weight of possible consequences when compared with reference to hazardous events (Table 10);
- W_{5III} provides the weights of the possible consequences (Table 9).

[Table 9-10 near here]

The numerical values of each matrix of Phase III are reported in Annex II.

5. Discussion of results

5.1. The case study outputs

The results obtained from the case study can be summarized in the following figures, where the weights (i.e. the overall priorities) of the hazard types (Figure 7), the hazardous events (Figure 8) and the possible consequences (Figure 9) are shown (note that the values of the "y" axes are dimensionless, as they are normalized values).

[Figure 7 near here]

Figure 7. Weights of hazard types.

[Figure 8 near here]

Figure 8. Weights of hazardous events.

[Figure 9 near here]

Figure 9. Weights of possible consequences.

According to these data, the most relevant consequence while operating the truck mixer is represented by C2, i.e. scrapes, lacerations, and bruises. Such a result augments the information provided by accident statistics, since this type of injuries are hardly reported as they normally require a few days to recover from. In fact, according to law requirements, if an accident causes an injury recoverable within three days (apart from the day when the accident occurred), it should not be reported. Hence, while accidents that caused serious injuries are reported correctly, accidents with minor consequences (e.g. those ones requiring few days of recovery) are reported with fewer details. Therefore, official statistics on accidents at work provide incomplete information on what happens in reality regarding the assessment of minor injuries. Moreover, it is consistent with results obtained in the second phase of the procedure, where the most important hazardous event concerns slipping when getting in/out from the truck's cabin (E1), followed by impacts while discharging the drum (E9). In other words, the results show (see Figures 8 and 9) the relevance of accidents related to slipping and impacts, which mainly lead to scrapes, contusions, lacerations, and bruises injuries, consistently with the findings of Lipscomb et al. [65]. This is also in line with findings by Shibuya et al. [66], who pointed out that slips and trips should be considered a contributing factor for occupational injuries among truck drivers. Accordingly, these results also confirm implications provided by Aminbakhsh et al. [67], who reported that "trips and falls" together with risks related to the use of "machinery and equipment" are among the most significant risks in the construction industry. This can help engineers in carrying out risk assessment more correctly and easily. In other words, when we consider the traditional approach followed to perform the hazard analysis, for instance by means of the Preliminary Hazard Analysis (PHA) method [52, 68], the likelihood of the events is usually classified into rather broad categories (e.g. using a scale ranging from 1 (very unlikely) to 5 (very likely)). Hence, in our case study, we should assign a score of 5 to C2 and 1 to C15 (death), which means that the ratio between them is 1 to 5, while following the proposed procedure such a relationship is extended to 1 to 20 (see Table 11). This wider range represents a value much closer to the reality.

To better evaluate these differences, the group of experts was asked to perform the occupational risk assessment following the rules of the PHA method [69] and the hints provided by the report ISO/TR 14121-2 [49]. More in detail, each risk type (Rs) corresponds to the occurrence of the related hazardous event (i.e. R1, R2, R3 etc. are the risks related to the occurrence of E1, E3, E3 etc. that lead to the consequence C1, C2, C3, etc. respectively). As for the traditional approach, the risk level (R_T) was estimated by means of the equation (7):

$$R_T = P \times S \tag{7}$$

where P is the probability of occurrence of a hazardous event estimated through a 1 to 5 scale (1 = very unlikely – 5 = very likely) and S indicates the severity of its consequences (estimated by means of a 1 to 5 scale, where 1 = minor effects and 5 = catastrophic effects (e.g. death)). The estimation of the risk level in accordance with the HFD methodology (R_{HFD}) was performed using the output of the proposed approach: the weight of the possible consequences (Cs) determined at the end of Phase III was multiplied per the corresponding values of Severity (S) obtained with the traditional approach (Table 11).

[Table 11 near here]

More precisely, the comparison between the results of the two risk assessment activities is shown in Figure 10, where the solid line connects the values (i.e. the importance levels) related to the risks computed following the traditional approach (R_T), while the broken line represents the results achieved by means of the HFD approach (R_{HFD}). These results bring to light that significant differences occur depending on the approach used to calculate risks. First, it has to be pointed out that the traditional approach provides slight differences among the various risks: i.e. risks vary in a small range of values of about 5.5 %. Conversely, the HFD approach leads to a higher level of differentiation of the risks' values: i.e. circa 11.5 %. Secondly, the HFD approach allows engineers to clearly distinguish the difference of one risk from another since risks with a similar weight were not found, while some strong resemblances can be observed among the results achieved through the traditional approach. In addition, also when hazardous situations that might lead to diseases were evaluated, the HFD approach provided a clearer level of resolution, as in the case of R10 (stress and fatigue).

[Figure 11 near here]

Figure 11. Risks' values determined through the traditional (R_T - solid line) and the HFD (R_{HFD} - broken line) approaches.

The results achieved were considered very positive from the group of experts, especially for what concerns the assessment of minor injuries, as their impact is often underestimated when performing traditional risk assessment. Hence, these issues need to be addressed better at the company level by means of a more specific training of the operators.

5.2. The methodology

From a safety management point of view, the proposed approach does not start from a standardized set of health and safety risks, but it relies on a process-oriented analysis considering all the activities related to a specific task. Hence, it provides a contribution to the research hints and clues stressed by Zhou et al. [21], who underlined the lack of construction safety research at the working task level. This is also in line with Gangolells et al. [16], who remarked the lack of construction safety research on the specific working tasks. Commonly with other research works in different fields (e.g.

in [70-72]), this study found that the coordinated use of QFD and ANP can offer a more precise analysis due to the integration of interdependent relationships among the attributes, providing consistent information as to improve the safety conditions at the company level. Hence, such an approach allowed us to effectively correlate working activities related to a specific task (such as the use of a working equipment), hazardous events and possible consequences.

These practical implications for companies are in line with research clues provided by Seker et al. [45] and Samantra et al. [73]), and can be considered beneficial when considering that traditional risk assessment activities provide a relatively limited scoring "resolution" (i.e. when different risks get the same score as well as when the scores vary in a limited range of values), especially when data concerning the likelihood of occurrence are poor. Such an aspect is quite relevant in SMEs, as observed by Bohm and Harris [74], who carried out a study on risk perception and risk assessment of dumper drivers operating in construction sites. On the contrary, the HFD approach allows a more accurate assessment of the risks, ensuring a clearer ranking of them that can lead to a more efficacious decision making. This result, answering our research question, also accomplishes research suggestions provided by Kines et al. [75], who stressed on the importance of providing a more thorough risk analysis approach to bring to light the relevance of minor injuries and uncomfortable working situation. In other words, HFD provides a more precise risk analysis and ranking than the traditional risk assessment approaches, even when the availability of official statistics concerning workers' accidents is limited.

Finally, the HFD approach was compared with the above mentioned studies from the literature concerning the application of the QFD method for risk assessment in the construction industry. As summarized in Table 12, the proposed approach can provide more practical insights for risk assessment of working tasks (e.g. the use of machinery or work equipment). This accomplishes the need of providing the improvement of safety conditions not relying on the compliance with normative requirements only, but also considering the practical context of working activities [76].

[Table 12 near here]

Hence, it has to be pointed out that such an approach can accomplish the need of developing new risk analysis methods to identify and assess risks in an acceptable way so that the information is reliable for decision making [3, 32, 77], augmenting the knowledge on the use of QFD in the safety management context.

5.3. Practical implications

From the practical point of view, the HFD methodology extends the benefits of the traditional JSA approach. In fact, on the one hand, it relies on a process of identifying activity-related factors that may result in potential hazards, as for example the use of a work equipment, with the aim of proposing rules to eliminate or control these hazards. On the other hand, the HFD provides a more structured framework, which takes into account the mutual influences that might arise among the different hazards and the related potential effects, augmenting the effectiveness of risk assessment activities, since carrying out risk assessment in a sequential manner (i.e. cause-effect analysis) is insufficient to consider the complexity of these interactions. Moreover, although the proposed methodology consists in the definition of a series of matrices that make the HFD's process more complex than other diffused ORA approaches (e.g. the JSA), it is worth nothing that the HFD assessment criteria rely on simple pairwise comparisons, enabling a clearer understanding and differentiation of the results.

Another contribution of the paper is the presentation of a concrete case of occupational risk assessment related to the use of a diffused work equipment in the construction sector, including the exemplification of each step of the HFD methodology. This contribution is more relevant to practice in this industry, but it is also useful to advance the scientific knowledge regarding ontologies in the adoption of task-based ORA models.

5.4. Limitations

However, despite these positive aspects, the present study presents some limitations. Firstly, the computational efforts required to apply the ANP approach might be problematic and time-consuming for unexperienced practitioners. The development of a procedure based on the implementation of an ease-to-use software can certainly reduce this drawback, making the usability of the HFD methodology larger and more suitable for an unexperienced audience. Similarly, the role of costs related to safety measures should also be taken into account to provide companies with a more complete approach [78-80]. Then, in the experts group, a difficulty emerged when the effects of noise and vibrations were considered, hence these concerns not taken into account in the final results. To address these limitations, a more detailed differentiation of possible consequences might help engineers in providing better results. The implementation of fuzzy logic could also facilitate the assessment of this type of hazardous effects, further reducing possible errors or inconsistencies in the evaluation [34, 81]. Finally, it has to be underlined that the results were obtained from a single case study. Hence, while the use of a single case-study as a research tool for exploratory investigation and to generate new understandings is recognized by several authors [82-83], caution is needed when generalizing the findings [84].

6. Conclusions

This study proposes a novel tool, based on the integrated use of QFD and ANP, which is aimed at supporting safety managers in performing risk assessment of working tasks in the construction sector. Practical results showed that the HFD approach can be used for the risk assessment effectively, allowing engineers to obtain the priority of hazards and possible consequences, and thus of the interventions aimed at increasing the safety level of the working activities considering the mutual relationships among these factors, while reducing the ambiguity of qualitative assessment criteria used in traditional risk assessment activities. Hence, this study can provide a basis for the development of occupational risk assessment methodologies and for practitioners in this type of industry. This article is the result of an initial stage of development of the HFD approach: to augment its validity reducing the above-mentioned limitations further work is needed. Currently, both the development of a procedure based on the use of an ease-to-use software as well as its application to different industries, e.g. the agricultural sector that presents similar peculiarities from the occupational safety point of view [85-87], are being analyzed.

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Table 1. The ANP judgement scores when considering two characteristics A and B.

Judgement	**Rule**	**Score**
Equal	If A and B have the same behaviour/performance in relation to the assessment criterion	1
Moderate	If the performance of A is moderately higher than the B's one.	2-3
Strong	If the performance of A is strongly higher than the B's one.	4-5
Very strong	If the performance of A is much higher than the B's one.	6-7
Extreme	If the performance of A is extremely higher than the B's one.	8-9

Table 2. Values of the Random Index (RI) depending on the number of elements [34].

Number of elements (*m*)	3	4	5	6	7	8	9	10	11	12	13	14	15
Value of the Random Index (RI)	0.52	0.89	1.11	1.25	1.35	1.40	1.45	1.49	1.52	1.54	1.56	1.58	1.59

Table 3. Types of causal factors that lead to fatal accidents in the period 2008-2015 (source: [59]).

CAUSAL FACTORS	2008	2009	2010	2011	2012	2013	2014	2015
Hit by falling materials when operating the machinery	3							
Unintended movement of the truck/Roll over			2		1	1	1	
Contact with the machinery parts		1					1	
Unintended starting of the machinery				1				1
Hit by ejected materials	1							
Electric shock (direct)	1		1				1	
Electric shock (indirect)	1	2					1	

Table 4. List of activities (As), hazard types (Hs), hazardous events (Es), and possible consequences (C).

ACTIVITIES (As)		HAZARD TYPES (Hs)	
A1	Arrival/Departure	H1	Mobility
A2	Preparation	H2	Mechanical
A3	Direct discharge	H3	Electrical
A4	Discharge into a concrete pump	H4	Environmental
A5	Discharge into a bucket	H5	Materials
A6	Final operations	H6	Ergonomics
		H7	Interferences

HAZARDOUS EVENTS (Es)		CONSEQUENCES/POSSIBLE HARMS (Cs)	
E1	Slipping when getting in/out of the truck	C1	Intoxication
E2	Contact with the rotating drum while operating	C2	Scrapes, Lacerations, Bruises, Abrasions
E3	Contact with heated surfaces while operating the drum	C3	Fractures
E4	Unexpected starting of the machinery while operating the drum	C4	Cutting, Severing upper limbs
E5	Unintended movement of the truck/Roll over while driving	C5	Cutting, Severing lower limbs
E6	Falls from heights when working on the drum	C6	Head injuries
E7	Direct/indirect contact with electrical parts	C7	Hearing illnesses
E8	Projection of high pressure fluids/materials while discharging the drum	C8	Eye illnesses
E9	Impacts while discharging the drum	C9	Respiratory illnesses
E10	Slipping/Low falls, Trips while discharging the drum	C10	Stress, Fatigue
E11	Cutting, severing during final operations (cleaning, maintenance, settings)	C11	Burns (including abrasive effects of sand)
E12	Inhalation or contact with dust and hazardous substances while operating the drum (caustic effect of the fresh concrete because of its alkaline nature)	C12	Back injuries
E13	Entanglement, trapping while cleaning the drum	C13	Thorax injuries
E14	Severing, cutting while cleaning the drum	C14	Loss of muscle control (electrical shock)
		C15	Death

Table 5. Correlation matrix used to calculate the eigenvector W_{1I}.

Activities (As)							Average values	W_{1I}
	A1	A2	A3	A4	A5	A6		
A1	1.000	7.000	5.000	5.000	5.000	3.000	3.714	0.472
A2	0.143	1.000	0.333	0.333	0.333	0.250	0.331	0.042
A3	0.200	3.000	1.000	1.000	1.000	0.333	0.765	0.097
A4	0.200	0.167	1.000	1.000	1.000	0.333	0.472	0.060
A5	0.200	3.000	1.000	1.000	1.000	0.333	0.765	0.097
A6	0.333	4.000	3.000	3.000	3.000	1.000	1.817	0.231

Table 6. Results of the pairwise comparisons to compute the relationship matrix W_{2I}.

W_{2I} (Correlation Matrix)						
	A1	A2	A3	A4	A5	A6
A1	0.280	0.247	0.247	0.247	0.247	0.227
A2	0.046	0.044	0.054	0.054	0.054	0.042
A3	0.102	0.100	0.109	0.109	0.109	0.100
A4	0.102	0.100	0.109	0.109	0.109	0.100
A5	0.102	0.100	0.109	0.109	0.109	0.100
A6	0.368	0.460	0.291	0.291	0.291	0.530

Table 7. Final results of Phase I, where W_{5I} provides the weights of hazards (Hs).

	W_{4I} x W_{3I}					
	A1	A2	A3	A4	A5	A6
H1	0.387	0.358	0.426	0.426	0.426	0.349
H2	0.174	0.162	0.189	0.189	0.189	0.158
H3	0.031	0.029	0.034	0.034	0.034	0.028
H4	0.074	0.066	0.082	0.082	0.082	0.063
H5	0.073	0.067	0.081	0.081	0.081	0.065
H6	0.085	0.081	0.092	0.092	0.092	0.079
H7	0.177	0.165	0.190	0.190	0.190	0.158

W_{2I} x W_{1I}	
A1	0.2580
A2	0.0473
A3	0.1034
A4	0.1034
A5	0.1034
A6	0.3896

W_{5I}	
H1	0.3849
H2	0.1727
H3	0.0310
H4	0.0721
H5	0.0723
H6	0.0850
H7	0.1740

Table 8. Final results of Phase II, where W_{5II} provides the weights of the hazardous events (Es).

	W_{4II} x W_{3II}						
	H1	H2	H3	H4	H5	H6	H7
E1	0.195	0.196	0.197	0.195	0.195	0.194	0.196
E2	0.088	0.089	0.090	0.089	0.089	0.088	0.089
E3	0.085	0.086	0.086	0.085	0.085	0.085	0.085
E4	0.036	0.036	0.036	0.036	0.036	0.036	0.036
E5	0.036	0.036	0.037	0.036	0.036	0.036	0.036
E6	0.055	0.054	0.055	0.054	0.054	0.054	0.055
E7	0.014	0.014	0.014	0.014	0.014	0.014	0.014
E8	0.064	0.064	0.064	0.063	0.063	0.063	0.064
E9	0.134	0.134	0.135	0.134	0.134	0.133	0.134
E10	0.115	0.116	0.117	0.115	0.115	0.115	0.116
E11	0.088	0.088	0.089	0.088	0.088	0.088	0.089
E12	0.063	0.063	0.064	0.063	0.063	0.063	0.063
E13	0.015	0.015	0.015	0.015	0.015	0.015	0.015
E14	0.011	0.011	0.011	0.011	0.011	0.011	0.011

W_{2II} x W_{1II}	
H1	0.382
H2	0.175
H3	0.031
H4	0.068
H5	0.070
H6	0.086
H7	0.181

W_{5II}	
E1	0.194
E2	0.088
E3	0.085
E4	0.036
E5	0.036
E6	0.054
E7	0.014
E8	0.063
E9	0.133
E10	0.115
E11	0.088
E12	0.063
E13	0.015
E14	0.011

Table 9. Final results of Phase III (a), where W_{5III} provides the weights of the possible consequences (Cs).

W_{2III} x W_{1III}	
E1	0.193
E2	0.088
E3	0.084
E4	0.036
E5	0.036
E6	0.054
E7	0.014
E8	0.064
E9	0.133
E10	0.115
E11	0.088
E12	0.062
E13	0.015
E14	0.011

W_{5III}		Ranking
C1	0.037	11
C2	0.216	1
C3	0.114	4
C4	0.116	2
C5	0.114	3
C6	0.095	5
C7	0.040	10
C8	0.057	7
C9	0.056	8
C10	0.068	6
C11	0.042	9
C12	0.033	12
C13	0.031	13
C14	0.014	14
C15	0.009	15

Table 10. Final results of Phase III (b): relationship matrix.

	W_{4III} x W_{3III}													
	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14
C1	0.037	0.038	0.038	0.038	0.038	0.037	0.037	0.037	0.038	0.037	0.038	0.037	0.037	0.037
C2	0.214	0.227	0.224	0.222	0.220	0.215	0.210	0.210	0.221	0.213	0.219	0.211	0.216	0.216
C3	0.113	0.118	0.118	0.117	0.118	0.113	0.111	0.111	0.118	0.113	0.117	0.112	0.114	0.114
C4	0.115	0.119	0.118	0.120	0.120	0.114	0.113	0.113	0.120	0.114	0.119	0.113	0.115	0.115
C5	0.113	0.117	0.117	0.118	0.118	0.113	0.111	0.112	0.118	0.113	0.117	0.112	0.114	0.114
C6	0.094	0.098	0.098	0.097	0.096	0.094	0.092	0.093	0.097	0.094	0.096	0.093	0.095	0.095
C7	0.040	0.042	0.041	0.041	0.041	0.040	0.039	0.039	0.041	0.040	0.041	0.039	0.040	0.040
C8	0.056	0.059	0.058	0.058	0.058	0.056	0.055	0.055	0.058	0.056	0.057	0.056	0.057	0.057
C9	0.056	0.058	0.058	0.058	0.057	0.056	0.055	0.055	0.058	0.056	0.057	0.055	0.057	0.057
C10	0.068	0.071	0.070	0.070	0.069	0.068	0.067	0.067	0.070	0.068	0.069	0.067	0.069	0.069
C11	0.042	0.044	0.043	0.044	0.043	0.042	0.041	0.041	0.044	0.042	0.043	0.041	0.043	0.043
C12	0.033	0.034	0.034	0.034	0.034	0.033	0.032	0.032	0.034	0.033	0.034	0.033	0.033	0.033
C13	0.030	0.032	0.031	0.032	0.031	0.030	0.030	0.030	0.032	0.030	0.031	0.030	0.031	0.031
C14	0.014	0.015	0.015	0.015	0.015	0.014	0.014	0.014	0.015	0.014	0.015	0.014	0.015	0.015
C15	0.009	0.010	0.010	0.010	0.010	0.009	0.009	0.009	0.010	0.009	0.009	0.009	0.009	0.009

Table 11. Comparison of the risk assessment's results.

List of Consequences (Cs)	Severity (1-5 scale)	HFD approach		Traditional approach		Values of Risk (normalized)		
		Weight of Consequences (normalized)	R_{HFD} (C × S)	P (1-5 scale)	R_T (R_T = P × S)	Risk code	R_T	R_{HFD}
C1	2	3.57	7.14	3	6	R1	6.67	2.91
C2	1	20.70	20.70	5	5	R2	5.56	8.45
C3	3	10.95	32.85	2	6	R3	6.67	13.41
C4	3	11.10	33.30	3	9	R4	10.00	13.60
C5	3	10.95	32.85	3	9	R5	10.00	13.41
C6	3	9.07	27.21	3	9	R6	10.00	11.10
C7	2	3.83	7.66	2	4	R7	4.44	3.13
C8	2	5.42	10.84	2	4	R8	4.44	4.43
C9	2	5.41	10.82	2	4	R9	4.44	4.42
C10	3	6.54	19.62	2	6	R10	6.67	8.01
C11	3	4.06	12.18	2	6	R11	6.67	4.97
C12	3	3.18	9.54	2	6	R12	6.67	3.90
C13	3	2.94	8.82	2	6	R13	6.67	3.60
C14	5	1.39	6.95	1	5	R14	5.56	2.84
C15	5	0.89	4.45	1	5	R15	5.56	1.82
Probability (P) = 1 (very unlikely) – 5 (very likely); Severity (S) = 1 (minor effects) - 5 (Catastrophic).								

Table 12. Comparison of the results of prior studies with the present study.

Method	Approach	n.o of phases (HoQs)	input	output	Correlations assessment	Risk assessment	Practical case study	Data source
Liu and Tsai [34]	Top-down	2	Construction items	Hazard causes	ANP	Augmentation by FMEA	Yes	Company experts
Bas [35]	Bottom-up	3	Set of working tasks	General set of preventive/protective measures	No	General assessment related to working tasks	No	Construction expert / Official statistics
Present study	Bottom-up	3	Activities that accomplish a working task	Specific set of preventive/ protective measures	ANP	Specific assessment related to working activities	Yes	Group of experts and operators