A Fuzzy-QFD approach for the enhancement of work equipment safety: a case study in the agriculture sector

Mario Fargnoli*[1], Mara Lombardi[2], Nicolas Haber[3]

Faculty of Civil and Industrial Engineering, Sapienza - University of Rome

Via Eudossiana, 18, Rome 00184, Italy

[1] mario.fargnoli@uniroma1.it; [2] mara.lombardi@uniroma1.it; [3] nicolas.haber@uniroma1.it

* Corresponding author

Mario Fargnoli is currently employed at the Italian Ministry of Agriculture as Technical Director and collaborates with Sapienza - University of Rome as Adjunct Professor since 2012. He worked at the Department of Precision Machinery of the University of Tokyo as JSPS Fellow Researcher from 2005 to 2007. He earned both his MD and PhD at Sapienza - University of Rome. His research interests and publications mainly concern design for safety, machinery safety, product-service systems, ecodesign as well as engineering design tools and methods.

Mara Lombardi is Assistant Professor at Sapienza - University of Rome, where she earned both master degree and PhD at the Department of Civil and Industrial Engineering. She is the Coordinator of the courses in Safety Engineering of the Sapienza - University of Rome. Her research activities and scientific publications mainly concern: Construction site safety; Fire Safety Engineering; Occupational Health and Safety; Risk Analysis; Safety engineering.

Nicolas Haber is an Industrial Engineer holding a PhD in Industrial Engineering and Engineering Management from Sapienza - University of Rome which he earned in 2017. His field of research is the design of product-service systems in a sustainable manner. He holds master's degrees in mechatronics engineering and industrial engineering management. Moreover, he has two years' experience at Heineken and obtained the 6-Sigma black belt certificate.

Abstract

The paper proposes a design for safety methodology based on the use of the Quality Function Deployment (QFD) method, focusing on the need to identify and analyse risks related to a working task in an effective manner, i.e. considering the specific work activities related to such a task. To reduce the drawbacks of subjectivity while augmenting the consistency of judgements, the QFD was augmented by both the Delphi method and the Fuzzy Logic approach. To verify such an approach, it was implemented through a case study in the agricultural sector. While the proposed approach needs to be validated through further studies in different contexts, its positive results in performing hazard analysis and risk assessment in a comprehensive and thorough manner can

contribute practically to the scientific knowledge on the application of QFD in design for safety activities.

Keywords: Design for safety, risk assessment, hazard analysis, Quality Function Deployment, fuzzy logic, agricultural machinery.

1. Introduction

The great popularity achieved by the Quality Function Deployment (QFD) method (Akao, 1990; ReVelle et al., 1998) in product development activities is due to its ability to allow engineers to translate customers' need into engineers' metrics effectively. The core of the method is based on the use of the House of Quality (HoQ), and a large number of studies focused on its use in different ambits, as for example (Carnevalli and Miguel, 2008; Shiu et al., 2013; Sivasamy et al., 2016; Vinayak and Kodali, 2012). In recent years, the use of QFD in specific fields of product development and assessment has been augmented, focusing on the solution of specific design problems, such as environmental, ergonomics, reliability, or safety concerns (Fargnoli and Sakao, 2017; Liu and Tsai, 2012; Younesi and Roghanian, 2015; Zhang et al., 2014).

In this study we focused our attention on the application of QFD in the Design for Safety field, where some examples can be found in literature e.g. (Bas, 2014; Fargnoli et al., 2012; Marsot, 2005). In particular, Bas (2014) argued that QFD can be used for risk assessment activities since it allows the definition of weighted importance scores to risks in a step-by-step manner starting from the tasks performed. In this study a three-phase model is proposed is proposed to consider the interrelationships between tasks and hazards, hazards and events, as well as events with preventive and protective measures. On one hand, such an approach certainly presents a complete risk assessment procedure, given that the events' importance factors are computed considering the probability of occurrence and the expected consequences of an event. On the other hand, the validation of this procedure through a real case study was not performed, while the use of the Delphi method (Buckley, 1994) to gather views from different experts, as well as the use of the Fuzzy Logic approach (Temponi et al., 1999) was suggested to augment the model effectiveness.

Accordingly, Sadeghi et al. (2016) addressed different types of QFD-based models in a design for safety framework. This analysis focused on the goal of the different approaches of QFD applied in the safety science field, remarking that they generally lack in considering work situations in a proper manner. At a more practical level, such a need has been also remarked by several studies. For example, Gangolells et al. (2010) and Zhou et al. (2015) remarked the lack of construction safety research on the specific working tasks, while similar concerns were addressed in the field of agriculture and forestry activities by (Fargnoli et al., 2010; Poje et al., 2016; Taattola et al., 2012; Fargnoli and Lombardi, 2018). This aspect is particularly relevant when considering the usage of a work equipment, since all the activities related to its use should be analysed during the risk assessment activities (Sadeghi et al., 2017).

On these research hints, the present study proposes a comprehensive design for safety methodology based on the use of QFD, which is aimed at dealing with the above-mentioned shortcomings. More in detail, we tried to augment the framework proposed by Bas (2014) with these goals in mind:

- To develop a procedure able to identify and analyse risks related to a working task (e.g. the use of a work equipment) more effectively, adapting such a framework as to include specific work activities related to such a task;

- To reduce the drawbacks of subjectivity while augmenting the consistency of judgements when performing hazard analysis and risk assessment.

Hence, the remainder of the paper is organized as follows. A background analysis is portrayed in Section 2, while Section 3 presents the main characteristics of the proposed methodology. The effectiveness of such an approach is demonstrated in Section 4 through its application to a real case study. The obtained results are discussed in Section 5, while Section 6 concludes the paper addressing future work.

2. Research background and motivations

2.1. Traditional Quality Function Deployment

Before analyzing the new developments of the method in the ambit of safety research, in this section a brief description of the traditional QFD is given, bringing to light its main characteristics while more detailed information can be found in the plethora of studies presented in literature, e.g. in (Carnevalli and Miguel, 2008; Chan and Wu, 2002; Mehrjerdi, 2010; Vinayak and Kodali, 2013). The core of the method is certainly the so-called “House of Quality” (HoQ), whose innermost part is represented by the relationship matrix (Figure 1), which in the HoQ links customer needs and expectations (i.e. the so-called Customer Requirements (CRs)) to appropriate technical attributes (i.e. the Engineering Characteristics (ECs)), providing their assessment and prioritization (Franceschini and Maisano, 2015).

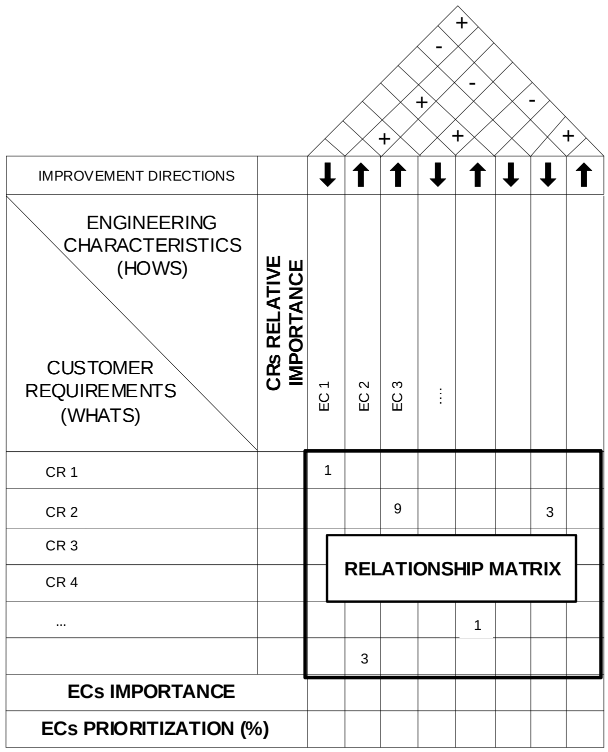

Figure 1. Traditional House of Quality (HoQ).

Based on this, different models of QFD have been proposed, starting from the simplest four-phase model (ReVelle et al. 1998; Shiu et al., 2013), where each step is characterized by a specific House of Quality (HoQ) as shown in Figure 2.

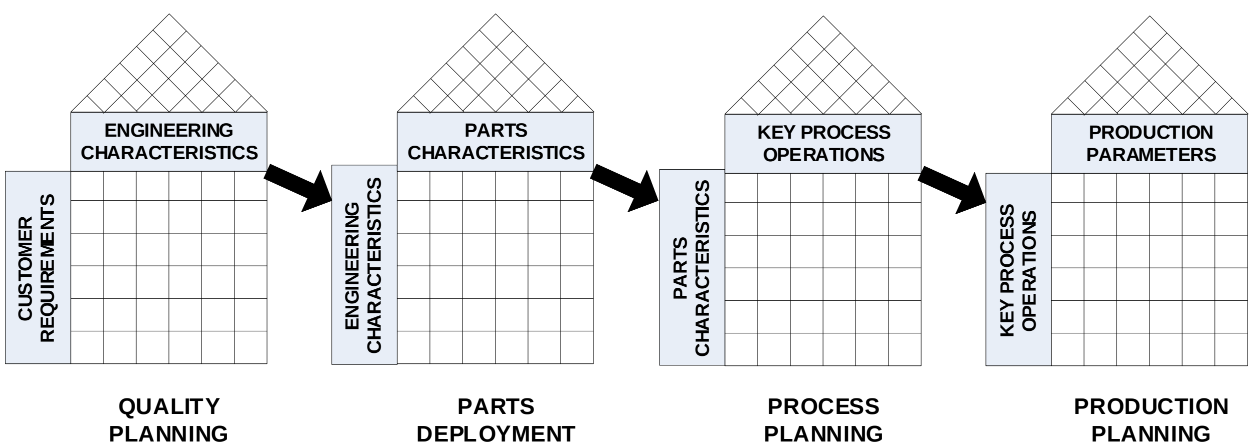

Figure 2. Traditional QFD four-phase model.

Without going into details (due to space constrain and to retain focus), two main aspects can be underlined when considering the use of QFD. On one hand, the use of the QFD during design activities need to be addressed. In fact, while the traditional approach can follow the phases of a conventional design process (Fargnoli and Sakao 2017), most of applications do not consider all the four phases illustrated in Figure 2, but mainly concern the use of the first HoQ and its extensions at the beginning of the design process (Vinayak and Kodali, 2012), focusing on the identification of customer requirements and their prioritization (Franceschini et al., 2015; Kamvsyi et al., 2014).

Secondly, it has to point out that results provided by the HoQ are of a qualitative nature and this can lead to an incorrect assessment of a characteristic/attribute of the system being analysed. Such a limitation concerns both the input data (i.e. the definition of customer needs and their level of importance), as well as the assessment of the ECs (Carnevalli et al., 2010; Franceschini and Maisano, 2015).

To reduce these drawbacks the prevailing literature (i.e. Carnevalli and Miguel 2008; ; Kahraman et al., 2006; Sivasamy et al., 2016; Temponi et al., 1999; Vinayak and Kodali 2013; Zare Mehrjerdi 2010; Zhang et al. 2015), agrees on recognizing that one of the most effective ways to improve the effectiveness of QFD consists in understanding the customers' needs in a more effective manner, as well as in rating the customers' preferences as accurately as possible by means of HoQ's supporting tools, such as:

- The Analytic Hierarchy Process (AHP) and the Analytic Network Process (ANP) methods, which allow the selection of the optimal solution to a complex problem by decomposing it in a systematic and hierarchical manner (Patriarca et al., 2016; Ho, 2012; Saaty, 1990; Saaty and Sodenkamp, 2008).
- The Kano Model to define the requirements that can effectively increase value for

customers (Kano, 1984; Tontini, 2007).

- An ordering based decision making approach based on the Yager's theory of aggregation to aggregate the CRs' judgments into a continuous interval scale (Chen et al., 2013; Franceschini and Maisano, 2015; Wang and Tseng, 2011; Yager, 1993; Zheng et al., 2016).
- The Fuzzy logic sets to deal with the uncertainty given by the imprecision and vagueness of the qualitative and subjective definitions of CRs (Abdolshah and Moradi, 2013; Kamvysi et al., 2014; Patriarca et al., 2016).

2.2. Quality Function Deployment in safety research

As argued by Fargnoli and Sakao (2017) few studies addressed the use of QFD in safety research, mostly consisting in including safety requirements into customer expectations and needs (Fargnoli et al., 2012; Marsot, 2005). Differently from such a conventional approach, both (Liu and Tsai, 2012) and (Bas, 2014) proposed novel methods based on the "cause-effect" mechanism of the HoQ. The former consists in a two-phase method aimed at assessing the relationships among construction items (first phase), and hazard types and hazard causes (second phase); instead, the latter uses three HoQs to consider the relationships between tasks and hazards, hazards and events, and events compared with preventive and protective measures (Figure 3).

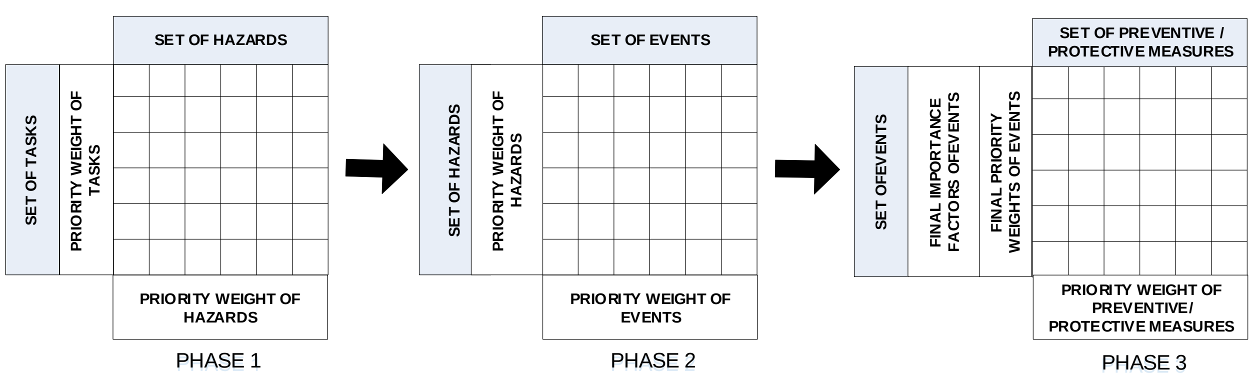

Figure 3. Scheme of the approach proposed by Bas (2014).

More in detail, this framework presents a more complete risk assessment procedure, since:

- It allows the analysis and evaluation of the influence that a certain hazard can have on different types of events, as well as the effect that a preventive/protective measure can have on more than one hazardous event;
- The final priority weight of events (in the third phase) is computed taking into account the probability of occurrence, the expected economic cost of each event, and the expected consequences of events.

Nevertheless, these studies (Liu and Tsai, 2012; Bas 2014) take into account only general tasks while the analysis of specific activities related to a single task (e.g. the use of a work equipment considering all the activities related to its practical utilization) is not included. Hence, they can be used only at a general level, when operations' planning is carried out. In fact, they provide insufficient information to perform risk assessment in a practical context, where work activities need to be evaluated more in detail, especially when the safety level of machinery or work equipment has to be assessed and augmented (Hale, 2007; Rausand and Utne, 2009). Thus, when considering the design activities, they ought to be applied during the detailed design stages of the design process, as suggested by (Sadeghi et al., 2016).

2.3. Research issues

On these considerations, it emerges that the use of a QFD based approach in the design for safety context can be beneficial thanks to its ability in determining cause-effect inter-relationships, and assigning weight to each item when performing risk assessment (Liu et al., 2009). In particular, the framework proposed by Bas (2014) can allow engineers to carry out risk assessment in a thorough manner suggesting them the preventive/protective interventions that have effect on multiple events. Nevertheless, such an approach lacks in addressing the analysis on specific work situations, considering that to properly enhance the safety level of a work task designers need to focus on what will be performed by the operators (the activities), which is often very different from what the they have imagined and stipulated (the task), as stressed by Lux et al. (2016). This is particularly true when considering the use of a work equipment (Hasan et al., 2003; Khanzode et al., 2012; De Galvez et al., 2016).

Hence, to limit the drawbacks discussed in the previous sections, this framework need to be augmented addressing both: the reduction of the imprecision and vagueness of the qualitative and subjective nature of the HoQ's data, as well as the analysis of detailed work activities, to provide effective information for enhancing the safety level practically.

3. Research approach

With this aim in mind, the proposed methodology relies on the approach proposed by Bas (2014) augmented as showed in Figure 4, where to fulfil the HoQ:

- Interviews with experts and operators are needed to define both the CRs and the ECs.
- The Delphi method is used to collect the scores of the relationships matrix by means of semi-structured questionnaires; the results are then "filtered" by the use of the fuzzy logic.

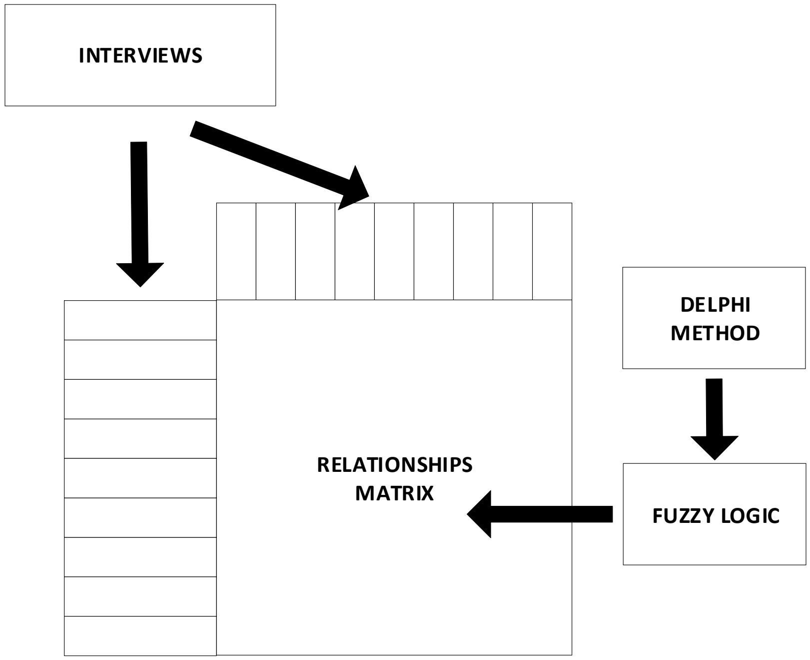

Figure 4. Scheme of the proposed HoQ's assessment approach.

Hence, the method proposed by Bas (2014) was augmented as follows:

- In the first HoQ the specific activities related to a general task are considered: for instance, if the analysis concerns the use of an agricultural tractor, all the work situations related to its use in a specific context should be considered, including the setting and maintenance operations.
- The interviews with experts and operators allows engineers to better define the inputs and outputs of each HoQ, i.e. the list of the activities, of hazards, of hazardous events, as well as of the preventive and protective measures.
- The combined use of the Delphi method and fuzzy logic allows a more objective assessment, reducing imprecisions and vagueness of the scoring system.

As per the scoring system used in the different HoQs, we followed the rules provided by Bas (2014), and in particular:

1. HoQ I (activities and hazards relationships evaluation): 0 (no relationship); 3 (weak relationship); 9 (strong relationship).
2. HoQ II (hazards and events relationships evaluation): 0 (no relationship); 3 (weak relationship); 9 (strong relationship).
3. HoQ III (comparison of the events with the preventive and protective measures): 0 (no relationship); 3 (weak relationship); 6 (medium relationship); 9 (strong relationship).

Consequently, to apply the fuzzy logic for the first two HoQs, we adapted the conversion values proposed by Vinodh et al. (2017) as shown in Table 1. More in detail, to transform the crisp CRs' importance ratings and relationships scores into fuzzy numbers, the use of triangular fuzzy numbers (TFNs) (Kaharaman et al., 2006) was considered. These TFNs are represented by the parameters (*l*, *m*, *u*), where, in accordance with (Zaim et al., 2014), they namely refer to the smallest possible value (*l*), the most promising value (*m*), and the largest possible value (*u*).

Table 1. Fuzzy relationship scores for HoQ I and HoQ II (adapted from Vinodh et al., (2017)).

	CRISP SCORE	TRIANGULAR FUZZY NUMBER EQUIVALENT		
		Lower value (*l*)	Middle value (*m*)	Upper value (*u*)
No relationship	0	0	0	0
Weak relationship	3	0.1	0.3	0.5
Strong relationship	9	0.7	1	1

Instead, for the third HoQ the degrees of relationships adopted are depicted in Table 2.

Table 2. Fuzzy relationship scores for HoQ III (adapted from Vinodh et al., (2017)).

	CRISP SCORE	TRIANGULAR FUZZY NUMBER EQUIVALENT		
		Lower value (l)	Middle value (m)	Upper value (u)
No relationship	0	0	0	0
Weak relationship	3	0	0,3	0,5
Medium relationship	6	0.5	0.7	0.9
Strong relationship	9	0.9	1	1

Accordingly, to obtain the final crisp values the equation proposed by Vinodh and Chintha (2011) is used:

$$S_{crisp} = \frac{l+2m+u}{4} \qquad (1)$$

Where, as previously discussed, *l*, *m* and *u* are lower, middle and upper limits of the fuzzy score.

4. Case study

To validate such an approach, the methodology was applied in a practical case study concerning the risk assessment of work activities related to the use of a wheeled agricultural tractor and its equipment (e.g. plough, ripper, trailers, etc.). The study was carried out in collaboration with a company that produces barley and wheat and uses a medium sized cabin tractor (80 kW). As for the group of experts who supported us, 10 technicians belonging to the Italian Workers' Compensation Authority (INAIL), the Italian Association of Dealers of Agricultural Machinery (UNACMA), and the Italian Federation of Agro-mechanics and Farmers (CAI-Agromecc) were involved, as well as the company manager and the tractor users.

4.1. Data collection

Interview with experts and users were carried out in order to define the different lists of the activities, hazards, hazardous events, and preventive and protective measures (Table 3 and Table 4).

Table 3. List of the activities (A), hazards (H) and events considered in the analysis.

ACTIVITIES	HAZARDS	EVENTS
A1 - Setting	H1 - Machinery mobility	E1 - Contact with high temperature parts
A2-Trailing	H2 - Moving elements	E2 - Contact with cutting parts
A3- Ripping	H3- Thermal hazards	E3 – Discomfort (muscular problems)
A4 - Plowing	H4 - Stability (machinery)	E4 -Loss of stability
A5 - Tilling	H5 - Environment (dust, heat, gradient)	E5 - Contact with ejected objects
A6 - Shredding	H6 – Noise/Vibrations	E6 - Exposure to noise
A7 -Sowing	H7 - Approach of a moving element to a fixed part	E7 - Exposure to vibrations
A8- Mowing	H8 - Ergonomic (access)	E8 -Slipping, falling
A9- Baling	H9 - Ergonomic (posture, commands)	E9 - Impacts with moving parts
	H10 - Combination (stress)	E10 - Crushing, entanglement
		E11 - Impacts with falling objects

Table 4. List of the preventive and protective measures considered in the analysis.

PREVENTIVE AND PROTECTIVE MEASURES	
P1 - Mower's guards	P11 -Seat's restraint system
P2 - Transmission belt protection	P12 - Mechanical block/unblock of parking
P3 - Protection of the gearbox	P13 - On/Off locking differential system
P4 - Access handles	P14 - Safety instructions (tractor and equipment)
P5 - Roll-over protective structure (ROPS)/cabin	P15 - PPE (Personal protective equipment)
P6 - Anti-vibration seat	P16 – Shredder and other equipment guards
P7 - Adequate muffler	P17 – Power take-off (PTO) protection
P8 - Cabin filters	P18 – Falling object protective structure (FOPS)
P9 - Seat's "dead-man switch"	P19 - Acoustic warning device
P10 - Seat's adjustment leverages	P20 – Information/Instructions

4.2. HoQ I

In this phase the relationships between the work activities (A) and the hazards (H) are evaluated. It has to point out that, following the procedure proposed by Bas (2014), the importance level of the activities (e.g. the priority weight) was assumed as t = 1/9 (since 9 different activities were considered) given that all the activities are required to accomplish the overall task, i.e. “use of the tractor”. The output of this phase consists in the evaluation of the priority weight of the hazards, as shown in Table 5.

Table 5. Results of the HoQ I.

	H1			**H2**			**H3**			**H4**			**H5**			**H6**			**H7**			**H8**			**H9**			**H10**		
	l	***m***	***u***	***l***	***m***	***u***	***l***	***m***	***u***	***l***	***m***	***u***	***l***	***m***	***u***	***l***	***m***	***u***	***l***	***m***	***u***	***l***	***m***	***u***	***l***	***m***	***u***	***l***	***m***	***u***
A1	0,01	0,04	0,06	0,18	0,39	0,56	0,21	0,36	0,44	0,01	0,04	0,06	0,13	0,24	0,31	0,09	0,13	0,13	0,00	0,00	0,00	0,31	0,53	0,63	0,40	0,65	0,75	0,14	0,28	0,38
A2	0,63	0,91	0,94	0,04	0,11	0,19	0,00	0,00	0,00	0,70	1,00	1,00	0,04	0,11	0,19	0,10	0,30	0,50	0,18	0,39	0,56	0,39	0,61	0,69	0,24	0,44	0,56	0,15	0,31	0,44
A3	0,31	0,53	0,63	0,28	0,41	0,44	0,00	0,00	0,00	0,33	0,56	0,69	0,55	0,83	0,88	0,33	0,56	0,69	0,70	1,00	1,00	0,09	0,26	0,44	0,25	0,48	0,63	0,04	0,11	0,19
A4	0,40	0,65	0,75	0,28	0,41	0,44	0,00	0,00	0,00	0,40	0,65	0,75	0,33	0,56	0,69	0,40	0,65	0,75	0,70	1,00	1,00	0,18	0,39	0,56	0,25	0,48	0,63	0,05	0,15	0,25
A5	0,31	0,53	0,63	0,13	0,24	0,31	0,00	0,00	0,00	0,33	0,56	0,69	0,33	0,56	0,69	0,40	0,65	0,75	0,70	1,00	1,00	0,09	0,26	0,44	0,10	0,30	0,50	0,05	0,15	0,25
A6	0,31	0,53	0,63	0,28	0,41	0,44	0,00	0,00	0,00	0,33	0,56	0,69	0,33	0,56	0,69	0,33	0,56	0,69	0,70	1,00	1,00	0,09	0,26	0,44	0,10	0,30	0,50	0,05	0,15	0,25
A7	0,33	0,56	0,69	0,13	0,24	0,31	0,04	0,11	0,19	0,33	0,56	0,69	0,18	0,39	0,56	0,10	0,30	0,50	0,25	0,48	0,63	0,10	0,30	0,50	0,10	0,30	0,50	0,05	0,15	0,25
A8	0,33	0,56	0,69	0,35	0,50	0,50	0,00	0,00	0,00	0,29	0,45	0,50	0,39	0,61	0,69	0,33	0,56	0,69	0,33	0,56	0,69	0,10	0,30	0,50	0,40	0,65	0,75	0,05	0,15	0,25
A9	0,63	0,91	0,94	0,14	0,28	0,38	0,04	0,11	0,19	0,29	0,45	0,50	0,31	0,53	0,63	0,29	0,45	0,50	0,63	0,91	0,94	0,31	0,53	0,63	0,39	0,61	0,69	0,24	0,44	0,56
Fuzzy Imp.	0,33	0,52	0,59	0,18	0,30	0,36	0,03	0,06	0,08	0,30	0,48	0,56	0,26	0,44	0,53	0,24	0,42	0,52	0,42	0,63	0,68	0,17	0,34	0,48	0,22	0,42	0,55	0,08	0,19	0,28
Crisp Imp.	0,50			0,29			0,06			0,47			0,42			0,40			0,61			0,34			0,41			0,19		
Relative Imp.	13,6%			7,8%			1,6%			12,7%			11,5%			11,0%			16,5%			9,2%			11,1%			5,1%		
Rank	2			8			10			3			4			6			1			7			5			9		

4.3. HoQ II

The second HoQ allows the assessment of the relationships between the hazards (H) and the events (E), i.e. the hazardous situations that may occur while operating a tractor, providing the priority weight of the latter. In Table 6 an excerpt of the HoQ II is shown.

Table 6. Excerpt of the HoQ II's relationship matrix.

	E1			**E2**			**E3**			**E4**			**E5**			**E6**			**E7**		
	l	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*
H1	0,00	0,00	0,00	0,15	0,25	0,35	0,00	0,00	0,00	0,70	1,00	1,00	0,20	0,31	0,39	0,50	0,75	0,85	0,50	0,75	0,85
H2	0,50	0,75	0,85	0,70	1,00	1,00	0,15	0,25	0,35	0,00	0,00	0,00	0,20	0,31	0,39	0,34	0,50	0,55	0,29	0,44	0,51
H3	0,00	0,00	0,00	0,00	0,00	0,00	0,70	1,00	1,00	0,09	0,13	0,13	0,19	0,31	0,44	0,00	0,00	0,00	0,00	0,00	0,00
H4	0,08	0,13	0,18	0,08	0,13	0,18	0,08	0,13	0,18	0,61	0,88	0,88	0,15	0,25	0,35	0,04	0,06	0,09	0,00	0,00	0,00
H5	0,04	0,06	0,09	0,04	0,06	0,09	0,09	0,13	0,13	0,15	0,25	0,35	0,15	0,25	0,35	0,00	0,00	0,00	0,00	0,00	0,00
H6	0,04	0,06	0,09	0,04	0,06	0,09	0,00	0,00	0,00	0,04	0,06	0,09	0,04	0,06	0,09	0,26	0,38	0,38	0,44	0,63	0,63
H7	0,00	0,00	0,00	0,04	0,06	0,09	0,00	0,00	0,00	0,04	0,06	0,09	0,15	0,25	0,35	0,44	0,63	0,63	0,30	0,44	0,46
H8	0,04	0,06	0,09	0,11	0,19	0,26	0,33	0,50	0,60	0,09	0,13	0,13	0,39	0,56	0,59	0,09	0,13	0,13	0,04	0,06	0,09
H9	0,15	0,25	0,35	0,19	0,31	0,44	0,04	0,06	0,09	0,04	0,06	0,09	0,39	0,56	0,59	0,19	0,31	0,44	0,19	0,31	0,44
H10	0,35	0,50	0,50	0,35	0,50	0,50	0,00	0,00	0,00	0,15	0,25	0,35	0,19	0,31	0,44	0,09	0,13	0,13	0,09	0,13	0,13
Fuzzy Imp.	0,20	0,56	0,87	0,32	0,88	1,33	0,15	0,45	0,71	0,51	1,25	1,60	0,44	1,20	1,83	0,57	1,38	1,76	0,52	1,28	1,69
Crisp Imp.	0,55			0,86			0,44			1,18			1,18			1,31			1,22		
Rel. Imp.	0,05			0,07			0,03			0,10			0,10			0,11			0,10		
Rank	10			8			11			6			7			4			5		

4.4. HoQ III

The last HoQ provides an evaluation of the preventive and protective measures (Table 7). It has to point out that, differently from Bas (2014), in this phase to calculate the final priority weight of the events w_i, we adopted a simplified equation:

$$w_i = w_{ei} * (o_{ei} * s_{ei})$$

where:

o_{ei} = probability of occurrence of the event e_i ;

s_{ei} = expected severity of the event e_i ;

w_{ei} = priority weight of the event e_i derived from HoQ II.

In detail, the group of experts was asked to estimate both the probability of occurrence and the expected severity by means of a Likert scale (Likert, 1932) of 1 to 5 as shown in Table 7, where the values for the transformation of crisp numbers into fuzzy triangular numbers are also reported (Vinodh et al., 2017). An excerpt of the HoQ III is reported in Table 8.

Table 7. Crisp to fuzzy conversion (adapted from Vinodh et al. (2017)).

Severity of injuries	Probability (Likelihood level)	LIKERT SCALE	TRIANGULAR FUZZY NUMBER EQUIVALENT		
			Lower value (*l*)	Middle value (*m*)	Upper value (*u*)
Very minor	Very low	1	0	0	0.3
Minor	Low	2	0.1	0.3	0.5
Moderate	Medium	3	0.3	0.5	0.7
Severe	High	4	0.5	0.7	0.9
Unsurvivable	Very high	5	0.7	1	1

Table 8. Excerpt pf the HoQ III's relationship matrix.

	P1			**P2**			**P3**			**P4**			**P5**		
	l	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*	*l*	*m*	*u*
E1	0,00	0,00	0,00	0,19	0,26	0,26	0,24	0,34	0,34	0,00	0,08	0,08	0,00	0,00	0,00
E2	0,69	0,80	0,80	0,69	0,80	0,80	0,24	0,34	0,34	0,00	0,00	0,00	0,00	0,00	0,00
E3	0,00	0,00	0,00	0,00	0,00	0,00	0,63	0,71	0,71	0,11	0,13	0,13	0,00	0,04	0,04
E4	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,06	0,16	0,16	0,34	0,53	0,53
E5	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,15	0,15
E6	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,04	0,04	0,00	0,00	0,00	0,00	0,04	0,04
E7	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,04	0,04	0,00	0,00	0,00	0,00	0,04	0,04
E8	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,04	0,04	0,75	0,89	0,89	0,11	0,13	0,13
E9	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,11	0,20	0,20	0,45	0,50	0,50
E10	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,06	0,09	0,09	0,45	0,61	0,61
E11	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,19	0,19
Fuzzy Imp.	0,70	2,23	3,37	0,74	2,38	3,60	0,29	1,14	1,73	0,15	0,94	1,22	0,74	2,78	3,57
Crisp Imp.	2,13			2,27			1,08			0,81			2,47		
Rel. Imp.	6,5%			6,9%			3,3%			2,5%			7,5%		
Rank	7			6			11			12			4		

5. Discussion of results

The results achieved by means of the proposed procedure are summarized in Figure 5 (where the prioritization of hazards is shown), Figure 6 (concerning the prioritization of events), and Figure 7 (where the relative importance of the preventive and protective measures is shown).

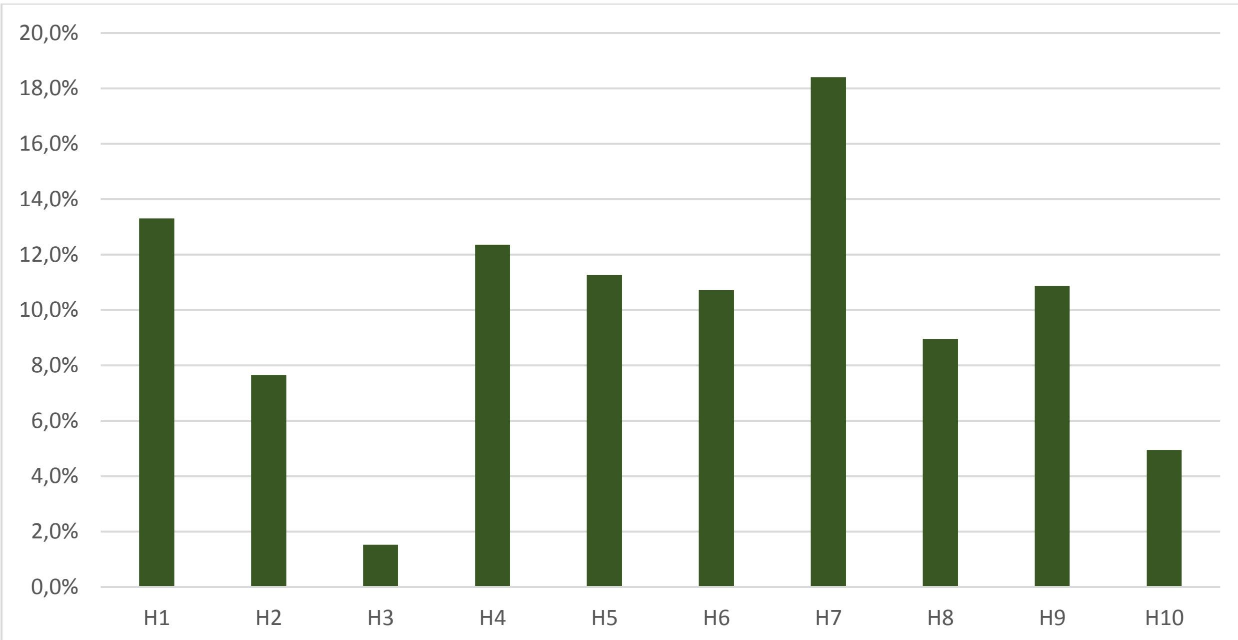

Figure 5. Prioritization of hazards.

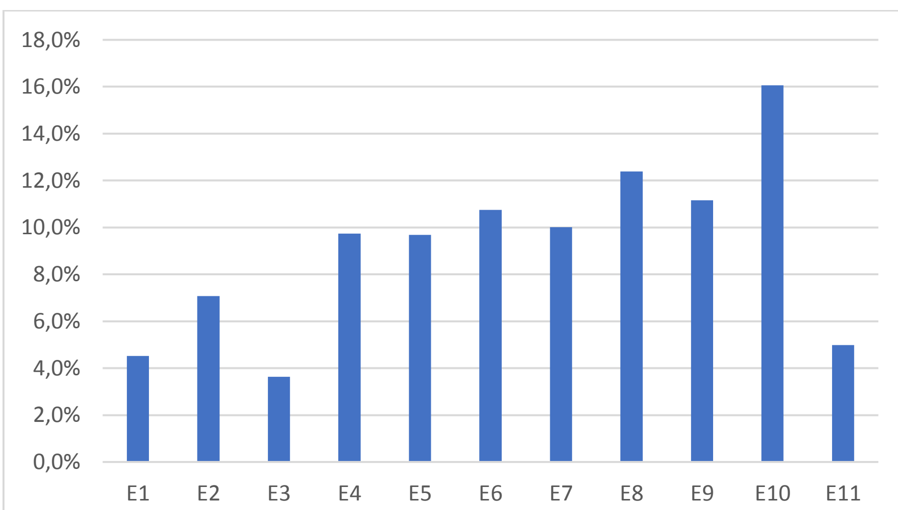

Figure 6. Prioritization of events.

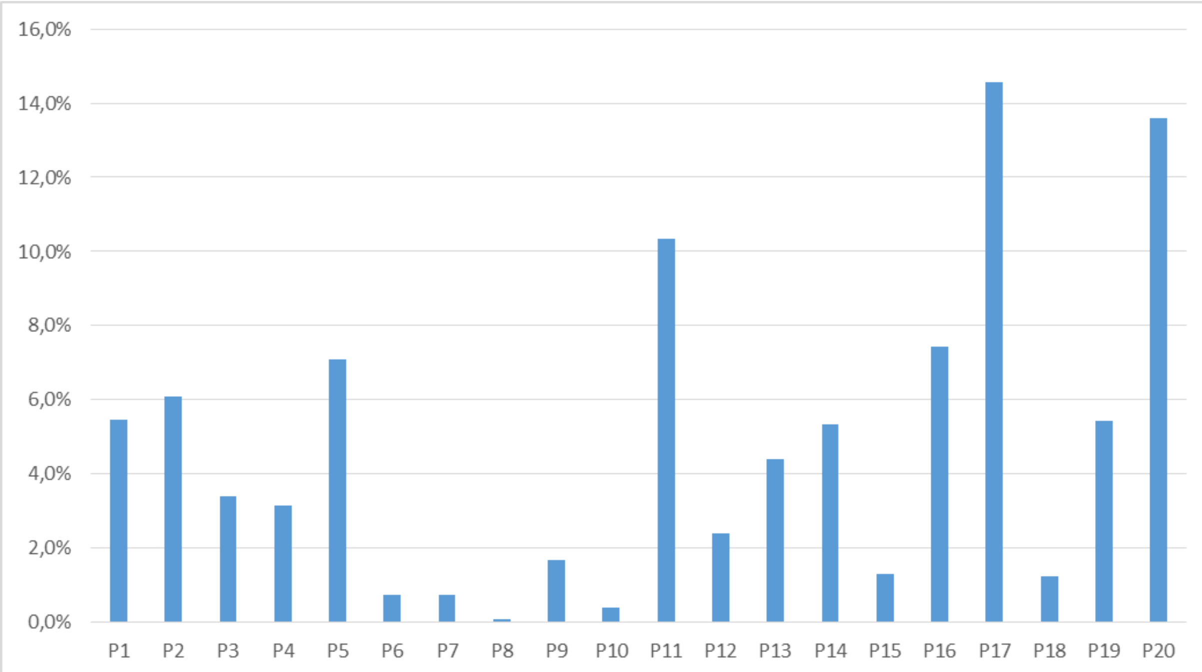

Figure 7. Prioritization of the preventive and protective measures.

From these data, it resulted that the most relevant priorities namely concern:

- The need of a proper protection of the PTO (power take-off) shaft (Figure 8);
- The provision of both safety pictograms and instructions for the tractor and for some equipment;
- The provision of a conformity certificate for the cabin (purchased on the aftermarket) and the ROPS; and
- The provision of seat's belt with a proper anchorage.

Figure 8. Detail of the tractor's PTO.

The priority of interventions reflects the practical safety level of the tractor and other equipment used by the company. In particular, while problems related to the PTO protection, the seat's restraint system and the handles are quite common in this sector (Kumar et al., 2000), the compatibility of the ROPS with the aftermarket cabin, as well as the lack of pictograms and other information systems (especially when connecting the tractor with other equipment) are rarely considered important when performing risk assessment (Caffaro and Cavallo, 2015).

These concerns are also due to the complex legislative framework in this sector (Fargnoli et al., 2010), obliging both designers and safety managers to consider a great number of parameters and constraints. In fact, when performing risk assessment several legislative sources of different nature need to be taken into account (e.g. in the European Union: the "tractor directive" 2003/37/EC (EC 2003) or the Regulation (EU) n. 167/2013 (EU, 2013); the "machinery directive" 2006/42/EC (EC, 2006) for certain requirements of tractors already in use; the "OHS Framework Directive" 89/391/EEC (EEC, 1989) for what concerns safety requirements of work equipment; the OECD Standard Codes for constructive requirements of agricultural and forestry tractors (OECD, 2017)).

Consequently, most of the companies operating in agricultural sector often have problems in the proper management of safety issues due to the lack of sufficient resources (Hasle and Limborg, 2006; Micheli and Cagno, 2010; Fargnoli et al., 2012; Kines et al., 2013; Cavallo et al., 2014).

Moreover, also problems related to hazardous events that might lead to minor injuries emerged from the analysis (for instance “slipping and falling” or “impacts with moving parts”). As in other similar sectors (e.g. the construction industry (Kines et al., 2007; Fargnoli et al., 2011)), accidents with minor consequences are often underestimated or neglected and official accident statistics provide incomplete information on them (Caffaro et al., 2017; Rautiainen et al., 2008). Hence, the results obtained underline the effectiveness of the proposed approach in handling the embedded complexities of risk assessment in this sector, allowing us to analyze in a comprehensive manner safety aspects related to different standpoints.

This output is in line with research clues provided by Underwood and Waterson (2013) and shows that the proposed approach can be considered as a possible answer to the need for a holistic approach to perform risk assessment of activities related to the use of a work equipment, enabling the identification and analysis of the interactions among different agents (operators, technical systems, working environment), as suggested by several authors as for example (Rausand and Utne, 2009; Sadeghi et al., 2016, Fargnoli et al., 2018).

As far as the quality of the results is concerned, although they were obtained by means of a semi-quantitative approach (Liu and Tsai, 2012), according to the group of experts’ opinions, the fuzzy logic allowed us to obtain more coherent results, reducing the biasness and imprecisions when using the traditional QFD, in line with findings provided by Abdolshah and Moradi (2013), and Cattaneo (2017) among others. This aspect appears relevant when performing risk assessment activities, since safety experts tend to use a single crisp value during risk assessments, which may lead to inaccurate assessment results, as stressed by Liu and Tsai (2012).

From a design for safety point of view, the proposed methodology can be considered a useful tool for the enhancement of the safety level of a system considering that the analysis focuses on working activities, following a bottom-up approach for hazard identification and assessment, providing more comprehensive and thorough results than the top-down approach (ISO 14121-2:2012). Thus, it can be applied from the early stages of the design process and in particularly when an upgrade is needed, which is a quite common situation in the production of durable goods (Xiong et al., 2016).

Thus, based on the above considerations, we believe that the contributions of this study in the design for safety context can be summarized as follows. The study reviews the recent studies on the use of QFD in the safety research field, providing research clues for the improvement of the existing models and thus contributing to augment the knowledge in such a specific field. In particular, capitalizing the research findings provided by Bas (2014), the proposed procedure on one hand, allows engineers to perform a more practical and thorough hazard analysis and risk assessment, taking into account work activities comprising a specific task, such as the use of a work equipment. On the other hand, the integrated use of the fuzzy logic and the Deplhi method with QFD reduces the drawbacks of subjectivity while augmenting the consistency of judgements that traditionally characterize the latter. The case study results highlight the potential benefits of the proposed approach in enhancing the safety level of a work equipment taking into account operators' practical concerns regarding its usage problems.

Beside these positive aspects, we have to underline that the present study also presents some limitations. Firstly, the proposed procedure does not provide a financial analysis. Costs related to the implementation of the preventive and protective measure need to be addressed to extend the validity of the proposed research approach (Liu et al., 2004; Hollnagel, 2008; Bas, 2014). Secondly, the use of quantitative tools and statistical data can certainly allow engineers to obtain more accurate data. Nevertheless, we opted for a simpler procedure as to extend its usability. Moreover, the application of other QFD's augmentation tools such as the analytic hierarchy process (AHP) by (Saaty, 2004) or the use of the alpha cuts to augment the fuzzy logic sets (Cattaneo, 2017) can also improve the quality of the results. Finally, the flexibility of the proposed procedure needs to be further verified by means of its application in different contexts and industries to validate the results achieved (Le Dain et al., 2013). In fact, 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 (e.g. (Yin, 2003)), the generalization of the above mentioned findings needs to be supported by the application of the proposed approach to different case studies.

6. Conclusions

Following the research clues provided by recent research works on the use of QFD in the design for safety field, the article proposed a practical methodology to support engineers when performing hazard analysis and risk assessment of work activities related to the use of an equipment. Such a procedure is based on the integrated use of QFD with fuzzy logic and the Delphi method, augmenting the effectiveness of the already proposed frameworks (Bas, 2014). In fact, the proposed approach can allow engineers to perform a more practical and thorough analysis, enhancing the safety level of a work equipment taking into account operators' practical concerns regarding its usage problems. The flexibility of the proposed procedure needs to be further verified by means of its application in different contexts to validate the results achieved. Thus, researchers and practitioners are invited to contribute to its possible development.

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