The use of Quality Function Deployment in hazard analysis and risk evaluation

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Abstract: Occupational health and safety (OHS) still represent a relevant problem at a global level despite the ever-increasing effort made in the last years at the normative level. Recent research on the factors influencing this phenomenon has shown the difficulties in bringing to light accidents' causalities and in the definition of the related measures for safety management. Actually, the risk assessment should take into account the mutual influences among the different risks and the related potential effects, while performing risk assessment in a sequential manner cannot always consider these interactions properly. To deal with such an issue, the use of the Quality Function Deployment (QFD) method has been proposed in several studies to perform hazard analysis and risk assessment more thoroughly. Nevertheless, although the above-mentioned studies provide remarkable research insights concerning the use of QFD in such a context, a comparative analysis bringing to light the effectiveness of the different approaches is missing. To reduce this gap the current study aims at investigating the recent research proposing QFD as a tool for hazard analysis and risk evaluation. The outcome of the study has shown that while all the approaches rely on the cause-effect mechanism inherent to the functioning of the House of Quality (HoQ), different goals and results can be achieved depending on the analysis standpoint (i.e. a top-down or a bottom-up approach) and the supportive tools used, such as analytic network process (ANP), or fuzzy logic. Accordingly, the study output can contribute practically to augmenting knowledge on the use of decision-making tools based on QFD in safety management.

Keywords: Quality Function Deployment (QFD), Machinery Safety, Risk Assessment, Multi-criteria Decision Making (MCDM).

I. Introduction

Accidents occurring during work activities remain a remarkable problem in most countries, despite the intervention of governments in issuing ever-stricter regulations and promoting occupational health and safety (OHS) guidelines. For example, in the European Union, in 2019, there were 3.1 million non-fatal accidents, which resulted in 3.408 fatal accidents [1]. These numbers show an increase between 2018 and 2019 both in the total number of non-fatal accidents at work in the EU (of about 0.5 %) and in fatalities (of about 2.3 %). In Figure 1 an excerpt of the incidence rates of accidents related to 2018 and 2019 is reported.

To deal with such a phenomenon from the engineering point of view, numerous tools to augment risk assessment have been proposed in recent years. As stressed by Pinto et al. [2], a large number of different occupational risk assessment (ORA) tools have been presented by researchers and practitioners, which mainly consist of three different steps:

1. Identification of potential hazards.
2. Assessment of the risks.
3. Hierarchy of risks.

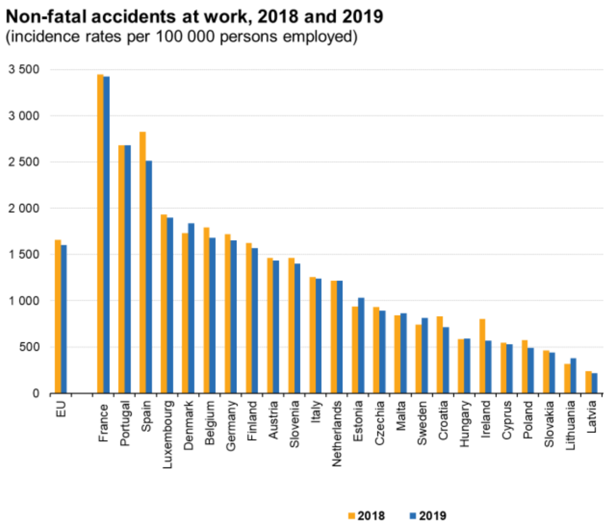

Fig. 1. Incidence rates of occupational accidents in the EU (adapted from: [1]).

ORA tools are usually based on data that are susceptible to uncertainty and imprecision due to lack of information, the use of expert judgments, or subjective interpretations

[3]. To reduce these uncertainties by providing more reliable results, several studies have proposed the adaptation of the Quality Function Deployment (QFD) method [4], whose mechanism allows engineers to filter subjective judgments and elicit critical factors by means of the assessment of mutual relationships among them [5]. Actually, the use of QFD's matrices reduces the limitations of sequential ORA tools, which can scarcely take into account the complexity of the interactions among the various risk assessment factors [2, 6]. However, the comparison between the different QFD approaches in the safety analysis context has not been sufficiently discussed in the literature. Accordingly, to reduce such a research gap the current study aims at investigating the recent research proposing QFD as a tool for hazard analysis and risk evaluation. More in detail, the remainder of the article is the following: in Section 2, the background analysis is provided, illustrating the extant research on the QFD applications in the safety analysis. Section 3 presents our research approach, while its application to a practical case study is described in Section 4. Then, Section 5 discusses the results achieved concluding the article.

II. Background Analysis

A. *The Quality Function Deployment method*

In the industrial world, the capability of a product or a service to effectively meet the needs and requirements of potential customers is a crucial factor in design and development activities. In this context, Quality Function Deployment (QFD) is one of the most widespread tools used to improve the quality of products, services, or their combinations (i.e. the so-called Product–Service Systems (PSSs)), allowing engineers to elicit customer requirements successfully [7]. A plethora of studies have demonstrated its benefits in different sectors (e.g. [8-12]. The main functioning of QFD is based on a set of matrices called the "House of Quality" (HoQ), which relies on a cause-effect mechanism to combine the so-called "whats" (i.e. the Customer Requirements (CRs)) with the so-called "hows" (i.e. the Engineering Characteristics (ECs)) by means of a relationship matrix [13]. In addition to such a basic scheme, the assessment of the "hows" is also provided as well as the mutual comparisons that can be performed by means of several correlation matrices. In figure 2 a scheme of the traditional HoQ is presented. The traditional QFD [4] relies on four phases, each one of them using a specific HoQ, which are aimed at identifying and prioritizing:

- Phase 1: engineering characteristics starting from customer requirements;
- Phase 2: parts characteristics starting from engineering characteristics;
- Phase 3: process parameters starting from parts characteristics;
- Phase 4: quality control parameters starting from process parameters.

Starting from this procedure, in recent years, researchers and practitioners have also proposed different tools based on the QFD main framework to analyze specific product/service properties. For instance, different examples of "environmental QFD" tools can be found, which are aimed at investigating the environmental performances of a product/service [14]. In such a context, an example is represented by the Quality Function Deployment for Environment (QFDE) method, whose goal is not represented by the development of a specific product/service, but consists in the assessment of its environmental priorities [15]. Actually, QFDE allows the comparison of different technical options, providing an estimation of the best performances in environmental terms.

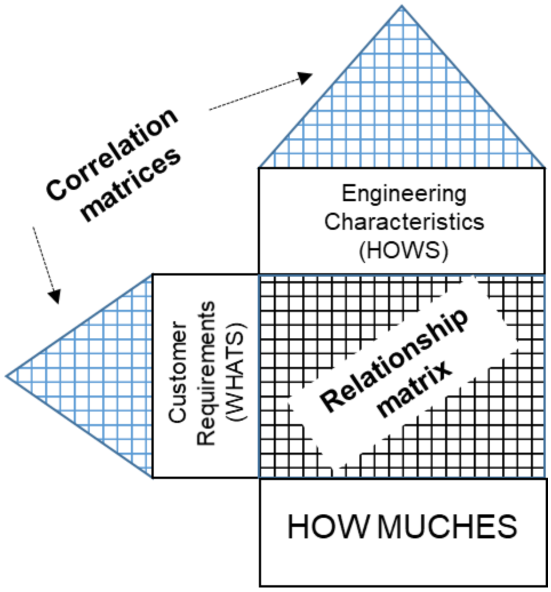

Fig. 2. Scheme of the House of Quality

Another example of QFD-based tools is represented by the ones aimed at the development Product/Service Systems (PSSs), where services should be considered as any kind of activity (such as installation, inspection, operation, maintenance, take-back, and consultation) included in a business offering [16]. In this ambit, a noteworthy example is represented by the QFD for Product/Service System (QFDfPSS) method [17], where the concept of Receiver State Parameters (RSPs) is included to replace CRs. RSPs should be intended as any aspects producing a positive or a negative effect on a PSS receiver [18].

B. *QFD in safety engineering*

Also in the field of safety different QFD-based solutions have been proposed, although in this sector the use of QFD is less diffused than in the environmental one. The main reasons for this are mainly related to the different nature of safety issues if compared to environmental concerns since the safety of products and processes is strictly correlated to the application of safety requirements by laws and regulations. Hence, the target levels for which engineers long are defined by mandatory requisites. Accordingly, most common QFD-based methods in engineering safety are based on the inclusion of safety requisites into customer requirements. Besides this conventional application of QFD, two novel approaches have been proposed in the literature, which rely on the cause-effect mechanism guaranteed by the HoQ:

1. Liu and Tsai [19] developed a two-phase approach capable of establishing a correlation between working tasks and hazard types (first phase), and between hazard types and hazard causes (second phase). A scheme of such a top-down approach for hazard analysis is reported in figure 3, where the use of the correlation matrices is supported by the Analytic Network Process (ANP) technique to address the inner relationships and interrelationships among the components of each HoQ. In this study, this approach was named "Liu and Tsai approach".

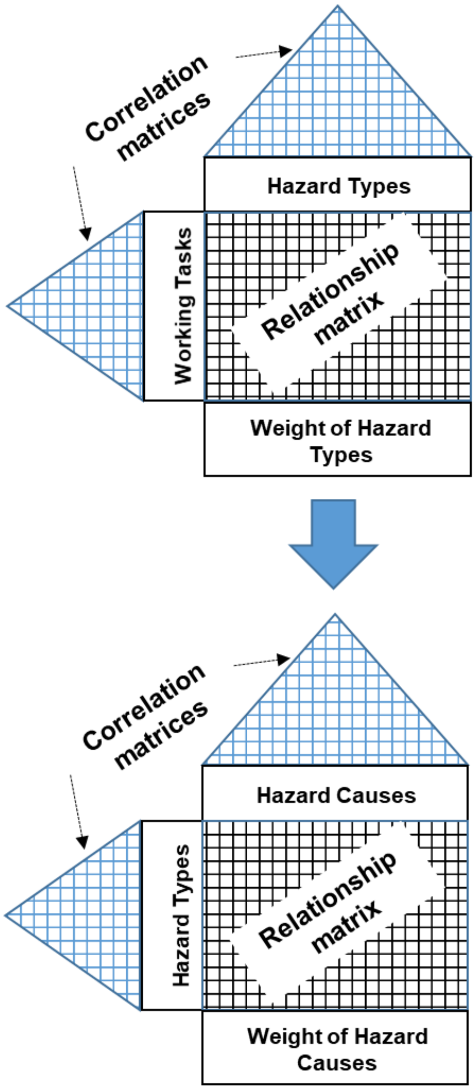

Fig. 3. Scheme of the approach proposed by Liu and Tsai [19]

2. Bas [20] proposed a three-phase approach where the different HoQs namely link tasks with hazards, hazards with events, and events with preventive and protective measures. The scheme of such a bottom-up approach risk analysis is illustrated in figure 4. This approach, augmented by the ANP method was further named Hazard Function Deployment (HFD) [5]. In this study, this approach was named "Bas approach".

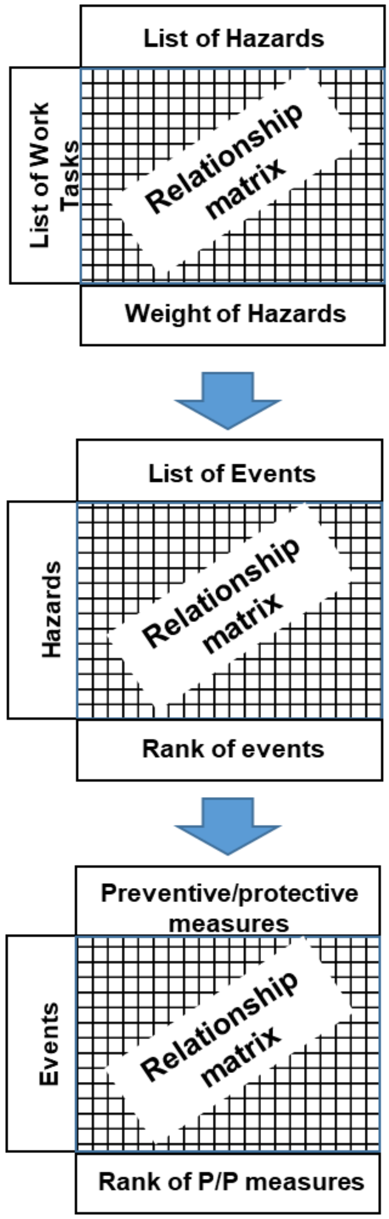

Fig. 4. Scheme of the Bas approach [20]

These approaches have been discussed and augmented by several studies [21-26]. However, these studies provide only partial analyses, while their practical comparison aimed at proposing a more thorough examination is missing.

III. Methods

To address this issue, both the above-mentioned safety QFD approaches were applied to the same case study, consisting of the risk analysis of a wheeled road paver machinery, which is used both for road repair work and for the construction of new roads. In figure 5 the main activities related to this process are summarized based on interviews with operators.

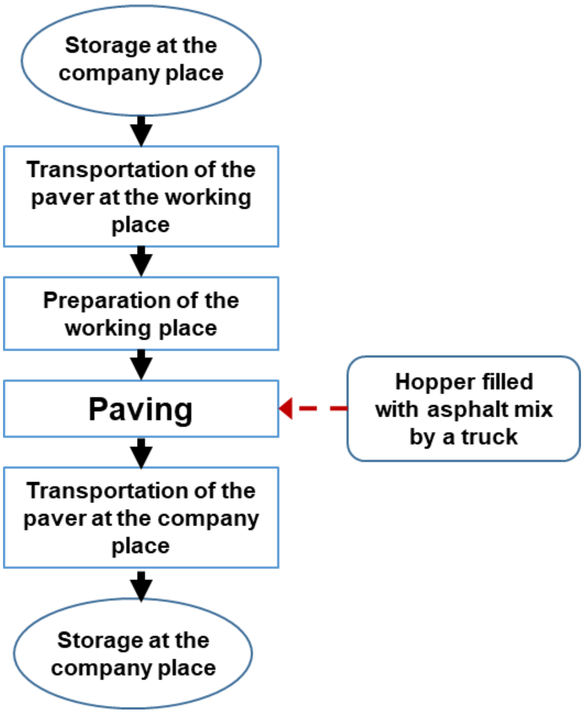

Fig. 5. Main phases of the paver use.

The working tasks related to the machinery use were obtained through interviews with the operators and safety experts. The following tasks were taken into account:

- T1 = preparation;
- T2 = hopper filling;
- T3 = conveyor operating;
- T4 = floating screed operating;
- T5 = blades regulation;
- T6 = material compacting;
- T7 = conclusive operations.

With reference to the Liu and Tsai approach, hazard types (K) and hazard causes (C) were elicited as shown in table 1.

TABLE I
HAZARD TYPES AND HAZARD CAUSES

Hazard Types	Hazard Causes
K1 = Mechanical h.	*C1 = Work environment*
K2 = Fire h.	*C2 = Machinery use*
K3 = Noise h.	*C3 = Materials*
K4 = Vibration h.	*C4 = External factors*
K5 = Heat h.	*C5 = Work organization*
K6 = Chemical h.	*C6 = Operator's behaviour*
K7 = Biological h.	
K8= Micro-climate h.	

As far as the Bas approach is concerned, the following elements were considered regarding the list of hazardous events (E) and the preventive/protective measures (P).

TABLE 2
HAZARDOUS EVENTS AND P/P MEASURES

Hazardous events	P/P measures
E1 = Cutting	*P1 = Lighting devices*
E2 = Crushing	*P2 = Obstacles' detection systems*
E3 = Contact with hot parts	*P3 = Motion delay device*
E4 = Falling	*P4 = Anti-slipping surfaces*
E5 = Hit by ejected materials	*P5 = Protection against falling*
E6 = Collision	*P6 = Hold-to-run control system*
E7 = Slipping	*P7 = Emergency stop device*
E8 = Hit by a falling object	*P8 = Guards*
E9 = Entrapment	*P9 = Pressure control system*
E10 = Explosion	*P10 = Roll over protective system*
	P11 = Personal protective equipment
	P12 = Operators' information and training

Based on this, to compare the two approaches the following assumptions were made.

In the Liu and Tsai approach, the ANP approach was used to develop each HoQ. With this goal in mind, a group of experts belonging to the Italian Compensation Authority (INAIL) was involved in the pair comparison assessment of the variables.

Regarding the integration of the ANP technique with the HoQ, in the literature, numerous examples can be found [27-29]. In this study, the augmented HoQ was obtained as schematized in figure 6, where:

- W1 represents an eigenvector reflecting the importance degree of each what.
- W2 represents the correlation matrix among the "whats", i.e. the results of the pairwise comparison of each "what" with respect to the others, i.e. it represents the inner dependency matrix of CRs.
- W3 represents the relationship matrix, where the pairwise comparison of each "what" with respect to each "how" is defined.
- W4 represents the correlation matrix among the "hows", i.e. the results of the pairwise comparison of each "how" with respect to the others, reflecting the inner dependency matrix of ECs.
- W5 represents an eigenvector reflecting the importance degree of each "how".

Accordingly, the overall priorities of the ECs are computed by multiplying the abovementioned eigenvectors/matrices as follows:

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

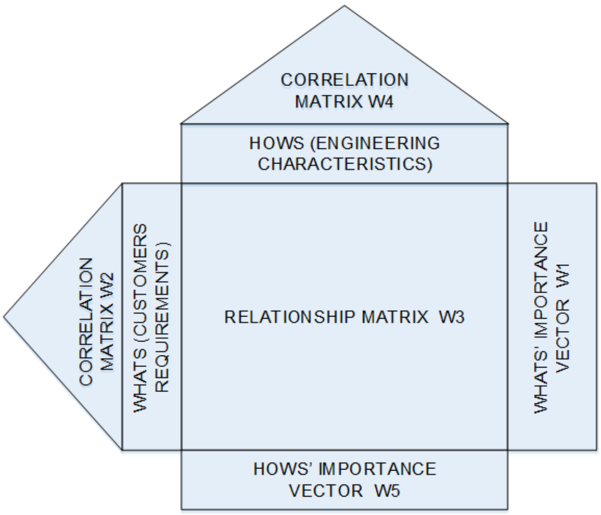

Fig. 6. Scheme of the HoQ augmented by the ANP technique.

In the Bas approach, to calculate the priority of the events (E) the probability of occurrence and the expected consequences of events based on the accident reports published by INAIL are considered. These values are computed for each event by means of the following equation:

$$w_E = w_{EP}\,(o_{nf} \times s_{nf} + o_f \times s_f)$$

where:

- w_E = represents the final priority of the event;
- w_{EP} = represents the preliminary priority of the event derived from the HoQ results;
- o_{nf} = is the probability occurrence of that leads to a non-fatal occupational injury;
- o_f = the probability occurrence of that leads to a fatal occupational injury;
- s_{nf} = represents the severity of the event that leads to a non-fatal occupational injury;
- s_f = represents the severity of the event that leads to a fatal occupational injury.

More in detail, the computation of the probability of occurrence is based on accident statistics related to fatal and non-fatal accidents that occurred in road paving activities, following the procedure proposed by Bas [20].

Differently, the severity was calculated using the criteria used by the Italian Compensation Authority, as reported in table 3.

TABLE 3
SEVERITY ASSESSMENT CRITERIA

Recovery period (days)	Severity description	Severity score
up to 15	*Minor injury*	*5*
16 – 50	*Moderate injury*	*10*
51-100	*Serious injury*	*20*
more than 100	*Critical injury*	*50*
---	*Death*	*75*

IV. Results

In the following table, the output of the Liu and Tsai approach are summarized. In particular, table 4 shows the values obtained for hazard types and causes, while figure 7 depicts the prioritization of the former.

TABLE 4
HAZARD TYPES AND HAZARD CAUSES

Hazard Types	Hazard Causes
K1 = 0.141	*C1 = 0.206*
K2 = 0.113	*C2 = 0.215*
K3 = 0.086	*C3 = 0.188*
K4 = 0.073	*C4 = 0.073*
K5 = 0.169	*C5 = 0.111*
K6 = 0.112	*C6 = 0.234*
K7 = 0.066	
K8= 0.100	

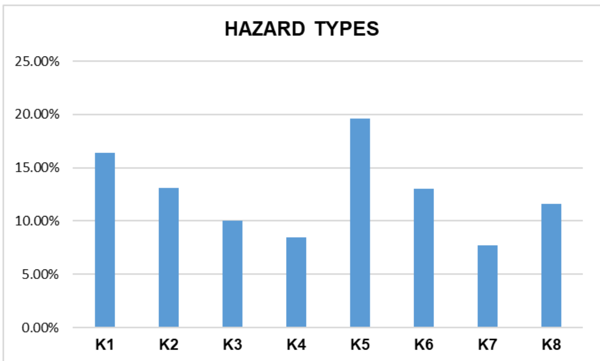

Fig. 7. Hazard types' relevance

From figure 7 it emerges that the most critical hazards are K5 (i.e. the presence of hot parts, surfaces, and materials), K1 (i.e. mechanical hazards due to moving parts), and K2 (noise hazard) respectively. As far as the hazard causes are concerned, the most relevant are C6 (the behavior of the operator), C2 (use of the machinery), and C1 (the work environment), as illustrated in figure 8.

Differently, as shown in table 5, the Bas approach showed that the most critical event is represented by E4, i.e. falls from the machinery or due to slips, followed by entrapment (E9) and crushing (E2).

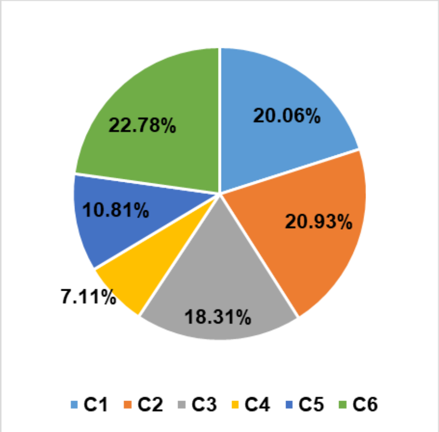

Fig. 8. Hazard causes relevance

TABLE 5
OUTPUT OF THE BAS APPROACH

Hazardous events	P/P measures
E1 = 0.0042	*P1 = 0.093*
E2 = 0.1468	*P2 = 0.088*
E3 = 0.0272	*P3 = 0.079*
E4 = 0.3571	*P4 = 0.076*
E5 = 0.0137	*P5 = 0.076*
E6 = 0.0970	*P6 = 0.042*
E7 = 0.1160	*P7 = 0.115*
E8 = 0.0525	*P8 = 0.041*
E9 = 0.1845	*P9 = 0.014*
E10 = 0.0007	*P10 = 0.111*
	P11 = 0.143
	P12 = 0.122

Accordingly, as per the priority of preventive/protective measures, most relevant interventions are represented by the use of personal protective equipment (P11), operator's information and training (P12), the presence of both the emergency stop device (P7) and a roll-over protective structure (P10), as shown in figure 9.

V. Discussion and Conclusions

The results achieved have shown interesting findings concerning the use of road paver machinery. On the one hand, from the Liu and Tsai approach, it emerged that the main causes of accidents are related to the behavior of the operator during the machinery use rather than during the transportation or storage phase. Additionally, also the work environment, i.e. hazards related to the work site resulted crucial from the OHS point of view. These outputs are in line with similar studies related to the use of work equipment in construction sites such as Su et al. [30], as well as in other sectors [31-32]. On the other hand, the Bas approach allowed us to elicit and prioritize the hazardous events and the related preventive and protective measures, bringing to light the relevance of minor accidents such as slips and falls. These accidents are rarely reported since they usually require a few days for recovering.

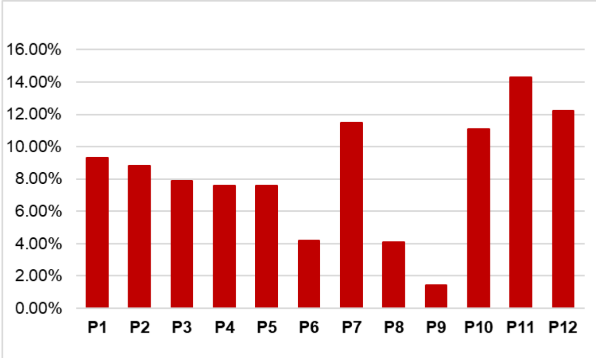

Fig. 9. Preventive/protective measures relevance

However, their occurrence is reasonably common, representing a contributing factor to OHS accidents among self-propelled machinery in line with research hints by Shibuya et al. [33] and Aminbakhsh et al. [34]. Accordingly, among the most relevant preventive measures, OHS information and training emerged.

From a more general perspective, it should be pointed out that both the QFD-based approaches considered in this study allow a clearer and more precise differentiation of the analyzed parameters thanks to the set of matrices of the HoQ. In particular, the Liu and Tsai approach, combining QFD and ANP, provides a more consistent analysis thanks to the integration of interdependent relationships among the different parameters, guaranteeing more precise information on the safety conditions. This confirms that the implementation of management tools for OHS allows bringing to light most critical factors related to the management of safety both at the individual and company level [35]. Although both approaches start from the analysis of working tasks, the Liu and Tsai approach relies on a top-down procedure as it focuses on what could cause harm. However, a bottom-up approach should be preferred to provide engineers with a more comprehensive procedure for hazard analysis and elicitation as suggested by the ISO/TR 14121-2:2012 report [36]. Based on this, the Bas approach appears more effective since it focuses on hazardous situations that can lead to harm, although the use of three HoQs is more time-consuming and the analysis should be supported by additional techniques such as ANP, Analytic Hierarchy Process (AHP), or fuzzy logic, as suggested by Sivasamy et al. [37].

In conclusion, the current study represents a first attempt to practically compare two different QFD-based tools for hazard analysis and risk evaluation, providing new insights for safety management capable of reducing the ambiguity of qualitative assessment criteria used in traditional risk assessment activities. However, further research is needed to evaluate the effectiveness of the proposed approaches also in different contexts.

REFERENCES

[1] Eurostat, Accident at work statistics (accessed on 24 March 2022: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Accidents_at_work_statistics#Number_of_accidents)

[2] Pinto, A., Nunes, I.L., and Ribeiro, R.A. (2011). Occupational risk assessment in construction industry–Overview and reflection. *Safety science*, 49(5), 616-624.

[3] Tixier, J., Dusserre, G., Salvi, O., and Gaston, D. (2002). Review of risk analysis methodologies of industrial plants. *Journal of Loss Prevention in the Process Industries*, 15, 291–303.

[4] Akao, Y. (1990). *Quality function deployment: Integrating customer requirements into product design*. Productivity Press, Cambridge, MA.

[5] Fargnoli, M., Lombardi, M., Haber, N., and Guadagno, F. (2020). Hazard function deployment: a QFD-based tool for the assessment of working tasks-a practical study in the construction industry. *International journal of occupational safety and ergonomics*, 26(2), 348-369.

[6] Rozenfeld, O., Sacks, R., Rosenfeld, Y., and Baum, H. (2010). Construction job safety analysis. *Safety Science*, 48 (4), 491–498.

[7] Fargnoli, M. and Sakao, T. (2017). Uncovering differences and similarities among quality function deployment-based methods in design for X: Benchmarking in different domains. *Quality Engineering*, 29(4), 690-712.

[8] Sakao, T. (2007). A QFD-Centred Design Methodology for Environmentally Conscious Product Design. *International Journal of Production Research*, 45 (18-19), 4143-4162.

[9] Carnevalli, J.A.and Miguel, P.C. (2008). Review, analysis and classification of the literature on QFD-Types of research, difficulties and benefits. *International Journal of Production Economics*, 114 (2), 737-754.

[10] Vinayak, K. and Kodali, R. (2013). Benchmarking the quality function deployment models. *Benchmarking: An International Journal*, 20 (6), 825 - 854.

[11] Sousa-Zomer, T.T. and Miguel, P.A.C. (2017). A QFD-based approach to support sustainable product-service systems conceptual design. *The International Journal of Advanced Manufacturing Technology*, 88(1), 701-717.

[12] Haber, N. and Fargnoli, M. (2019). Prioritizing customer requirements in a product-service system (PSS) context. *The TQM Journal*, 31(2), 257-273.

[13] Hauser, J.R. and Clausing, D. (1996). The house of quality. *IEEE Engineering Management Review*, 24(1), 24-32.

[14] Puglieri, F.N., Ometto, A., and Cauchick Miguel, P.A. (2011). Eco-design methods for developing new products based on QFD: a literature analysis. *Product: Management & Development*, 9 (1), 23-29.

[15] Masui, K., Sakao, T., Kobayashi, M. and Inaba, A. (2003). Applying quality function deployment to environmentally conscious design. *International Journal of Quality & Reliability Management*, 20 (1), 90-106.

[16] Tukker, A. and U. Tischner (2006). Product-services as a research field: past, present and future. Reflections from a decade of research. *Journal of Cleaner Production*, 14(17): 1552-1556.

[17] Sakao, T., Y. Shimomura, E. Sundin and M. Comstock (2009). Modeling Design Objects in CAD System for Service/Product Engineering. *Computer-Aided Design*, 41(3): 197-213.

[18] Fargnoli, M., Haber, N., and Sakao, T. (2019). PSS modularisation: a customer-driven integrated approach. *International Journal of Production Research*, 57(13), 4061-4077.

[19] Liu, H.T. and Tsai, Y.L. (2012). A fuzzy risk assessment approach for occupational hazards in the construction industry. *Safety Science*, 50, 1067–1078.

[20] Bas, E. (2014). An integrated quality function deployment and capital budgeting methodology for occupational safety and health as a systems thinking approach: The case of the construction industry. *Accident Analysis & Prevention*, 68, 42–56.

[21] Sadeghi, L., Dantan, J.Y., Siadat, A., and Marsot, J. (2016). Design for human safety in manufacturing systems: applications of design theories, methodologies, tools and techniques. *Journal of engineering design*, 27(12), 844-877.

[22] Shaker, F., Shahin, A. and Jahanyan, S. (2019), Developing a two-phase QFD for improving FMEA: an integrative approach, *International Journal of Quality & Reliability Management*, 36 (8), 1454-1474.

[23] Gul, M., Ak, M.F., and Guneri, A.F. (2017). Occupational health and safety risk assessment in hospitals: A case study using two-stage fuzzy multi-criteria approach. *Human and Ecological Risk Assessment: An International Journal*, 23(2), 187-202.

[24] Li, Y.L., Yang, Q., and Chin, K.S. (2019). A decision support model for risk management of hazardous materials road transportation based on quality function deployment. *Transportation research part D: transport and environment*, 74, 154-173.

[25] Fargnoli, M., Lombardi, M., and Haber, N. (2018). A fuzzy-QFD approach for the enhancement of work equipment safety: A case study in the agriculture sector. *International Journal of Reliability and Safety*, 12(3), 306-326.

[26] Gul, M. (2018). A review of occupational health and safety risk assessment approaches based on multi-criteria decision-making methods and their fuzzy versions. *Human and ecological risk assessment: an international journal*, 24(7), 1723-1760.

[27] Zaim, S., Sevkli, M., Camgöz-Akdağ, H., Demirel, O.F., Yayla, A.Y., and Delen, D. (2014). Use of ANP weighted crisp and fuzzy QFD for product development. *Expert Systems with Applications*, 41(9), 4464-4474.

[28] Lam, J.S.L. (2015). Designing a sustainable maritime supply chain: A hybrid QFD–ANP approach. *Transportation Research Part E: Logistics and Transportation Review*, 78, 70-81.

[29] Fargnoli, M. and Haber, N. (2019). A practical ANP-QFD methodology for dealing with requirements' inner dependency in PSS development. *Computers & Industrial Engineering*, 127, 536-548.

[30] Su, X., Pan, J., and Grinter, M. (2015). Improving construction equipment operation safety from a human-centered perspective. *Procedia Engineering*, 118, 290-295.

[31] Horberry, T., Larsson, T. J., Johnston, I., and Lambert, J. (2004). Forklift safety, traffic engineering and intelligent transport systems: a case study. *Applied ergonomics*, 35(6), 575-581.

[32] Fargnoli, M., Lombardi, M., Haber, N., and Puri, D. (2018). The impact of human error in the use of agricultural tractors: A case study research in vineyard cultivation in Italy. *Agriculture*, 8(6), 82.

[33] Shibuya, H., Cleal, B., and Kines, P. (2010). Hazard scenarios of truck drivers' occupational accidents on and around trucks during loading and unloading. *Accident Analysis & Prevention*, 42(1), 19-29.

[34] Aminbakhsh, S., Gunduz, M., and Sonmez, R. (2013). Safety risk assessment using analytic hierarchy process (AHP) during planning and budgeting of construction projects. Journal of safety research 46, 99-105.

[35] Fargnoli, M., De Minicis, M., and Di Gravio, G. (2011). Knowledge Management integration in Occupational Health and Safety systems in the construction industry. *International Journal of Product Development*, 14(1-4), 165-185.

[36] International Organization for Standardization (2012). Safety of Machinery—Risk Assessment—Part 2: Practical Guidance and Examples of Methods; ISO/TR 14121-2:2012; International Organization for Standardization: Geneva, Switzerland.

[37] Sivasamy, K., Arumugam, C., Devadasan, S.R., Murugesh, R., and Thilak, V.M.M. (2016). Advanced models of quality function deployment: a literature review. *Quality & quantity*, 50(3), 1399-1414.