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Digital solutions for workplace safety: An empirical study on their adoption in Italian metalworking SMEs

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ABSTRACT

Occupational safety is a critical aspect of the manufacturing sector, especially for small and medium-sized enterprises, which often face a safety divide compared to large companies due to significant differences in resources and awareness. Digital solutions can provide interesting support for dealing with specific hazardous situations and improving safety performance. However, there is a digital divide based on company size when it comes to the adoption of innovative digital solutions by small and medium-sized enterprises. This digital divide could widen the safety divide. To bridge these divides, the present research, through an extensive survey conducted among employers of Italian metalworking small and medium enterprises, explores various digital solutions and their potential to tackle hazardous situations in the workplace; it also addresses barriers and drivers influencing the adoption of the solutions and evaluates the results against different contextual factors characterizing the studied enterprises. Key barriers adopting digital solutions include the lack of perceived benefits, privacy concerns, implementation difficulties, and cost. On the other hand, the clarity and trustworthiness of the data collected and the ease of use of a digital solution can support the adoption. The study offers academic and managerial insights and contributes to the debate on the transition to Industry 5.0.

1. Introduction

Occupational safety is a crucial aspect of the European manufacturing sector. The manufacturing sector accounts for approximately 15% of the fatal and 19% of the non-fatal total accidents at work in the European Union (Eurostat, 2022). Examining the issue from the standpoint of company size, a *safety divide* becomes apparent between large and small and medium-sized enterprises (SMEs), pointing out a significant disparity in occupational safety performance. SMEs often face considerably more challenges related to organization, operations, regulations, and safety management, resulting in lower safety performance than larger enterprises (Al-Bayati, 2021; Micheli et al., 2021). Indeed, as firm size decreases, the frequency and severity of accidents, proportionally to the number of workers, increase (Al-Bayati, 2021; Walters and Wadsworth, 2016). The academic debate discusses the potential benefits of a managerial structured approach to occupational safety for improving related performance (Masi et al., 2019; Micheli et al., 2018); however, this approach may be feasible in large and structured enterprises, but difficult to sustain if applied to SMEs (Cagno et al., 2014; Masi et al., 2014; Micheli et al., 2021): consequently, workers employed in SMEs are generally more exposed to work-related risks than those working in larger companies.

Various solutions to improve occupational safety were proposed based on Industry 4.0 (I4.0). However, the evolution of I4.0 into Industry 5.0 (I5.0) (Barata and da Cunha, 2019; Kritzler et al., 2015) appears even more promising, as I5.0 emphasizes the interaction between humans and technology. Indeed, the benefits of I5.0 go far beyond enterprises' business operations (Park et al., 2019). Advanced sensor technology can be utilized not only for monitoring production and improving energy efficiency (Neri et al., 2023b), but also for monitoring the conditions of employees (Podgórski et al., 2017). The human-centric aspect of I5.0, as defined by the European Commission (2021), is often discussed solely in terms of cobots and human–machine interactions, see for example (Boschetti et al., 2023; Lu et al., 2022). However, recent discussions highlighted the potential for I5.0 to improve worker conditions and occupational safety (Kim et al., 2022; Wang et al., 2023). A *digital divide* based on enterprise size arises when adopting innovative digital solutions, as SMEs inherently have lower capacity than larger

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Abbreviations: PPE, Personal Protection Equipment; PPSM, Prevention and Protection Service Manager; PPSO, Prevention and Protection Service Officer; SMEs, Small and Medium Enterprises.

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firms (Sommer, 2015; Stentoft et al., 2019). This phenomenon can be explained by SMEs' limitations regarding organization, operations regulation, and management-related aspects (Hidalgo et al., 2020; Stentoft et al., 2019). As I5.0 becomes more prevalent, larger enterprises may experience significant improvements in occupational safety. However, SMEs, which lag in adoption compared to larger enterprises (Clemente-Almendros et al., 2024), may be limited in their ability to fully benefit from digital solutions regarding the support they could provide for occupational safety performance improvement (Zorzenon et al., 2022). The *digital divide* might widen the *safety divide* to the detriment of SMEs. To mitigate the disadvantage that SMEs face compared to larger enterprises, and to promote the widespread adoption of digital solutions to improve occupational safety conditions in manufacturing, it is crucial to identify the digital solutions that can be implemented to enhance occupational safety performance in SMEs, as well as the factors that may impede or facilitate their adoption, such as barriers and drivers.

This study contributes to the current debate by analyzing through a survey the adoption of digital solutions for hazardous situations in Italian metalworking SMEs, including an analysis of the barriers and drivers to the adoption. Metalworking is chosen as the context of interest given its significant economic value for the European and Italian economies and its critical role in safety and workplace accidents. The remainder of the paper follows. Section 2 analyses the literature to identify hazardous situations and digital solutions that can prevent or mitigate them. It also discusses barriers and drivers that hinder or foster the adoption of the solutions. Section 3 explains the research framework and the methodology for collecting and analyzing empirical data. Section 4 presents and discusses the results. Finally, Section 5 provides concluding remarks and suggests areas for future research.

2. Literature background

The section provides an overview of the background literature relevant to the present research. Hazardous situations in the manufacturing, mining, and construction sectors are identified for their relevance in terms of safety implications (Section 2.1), and the possible digital solutions to deal with them (Section 2.2). Although the focus of the present study is on the metalworking sector, the analysis of the literature has been extended also focusing on other neighboring sectors, in terms of work processes, solutions, and methods, to have a more comprehensive understanding. Barriers and drivers to the adoption of digital solutions are then identified and discussed (Section 2.3). Based on the provided literature analysis, emerging gaps are identified (Section 2.4).

2.1. Hazardous situations

Hazardous situations might not always be recognized in the workspace (Jeelani et al., 2017), and a failed assessment is one of the main reasons for accidents (Albert et al., 2014). As such, identifying sources of hazards represents a fundamental element of international and national occupational safety regulations. A systematic study of sources of hazards and circumstances of accidents is proposed by the *European Statistics on Accidents at Work* (ESAW) model (EU, 2001). Following a detailed description of the work context, through individual and workplace characteristics, the ESAW model evaluates the accident dynamics by analyzing the activity performed, the equipment and materials used, and the deviation from normal operating conditions. In Italy, Legislative Decree 81/2008 proposes an initial classification of hazardous situations and sources based on the characteristics of workplaces and equipment, the activities performed, and the substances and physical agents present in the workplace. Similarly, a systematic analysis is proposed by the National Institute for Insurance against Accidents at Work (INAIL) through the *PRE.VI.S* (INAIL, 2022) and *Infor.MO* (INAIL, 2006) models. *PRE.VI.S* model identifies 25 families of hazards, closely aligned with the categorization introduced by Legislative Decree 81/2008, and connects them to 26 risk factors, categorized into technical, procedural, and managerial. *Infor.MO* model, exploring the causal dynamics between hazardous situations and accidents, considered 6 families of hazards, related to activities, use and interaction with tools and machinery, personal protective equipment (PPE) and clothing, characteristics of materials, and the working environment.

The academic literature proposed frameworks to classify hazardous situations as well. Gul et al. (2024) evaluated hazardous situations in production facilities referring, for example, to the presence of equipment and machines (such as trucks, silos, compressors, etc.) operating in the proximity of workers, or to the characteristics of the working environment (such as work at height, presence of chemicals and electrical components leading to fires and explosions, etc.). Yu et al. (2024) classified hazard sources into six categories, namely mechanical, electrical, chemical (substance), biological, task-specific, and work environment factors.

The literature also focused on specific hazardous situations. Several examples can be brought focusing on hazardous situations that can be addressed by adopting digital solutions. Studies focused on the interaction between operators and working spaces, addressing, for instance, the presence of environmental parameters not suitable for workers (Kodali and Sahu, 2018; Thomas et al., 2018). Other studies addressed the interaction between operators and machines. Some studies focused on fixed machines, studying, for example, proximity to hanging loads on cranes (Kim and Kim, 2012; Teizer and Cheng, 2015) or robotic arms (Bragança et al., 2019; Khalid et al., 2017); other studies focused on moving machines, such as trucks (Ruff and Frederick, 2007; Teizer and Cheng, 2015) or forklifts (Barral et al., 2019; Palazon et al., 2013). Hazardous situations tackled by digital solutions could also be related to the characteristics of the working environment, for example, the presence of toxic or flammable substances or areas with restricted access (Teizer and Cheng, 2015) or the activity performed, for instance, work at height (Awolusi et al., 2018), lone workers (Bernal et al., 2017) or work in confined space (Teizer and Cheng, 2015). The literature suggested that digital solutions could also offer support to tackle hazardous situations connected to workers' behaviors, related for example to the lack of use of PPE (Kelm et al., 2013) or to the use of equipment for which a specific authorization may be required (Barata and da Cunha, 2019). Digital solutions could also offer support in managing emergencies, such as facilitating evacuations (Depari et al., 2018) or tracking workers' positions (Guo et al., 2017).

2.2. Digital solutions to tackle hazardous situations

The previous literature focused on the adoption of digital solutions to tackle hazardous situations (Liu et al., 2007). The topic is mainly addressed from a general perspective, meaning that digital solutions are identified and proposed, but not directly related to a specific hazardous situation. Focusing on the proposed digital solutions, Dodoo et al. (2024) identified four main categories of digital safety systems: wearable-based systems, augmented/virtual reality-based systems, artificial intelligence-based systems, and navigation-based systems. Li et al. (2018) focused on virtual and augmented reality applications in construction, defining a taxonomy comprising key characteristics of the solutions and application domains. Linking I4.0 and occupational safety management, Badri et al. (2018) considered big data, the Internet of Things, cyber-physical systems, cobots, artificial intelligence, and simulation.

The literature provided insights into more specific applications of digital solutions. For instance, environmental sensors, laser scanners (Vasumathi et al., 2019), and cameras (Guo et al., 2017; Ruff, 2008) might be applied to avoid collisions between operators and machines by identifying the relative position and distance (Awolusi et al., 2018). Examples of machines include trolleys, cranes (Kim and Kim, 2012), and industrial robots (Bortot et al., 2012). The adoption of wireless and operator wearable sensors (Barata and da Cunha, 2019) can send alarm signals in case of imminent collision (Kanan et al., 2018) and stop the machine (Vasumathi et al., 2019). Digital solutions can be applied for the safeguarding of machinery (Ruff, 2008), and for localizing personnel in case of emergency, lone workers, or work at height (Byeon et al., 2018; Mehata et al., 2019). Digital solutions could also support the monitoring of human behaviors, such as the correct use of PPE (Awolusi et al., 2018; Guo et al., 2017; Kelm et al., 2013), or the interactions with the surrounding environment (Kodali et al., 2018).

2.3. Barriers and drivers to the adoption of digital solutions

The adoption of digital solutions to address hazardous situations is influenced by a multitude of factors, which can either act as barriers to adoption or serve as drivers that promote it, especially when dealing with SMEs (Ghobakhloo et al., 2022; Nnaji and Karakhan, 2020). Dodoo et al. (2024) classified barriers into behavioral, technological, and organizational ones. Among behavioral barriers, privacy concerns (Choi et al., 2017; Schall et al., 2018) and management supervision (Badri et al., 2018) are significant obstacles to adoption, as digital solutions may be perceived as tools for controlling workers (Dodoo et al., 2024). However, clear and trustworthy information on the use of data by the employer could mitigate such perceptions (Chae and Yoshida, 2010). Additional behavioral barriers include resistance to change (Choi et al., 2017; Lee and Lee, 2018) and social influence exerted by colleagues (Anderson and Lee, 2008; Rubin and Ophoff, 2018; Safeea et al., 2019). The latter, however, could also serve as a driver if colleagues vouch for a digital solution (Safeea et al., 2019). According to various theories, such as the unified theory of acceptance and use of technology (Venkatesh et al., 2003) or the technology acceptance model (Davis, 1989), the willingness to adopt a technological solution depends on its perceived usefulness. Consequently, adoption is likely favored when hazards are perceived (Choi et al., 2017; Ferraro et al., 2019; Mayton et al., 2012) and operators feel more vulnerable (Choi et al., 2017). Conversely, rooted attitudes such as overconfidence and lack of risk awareness, or even distraction or tiredness, discourage the adoption and favor unsafe behaviors (Bernal et al., 2017). The use of digital solutions could lead workers to dependency (Hallowell et al., 2010), increase distraction from work (Bernal et al., 2017; Schall et al., 2018), and reduce productivity (Reid et al., 2017). Wearable solutions could also be perceived as bothersome (Kim and Shin, 2015; Taib et al., 2017; Yu et al., 2019). Favorable technical features, such as reduced weight and bulk, high sensor durability, and adaptability to job characteristics, could facilitate their adoption (Dodoo et al., 2024; Wu et al., 2018). Similarly, the usability and acceptance of digital solutions could be affected by the characteristics of the underlying technologies, namely the operative range, data accuracy, latency, and resolution (Jo et al., 2017; Liu et al., 2007; Neill et al., 2016), as well as the perceived complexity of use (Basoglu et al., 2017; Chuah et al., 2016; Sivathanu, 2018). Difficulties stemming from low technological maturity were also underlined. These difficulties might be due to a lack of skills (Debnath et al., 2018), a lack of technical and organizational support (Lee and Coughlin, 2015), and low availability of experts capable of providing training (Hallowell et al., 2010; Yi et al., 2016b). Adoption is also influenced by the availability of information referring to technological features and performance, such as accuracy, validity, and effectiveness (Reid et al., 2017; Schall et al., 2018); indeed, the lack of trust in technology could hinder adoption unless proper training is provided (Dodoo et al., 2024). From both technological and organizational standpoints, challenges arise in managing technological solutions, encompassing data collection, system governance and management, and ensuring data security and privacy (Badri et al., 2018; Bloom et al., 2018; Yi et al., 2016a). Additionally, there are concerns regarding the investment and operational costs associated with these solutions, although economic incentives could mitigate these factors (Ferraro et al., 2019). Additional drivers pertain to the creation of a safe atmosphere and enhanced company image (Bragatto et al., 2018), as well as to competitiveness, due to reduced absenteeism from work (Carr et al., 2010).

2.4. Emerging literature gaps and objectives of the research

The literature background highlighted that efforts focusing on understanding what digital solutions can tackle hazardous situations are relatively scarce. The literature mainly deals with a specific hazard tackled by one selected digital solution at a time. A systematic approach mapping the relationships between hazardous situations present in manufacturing SMEs and digital solutions available in the market is still lacking, leaving ample room for further detailed analysis. Similarly, barriers and drivers to digital solutions in occupational safety management have been mainly addressed from the general perspective of technological adoption, without a direct link to specific digital solutions and their intrinsic characteristics (Choi et al., 2017). Moreover, the perceived barriers and drivers might be strongly influenced by different contextual factors, such as the industry or the size of an organization (Neri et al., 2021; Yu and Schweisfurth, 2020), but an analysis from this perspective is missing.

The extant literature thus falls short in providing an empirical analysis comprehensively describing the adoption of digital solutions for addressing an array of hazardous situations. Such analysis should also include the identification of associated barriers and drivers, along with considering the effect of contextual factors. The research would be particularly pertinent for metalworking SMEs, given their unique challenges stemming from the digital and safety divides. However, current knowledge lacks a specific and empirical focus on metalworking SMEs, as literature contributions are mainly conceptual (Podgórski et al., 2017; Venkatesh, 2003) or do not focus on a specific firm size and sector (Barata and da Cunha, 2019; Schall et al., 2018).

Therefore, focusing on metalworking SMEs, the present study aims to empirically investigate the adoption of digital solutions to address hazardous situations, and the barriers and drivers influencing the adoption. Specifically, the study aims to answer the following research questions:

RQ1. Which digital solutions are adopted to mitigate specific hazardous situations in metalworking SMEs?

RQ2. Which factors influence the adoption of the digital solutions by metalworking SMEs?

And specifically:

RQ2a. Which barriers hinder the adoption of digital solutions by metalworking SMEs?

RQ2b. Which drivers facilitate the adoption of digital solutions by metalworking SMEs?

3. Materials and methods

To answer the research questions, we conducted empirical research, selecting a survey as the preferred method. Survey research is mainly based on deductive reasoning and variables used in the questionnaire are derived from existing knowledge about the phenomenon. To perform the deductive analysis, a framework of analysis was developed based on the extant literature (Section 3.1).

3.1. Framework of analysis

The framework aims at providing the variables to be used in the questionnaire, based on the research questions. The framework thus consists of five areas, namely: (i) hazardous situations (ii) digital solutions to tackle the hazardous situation, (iii) barriers, (iv) drivers related to the adoption of digital solutions, and (v) contextual factors. Based on Section 2, a concise yet comprehensive list of variables to be considered in the questionnaire has been developed. Hazardous situations were selected and classified based on the literature provided in Section 2.1, consolidated and grouped considering various systematic classifications (*PRE.VI.S.*, *ESAW,* and *Infor.MO* models). Similarly, digital solutions were selected based on literature (Section 2.2) and grouped according to their characteristics and similarities (e.g., smartphones, tablets, and palmtop were considered altogether). To guarantee the selection of relevant hazardous situations and digital solutions, we performed a cross-analysis. In total, 11 hazardous situations and 8 digital solutions were considered (Table 1). A similar process has been employed to define the set of barriers and drivers. Barriers and drivers retrieved from the literature (Section 2.3) were grouped according to their similarities, following a bottom-up approach to maintain coverage while avoiding overlapping. In total, 15 barriers and 12 drivers were selected (Table 2).

Contextual factors emerged critical for their influence on the relationships investigated (Section 2.4). To account for this, the framework also includes relevant contextual factors, such as firms' size and sector, safety organization, or level of digitization (Table 3).

A snapshot of the areas and elements considered and their relationship is provided in Fig. 1, while Table 3 reports the complete list of variables.

3.2. Questionnaire structure

The questionnaire was divided into five sections (Fig. 2). The first section deals with a general overview of the respondent and the SME (working environment, product and process, safety organization, and digitalization). The second section deals with hazardous situations. Respondents were presented with the 11 hazardous situations selected and asked to characterize them in terms of presence in their organization (i.e., *hazardous situation not present; hazardous situation present, and accident already occurred; hazardous situation present but accident never occurred*). If the hazardous situation was present, respondents were asked to rate the probability of the risk associated with the situation (*1: very low; 2: low; 3: high; 4: very high*) and its severity (*1: only material damage – to machines, equipment, installations; 2: slight injury to one person; 3: slight injury to several persons involved; 4: serious injury to one person; 5: serious injury to several persons involved*). To test aspects closely related to the capabilities of digital solutions, the difficulty of perceiving the risk before the accident's occurrence and the ability to intervene in the event of an accident with warnings and alarms were evaluated. The third section focused on the digital solutions considered to tackle each hazardous situation. For each digital solution, barriers (fourth section) and drivers (fifth section) affecting the adoption were asked.

3.3. Sample selection

The study focuses on Italian metalworking SMEs. According to the *International Standard Industrial Classification of All Economic Activities* (ISIC), the metalworking sector includes the subsectors of the *Manufacture of basic metals* (C24), *Manufacture of fabricated metal products* (C25), and *Manufacture of machinery and equipment* (C28). The metalworking sector plays a relevant role in the European industry from an economic and employment perspective (Eurostat, 2023a) and poses significant issues in terms of occupational safety, accounting for 6% of all fatal accidents in the manufacturing sector (Eurostat, 2023b). The metalworking sector is one of the most relevant sectors in Italy, considering the level of employment and its added value (Federmeccanica, 2023). The sector accounts for 24.4% of the total fatal accidents in the Italian manufacturing sector (Eurostat, 2023b). These figures are underscored by the sector economic and social significance in Italy, contributing 14.5% of the manufacturing sector value added and

Table 1

Overview of the digital solutions to tackle hazardous situations considered in the framework of analysis. The table provides information on the digital solutions and the hazardous situations considered in the framework of analysis. Supporting references are offered.

		Digital Solution									
		No specific digital solution	Smartphone; tablet and palmtop	Smart-band; smartwatch	Smart glasses	Smart helmet	Smart clothing	General wearable device	Camera	Laser scanner	Environmental sensors
Hazardous Situation	No specific hazardous situation		[1]; [35]; [40]; [49]	[13]; [16]; [31]; [36]; [44]; [47]; [49]; [56]; [58]; [69]	[40]; [58]	[57]	[7]; [16]; [36]; [44]; [49]; [51]; [57]; [58]; [71]; [74]		[33]	[65]	[1]; [43]; [48]; [72]; [74]; [76]
	Man-moving machine interaction	[54]; [6]; [8]; [9]; [23]; [24]; [25]; [34]; [38]; [63]; [65]; [69]; [72]	[10]	[4]		[14]	[29]	[2]; [13]; [26]; [27]; [28]; [33]; [36]; [40]; [57]; [62]; [67]; [68]	[3]; [26]; [40]; [60]; [61]		
	Man-stationary machine interaction	[2]; [3]; [4]; [6]; [8]; [9]; [10]; [13]; [14]; [23]; [24]; [25]; [26]; [27]; [28]; [33]; [34]; [36]; [38]; [40]; [54]; [60]; [62]; [63]; [67]; [68]; [69]				[41]		[57]; [65]		[72]	[29]
	Accidents related to the entry into limited access areas or dangerous areas, forbidden to certain categories of people	[1]; [10]; [27]; [35]; [40]; [49]; [51]; [69]		[4]		[41]		[26]; [28]; [36]; [37]; [50]; [55]	[26]		[36]
	Accidents related to the improper use of machinery			[4]							
	Absolute position – accidents related to the missed position monitoring of external or internal personnel	[5]; [18]; [35]; [41]; [49]; [55]; [63]; [75]; [76]	[21]; [75]	[75]		[11]; [76]	[45]	[2]; [7]; [15]; [16]; [21]; [26]; [39]; [40]; [46]; [51]; [57]; [74]	[26]; [40]		
	Absolute position – accidents related to the impossibility of position monitoring in case of emergency			-				[18]	-		[18]
	Accidents due to work at height	[12]; [19]; [20]; [21]; [32]; [39]; [40]; [46]; [57]; [60]; [64]; [76]; [71]		[53]		[11]; [53]	[24]; [52]; [54]	[7]; [26]; [56]	[26]; [52]; [56]		
	Accidents due to incorrectly secured machinery								[60]		
	Accidents related to the missed use or improper use of PPE (despite correct information and training by company)			[47]		[11]; [42]	[24]; [54]	[26]; [37]; [57]	[26]		
	Accidents related to the incorrect movements/actions or to incorrect vital parameters in relation to the performed activity	[58]; [73]	[10]; [21]; [75]	[4]; [32]; [53]; [75]		[11]; [19]; [39] [53]; [76]	[52]; [45]	[1]; [2]; [7]; [21]; [26]; [31]; [44]; [46]; [51]; [57]; [64]; [66]; [71]; [74];	[20]; [26]; [52]; [60]; [77]		
	Accidents related to significantly different environmental parameters values with respect to the normal values	[73]	[10]; [21]	[4]	[22]	[11]; [17]; [76]	[45]; [52]	[1]; [2]; [7]; [21]; [39]; [43]; [44]; [46]; [51]; [56];[57]; [74]			[30]; [48]; [59]; [70]; [75]

Legend: [1] (Andrushevich et al., 2017); [2] (Awolusi et al., 2018) [3] (Banerjee et al., 2019); [4] (Barata and da Cunha, 2019); [5] (Barral et al., 2019); [6] (Beetz et al., 2015); [7] (Bernal et al., 2017); [8] (Bortot et al., 2012); [9] (Bragança et al., 2019); [10] (Bragatto et al., 2018); [11] (Byeon et al., 2018); [12] (Cardillo and Caddemi, 2019); [13] (Carr et al., 2010); [14] (Chae and Yoshida, 2010); [15] (Cheng and Teizer, 2013); [16] (Choi et al., 2017); [17] (Colombo et al., 2019); [18] (Depari et al., 2018); [19](Dhole et al., 2019); [20] (Escorcia et al., 2012)); [21] (Faramondi et al., 2019); [22] (Ferraro et al., 2019); [23] (Geiger and Waldschmidt, 2019); [24] (Gisbert et al., 2014); [25] (Golan et al., 2020); [26] (Guo et al., 2017); [27] (Hallowell et al., 2010); [28] (Han et al., 2019); [29] (Hayek et al., 2018); [30] (Henriques and Malekian, 2016); [31] (Hwang and Lee, 2017); [32](Jebelli et al., 2019); [33] (Jo et al., 2017); [34] (Jobes et al., 2013); [35] (Kamaludin et al., 2017); [36] (Kanan et al., 2018); [37] (Kelm et al., 2013); [38] (Khalid et al., 2017); [39] (Khurana et al., 2018); [40] (Kim and Kim, 2012); [41] (Kim et al., 2017); [42] (Kim et al., 2018); [43] (Kodali and Sahu, 2018); [44] (Kodali et al., 2018); [45] (Komane and Mathonsi, 2019); [46] (Kozlovszky et al., 2015); [47] (Kritzler et al., 2015) [48] (Lima da Gama et al., 2015); [49] (Liu et al., 2007); [50] (Luo et al., 2016); [51] (Mamun and Yuce, 2019); [52](Mayton et al., 2012) [53] (Mehata et al., 2019); [54] (Palazon et al., 2013); [55] (Park et al., 2018); [56] (Park et al., 2019); [57] (Podgórski et al., 2017); [58] (Price Waterhouse Coopers, 2016); [59] (Rao et al., 2019); [60] (Ruff, 2008); [61] (Ruff, 2001); [62] (Ruff and Frederick, 2007); [63] (Ruff and Holden, 2003); [64] (Ryu et al., 2019); [65] (Safeea et al., 2019b); [66] (Sedighi Maman et al., 2017); [67] (Sepulcre et al., 2011); [68] (Teizer et al., 2010); [69] (Teizer and Cheng, 2015); [70] (Thomas et al., 2018); [71] (Valero et al., 2016); [72] (Vasumathi et al., 2019); [73] (Rao et al., 2019); [74] (Xu et al., 2014); [75] (Yi et al., 2016a); [76] (Yi et al., 2016b); [77] (Yu et al., 2019).

Table 2
Overview of barriers and drivers to the adoption of digital solutions considered in the framework of analysis.

		Supporting references
Barriers	**Privacy concerns**	(Barata and da Cunha, 2019; Bloom et al., 2018; Choi et al., 2017; Golan et al., 2020; Reid et al., 2017; Schall et al., 2018)
	Constant control over employees	(Awolusi et al., 2018; Xu et al., 2014)
	Forced change in work habits	(Rubin and Ophoff, 2018; Venkatesh et al., 2003)
	Technological solutions frowned upon by colleagues	(Anderson and Lee, 2008; Barata and da Cunha, 2019; Basoglu et al., 2017; Buenaflor and Kim, 2013; Choi et al., 2017; Debnath et al., 2018; Gao et al., 2015; Lee and Lee, 2018; Rubin and Ophoff, 2018; Taib et al., 2017; Venkatesh et al., 2003)
	Distraction from work	(Schall et al., 2018)
	No perception of benefits in the use	(Barata and da Cunha, 2019; Basoglu et al., 2017; Choi et al., 2017; Chuah et al., 2016; Davis, 1989; Debnath et al., 2018; Kim and Shin, 2015; Lee and Coughlin, 2015; Neill et al., 2016; Reid et al., 2017; Schall et al., 2018; Taib et al., 2017)
	Complexity in usage	(Basoglu et al., 2017; Choi et al., 2017; Chuah et al., 2016; Debnath et al., 2018b; Hallowell et al., 2010b; Kim and Shin, 2015b; Lee and Coughlin, 2015b; Reid et al., 2017b; Sivathanu, 2018; Taib et al., 2017b)
	Burdernsome in usage (example, short duration of battery, extra concentration required…)	(Barata and da Cunha, 2019; Jo et al., 2017; Price Waterhouse Coopers, 2016; Schall et al., 2018)
	Heavy or bulky devices	(Awolusi et al., 2018; Cheng and Teizer, 2013; Ferraro et al., 2019; Kanan et al., 2018; Kim and Shin, 2015; Mamun and Yuce, 2019; Mehata et al., 2019; Schall et al., 2018; Taib et al., 2017; Wu et al., 2018)
	High implementation cost	(Barata and da Cunha, 2019; Basoglu et al., 2017; Debnath et al., 2018; Lee and Lee, 2018; Reid et al., 2017; Schall et al., 2018)
	Fast obsolescence of the technological solution	(Neill et al., 2016)
	Lack of available information on the technology (from suppliers, external experts…)	(Debnath et al., 2018; Hallowell et al., 2010; Reid et al., 2017)
	Difficult to implement	(Jo et al., 2017)
	Difficult to manage the system and the connected data security	(Bloom et al., 2018; Reid et al., 2017)
Drivers	**Improved company image (example, image as a safety and wellbeing concerned company)**	(Andrushevich, Biallas, et al., 2017; Bragatto et al., 2018; Kamaludin et al., 2017; Kim et al., 2017; Liu et al., 2007)
	Higher company competitiveness (example, by reducing the on-the-job injuries number)	(Carr et al., 2010; Choi et al., 2017; Hwang and Lee, 2017; Jebelli et al., 2019; Kanan et al., 2018; Kodali and Sahu, 2018; Liu et al., 2007; Mehata et al., 2019; Park et al., 2019; Price Waterhouse Coopers, 2016)
	Economic support to the company (example, through public incentives, tax deductions, …)	(Ferraro et al., 2019; Kim et al., 2017; Price Waterhouse Coopers, 2016)
	Laws and norms compliance	(Byeon et al., 2018; Chae and Yoshida, 2010; Dhole et al., 2019; Khurana et al., 2018; Kim and Kim, 2012; Kim et al., 2018; Mehata et al., 2019; Podgórski et al., 2017; Wen Yi et al., 2016)
	Clear and trustworthy information on the use of data by the employer	(Chae and Yoshida, 2010; Dhole et al., 2019; Khurana et al., 2018; Kim and Kim, 2012; Mehata et al., 2019; Podgórski et al., 2017; W Yi et al., 2016)
	Availability of technical and economic information, and of information about the benefits brought by the technological solutions	(Bernal et al., 2017; Choi et al., 2017; Gisbert et al., 2014; Hayek et al., 2018; Kanan et al., 2018; Kodali and Sahu, 2018; Komane and Mathonsi, 2019; Liu et al., 2007)
	Management support to the use of the technological solution	(Mamun and Yuce, 2019; Mayton et al., 2012; Palazon et al., 2013; Podgórski et al., 2017; Price Waterhouse Coopers, 2016; Valero et al., 2016; Xu et al., 2014)
	Presence of a "champion" among the company employees that supports and pushes the technological solution adoption	(Safeea et al., 2019)
	Ease in use (example, through simple interfaces)	(Banerjee et al., 2019; Escorcia et al., 2012; Jo et al., 2017; Kim et al., 2017; Mayton et al., 2012; Park et al., 2019; Ruff, 2008; Yu et al., 2019)
	Light in weight and tiny in volume	(Price Waterhouse Coopers, 2016; Safeea et al., 2019; Valero et al., 2016; Xu et al., 2014)
	External technical support (example, through service providers)	(Kim and Kim, 2012; Kim et al., 2018; Mehata et al., 2019; Podgórski et al., 2017; Wen Yi et al., 2016)
	Enjoyable and satisfactory use of the technological solution for the operator	(Kodali and Sahu, 2018; Liu et al., 2007; Mayton et al., 2012; Mehata et al., 2019; Palazon et al., 2013; Park et al., 2019; Podgórski et al., 2017)

encompassing more than 70,000 companies (ISTAT, 2023), the highest number in Europe (Eurostat, 2023c).

SMEs are at the center of our analysis due to the digital and safety divide to which they are exposed. SMEs also play a relevant role in the European economy, representing 52.5 % of the total value added of the non-financial business economy (Eurostat, 2023d) and they are particularly critical for Italy, where they represent the largest share (99.7 %) of industrial firms (ISTAT, 2019).

3.4. Data collection

The survey was conducted through a multiple-choice questionnaire, developed by the authors through a joint effort of *ApiTech* and *Innovazione Apprendimento Lavoro* (IAL). *ApiTech* is the digital innovation hub of *Confapi*, the main association representing small and medium manufacturing and service companies in Italy. IAL is a social enterprise and network of companies operating in the field of vocational training and education in Italy. IAL was founded by the *Confederazione Italiana Sindacati Lavoratori* (CISL), the second-largest trade union confederation in Italy.

Data were collected by *ApiTech* and IAL and anonymized before being provided to the authors. The target respondents were the employers of the SME, given their role as decision-makers; employers have an overview of their SME that is usually denied to others. To properly manage occupational safety, the employer is advised by the coordinator of the Prevention and Protection Service Unit of the firm – here indicated as PPSM (Prevention and Protection Service Manager). In addition, the employer may appoint a Prevention and Protection Service Officer (PPSO), as an additional member of the Prevention and Protection Service Unit that supports the work of the PPSM.

Seminars were conducted to enhance SMEs' participation in the questionnaire and ensure a thorough understanding of its content. Before distributing the survey, a preliminary validation was conducted with selected SMEs to ascertain the completeness, relevance, and, most importantly, comprehensibility of the questions, thereby ensuring the survey's validity. Conversely, the survey's reliability and applicability to industries beyond the metalworking sector are assured by its design, which pertains to the broader manufacturing and construction sector. To increase the response rate, the questionnaire was accompanied by supplementary material describing the overall research project and objective.

4. Results and discussions

4.1. Sample characteristics

A total of 188 SMEs were surveyed (Table 4). As for size, 77% of the surveyed SMEs are small enterprises (<50 employees). SMEs are mostly located in Northern Italy, especially in the Lombardy region (70%). The share is a good representation of the geographical distribution of the metalworking industry in Italy. Surveyed SMEs mainly belong to the C25 – Manufacture of fabricated metal products (56%). Most SMEs produce personalized products according to customer specifications (60%) and do not adopt a specific batch policy as a production method. The level of automation in production is not high (only 5% of the sample is in this situation) and, overall, 67% of the SMEs declared to have a low level of digitalization; the information systems infrastructure is usually located in the SME's premises (52%). Regarding the internal organization of occupational safety, most SMEs do not have an internal office (73%), but they do have an internal PPSM (59%) and a PPSO (57%).

Characteristics of respondents were analyzed as well (Table 5). Most respondents were between 45 and 64 years old, identified as male, and had at least 10 years of experience. Respondents showed a good understanding of wearable and non-wearable digital solutions, despite their occasional use.

Interesting correlations emerged between the different characteristics of the sampled SMEs (Appendix A1). The level of digitalization appears influenced by the size, confirming previous literature (Al-Bayati, 2021; Luo and Yu, 2022), and reinforcing the concept of the digital divide (Kim et al., 2021; Sommer, 2015). The level of digitalization appears also influenced by the degree of process automation. More in detail, the level of digitalization seems to increase with the

Table 3
The framework of analysis.

Hazardous Situation	**H1**	Man-moving machine interaction
	H2	Man-stationary machine interaction
	H3	Entry into limited access areas or dangerous areas, forbidden to certain categories of people
	H4	Improper use of machinery
	H5	Absolute position – lack of position monitoring of external or internal personnel
	H6	Absolute position – lack of position monitoring in case of emergency
	H7	Work at height
	H8	Incorrectly secured machinery
	H9	Lack of or improper use of PPE (despite correct information and training by company)
	H10	Incorrect movements/actions or incorrect vital parameters in relation to the performed activity
	H11	Significantly different environmental parameters values with respect to the normal values
Digital Solutions	**S1**	Smartphone; tablet and palmtop
	S2	Smart band; smartwatch
	S3	Smart glasses
	S4	Smart helmet
	S5	Smart clothing
	S6	Camera
	S7	Laser scanner
	S8	Environmental sensors
Barriers	**B1**	No barriers
	B2	Forced change in work habits
	B3	Distraction from work
	B4	High implementation cost
	B5	Fast obsolescence of the digital solution
	B6	Difficult to manage the system and the connected data security
	B7	Privacy concerns
	B8	No perception of benefits in the use
	B9	Concerns of constant control over employees
	B10	Complexity in usage
	B11	Burdensome in usage (example, short duration of battery, extra concentration required…)
	B12	Lack of available information on the technology (from suppliers, external experts…)
	B13	Digital solutions frowned upon by colleagues
	B14	Heavy or bulky devices
	B15	Difficult to implement
Drivers	**D1**	Improved company image (example, image as a safety and wellbeing concerned company)
	D2	Higher company competitiveness (example, by reducing the on-the-job injuries number)
	D3	Economic support to the company (example, through public incentives, tax deductions, …)
	D4	Laws and norms compliance
	D5	Clear and trustworthy information on the use of data by the employer
	D6	Availability of technical and economic information, and of information about the benefits brought by the digital solutions
	D7	Management support to the use of the digital solution
	D8	Presence of a “champion” among the company employees that supports and pushes the digital solution adoption
	D9	Ease in use (example, through simple interfaces)
	D10	Light in weight and tiny in volume
	D11	External technical support (example, through service providers)
	D12	Enjoyable and satisfactory use of the digital solution for the operator
Contextual Factors	**SME identification**	Firm size
		Location in Italy
		ISIC Sector
	Occupational safety organization	Internal or external PPSM
		Presence of PPSO
		Presence of an internal occupational safety office
	Production organization	Product standardization degree
		Production method
		Process automation level
	Digitalization	Digitalization level
		Information infrastructure
	Respondent identification	Age
		Seniority
		Gender
		Awareness of wearable devices
		Awareness of not wearable devices

increase in process automation and size. The result aligns with previous literature, as smaller firms are typically less prepared for digital transformation and less able to reap its benefits (Kim et al., 2021; Yu and Schweisfurth, 2020).

The complexity of the occupational safety organization (the presence of only PPSM; the presence of PPSM and PPSO; and the existence of a structured occupational safety office supporting the PPSM) appears influenced by the size and the degree of standardization of products.

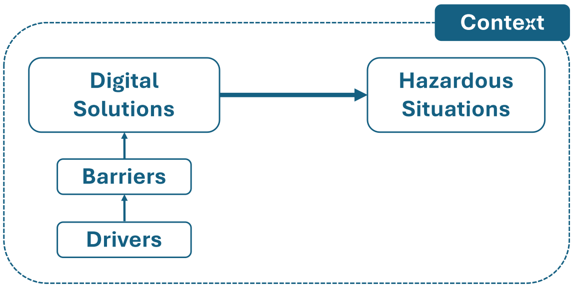


Fig. 1. Relationships between the elements of the framework of analysis. The framework investigates the digital solutions adopted to deal with hazardous situations, as well as the barriers hindering and the drivers supporting their adoption.

Sections of the questionnaire

Section 1. Respondent and SME overview

Section 2. Hazardous situations

Section 3. Digital solutions

Section 4. Barriers to adopting digital solutions

Section 5. Drivers to adopting digital solutions

Fig. 2. The five sections composing the questionnaire.

With increasing size, the complexity of the occupational safety organization tends to increase, as larger firms are more likely to have an internal PPSO that acts as the coordinator of an occupational safety office. Previous literature underlined a positive correlation between firm size and safety culture regarding safety-related behaviors and actions taken by top management and safety personnel (Al-Bayati, 2021; Micheli and Cagno, 2010). Smaller firms are more likely to adopt non-systematic and informal occupational safety systems and practices (Bonafede et al., 2016; Cagno et al., 2016; Masi and Cagno, 2015), which often result in poorer safety performance (Cagno et al., 2011; Mills and Lin, 2004). Also, the complexity of the occupational safety organization seems to increase in SMEs that produce standardized products with the possibility of adding variants.

4.2. Hazardous situations

4.2.1. Hazardous situation from a general perspective

Hazardous situations were analyzed according to their presence and occurrence, likelihood, and severity as reported by respondents (Table 6).

Interaction between operators and stationary machinery (H2) emerges as the most common hazardous situation leading to accidents, followed by lack of or incorrect use of PPE (H9) and interaction between operators and mobile machinery (H1). Among the least frequent hazardous situations, entry into potentially dangerous areas (H3), incorrect environmental parameters (H11) and lack of position monitoring of external personnel (H5) can be listed.

Focusing on the cases where the hazardous situation is present, the most probable occurrences of accidents relate to work at heights (H7), lack of or incorrect use of PPE (H9), and interaction between operators and stationery or mobile machinery (H1 and H2). In terms of severity, the most severe accidents relate to the hazardous situations of work at height (H7), lack of position monitoring in case of emergency (H6), interaction between operators and stationary machinery (H2), incorrectly secured machinery (H8) and incorrect environmental parameters (H11). Accidents due to interactions between operators and mobile machinery (H1) are frequent but not considered highly severe. To assess the overall risk of hazardous situations, when they are present and regardless of whether an accident happened, a risk index is defined as the product of the probability of occurrence and severity of the accident (Fig. 3). The riskiest hazardous situations are, in order, work at heights (H7), incorrectly secured machinery (H8), lack of position monitoring in case of emergency (H6), the interaction between operators and stationary machinery (H2), and the lack of or incorrect use of PPE (H9).

4.2.2. Contextual factors influencing the perception of risk of hazardous situations

The risk perception seems influenced by the respondent and context's characteristics (Appendix A2). Perceived risk decreases as the respondent's age increases (except for situations that could lead to accidents due to incorrect vital parameters). The result contrasts previous literature that asserted that risk perception is higher for individuals who experienced more accidents and injuries (Oah et al., 2018; Taylor and Snyder, 2017), which might be respondents with higher seniority. The contrasting result could be related to the sampled investigated, constituted by SMEs. Indeed, SMEs usually experience a limited number of accidents (Micheli et al., 2021), possibly influencing the learning experience of the respondents. This might reduce the influence of personal experience on risk perception, possibly favoring the influence of other factors such as educational level, risk aversion, working conditions, and safety climate (Cheng et al., 2022; Eiter and Bellanca, 2020).

The perceived risk of hazardous situations seems to increase in larger firms, despite being characterized by a proportionally lower frequency and severity of accidents (Fabiano et al., 2004), and in firms with a more structured occupational safety organization. The presence of a PPSM seems to affect risk perception, but no clear trend can be observed. According to the previous literature, risk perception is correlated with endogenous and exogenous factors, such as working conditions, organizational pressure, attitudes towards safety and accident prevention work, management commitment and involvement in safety promotion, and safety climate (Oah et al., 2018; Taylor and Snyder, 2017). As larger firms are generally characterized by a more structured occupational safety organization and perceive occupational safety management as an added value rather than a mere legal obligation (Bonafede et al., 2016), they show a more mature safety culture (Al-Bayati, 2021) and greater sensitivity in terms of risk assessment. Perceived risk is also higher in SMEs characterized by continuous production and a higher degree of automation.

4.3. Digital solutions for dealing with hazardous situations

The present section answers the research question RQ1, *"Which digital solutions are adopted to mitigate specific hazardous situations in metalworking SMEs?"*. Section 4.3.1 describes the level of adoption of the selected digital solutions for tackling each hazardous situation. Additional details are then offered regarding the influence of risk perception (Section 4.3.2) and sample's characteristics (Section 4.3.3) on the adoption rate of digital solutions.

4.3.1. Digital solutions for dealing with hazardous situations from a general perspective

The level of adoption of digital solutions for the main hazardous situations is reported in Table 7. The values in the tables indicate the share of SMEs that, concerning a specific hazardous situation: (i) have already adopted or are currently adopting the digital solution (Table 7a), (ii) are interested in adopting or are currently evaluating the digital solution (Table 7b), or (iii) do not consider the digital solution as interesting (Table 7c). A limited number of SMEs showed interest in adopting digital solutions, and of these, a few have proceeded to evaluate the feasibility and cost-benefit of adoption; only a limited share of SMEs already adopted the digital solutions. As such, this implies an overall low practical knowledge of the adoption of digital solutions by

Table 4
The investigated sample. *The digitalization level is a score attributed to companies according to the presence of one or more of the following information systems and on their combination: Enterprise Resource Planning, Scheduler, Manufacturing Execution System, Computerized Maintenance Management System, Product Lifecycle Management/Product Data Management, CAD, Warehouse Management System, Quality Management System.

	Characteristic	Specific Features	# of SMEs	(%)
SME identification	**SME size**	Very small (<20 employees)	99	53%
		Small (20-49 employees)	46	24%
		Medium-small (50-149 employees)	28	15%
		Medium-large (150-249 employees)	15	8%
	Location in Italy	North-East	12	6%
		North West - Lombardy	132	70%
		North West - Other	14	7%
		Center	14	7%
		South	16	9%
	ISIC Sector	C24 - Manufacture of basic metals	33	18%
		C25 - Manufacture of fabricated metal products	106	56%
		C28 - Manufacture of machinery and equipment	49	26%
Occupational safety organization	**PPSM** (Prevention and Protection Service Manager)	External	78	41%
		Internal	110	59%
	PPSO (Prevention and Protection Service Officer)	Present	107	57%
		Not present	81	43%
	Internal occupational safety office	Present	51	27%
		Not present	137	73%
Production organization	**Product standardization degree**	Personalized product on customers' specifications	112	60%
		Single standard product	9	5%
		Single standard product with variants	11	6%
		Multiple standard products	10	5%
		Multiple standard products with variants	46	24%
	Production method	Single products	57	30%
		Small-sized lots	43	23%
		Batch	66	35%
		Continuous production	22	12%
	Process automation level	Manual	54	29%
		Mechanically assisted	48	26%
		Semi-automatized	76	40%
		Highly or completely automatized	10	5%
Digitalization	**Digitalization level***	Very low	82	44%
		Low	44	23%
		High	27	14%
		Very high	35	19%
	Information infrastructure	In company premises	97	52%
		On cloud	21	11%
		Mixed (on cloud and in company premises)	70	37%

the respondents. Therefore, the results describe the respondents' perception of adoption, rather than the practical experience of adoption. However, leveraging (Cagno et al., 2013), results are valid because the outcome of the adoption process is mainly determined by perception rather than actual knowledge.

Environmental sensors, smartphones, with possible overlap with smartwatches due to their similarity and interchangeability of use, and cameras are the digital solutions most adopted by the surveyed SMEs to tackle almost all hazardous situations. These digital solutions are characterized by familiarity on the part of users, either due to their more traditional nature (environmental sensors and cameras) or to their increasing use in everyday life (smartphones). The latter also guarantees the availability of the selected digital solutions at low or no cost, for example, if the worker already owns a smartphone (Awolusi et al., 2018). The previously listed solutions are also characterized by high application flexibility. Indeed, smartphones can be used to locate remote workers, monitor environmental and vital parameters, control access to restricted areas, and work at heights, whereas cameras offer support for the monitoring of environmental parameters. Laser scanners and smartwatches present relatively high adoption rates, with differences depending on the specific hazardous situation. Smartwatches, smartphones, cameras, and environmental sensors, if not already adopted, were often under evaluation by surveyed SMEs to improve occupational safety.

Smart glasses, smart helmets, and smart clothing appear of limited interest. They involve a high level of innovation and are not widely used in everyday life, so the related level of awareness among respondents might be limited. The few reported adoptions of these digital solutions relate to specific hazardous situations, such as external personnel location, possibly underlying a perceived limited application flexibility. Overall, the results highlight that a limited set of digital solutions (cameras, environmental sensors, and smartphones) can mitigate the risks arising from the most hazardous situations in the metalworking sector.

4.3.2. Risk perception influencing the digital solutions for dealing with hazardous situations

The level of interest in digital solutions varies according to the specific hazardous situation (Table 7) and its perceived risk (Appendix A3). The protective motivation theory (Rogers, 1975) and the health belief model (Rosenstock, 1974) confirm that a higher risk perception encourages individuals to behave safely, and engage in protective behaviors and safety management (Kouabenan et al., 2015; Taylor and Snyder, 2017). Therefore, the perception of vulnerability in the workplace is a critical factor in adopting digital solutions to enhance safety (Choi et al., 2017). Digital solutions addressing primary needs, such as safety in

Table 5
Characteristics of the respondents.

Characteristics	Specific Feature	# of respondents	%
Age	<25 years	3	2 %
	25–34 years	10	5 %
	35–44 years	29	15 %
	45–54 years	66	35 %
	55–64 years	49	26 %
	65–74 years	22	12 %
	> 74 years	9	5 %
Seniority	<1 year	1	1 %
	1–4 years	10	5 %
	5–9 years	16	9 %
	10–24 years	53	28 %
	25–39 years	68	36 %
	> 39 years	40	21 %
Gender	Male	140	74 %
	Female	48	26 %
Awareness of wearable devices	0 = never heard of them	8	4 %
	1 = just heard of them	72	38 %
	2 = I sometimes used/use them for professional or private reasons	65	35 %
	3 = I often used/use them for professional or private reasons	34	18 %
	4 = I often used/use them for professional or private reasons and/or I have technical competencies on them	9	5 %
Awareness of not wearable devices	0 = never heard of them	3	2 %
	1 = just heard of them	97	52 %
	2 = I sometimes used/use them for professional or private reasons	55	29 %
	3 = I often used/use them for professional or private reasons	25	13 %
	4 = I often used/use them for professional or private reasons and/or I have technical competencies on them	8	4 %

critical working conditions, are thus perceived as more attractive than solutions addressing less pressing needs (Buenaflor and Kim, 2013). However, the perception of vulnerability is not always easy to objectify. In heavy industry, for example, overconfidence can reduce perceptions of vulnerability (Bernal et al., 2017), highlighting the importance of training and information provided to workers.

4.3.3. *Sample characteristics influencing the digital solutions for dealing with hazardous situations*

The respondents' interest in digital solutions appears influenced by contextual factors (Appendix A4). The interest in digital solutions tends to decrease with the increase in respondents' seniority; the result might be related to the well-known resistance to change associated with an aging workforce (Yap et al., 2022). Conversely, as respondents' knowledge of wearable and non-wearable digital solutions increases, their level of interest tends to increase. The findings support previous literature (Badri et al., 2018; Choi et al., 2017; Yu and Schweisfurth, 2020), confirming the influence of age and experience in adopting digital solutions. Additionally, higher levels of interest seem associated with safety-related roles (Choi et al., 2017)), reinforcing the need for additional training (Badri et al., 2018). High levels of interest seem also associated with increased levels of digitalization and firm size, supporting the idea of a digital divide

4.4. *Barriers to the adoption of digital solutions*

The present section answers the research question RQ2a, *"Which barriers hinder the adoption of digital solutions by metalworking SMEs?"*. Section 4.4.1 offers a general overview of the results on barriers. Additional details are then offered by mapping barriers to specific digital solutions (Section 4.4.2) and understanding the influence of sample's characteristics (Section 4.4.3) on barriers.

4.4.1. *General perspective*

The most critical barriers emerging from the investigation are the lack of benefits perceived from the use of digital solutions (B8), concerns about privacy (B7) and constant control (B9), high implementation cost (B4), and difficult implementation (B15) (Fig. 4). Conversely, rapid obsolescence (B5) and heavy or bulky design of a solution (B14) emerged as less relevant barriers. The results are consistent with previous literature. Indeed, the perceived absence of benefits from the use of digital solutions (B8), or the lack of awareness of such benefits, was already identified in the previous literature as a relevant barrier (Yu and Schweisfurth, 2020). If the perceived usefulness of technology strongly influences its adoption, in line with different theoretical lenses, such as the unified theory of acceptance and use of technology (Venkatesh, 2003), the theory of diffusion of innovation (Rogers, 1983), and the technology acceptance model (Davis, 1989), the absence of perceived benefits hampers its penetration. The same concept also applies to digital solutions (Adapa et al., 2018; Debnath et al., 2018; Gao et al., 2015), including those specifically intended for occupational safety applications (Choi et al., 2017). Moreover, the lack of awareness might be explained by the lack of trust in the reliability of the digital solutions and the collected data (Hallowell et al., 2010; Schall et al., 2018; Barata and da Cunha, 2019). Interestingly, the literature suggests the contemporary adoption of multiple digital solutions to improve reliability (Awolusi et al., 2018; Neri et al., 2023a). However, this option would increase the overall implementation cost and it is usually carried out only in the case of high criticality of the hazardous situation (Guo et al., 2017; Hayek et al., 2018). High implementation cost (B4) is considered a central barrier in the existing literature (Schall et al., 2018), both in terms of capital (Yap et al., 2022) and operational cost (Okonkwo et al., 2023), confirming the present results. The relevance of concerns about privacy (B7) and constant control (B9) is also aligned with previous literature (Reid et al., 2017; Schall et al., 2018), especially as the privacy of collected data is a widely recognized issue when dealing with digital solutions (Lin et al., 2017). Newly compared to previous literature (Schall et al., 2018), respondents also highlighted the lack of barriers (B1) to the adoption of digital solutions.

4.4.2. *Barriers to specific digital solutions*

Focusing on barriers to adoption, interesting differences emerge among different digital solutions (Table 8). The lack of perception of benefits from the use (B8) represents the main barrier for all digital solutions, but it is slightly less relevant for cameras and environmental sensors, which previously (Section 4.3) emerged as the most adopted digital solutions. On the other hand, the highly adopted digital solutions seem associated with a higher relevance of operational barriers such as concerns about privacy (B7) and constant control (B9), probably due to a higher level of awareness of benefits among the respondents. Conversely, smart glasses, smart helmets, and smart clothing, which show a low adoption rate and a considerable lack of perceived benefits (B8) (Section 4.3), are associated with high barriers related to a lack of information (B12) and difficult implementation (B15). The high relevance of these barriers may therefore be explained due to a lack of knowledge rather than direct experience. Smartphones, smartwatches,

Table 6
Presence, probability, and severity of the hazardous situations.

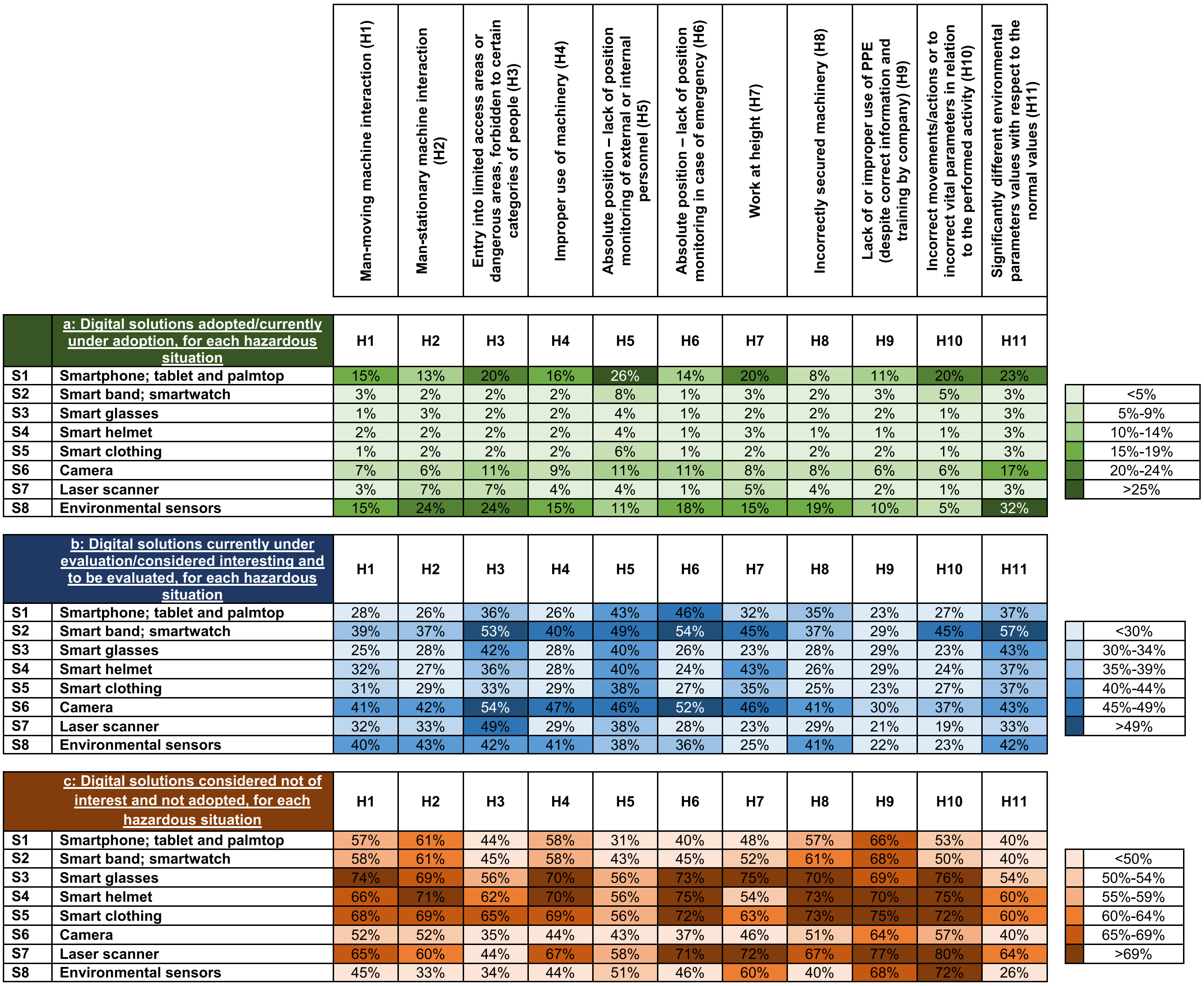
			Presence			Probability				Severity				
			Accident occurred	Accident never occurred but potentially present	Hazard situation not present	*1 Very low*	*2 Low*	*3 High*	*4 Very high*	*1 Only material damage*	*2 Slight injury to one person*	*3 Slight injuries to several persons involved*	*4 Serious injury to one person*	*5 Serious injuries to several persons involved*
Hazardous situation	**H1**	Man-moving machine interaction	19%	68%	13%	48%	45%	7%	0%	13%	55%	9%	24%	1%
	H2	Man-stationary machine interaction	36%	44%	21%	40%	49%	11%	0%	2%	57%	5%	35%	1%
	H3	Entry into limited access areas or dangerous areas, forbidden to certain categories of people	76%	23%	2%	59%	33%	9%	0%	30%	35%	15%	15%	4%
	H4	Improper use of machinery	54%	43%	3%	49%	47%	3%	1%	13%	41%	15%	29%	2%
	H5	Absolute position – lack of position monitoring of external or internal personnel	71%	27%	2%	52%	48%	0%	0%	13%	46%	13%	22%	6%
	H6	Absolute position – lack of position monitoring in case of emergency	60%	39%	1%	47%	51%	1%	1%	12%	17%	31%	20%	20%
	H7	Work at height	68%	27%	5%	34%	43%	23%	0%	5%	33%	5%	56%	2%
	H8	Incorrectly secured machinery	46%	49%	5%	45%	51%	4%	0%	9%	53%	9%	28%	1%
	H9	Lack of or improper use of PPE (despite correct information and training by company)	36%	46%	18%	33%	52%	14%	2%	2%	69%	8%	20%	1%
	H10	Incorrect movements/actions or incorrect vital parameters in relation to the performed activity	57%	40%	3%	43%	51%	6%	0%	5%	69%	5%	21%	0%
	H11	Significantly different environmental parameters values with respect to the normal values	84%	15%	2%	61%	32%	3%	3%	16%	35%	19%	13%	16%

Fig. 3. The average value for the risk index of hazardous situations.

and cameras are associated with the relevance of concerns about privacy (B7) and constant control (B9). Environmental sensors are overall characterized by a high perception of no barriers to their adoption, which is reasonable as the solution is well-known within the industry, as shown by its relatively high adoption rate (Section 4.3). Overall, a limited set of barriers seems to play the lion's share for most of the digital solutions: actions aimed at tackling these barriers may be sufficient, at least in an initial stage, to encourage more widespread adoption of digital solutions to improve occupational safety conditions in metalworking SMEs.

Table 7

Level of adoption of digital solutions for dealing with different hazardous situations. The values in the tables indicate the percentage of companies in the sample that, concerning a specific hazard situation: (i) have adopted or are currently adopting a digital solution (Table 7a), (ii) are interested in adopting or are currently evaluating the adoption of a digital solution (Table 7b), or (iii) do not consider a digital solution interesting (Table 7c).



		Man-moving machine interaction (H1)	Man-stationary machine interaction (H2)	Entry into limited access areas or dangerous areas, forbidden to certain categories of people (H3)	Improper use of machinery (H4)	Absolute position – lack of position monitoring of external or internal personnel (H5)	Absolute position – lack of position monitoring in case of emergency (H6)	Work at height (H7)	Incorrectly secured machinery (H8)	Lack of or improper use of PPE (despite correct information and training by company) (H9)	Incorrect movements/actions or to incorrect vital parameters in relation to the performed activity (H10)	Significantly different environmental parameters values with respect to the normal values (H11)
	a: Digital solutions adopted/currently under adoption, for each hazardous situation	**H1**	**H2**	**H3**	**H4**	**H5**	**H6**	**H7**	**H8**	**H9**	**H10**	**H11**
S1	**Smartphone; tablet and palmtop**	15%	13%	20%	16%	26%	14%	20%	8%	11%	20%	23%
S2	**Smart band; smartwatch**	3%	2%	2%	2%	8%	1%	3%	2%	3%	5%	3%
S3	**Smart glasses**	1%	3%	2%	2%	4%	1%	2%	2%	2%	1%	3%
S4	**Smart helmet**	2%	2%	2%	2%	4%	1%	3%	1%	1%	1%	3%
S5	**Smart clothing**	1%	2%	2%	2%	6%	1%	2%	2%	2%	1%	3%
S6	**Camera**	7%	6%	11%	9%	11%	11%	8%	8%	6%	6%	17%
S7	**Laser scanner**	3%	7%	7%	4%	4%	1%	5%	4%	2%	1%	3%
S8	**Environmental sensors**	15%	24%	24%	15%	11%	18%	15%	19%	10%	5%	32%

▨	<5%
▨	5%-9%
▨	10%-14%
▨	15%-19%
▨	20%-24%
▨	>25%

	b: Digital solutions currently under evaluation/considered interesting and to be evaluated, for each hazardous situation	**H1**	**H2**	**H3**	**H4**	**H5**	**H6**	**H7**	**H8**	**H9**	**H10**	**H11**
S1	**Smartphone; tablet and palmtop**	28%	26%	36%	26%	43%	46%	32%	35%	23%	27%	37%
S2	**Smart band; smartwatch**	39%	37%	53%	40%	49%	54%	45%	37%	29%	45%	57%
S3	**Smart glasses**	25%	28%	42%	28%	40%	26%	23%	28%	29%	23%	43%
S4	**Smart helmet**	32%	27%	36%	28%	40%	24%	43%	26%	29%	24%	37%
S5	**Smart clothing**	31%	29%	33%	29%	38%	27%	35%	25%	23%	27%	37%
S6	**Camera**	41%	42%	54%	47%	46%	52%	46%	41%	30%	37%	43%
S7	**Laser scanner**	32%	33%	49%	29%	38%	28%	23%	29%	21%	19%	33%
S8	**Environmental sensors**	40%	43%	42%	41%	38%	36%	25%	41%	22%	23%	42%

▨	<30%
▨	30%-34%
▨	35%-39%
▨	40%-44%
▨	45%-49%
▨	>49%

	c: Digital solutions considered not of interest and not adopted, for each hazardous situation	**H1**	**H2**	**H3**	**H4**	**H5**	**H6**	**H7**	**H8**	**H9**	**H10**	**H11**
S1	**Smartphone; tablet and palmtop**	57%	61%	44%	58%	31%	40%	48%	57%	66%	53%	40%
S2	**Smart band; smartwatch**	58%	61%	45%	58%	43%	45%	52%	61%	68%	50%	40%
S3	**Smart glasses**	74%	69%	56%	70%	56%	73%	75%	70%	69%	76%	54%
S4	**Smart helmet**	66%	71%	62%	70%	56%	75%	54%	73%	70%	75%	60%
S5	**Smart clothing**	68%	69%	65%	69%	56%	72%	63%	73%	75%	72%	60%
S6	**Camera**	52%	52%	35%	44%	43%	37%	46%	51%	64%	57%	40%
S7	**Laser scanner**	65%	60%	44%	67%	58%	71%	72%	67%	77%	80%	64%
S8	**Environmental sensors**	45%	33%	34%	44%	51%	46%	60%	40%	68%	72%	26%

▨	<50%
▨	50%-54%
▨	55%-59%
▨	60%-64%
▨	65%-69%
▨	>69%

4.4.3. *Influence of the sample's characteristics*

The respondent's interest in digital solutions seems to influence their perception of barriers (Table 9). Respondents were divided into interested and not interested in a digital solution; the former cluster groups respondents who have already adopted the solutions, are currently adopting the solution, or are interested in adopting the solution (Section 4.3). The lack of perception of benefits from the use (B8) is generally stronger in the eyes of not interested respondents, in line with previous literature (Okonkwo et al., 2023; Yap et al., 2022), as prior experience with a digital solution, either adoption or evaluation, seems to increase the perception and awareness of the associated benefits. Respondents interested in digital solutions nonetheless experience barriers. Respondents currently adopting or considering the adoption perceive especially barriers related to operational issues, such as concerns about privacy (B7) and constant control (B9), high implementation cost (B4), lack of information on the technology (B12), and difficult implementation (B15); respondents who have already adopted digital solutions perceive mainly concerns about privacy (B7) and constant control (B9), especially for the cameras, supporting (Schall et al., 2018). Newly compared to previous literature (Schall et al., 2018), among the respondents who have already adopted digital solutions some do not perceive any barriers (B1). The result might be justified by the fact that the digital solutions adopted by the surveyed metalworking SMEs are either well-known in the industry (camera, environmental sensors) or close to the respondents' daily experience (smartwatch and smartphone) (Section 4.3).

The context of adoption also seems to influence the perception of barriers. Larger SMEs perceive concerns about constant control (B9) and the frowned upon by colleagues (B13) as more critical, while also identifying no barriers for a consistent set of situations (B1). Conversely, smaller SMEs are mainly hindered by the lack of perception of benefits from the use of digital solutions (B8).

The level of digitalization is also relevant. Metalworking SMEs with a lower level of digitalization are mainly hindered by the lack of perception of benefits from the use of digital solutions (B8), supporting (Price Waterhouse Coopers, 2016). Conversely, metalworking SMEs with a higher level of digitalization perceive mainly concerns about privacy (B7) and constant control (B9), high implementation cost (B4), and difficult implementation (B15).

The perception of barriers may also be influenced by the perceived risk of hazardous situations. The lack of perception of benefits from the use of digital solutions (B8) is more relevant in situations with lower

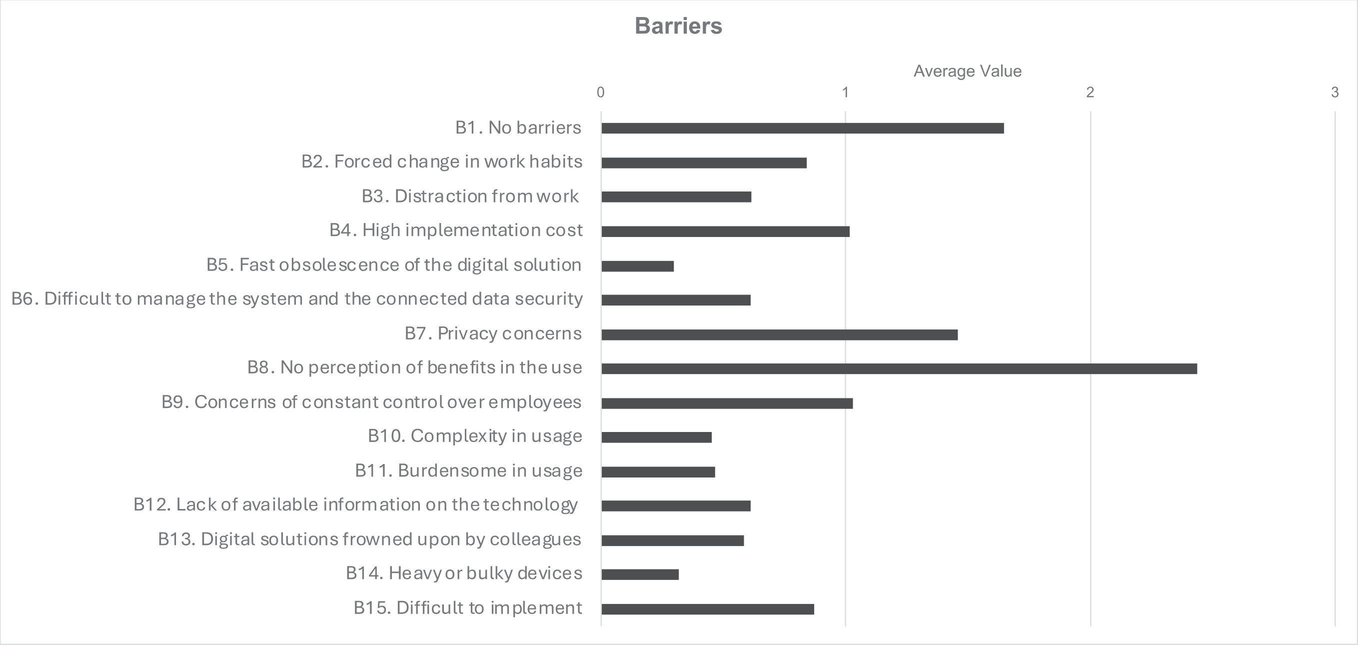
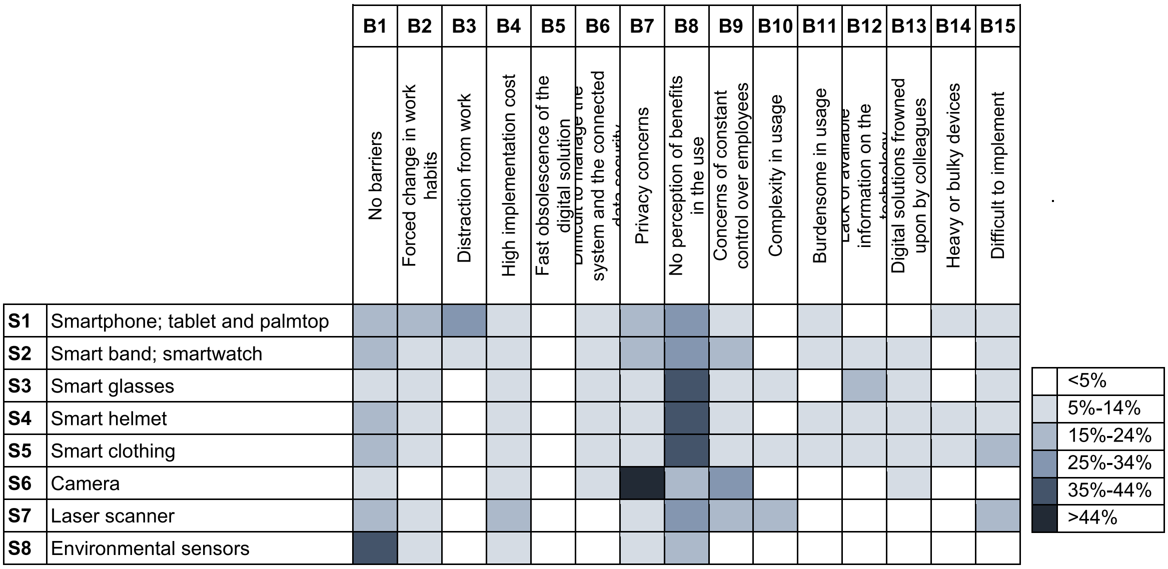


Fig. 4. Barriers to the adoption of digital solutions. Values represent the average number of times each barrier was indicated by each respondent, considering the total sample of digital solutions.

Table 8
Main barriers to digital solutions. The percentage range indicates the percentage of respondents who perceived the selected barrier concerning the adoption of a specific digital solution.



		B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15
		No barriers	Forced change in work habits	Distraction from work	High implementation cost	Fast obsolescence of the digital solution	Difficult to manage the system and the connected data security	Privacy concerns	No perception of benefits in the use	Concerns of constant control over employees	Complexity in usage	Burdensome in usage	Lack of available information on the technology	Digital solutions frowned upon by colleagues	Heavy or bulky devices	Difficult to implement
S1	Smartphone; tablet and palmtop	▒	▒	▓	░		░	▒	▓	░		░			░	░
S2	Smart band; smartwatch	▒	░	░	░		░	▒	▓	▒		░	░	░		░
S3	Smart glasses	░	░		░		░	░	█	░	░		▒	░		░
S4	Smart helmet	▒	░		░		░	░	█	░		░	░	░	░	░
S5	Smart clothing	▒	░		░		░	░	█	░	░	░	░	░	░	▒
S6	Camera	░			░		░	■	▒	▓				░		
S7	Laser scanner	▒	░		▒			░	▓	▒	▒					▒
S8	Environmental sensors	█	░		░			░	▒							

	<5%
░	5%-14%
▒	15%-24%
▓	25%-34%
█	35%-44%
■	>44%

perceived risk, where reducing the vulnerability of workers might not be a primary need (Buenaflor and Kim, 2013). Conversely, the adoption in situations with higher perceived risk is mainly hindered by barriers related to the forced change in work habits (B2), the lack of information on the technology (B12), and difficult implementation (B15).

4.5. *Drivers for the adoption of digital solutions*

The present section answers the research question RQ2b, "*Which drivers facilitate the adoption of digital solutions by metalworking SMEs?*". Section 4.5.1 offers a general overview of the results on drivers. Additional details are then offered by discussing the mechanisms between barriers and drivers (Section 4.5.2) and understanding the influence of the sample's characteristics (Section 4.5.3) on drivers.

4.5.1. *General perspective*

The most relevant drivers emerging from the investigation are the ease of use of a digital solution (D9), such as a simple and intuitive interface, and the clarity and trustworthiness of the data collected (D5) (Fig. 5). Regarding the ease of use of a digital solution (D9), the user-friendly experience of a digital solution, or effort expectancy (Venkatesh, 2003), is often considered a strong driver to support adoption,

Table 9

Perception of the barriers according to the level of adoption. The values in the tables indicate the percentage of companies in the sample that, regarding a specific digital solution, perceive a specific barrier (i) in case the digital solution is adopted (Table 9a), (ii) are interested in adopting or are currently evaluating the adoption of the digital solution (Table 9b), or (iii) do not consider a digital solution interesting (Table 9c).

		No barriers	Forced change in work habits	Distraction from work	High implementation cost	Fast obsolescence of the digital solution	Difficult to manage the system and the connected data security	Privacy concerns	No perception of benefits in the use	Concerns of constant control over employees	Complexity in usage	Burdensome in usage	Lack of available information on the technology	Digital solutions frowned upon by colleagues	Heavy or bulky devices	Difficult to implement
	a: barriers to adopted digital solutions	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**	**B12**	**B13**	**B14**	**B15**
S1	**Smartphone; tablet and palmtop**	42%	18%	18%	6%	0%	3%	21%	3%	9%	9%	6%	0%	3%	9%	3%
S2	**Smart band; smartwatch**	63%	13%	0%	0%	0%	0%	25%	0%	0%	0%	0%	0%	0%	0%	0%
S3	**Smart glasses**	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S4	**Smart helmet**	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S5	**Smart clothing**	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S6	**Camera**	25%	15%	0%	5%	5%	5%	65%	0%	40%	0%	0%	0%	15%	0%	0%
S7	**Laser scanner**	71%	21%	7%	7%	0%	7%	0%	0%	0%	0%	0%	0%	0%	0%	0%
S8	**Environmental sensors**	67%	13%	2%	8%	0%	2%	4%	6%	4%	0%	0%	2%	0%	0%	6%

0%
1%-14%
15%-24%
25%-34%
35%-44%
45%-54%
55%-64%
>65%

	b: barriers to digital solutions considered interesting and/or currently under evaluation.	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**	**B12**	**B13**	**B14**	**B15**
S1	**Smartphone; tablet and palmtop**	17%	26%	43%	19%	9%	15%	30%	19%	17%	6%	9%	7%	7%	7%	13%
S2	**Smart band; smartwatch**	20%	7%	12%	16%	5%	9%	31%	9%	26%	4%	11%	15%	14%	0%	11%
S3	**Smart glasses**	17%	14%	3%	10%	3%	7%	7%	14%	12%	3%	7%	24%	10%	0%	16%
S4	**Smart helmet**	21%	11%	3%	10%	3%	10%	10%	19%	16%	2%	8%	16%	15%	13%	11%
S5	**Smart clothing**	12%	9%	0%	17%	0%	7%	5%	17%	12%	7%	9%	19%	16%	17%	21%
S6	**Camera**	14%	2%	0%	7%	1%	12%	73%	5%	43%	1%	1%	2%	12%	0%	1%
S7	**Laser scanner**	20%	11%	0%	31%	0%	7%	5%	7%	5%	4%	4%	9%	11%	0%	18%
S8	**Environmental sensors**	36%	17%	3%	15%	6%	5%	8%	8%	5%	5%	3%	5%	3%	0%	15%

0%
1%-14%
15%-24%
25%-34%
35%-44%
45%-54%
55%-64%
>65%

	c: barriers to digital solutions considered not interesting.	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**	**B9**	**B10**	**B11**	**B12**	**B13**	**B14**	**B15**
S1	**Smartphone; tablet and palmtop**	11%	13%	33%	14%	5%	11%	20%	51%	13%	6%	9%	2%	3%	5%	9%
S2	**Smart band; smartwatch**	14%	13%	17%	5%	3%	9%	20%	58%	14%	6%	5%	1%	7%	0%	6%
S3	**Smart glasses**	11%	12%	4%	14%	4%	10%	9%	54%	8%	9%	5%	12%	8%	3%	13%
S4	**Smart helmet**	14%	8%	2%	14%	4%	6%	6%	49%	7%	7%	5%	10%	5%	8%	14%
S5	**Smart clothing**	13%	8%	3%	12%	4%	10%	8%	48%	10%	11%	5%	10%	7%	11%	12%
S6	**Camera**	8%	3%	3%	7%	3%	8%	59%	31%	20%	4%	7%	1%	7%	0%	7%
S7	**Laser scanner**	15%	8%	3%	13%	3%	5%	9%	41%	8%	10%	6%	5%	3%	1%	15%
S8	**Environmental sensors**	18%	2%	0%	12%	4%	12%	9%	47%	7%	4%	5%	9%	4%	0%	12%

0%
1%-14%
15%-24%
25%-34%
35%-44%
45%-54%
55%-64%
>65%

Fig. 5. Drivers for overcoming barriers to the adoption of digital solutions. Values represent the average number of times each driver was indicated by each respondent, considering the totality of barriers.

also by the previous literature (Choi et al., 2017; Debnath et al., 2018; Taib et al., 2017). The clarity and trustworthiness of the data collected (D5) relate to the fact that collected data is used only to improve occupational safety conditions and not to exert more control over the workers (Schall et al., 2018). Previous literature pointed out that personal data should not be shared with employers, especially if the data could reveal inefficiencies in the workplace (Golan et al., 2020). Such a sharing could indeed have a negative impact on labor productivity (Dhole et al., 2019) and, consequently, on competitiveness (Neri et al., 2022). Previous literature also suggested the adoption of less intrusive digital solutions, such as cameras, rather than more intrusive ones, to reduce the perception of constant control (Cardillo and Caddemi, 2019). The availability of technical and economic information, as well as information on benefits (D6), the lightweight and small volume of the digital solution (D10), and the need to comply with legal obligations (D4) also emerge as important drivers.

4.5.2. *Mechanisms between barriers and drivers*

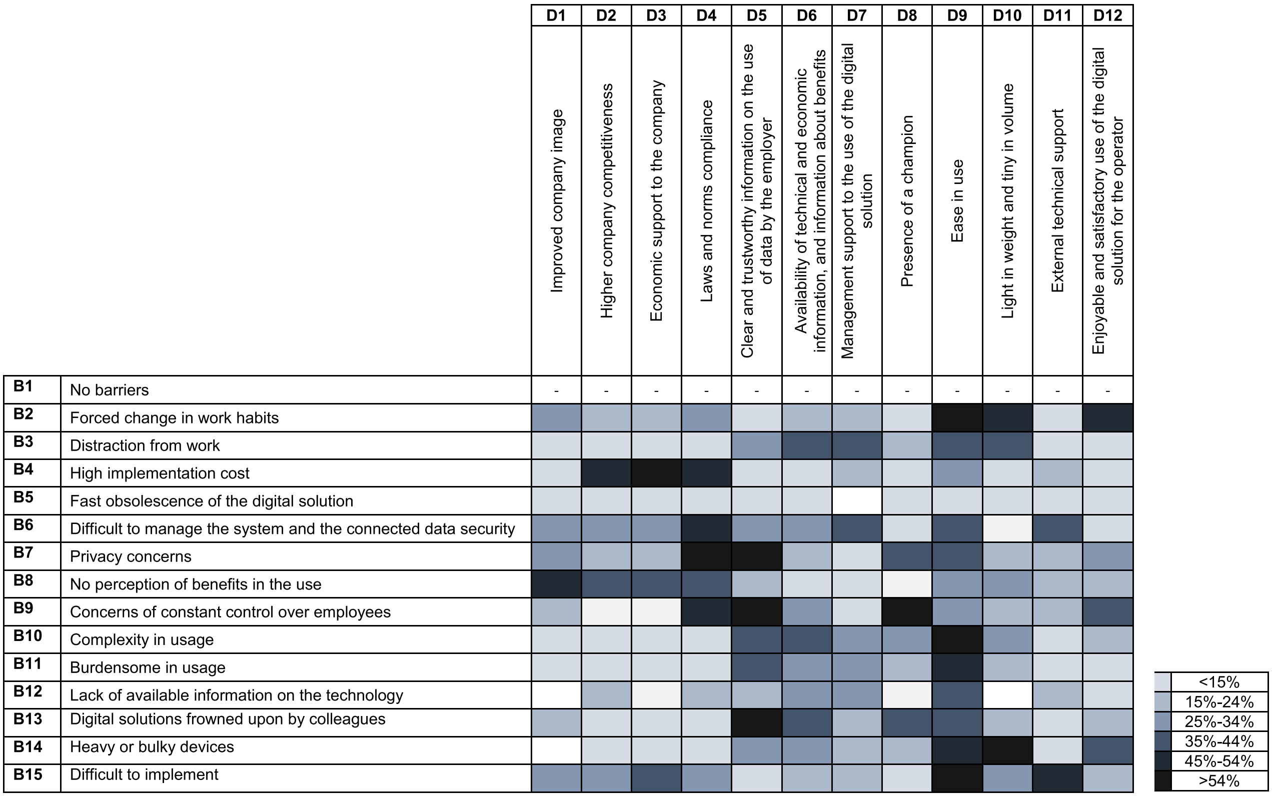
The mechanisms between drivers and barriers are shown in Table 10. Focusing on the main barriers (Section 4.4), respondents who did not perceive any benefits (B8) related to the adoption of digital solutions pointed out that this could not be the case if the company's image (D1) or competitiveness (D2) would be improved because of the adoption, or if the adoption is related to a legal obligation to comply (D4). Receiving economic support (D3) through incentives or tax deductions could also support the adoption of digital solutions. To address the lack of perception of benefits from the use of digital solutions (B8) the previous literature emphasized the importance of proper communication with workers about the usefulness of the solution (Debnath et al., 2018) and associated benefits (Choi et al., 2017; Schall et al., 2018). Said communication can be done, for example, by informing workers in real time about possible hazards they might face and how the digital solution could help them (Bernal et al., 2017). Nevertheless, the proposed solution is thought for the users of the digital solutions rather than for the decision-makers responsible for the adoption. Increased competitiveness (D2), laws and norms compliance (D4), and economic support (D3) also help the adoption of digital solutions when the cost of implementation (B4) is a relevant barrier. The previous literature pointed out the importance of advocating for upfront investment from top management, as well as other strategies such as incentives to actors that adopt safety solutions (Okonkwo et al., 2023). Clarity of information (D5), the presence of a champion to support adoption (D8), and the presence of a legal obligation (D4) may help overcome barriers related to privacy and control concerns (B7 and B9). The need for a champion has already been explored in the literature (Okonkwo et al., 2023), but it seems to be intended as a champion from top management (D7) rather than among employees (D8); nevertheless, it is undoubted that social influence interferes when dealing with the adoption of innovative solutions (Venkatesh, 2003). The impact of barriers could be also addressed by integrating different digital solutions in the same device (Awolusi et al., 2018; Barata and da Cunha, 2019) taking advantage of synergies and ultimately improving the reliability of the final device while reducing issues related to comfort and ease of use.

4.5.3. *Influence of the sample's characteristics*

When assessing different contextual factors, the most perceived drivers remain unchanged. The only relevant influence seems associated with the size and level of digitalization of the SMEs. Smaller SMEs need

Table 10

Main drivers acting to overcome barriers for digital solutions. The percentage range indicates the percentage of respondents who selected a certain driver to tackle the specific barrier.



		D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12
		Improved company image	Higher company competitiveness	Economic support to the company	Laws and norms compliance	Clear and trustworthy information on the use of data by the employer	Availability of technical and economic information, and information about benefits	Management support to the use of the digital solution	Presence of a champion	Ease in use	Light in weight and tiny in volume	External technical support	Enjoyable and satisfactory use of the digital solution for the operator
B1	No barriers	-	-	-	-	-	-	-	-	-	-	-	-
B2	Forced change in work habits	25%-34%	15%-24%	15%-24%	25%-34%	<15%	15%-24%	15%-24%	<15%	>54%	45%-54%	<15%	45%-54%
B3	Distraction from work	<15%	<15%	<15%	<15%	25%-34%	35%-44%	35%-44%	15%-24%	35%-44%	35%-44%	<15%	<15%
B4	High implementation cost	<15%	45%-54%	>54%	45%-54%	<15%	<15%	15%-24%	<15%	25%-34%	<15%	15%-24%	<15%
B5	Fast obsolescence of the digital solution	<15%	<15%	<15%	<15%	<15%	<15%		<15%	<15%	<15%	<15%	<15%
B6	Difficult to manage the system and the connected data security	25%-34%	25%-34%	25%-34%	45%-54%	25%-34%	25%-34%	35%-44%	<15%	35%-44%		35%-44%	<15%
B7	Privacy concerns	25%-34%	15%-24%	15%-24%	>54%	>54%	15%-24%	<15%	35%-44%	35%-44%	15%-24%	15%-24%	25%-34%
B8	No perception of benefits in the use	45%-54%	35%-44%	35%-44%	35%-44%	15%-24%	<15%	<15%		25%-34%	25%-34%	15%-24%	15%-24%
B9	Concerns of constant control over employees	15%-24%			45%-54%	>54%	25%-34%	<15%	>54%	25%-34%	15%-24%	15%-24%	35%-44%
B10	Complexity in usage	<15%	<15%	<15%	<15%	35%-44%	35%-44%	25%-34%	25%-34%	>54%	25%-34%	<15%	15%-24%
B11	Burdensome in usage	<15%	<15%	<15%	<15%	35%-44%	25%-34%	25%-34%	15%-24%	45%-54%	15%-24%	<15%	<15%
B12	Lack of available information on the technology		15%-24%		15%-24%	15%-24%	25%-34%	25%-34%		35%-44%		15%-24%	<15%
B13	Digital solutions frowned upon by colleagues	15%-24%	<15%	<15%	<15%	>54%	35%-44%	15%-24%	35%-44%	35%-44%	15%-24%	<15%	15%-24%
B14	Heavy or bulky devices		<15%	<15%	<15%	25%-34%	25%-34%	15%-24%	15%-24%	45%-54%	>54%	<15%	35%-44%
B15	Difficult to implement	25%-34%	25%-34%	35%-44%	25%-34%	<15%	15%-24%	15%-24%	<15%	>54%	25%-34%	45%-54%	15%-24%

░	<15%
▒	15%-24%
▒	25%-34%
▓	35%-44%
▓	45%-54%
█	>54%

more drivers than larger ones to overcome barriers, especially in terms of cooperation and support from external entities, both technical (D11) and economic (D3). Furthermore, smaller SMEs seem more driven by legal obligations (D4) than larger ones, in line with (Bonafede et al., 2016; Micheli et al., 2021). Additionally, the relevance of clarity of information (D5) and information on benefits (D6) increases as the level of digitalization increases.

4.6. General discussion

The results provide insights for the implementation of an I5.0 human-centric perspective. The operator is no longer seen as a passive object of digitalization, akin to a “sensorized machine” but becomes an active participant in the digital transformation, fully aware of the opportunities and threats arising from digital solutions and capable of leveraging the former to enhance occupational safety (Romero et al., 2016). As such, the results highlight the paramount relevance of respondents’ awareness and familiarity with the adopted digital solutions. When respondents are more familiar with digital solutions, their perception is generally improved, and the adoption process is simplified. This is the case for more traditional solutions, also owned and used privately by adopters, such as smartphones, cameras, and environmental sensors. For these digital solutions, the related benefits appear evident to the adopters, or are, at least, perceived. Besides being the most adopted solutions by the sampled metalworking SMEs, smartphones (and smartwatches), cameras, and environmental sensors proved high application flexibility. Indeed, the solutions proved to tackle almost all hazardous situations, ranging from interactions between human and machines to parameter monitoring. The results thus suggest a potential for improving occupational safety management by utilizing off-the-shelf bundles of standard and readily deployable digital solutions, uniform across the board. A standardized approach could be particularly beneficial for SMEs, given their usual lack of internal resources (capital, time, skills) (Micheli et al., 2021), and their typical disadvantage with complex solutions.

Given the current low implementation rate of digital solutions for occupational safety, the presence of barriers is evident. The perception of barriers appears influenced by the characteristics of context and respondents. Especially for the latter aspect, the present work offers significant advancements compared to the extant literature on digital solutions for occupational safety. Among the most critical barriers are concerns related to privacy and control of workers. The results align with and support previous evidence (Reid et al., 2017; Schall et al., 2018). The most frequently cited barrier is the perceived lack of benefits from use. The barrier is more present and relevant in SMEs characterized by a low level of digitalization, which are also associated with a lower risk perception. Low levels of digitalization (Clemente-Almendros et al., 2024) and limited experience with occupational safety management (Al-Bayati, 2021; Micheli et al., 2021) are usually associated with SMEs. A path-dependent perspective might thus suggest an increased safety divide due to a digital divide in SMEs. The situation could be potentially contrasted by the availability of more information to the SMEs, one of the main drivers emerging from our investigation. The results also underline that the perceived lack of benefits from the use of digital solutions is more relevant for less appealing solutions and for solutions on which respondents have less knowledge and direct experience. Support from third parties, such as service and technology providers, might represent an interesting fostering factor. Training and educational programs might also support ideological shifts toward technology acceptance among anti-technology workers (Dodoo et al., 2024). Additionally, to present advantages to stakeholders and improve the business case for investment, previous case studies and pilot implementation could be exploited (Trianni et al., 2017). Other relevant drivers that emerged relate to the development of a user-friendly and intuitive system, in line with (Li et al., 2018), as well as the appropriate management of privacy, for example by providing prior notification of the final use of the collected data (Chae and Yoshida, 2010).

Finally, the results showed a strong influence of the characteristics of the context of adoption and the respondents. Personal and professional characteristics of the respondents (seniority, experience, etc.), characteristics of the SMEs (size in particular), and risk perception influence the interest in and willingness to adopt digital solutions and, ultimately, their actual adoption rate. The assessment of these factors is crucial to favor the integration of digital solutions within safety management in Italian metalworking SMEs.

5. Conclusions

The present study analyzed the adoption of digital solutions for occupational safety purposes in Italian metalworking SMEs, together with barriers and drivers to their adoption. All the investigated hazardous situations were present in the investigated sample. A few digital solutions, namely smartphones (and smartwatches for similarity), cameras, and environmental sensors emerged as the most adopted by and interesting for industrial decision-makers in metalworking SMEs. Regarding barriers, only a few emerged as highly perceived by respondents, with the lion’s share played by lack of benefits awareness and privacy concerns. Information and ease of use appeared as the main drivers. The results highlighted the critical role played by the characteristics of the SMEs and respondents in influencing the digital solutions adopted and the perception of barriers and drivers.

The study offers contributions for academics, practitioners, and policymakers likewise. The lack of significant differences concerning perceived risk for various hazardous situations indicates the need for practitioners and policymakers to act across all areas. The study highlights the possibility of taking advantage of a limited number of standardized and off-the-shelf digital solutions to address all hazardous situations. To leverage such an approach, the intrinsic characteristics of metalworking SMEs (e.g., lack of resources and limited capabilities, lack of an internal structure for occupational safety management) and the perception and knowledge of respondents regarding occupational safety digital solutions, should be considered. By developing user-friendly technological bundles, providers could offer services and technologies to support employers in managing hazardous situations. These efforts could be complemented by informative and educational efforts, through, for example, industrial associations or informative governmental instruments, to highlight the potential benefits deriving from the adoption of digital solutions. In any case, it is crucial to establish clear guidelines for maintaining compliance with privacy regulations and to develop an appropriate atmosphere of trust and compliant data management practices among industrial decision-makers for data acquired through digital solutions.

The study is not free of caveats, that nonetheless pave the way for future research. The analysis was conducted from the perspective of employers only. However, as the adoption of digital solutions affects the entire organization, it would be interesting to assess the perspective of employees as well. After all, employees are the real users of digital solutions and could offer a different perspective on the topic under investigation. Important insights could be obtained by comparing the two perspectives, identifying differences as well as a common ground that could promote adoption. The analysis carried out is limited to a specific point in time. However, digital solutions could be better integrated within safety management policies within a long-term horizon. A longitudinal analysis could provide interesting insights to support aspects such as specific training activities, changes in the layout of the plant, or the development of tailored safety policies. Additionally, the survey could be extended to sectors other than metalworking, such as the manufacturing or construction sectors, or different geographies. This could provide valuable points of comparison and reflection on the specificity of the situations, besides highlighting contextual dependencies or cross-industry commonalities, thus contributing to the generalizability of the current findings. The replication of the study in other sectors and contexts would be also facilitated as the developed framework of analysis is not sector-specific, thus holding applicability to contexts other than metalworking. The adoption of digital solutions could also generate new and specific hazardous situations that were not considered in the present study, but that could be addressed by future research to provide practitioners and users with a holistic view of adoption. Finally, it would be of great interest to practitioners to understand how to integrate occupational safety digital solutions within an enterprise's occupational safety management practices and whether and to what extent digital solutions adopted for safety reasons can lead to benefits in other areas, such as productivity, competitiveness, or even sustainability-related performance. These benefits could further encourage the adoption of digital solutions to address hazardous situations.

CRediT authorship contribution statement

Enrico Cagno: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Davide Accordini:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Alessandra Neri:** Writing – review & editing, Writing – original draft, Visualization, Validation. **Elisa Negri:** Writing – review & editing, Validation, Methodology. **Marco Macchi:** Writing – review & editing, Validation, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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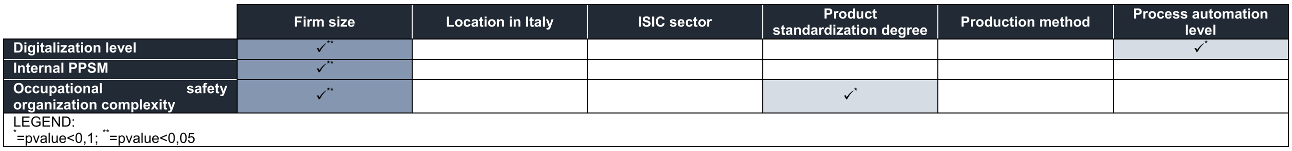
Appendix A

The appendix reports the results of the chi-square statistical tests performed.

Appendix A1

Results of chi-square statistical test for the influence of contextual factors in terms of company size, location, sector, and production organization on the occupational safety organization and level of digitalization of companies.

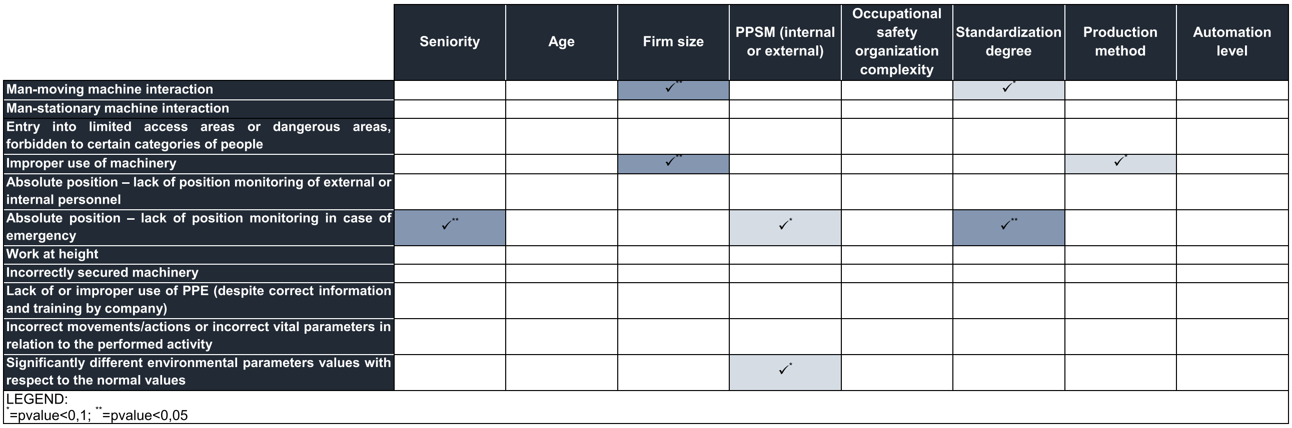


	Firm size	Location in Italy	ISIC sector	Product standardization degree	Production method	Process automation level
Digitalization level	✓**					✓*
Internal PPSM	✓**					
Occupational safety organization complexity	✓**			✓*		

LEGEND:
*=pvalue<0,1; **=pvalue<0,05

Appendix A2

Results of the chi-square statistical test for the influence of contextual factors on the perceived risk for different hazardous situations.



	Seniority	Age	Firm size	PPSM (internal or external)	Occupational safety organization complexity	Standardization degree	Production method	Automation level
Man-moving machine interaction			✓**			✓*		
Man-stationary machine interaction								
Entry into limited access areas or dangerous areas, forbidden to certain categories of people								
Improper use of machinery			✓**				✓*	
Absolute position – lack of position monitoring of external or internal personnel								
Absolute position – lack of position monitoring in case of emergency	✓**			✓*		✓**		
Work at height								
Incorrectly secured machinery								
Lack of or improper use of PPE (despite correct information and training by company)								
Incorrect movements/actions or incorrect vital parameters in relation to the performed activity								
Significantly different environmental parameters values with respect to the normal values				✓*				

LEGEND:
*=pvalue<0,1; **=pvalue<0,05

Appendix A3

Results of the chi-square statistical test for the variation in the interest level for the digital solution when the perceived risk of the hazardous situation changes.

	Smartphone, tablet and palmtop	Smartwatch and smart-band	Smart glasses	Smart helmet	Smart clothing	Camera	Laser Scanner	Environmental sensors
Man-moving machine interaction		✓**			✓*		✓**	
Man-stationary machine interaction				✓**				
Entry into limited access areas or dangerous areas, forbidden to certain categories of people				✓*	✓**			
Improper use of machinery		✓**	✓**	✓**	✓**		✓**	
Absolute position – lack of position monitoring of external or internal personnel				✓*				
Absolute position – lack of position monitoring in case of emergency				✓*				
Work at height		✓*						
Incorrectly secured machinery		✓**						
Lack of or improper use of PPE (despite correct information and training by company)								
Incorrect movements/actions or incorrect vital parameters in relation to the performed activity			✓*	✓**	✓**			
Significantly different environmental parameters values with respect to the normal values		✓**						
Legend: *=pvalue<0,1; **=pvalue<0,05								

Appendix A4

Results of the chi-square statistical test for the variation in the level of interest in digital solutions as contextual conditions change.

	Smartphone; tablet and palmtop	Smart-band; smartwatch	Smart glasses	Smart helmet	Smart clothing	Camera	Laser scanner	Environmental sensors
Seniority		✓**			✓**		✓*	
Age								
Awareness of wearable devices	✓*	✓**	✓**	✓**	✓**		✓**	
Awareness of not wearable devices	✓**	✓**	✓**	✓**	✓**	✓**	✓**	✓**
Company size	✓*	✓**	✓**	✓**	✓**		✓**	✓**
Digitalization level	✓**	✓**	✓**	✓**	✓**	✓**	✓**	✓**
Legend: *=pvalue<0,1; **=pvalue<0,05								

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