Safety Is the New Black: The Increasing Role of Wearables in Occupational Health and Safety in Construction

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Abstract. As wearable technologies are gaining increased attention in construction, we present an integrated solution for their adoption in occupational health and safety (OHS). Research methods include a structured literature review of 37 articles and a year-long design science research project in a construction group. The main results are (1) the identification of new wearable solutions made available by industry 4.0 to prevent hazards, and (2) a wearable model for voluntary regulations compliance. For theory, our research identifies key application areas for integrated smart OHS in construction and highlights the importance of continuous monitoring and alerts to complement the traditional sampling techniques. For practice, we offer recommendations for managers wishing to implement continuous compliance checking and risk prevention using wearable technology. Our findings help improve health and safety audits supported by digital evidence in the sector with most risks of accidents in the European Union.

Keywords: Occupational health and safety · Industry 4.0 · Construction · Internet-of-Things · Wearables · Regulatory compliance

1 Introduction

Occupational health and safety (OHS) is a priority for the construction sector and one of the areas with more potential for improvements with the technological transformation of industry 4.0 (I4.0) [1]. This claim is confirmed by the positive impact of sensors in construction equipment and wearable devices available to construction workers, allowing real-time alerts to prevent accidents [1–5]. Nevertheless, there are also barriers to the adoption of smart devices in construction, including privacy issues and the perceived usefulness and ease of use of each device [6]. Despite the extensive research in augmented reality, wearables, and sensors for construction safety management [2, 7–9], most studies focus on specific applications for preventing accidents (e.g. collision alert), safety training [10], or monitoring specific parameters of work conditions using biosensors [7]. Other authors address the reduction of consequences in accidents via internet-of-things (IoT), detecting falls and ensuring the earliest possible assistance [11]. More recently, [12] explores continuous monitoring of environmental

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factors such as carbon monoxide and noise in factories. Interestingly, we could not find any studies that integrate these important sources of data for compliance, as it happens in audits required by OHSAS 18001 safety standards and legal regulations.

Our project started with a European co-funded research project involving a Portuguese construction group. Two companies in the consortium (C1: consulting, training, safety inspections; C2: construction equipment supplier) had industry 4.0 in their agendas. They were aware of experiments in academic projects, such as the use of sensors to avoid collisions between vehicles and workers in construction sites [1]. Yet, according to them, such an application only scratches the surface of what's possible for OHS. For example, the same system used to identify the worker in collision detection could be important to avoid falls – using the same wearable to detect proximity to danger areas or to prevent unauthorized access to the construction site. Accordingly, we formulated two main research questions:

- RQ1. What are the opportunities for using wearable technologies in industry 4.0 for occupational health and safety in construction?
- RQ2. How do we design an information system for OHS in construction, for real-time integrated prevention (e.g. user alerts), correction (e.g. minimize accident consequences), and compliance (e.g. ensuring the correct adoption of regulations)?

The remainder of our paper is presented as follows. Section 2 describes the research approach. Subsequently, we present the literature survey, and, in Sect. 4, we detail the different phases of our project. Section 5 discusses the findings and the implications for theory and practice. The paper closes with opportunities for future research.

2 Research Approach

To address the two research questions we have selected a design-science research (DSR) approach [13], having its foundations in the work of [14]. DSR enables the creation and evaluation of artifacts to solve specific organizational problems, which can "be in the form of a construct, a model, a method, or an instantiation" [13], integrating informational, technological, and social aspects [15]. Figure 1 outlines our DSR.

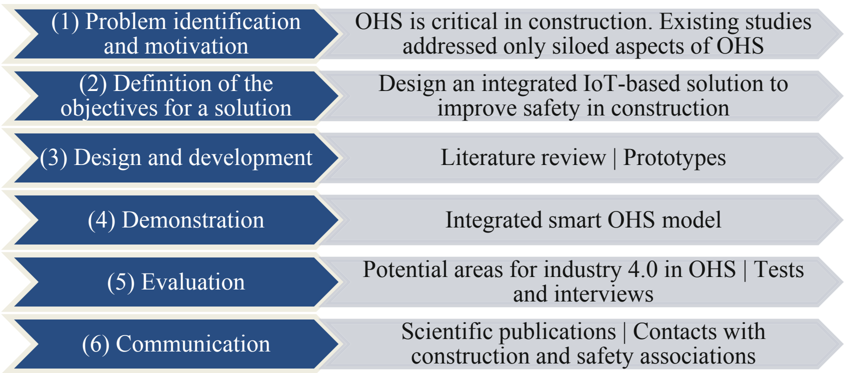

Fig. 1. Design science research approach (adapted from [16]).

The sequence of DSR activities is particularly suitable for our research and the reasons are fourfold. First, the necessity to conduct a comprehensive literature review to identify wearable industry 4.0 solutions for OHS, which contributes to RQ1 and guides the field activities in RQ2. Second, the development of artifacts justified by business needs and tests in a real environments [13]. Third, new wearable solutions for OHS should be supported by theory and practice (RQ2). Fourth, the examples obtained through the field work, contributing to demonstrate and communicate industry 4.0 opportunities to construction practitioners. Having identified the problem and the objectives for a solution, in the next section, we review key contributions from the literature.

3 Literature Review: What Are the Opportunities?

We have followed the recommendations made by [17] to guide the steps of the literature review and used a concept-centric approach to summarize the results [18]. First, we made searches in Google Scholar using different combinations of keywords, for example, “safety management” + “industry 4.0” + construction, returning 278 results (excluding patents and citations) and wearable + “occupational health and safety” + construction yielding 611 results. Then, we screened the title and abstract to identify studies about wearable industry 4.0 technologies applied to construction. Afterwards, we made searches in other databases such as IEEEXplore (e.g. 16 results using “construction safety iot”) and EBSCOhost (e.g. 2 results with construction + “internet of things” + safety). A total of 37 papers were classified in three main concepts presented below.

3.1 Site Oriented OHS

Significant research has been conducted to improve safety in the relation between humans and the environment in construction. For example, the work of [11] to detect falls using wearable technologies and reduce response time. Other authors focus on prevention. Examples include the creation of safety barriers [19], the detection and alert of unsafe conditions of moving objects [20], and monitoring the inclination of retaining walls to anticipate structural failures [21]. Proximity detection is another popular area of research. The work of [1, 22–24] uses IoT, mobile, and wearable technologies to sense and alert users of danger zones (e.g. equipment operations). Computer vision has also been tested in the forms of (1) scene-based; (2) location-based; and (3) action-based risk identification [8], while other studies mix multiple technologies, for example [2], taking advantage of building information modeling, augmented reality, wearables, and sensors to assist safety planning, training, and control.

An important gap is the monitoring of environmental parameters and its correlation with OHS. We found a recent example, in factory settings, using low cost sensors to monitor particles, noise, or carbon monoxide [12]. This research is inspiring for proposals that combine different environmental factors, with the potential of continuous monitoring and correlation with biometric parameters and logging of risk alerts.

3.2 User Oriented OHS

The interest of monitoring health parameters in construction is increasing, as revealed by [25] for stress recognition, [26] for psychological status based on heart rate, energy expenditure, metabolic equivalents, and sleep efficiency, or [27] using biosensors. It is now clear that continuously collected data can be used, for example, using a photoplethysmography (PPG) sensor embedded in a wristband-type activity tracker [7].

Personal protective equipment (PPE) is key in OHS activities and the risks increase when the staff does not comply with its use [28]. Taking advantage of cloud, wireless, and wearable technologies, [29] presents a proof of concept to ensure the use of PPE. The results were positive, although privacy (e.g. using technology to monitor performance, number of steps taken, and heart rate) was pointed as a major concern of the workers. Other barriers include “employee compliance, sensor durability, the cost/benefit ratio of using wearables, and good manufacturing practice requirements” [30]. Perceived usefulness, social influence, and perceived privacy risk are key aspects that influence the intention to use equipment, such as smart vests and wristbands [6]. Therefore, additional sociotechnical research is necessary in business information systems.

A group of studies aim at human health improvements, including ergonomics [31], stress control [32], and the prevention of construction workers’ musculoskeletal disorders [33]. An example specifically developed to identify the exposure of the worker to hazardous vibrations is presented by [34]. Yet, these solutions are not yet currently implemented by construction companies. In a recent review about OHS in the industry 4.0 era, the authors of [35] argue that “emotion sensors need to be developed to monitor workers and ensure their safety continuously”. The work of [4] reinforces the need to monitor physical demands of construction workers because it is highly variable depending on the tasks. Monitoring of physiological status can be conducted at work but also off-duty, as presented in [26], opening opportunities for OHS improvements and uncovering new risks for privacy [36]. If taken in isolation, biometric measurements are also challenging, because the correlation between work and fatigue varies with each person and, to be valid, fatigue based on heart rate requires context information [37].

3.3 Integration of Smart OHS in Construction

Nine literature reviews were included in our survey (4 done in 2018, 4 done in 2017, and 1 done in 2015). One of the studies highlights that the number of papers addressing innovative technologies is increasing since 2012, but most of them remain in the academic field [38]. According to these authors, researchers and practitioners should work together in “the effective path of innovative technology transition from construction safety research into construction safety practice”. Two recent works expressly mention “industry 4.0” in the title: [35], who anticipates significant changes in OHS practices due to the closer connection between humans and machines, including risk management in real time; and [39] mentioning the importance of wearables for worker safety.

Wearable technologies were the focus of different literature reviews. The work of [3] presents a comprehensive list of technologies applicable to physiological and environmental monitoring, proximity detection, and location tracking. The authors conclude that it is necessary to “derive meaning from multiple sensors” [3]. The authors of [40] also suggest involving researchers and practitioners in wearables adoption for monitoring, augmenting, assisting, delivering, and tracking in construction. These authors have previously detailed the application of wearables in the workplace [41].

On one hand, user oriented OHS reviews can be found in [5], that collected data via smart watch and showed the correlation between psychological status and physical indicators. On the other hand, [42] reviews earthmoving equipment automation. Examples of technologies used to improve safety with these types of equipment include artificial vision, GPS, and RFID, but the authors state that "advanced sensing technologies (e.g. computer vision) for tracking and safety, are still in experimental stage and yet have to prove their efficiency in practice". IoT is also important to implement visualization techniques for safety management [43]. Yet, we could not find a proposal that integrates the user physical indicators with the environmental conditions. The combination of human, machines, and context data is determinant for compliance.

4 Hands-On Experiment: Integrated Smart OHS

The design and development of our prototypes involved two researchers and a student of informatics, responsible for the coding. This phase was conducted in close collaboration with the practitioners designated by the construction group, namely, two OHS assessors, the top managers of the construction equipment company and of the consulting company, and two construction technicians designated to assist in the field tests. There were two major steps. First, a preliminary research with sensors, wristbands, and mobile devices, described in Sect. 4.1. Second, the design of an integrated smart OHS information system, described in Sect. 4.2.

4.1 Testing Opportunities and Integrating Technologies

In this step we tested proposals found in the literature (e.g. RFID for proximity warning system). Figure 2 presents the example for the worker oriented OHS.

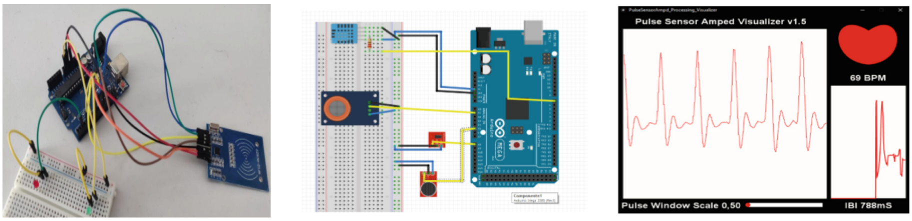

Fig. 2. Smart OHS – worker oriented preliminary (non-integrated) experiments.

Our purpose with the experiments presented in Fig. 2 was to test low cost equipment: Arduino UNO and RC522 RFID sensor presented on the left of Fig. 2; environmental sensors for temperature and humidity (DHT11), noise (SEN-12642 sound detector), and air quality (MQ135) in the middle; and a simple visualization tool to display data and compare to real values – rightmost image. It was important for three reasons. First, it facilitated the discussion with the practitioners about the potential of wearables and technologies emerging from industry 4.0. Second, it confirmed previous research pointing to the applicability of using low cost IoT material in real applications [12]. Third, it identified synergies in the systems described in the literature. For example, the RFID system for collision detection can also be used for site access (identification of workers in the site) and control if PPE is in use. Each of these examples have already been studied independently (e.g. [22] or [29]), missing an integrated solution.

These cases were selected on the basis of the (1) need to protect the worker from collisions and falls, (2) legal requirements of OHS (e.g. noise and air quality), and (3) potential to contrast biometric and environmental parameters to alert the user. We were also looking for synergies when using different technologies. For example, RFID to protect the worker from collisions and also (1) avoid unauthorized access to the site and (2) prevent equipment use by non-qualified staff (block the engine of the equipment). Other examples are the continuous monitoring of environmental conditions for OHS audits and the combination with biometric parameters (e.g. heart rate) and improvement of work conditions.

An integrated OHS system should be aware of the workers but also their context. Yet, according to the company managers, most of the prototypes found in the literature are difficult to deploy in practice: "it is already difficult to ensure the proper use of PPE; the wearable will also need some sensor to ensure that it is being used (…) the best way is to create a unique wearable such as wristband that integrates RFID, GPS, biometric monitoring, and other functionalities (…) which is available in the market but not yet adopted in OHS and not fully explored for compliance checking".

4.2 Proposing the Integrated Smart OHS Model in Construction

Table 1 presents the candidate technologies for integrated smart OHS that we found in the literature and discussed in our meetings.

Table 1. Summary of Industry 4.0 opportunities for integrated smart OHS.

	VR	AR	IoT	Cloud	M	ARO	BDA	BIM	BC
Site oriented	+	+	+	+	+/-	-	-	+	-
User oriented	+/-	+/-	+	+	+	-	-	+/-	-
Audit oriented	-	+	+/-	+/-	+/-	+/-	+	-	+

Legend: light grey – short-term priority for development; dark grey – medium-term; white: long-term project.

The list of technologies includes Virtual Reality (VR), Augmented Reality (AR), IoT, Cloud, Mobile (M), Autonomous Robots (ARO), Big Data and Analytics (BDA), Building Information Modeling (BIM), and Blockchain (BC). The list is not exhaustive, for example, we did not include 3D printing and additive manufacturing, which raise issues for safety while using them, but they are not tools for OHS. We also did not include fog computing [44] because it was considered too technical for the discussion with construction experts (although important for implementation purposes).

The possible applications vary according to each technology. For example, VR, AR, and BIM (dark grey background) are important to digitalize the construction information, which can assist in the users training and guidance while executing tasks. AR seems promising for inspection and auditing, contrasting the real with the virtual scenario (e.g. evaluate if specific safety equipment is on site). IoT (includes related technologies such as RFID, wireless, and location systems), cloud, and mobile can assist OHS efforts in all aspects of construction. However, when combined with big data and analytics and blockchain, the potential increases for inspection and auditing (light grey background in the table). One important conclusion is that full industry 4.0 potential requires a combination of technologies for specific purposes.

The interest in blockchain emerged during our discussions about the relation with external entities, such as government and insurance companies. The experts that we interviewed confirm the importance of wearables for improvement actions or standards audits (voluntary regulations). Yet, if lacking evidence of data quality and reliability, the use for insurance communications or legal compliance is limited. It is necessary to prove to third parties that the company implemented all the measures for prevention and that the OHS data was in fact collected on the specific site, user, or context. The proposal for our companies is presented in Fig. 3.

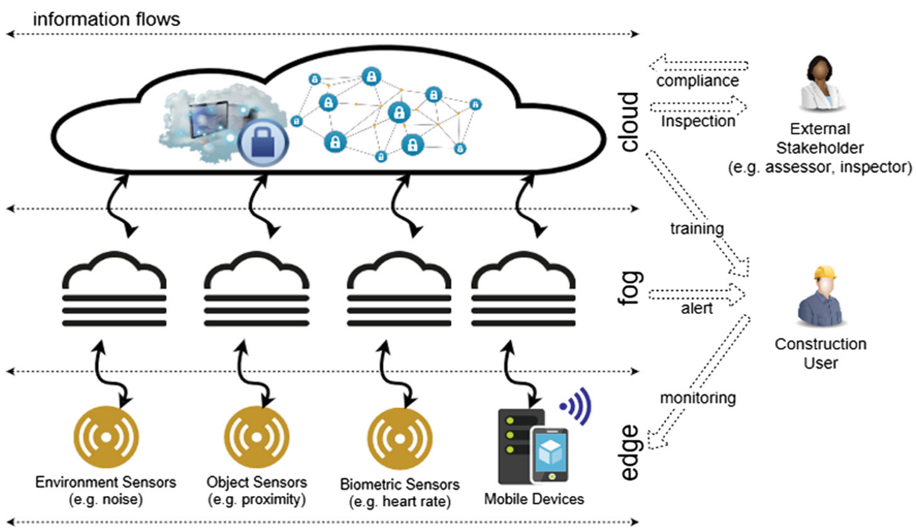

Fig. 3. Integrated smart OHS – conceptual model.

The proposed model is inspired in the architecture proposed by [44] for IoT, which considers a fog layer between the cloud and the edge devices. In this proposal we have integrated the platforms and sensors in the lower layer, considering four different elements in the cyber-physical IoT infrastructure (on the bottom): the *environment sensors* (nowadays unpractical to embed in the worker wearables) including light conditions, temperature and humidity, noise, and air quality (requires GPS tracking); the *objects sensors* including RFID antennas (collision detection or fall protection), personal protection (e.g. identify helmet presence), and site access; the *biometric sensors* including worker monitoring and alert system based on a smart wristband – biometric information, RFID, and GPS; and the *mobile devices* for communication with the OHS.

There are advantages in this design. First, minimizes the wearable burden while making it essential to enter the site. Second, concentrates the environmental parameters in a portable, low cost toolkit (<200€ each in our prototypes), making it affordable to use in different areas of the site. Third, ensure wearable use – if the wearable is not in use, the worker may not enter the site or use specific equipment. The arrows connecting the OHS stakeholders (on the right) represent the value obtained from data analysis in the OHS (training, alerts, and inspections), and the purpose of data collected via IoT (monitoring and compliance). On the top is represented the OHS cloud supported by a private blockchain and, bellow, the fog layer to support for IoT infrastructure [44].

5 Discussion

Few studies have addressed occupational health and safety in the industry 4.0, and those that do have identified challenges [35]. Most of the research in I4.0 technologies for safety in construction is diverse but also disperse. But integration is key, as stated by [35] “if the technologies driving Industry 4.0 develop in silos and the OHS initiatives of manufacturers are fragmentary, hazards will multiply and some of the gains made in accident prevention will be lost”.

According to the company managers in our project consortium, a comprehensive model for wearable technologies in construction needs to support (1) training, (2) monitoring worker critical parameters, (3) user alerts (collision, fall, environment parameters), and (4) voluntary regulatory compliance (OHS standards audit and improvement evidences). Future research is needed to address requirements of insurance companies and government authorities for legal compliance checking.

Only the combination of technologies can turn industry 4.0 into a reality in OHS. According to the companies participating in our work, they were interested in investing only if (1) the solution is integrated, and (2) the data collected is not merely for monitoring and alert, but also valuable for improvement and compliance checking. According to our case companies “sometimes the problem is not in the existence of solutions for OHS; it is in convincing the users of the need to use it, in a daily basis”. One of the OHS experts also told us that “we can monitor all the parameters in the world but for regulatory compliance, it is also crucial to prove that the data is reliable and not easily manipulated (…) that is essential to demonstrate our commitment to safety when dealing with insurance companies and assessors”. She presents an example "if the environmental conditions are continuously monitored in 'friendly' locations – the term used to designate a location of the site that is far away from specific machinery – the data will be irrelevant for prevention and warning systems". Moreover, "if the collected data is not reliable" – she gave the examples of a worker that gives the wristband to another colleague or if the large amounts of historical data about warnings and environmental conditions can be changed by the organization – "then, the benefits will be limited".

The insights gathered in our literature review and the practitioners' feedback allowed us to identify critical elements of integrated smart OHS:

- Continuous monitoring is complementary to traditional sampling. We confirmed previous findings that used low cost sensors, however, at this moment, there are risks in trusting solely in this type of systems. For example, the error of measurements and obtaining data in wrong locations;
- Non-integrated developments may lead to duplicated investments and the proliferation of tools and may demotivate the workers from using a plethora of systems;
- Industry 4.0 opportunities are critical to improve health and safety, but the users must use it. Wearables must be friendly and useful, but the possibility of making them mandatory (e.g. if PPE is not identified, the worker is not allowed to enter the site; worker recognition for equipment start; site access), is interesting;
- Data quality should be a priority for integrated smart OHS. Trusting in single systems for health and safety is a risk too high. For example, there are risks of over confidence by the workers (e.g. collision detection) that may decrease the surveillance level. These aspects have not yet been addressed in the BIS literature.

6 Conclusions

We reviewed key literature for wearable implementation in OHS and proposed an integrated smart OHS system design for construction. Our findings emerged from a year-long design science research [13] project with two construction companies. Industry 4.0 opens the opportunity to adopt wearables for continuous monitoring and innovative regulatory compliance systems in OHS. Private blockchains [45] can be a viable solution to test in construction compliance and audit, when third party entities are involved, for example, insurance companies. To our knowledge, this is the first proposal taking advantage of wearables connected to site IoT-based solutions, and context information.

The system was designed in collaboration with practitioners, thus enabling testing and evaluation of current academic proposals. According to the construction group experts, independent single purpose solutions, such as collision detection, are interesting for specific stakeholders but it is difficult to equip workers with multiple wearables.

Continuous monitoring via wearables is complementary to the sampling techniques normally used for OHS, with the benefit of providing real-time alerts and valuable data for improvement and compliance checking. The prototypes that we have developed showed positive results for compliance with OHS standards, namely evidence of prevention efforts, but are not suitable for insurance and legal purposes. To that effect, additional requirements are mandatory, such as data source traceability (e.g. GPS location, timestamp, user); contextual data; and protection of the digital traces. Another important implication for practice is to ensure that the wearables are effectively used – one possibility is to ensure that the technology is friendly and necessary to use specific equipment or access the site, thus becoming a working tool.

Our research has limitations that need to be stated. First, is the selection of papers for our literature review. Industry 4.0 is a vibrant field of research and other studies could be included. Second, our research considers two different companies with important roles in OHS for construction, but belonging to the same group. Other companies may have different priorities for OHS investments. Third, despite including certified OHS auditors and senior consultants, the data collected with interviews with the experts did not involve external assessors and legal advisors.

Future research is necessary to test the part of the model that involves third party entities using a private blockchain. In addition, there are opportunities for comparative studies of different models, for example, mobile systems for diagnostics procedures [46] and solutions for ambient intelligence in OHS [47]. Our preliminary contacts with an integrated management system consulting company and two associations of construction in Portugal already provided results. A quantitative survey will be deployed with the support of the associations that represent hundreds of companies to understand their perspective about wearable investments for OHS and identify potential actions by their associations (e.g. ask government to enforce collision detection systems or continuous monitoring of critical parameters, with benefits in insurance policies).

We hope that our work may inspire other researchers to empirically evaluate the vast amount of academic proposals for industry 4.0 in traditional sectors of the economy. It is important to identify combinations of technologies to fully explore the potential in the fourth industrial revolution to improve business information systems.

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