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OSH TRAINING FOR VULNERABLE GROUPS IN THE INDUSTRY 4.0 CONTEXT

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Abstract: *This paper highlights the critical need for specialized OSH training for vulnerable groups in the era of Industry 4.0. Despite the significant rise in the variety of studies, roadmaps, and maturity models related to identifying measures necessary to support the change process, in terms of occupational safety, there is still a noticeable lack of focus on the vulnerable groups of workers in Industry 4.0. both worldwide as in Romania. To address this gap, the aim of our paper is to analyses the problematics of vulnerable groups in the context of Industry 4.0 with a specific focus on occupational safety training by proposing an in-depth literature review in order to identify and propose recommendation for ensuring Safety 4.0 - a "safe trip" in this journey that is the transition to Industry 4.0.*
Keywords: *Industry 4.0, health and safety, vulnerable groups, occupational safety training*

1. INTRODUCTION

In 2015, at the World Economic Forum, was introduced the concept of the Fourth Industrial Revolution to discuss a new era of innovation that merges the physical, digital, and biological realms. This concept, later known as Industry 4.0 (I4.0), encompasses three main technological developments that apply across various sectors, not just manufacturing. Firstly, it focuses on creating connections between devices and systems within organizations and with outside entities on a global scale. Secondly, it utilizes vast amounts of data to extract valuable insights, helping organizations make more informed decisions. Lastly, it integrates available physical and non-physical assets into cyber-physical systems, ultimately improving efficiency, productivity, and fostering innovation [1].

The rapid development of Industry 4.0 has introduced new technologies that significantly alter workplace dynamics. While these advancements offer efficiency gains, they also create new occupational risks, particularly for vulnerable groups [2].

Although there is no universally accepted definition of "vulnerable worker," the term typically refers to individuals in precarious, low-paid, and sometimes hazardous employment, often facing discrimination. They are not limited to a specific sector or confined to a single country or region and they share several common characteristics: their vulnerability is often related to their gender or age (pregnant women, young workers below the age of 18, older workers); are often economically, socially and/or politically marginalized (migrant workers); are subject to discrimination, psychosocial pressures, abuse or harassment (disabled workers) [3,4,5].

Problem description. Despite the significant rise in the variety of studies, roadmaps and maturity models [6] related to identifying measures necessary to support the change process, in terms of occupational safety in I4.0, there is still a noticeable lack of focus on the vulnerable groups of workers in Industry 4.0. both worldwide and in Romania.

The limited focus of I4.0 research on occupational safety and health (OSH) is raising increasing concerns that researchers may overlook the critical aspects of human-machine

interactions in the systems they are developing [7].

To address this gap, the aim of our paper is to analyses the problematics of vulnerable groups in the context of I4.0 with a specific focus on occupational safety training by proposing an in-depth literature review in order to identify and propose recommendation for ensuring Safety 4.0 - a "safe trip" in this journey that is the transition to Industry 4.0.

2. METHODOLOGY

2.1 Literature review methodology

In this paper, we conducted our literature review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology. Although PRISMA is primarily designed for systematic reviews evaluating the effects of health interventions, it was utilized in our study because its checklist items are also applicable to systematic reviews assessing non-health-related interventions, such as occupational safety and health [8].

Our literature search was performed using three of the most widely recognized and influential English-language databases: Web of Science - Core Collection, Scopus, and Taylor & Francis.

The review process began with a preparatory phase, which involved defining the search parameters, including search terms, thesaurus terms, language restrictions, and other relevant criteria. We then followed the PRISMA flowchart steps. The first step entailed conducting database searches using Boolean operators (AND, OR) and applying predefined limits such as publication years, full-text availability, and English language restrictions (table 1).

Unfortunately, search words: „occupational safety for vulnerable workers in Industry 4.0" return no results, no matter how many combinations we tried. We find ourselves in need to broaden our search by removing the word "vulnerable" from our search criteria (table 1).

Table 1

Search engine criteria and results

Database	Search engine syntagma	Results	Final papers
Scopus Elsevier	[TITLE-ABS-KEY] (safety AND training AND workers AND Industry 4.0) **[OR]** [TITLE-ABS-KEY] (occupational AND safety AND training AND workers AND Industry 4.0) **[OR]** [TITLE-ABS-KEY] (health and safety for workers in Industry 4.0)	254 documents	46 Papers Selected by type of journals, title, and by reading the abstracts where it was the case
Web of Science	[TOPIC] (safety training for workers in Industry 4.0) **[OR]** [TOPIC] (occupational safety for workers in Industry 4.0) **[OR]** [TOPIC] (health and safety for workers in Industry 4.0)	60 documents	14 Papers Selected by type of journals, title, and by reading the abstracts where it was the case
Taylor Francis	[occupational safety for workers in Industry 4.0] **[OR]** [safety training for workers in Industry 4.0] **[OR]** [health and safety for workers in Industry 4.0]	366 documents	25 Papers Selected by type of journals, title, and by reading the abstracts where it was the case

After combining all search terms, applying the necessary filters, and removing duplicate records, we identified 85 articles. This number was recorded in the top-left box of the PRISMA flowchart.

During the eligibility phase, articles were screened, and those not relevant to our research were excluded. The number of excluded articles was subtracted from the total records screened, and the remaining count was entered in the box titled "Full-text articles assessed for eligibility."

All full-text articles were then carefully reviewed based on predefined inclusion criteria. At this stage, we referred to our guidelines to determine the expected number of articles to be retained. The articles excluded in this phase were documented in the "Full-text articles excluded" box, along with a brief justification for exclusion (which, in some cases, mirrored the reasons used during the screening phase).

Finally, we subtracted the number of excluded articles from the total assessed full-texts, arriving at the final selection of 17 articles. This number was recorded in the last box of the PRISMA flow diagram, completing the review process (Fig. 1).

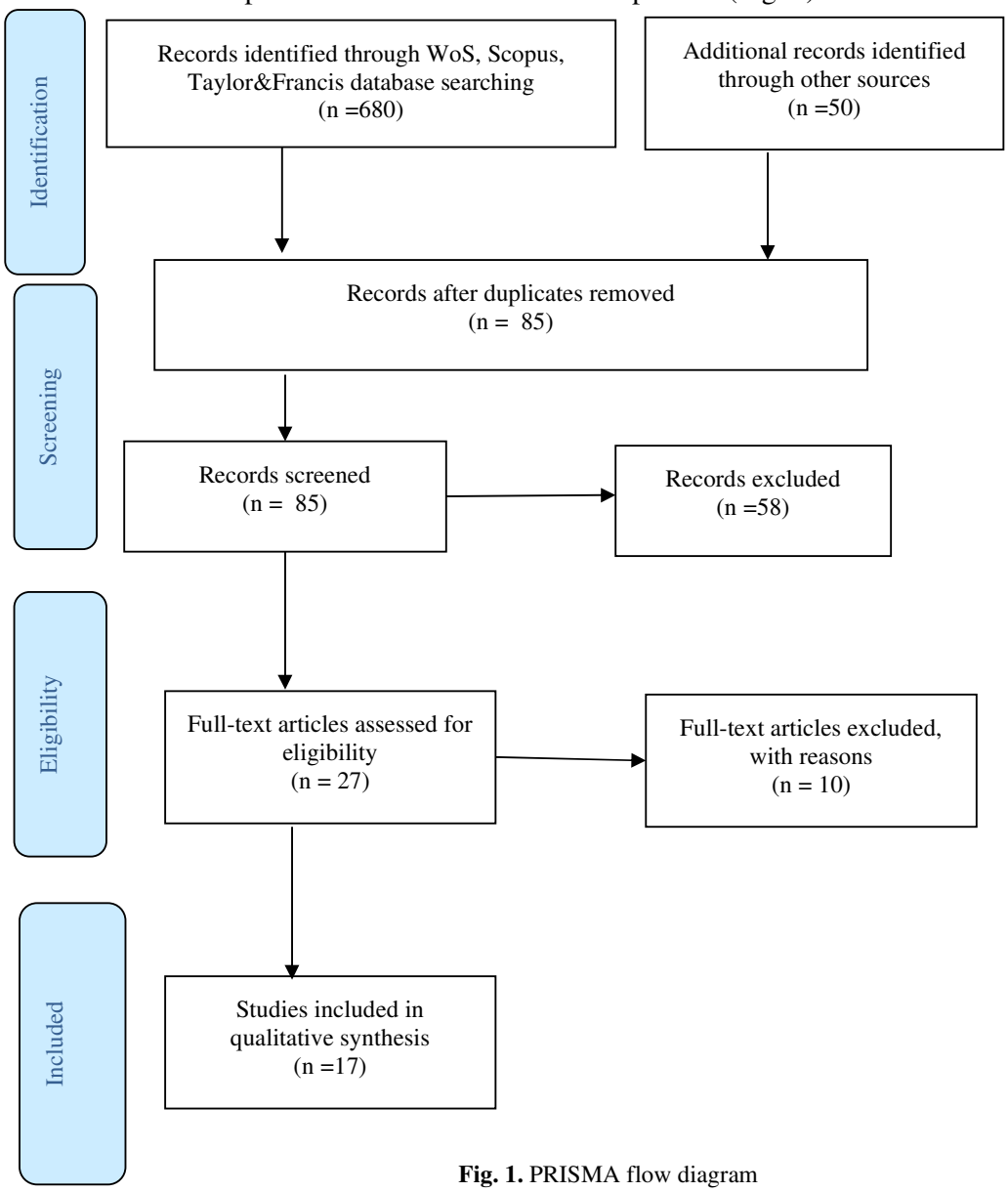

Fig. 1. PRISMA flow diagram

2.2 Case study

In order to identify and propose recommendation, this section highlights a successful OSH training initiatives for vulnerable workers. Our case study example includes training migrant workers with virtual reality-based safety simulations on a construction site.

Occupational Safety and Health (OSH) training is essential for ensuring the well-being of workers, particularly those in high-risk industries such as construction. Migrant workers, often facing language barriers and unfamiliar work environments, are especially vulnerable to workplace accidents. To address this, innovative training methods leveraging Industry 4.0 technologies, such as Virtual Reality (VR), can enhance learning retention and safety compliance. This case study examines the effectiveness of VR-based safety simulations in construction and proposes an analytical model to evaluate knowledge retention over time.

Migrant workers often experience challenges in traditional OSH training due to language barriers, cultural differences, and varying educational backgrounds. Traditional training methods, such as printed safety manuals or instructor-led sessions, may not be effective in ensuring long-term knowledge retention.

VR-based training presents a dynamic, immersive learning environment that enhances understanding by allowing workers to interact with safety scenarios in a simulated construction site.

In order to analyze the retention of OSH training, we propose the use of the Ebbinghaus original Forgetting Curve, which describes knowledge decay over time [42]:

$$R(t) = R_0 e^{-\lambda t} \quad (1)$$

where:

$R(t)$ = knowledge retention at time t;

R_0 = initial knowledge retention after training;

λ = forgetting rate;

t = time elapsed since training.

For Industry 4.0, adaptive learning (VR, AI-based training) can reduce forgetting. We introduce Hinton's Reinforcement Factor (δ), which accounts for retraining interventions [43].

$$R_{enhanced}(t) = R_0 e^{-(\lambda-\delta)t} \quad (2)$$

where:

$R_{enhanced}(t)$ = knowledge retention at time t;

R_0 = initial knowledge retention after training;

λ = forgetting rate;

δ = effectiveness of a training methods;

t = time elapsed since training.

To optimize OSH training schedules, we use the Spaced Repetition Algorithm [44]:

$$T_{next} = T_{prev} + \kappa \times R_{enhanced}(T_{prev}) \quad (3)$$

where:

T_{next} = recommended next training session time;

T_{prev} = previous training session time;

K = training effectiveness coefficient (higher for AI-enhanced methods);

$R_{enhanced}(T_{prev})$ = retention at previous training time.

This model adapts training schedules based on worker performance, ensuring vulnerable groups receive training at the right time.

We conducted a simulation of the Forgetting Curve for traditional training versus AI-enhanced VR-based training over 30 days for migrant workers in construction who face language barriers in safety training.

The initial retention value was set to $R_0 = 1.0$, with the following parameters:

- $\lambda = 0.05$ (in traditional training);
- $R_0 = 1.0$ (in traditional training);
- $R_0 = 1.0$ (VR-based training);
- $\delta = 0.02$ (VR-based training).

VR-based multilingual safety simulations were introduced with $R_0 = 1.0$, $\lambda = 0.05$ (in traditional training) and $R_0 = 1.0$, $\delta = 0.02$ VR-based training benefit (in Industry 4.0 enhanced training):

$$R_{traditional}(t) = R_0 e^{-0.05t} \quad (4)$$

$$R_{enhanced}(t) = R_0 e^{-(0.05-0.02)t} \quad (5)$$

We obtained a visual retention decay, an OSH training retention curve for vulnerable workers.

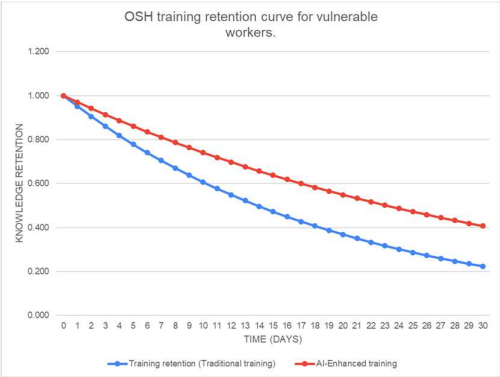

Fig. 2. OSH training retention curve for vulnerable workers

The graph shows that AI-enhanced training (blue line) leads to slower knowledge decay compared to traditional training (red dashed line). After 30 days, retention remains significantly higher with Industry 4.0 training tools (Fig.2).

The results of our simulations provide strong evidence that Industry 4.0 training methods, such as VR-based safety simulations, significantly improve knowledge retention and compliance with OSH protocols among vulnerable workers, particularly migrant workers in smart construction.

This model will be used for further research in order to adapt training schedules based on worker performance, ensuring vulnerable groups receive training at the right time.

3. RESULTS AND FINDINGS

Digitalization has reshaped the workplace, offering undeniable benefits to both employers and employees through digital tools, automation, and remote work. However, these advancements also introduce unique risks to employee health and well-being. Understanding and knowing how to mitigate these risks is essential for fostering a sustainable and healthy work environment in the digital era [9].

In Industry 4.0, employees responsible for monitoring smart machines and robots or engaging in decentralized decision-making and complex engineering projects must work more independently, possess strong digital competencies, and take full responsibility for organizing their tasks efficiently. They are expected to have comprehensive access to information and advanced technological skills to navigate these evolving work environments. However, research consistently highlights a critical shortage of qualified personnel, with particularly low levels of digital proficiency among older workers, migrants, and individuals with disabilities [10].

This situation may result in a reduction of the qualified workforce, leading to increased excessive fatigue, higher absenteeism due to illness, and a rise in workplace accidents. The growing importance of information and communication technologies (ICT) in the Industry 4.0 system further widens the overall qualification gap in the workforce, particularly exacerbating the disparity between newly qualified young workers and experienced senior employees [11].

Prolonged screen time, extended sitting, and inadequate ergonomics can contribute to various health issues, including musculoskeletal disorders (MSDs), eye strain, and headaches. Repetitive tasks and poorly designed workstations that do not support long-term comfort contribute significantly to these issues [12,13].

Regarding the mental health challenges, the rise of the “always-on” culture, driven by constant connectivity to emails, instant messaging, and work-related notifications, has significantly blurred the boundaries between professional and personal life. Employees often feel pressured to remain available beyond standard working hours, leading to increased stress, anxiety, and a higher risk of burnout. The inability to fully disconnect from work prevents proper mental recovery, impacting overall well-being and productivity [14].

In addition, digitalization has introduced new forms of workplace isolation, particularly for remote workers. Without regular in-person interactions, employees may struggle to build strong professional relationships or feel a sense of belonging within their organization. The absence of spontaneous conversations, informal brainstorming sessions, and casual social interactions - common in traditional office settings - can lead to feelings of loneliness and emotional disengagement [15].

Over time, this social disconnect can take a serious toll on mental health. Loneliness has been strongly linked to increased rates of depression, anxiety, and reduced job satisfaction. Workers who experience prolonged isolation may also struggle with motivation and feel less connected to their organization's mission and team dynamics.

Addressing these challenges requires proactive measures, such as promoting work-life balance, setting clear boundaries for digital communication, and fostering virtual or in-person opportunities for social interaction and team cohesion [16].

In today's digital work environment, employees are bombarded with a continuous stream of emails, notifications, messages, and data from multiple platforms. This constant influx of information can quickly lead to cognitive overload, where the brain struggles to process and prioritize tasks effectively [17].

When employees are expected to juggle multiple digital tools, switch between applications, and respond to various demands in real time, their ability to concentrate and make well-informed decisions is significantly diminished.

Multitasking, often seen as a necessity in the digital workplace, further exacerbates this issue. While switching between tasks may create the illusion of productivity, it actually reduces efficiency, increases the likelihood of errors, and prolongs the time needed to complete complex assignments.

The mental strain caused by excessive digital input can also lead to decision fatigue, where individuals struggle to make sound judgments due to prolonged cognitive effort [18].

Beyond productivity concerns, information overload has direct implications for employee well-being. The relentless demand for attention contributes to higher stress levels, mental exhaustion, and difficulties in maintaining focus throughout the workday. Over time, this can result in decreased job satisfaction, burnout, and a diminished capacity for creative problem-solving [19].

In order to address the unique set of risks and challenges brought upon OSH by this complex web of intricate technologies, **investment in training** is imperative for a successful transition into this new industrial era [1, 28].

Our research found that training and updating to prevent „accidents 4.0" are suggested as possible preventive measures or actions for the issues or concerns regarding engineering and human errors or mistakes in programming and interfacing with automated devices [20].

The importance of OSH training for vulnerable groups is further emphasized by the decreasing share of blue-collar workers and the growing prevalence of intellectual work in the production process, as low-wage workers without additional training and abilities face an immense risk of job loss [21].

Ensuring occupational safety and health for vulnerable groups in the digital workplace requires targeted education and training initiatives. Vulnerable employees, including older workers, individuals with disabilities, migrant workers, and those in precarious employment, often face unique challenges related to digitalization, workplace ergonomics, and mental well-being [31].

Tailored training programs can help these groups navigate risks effectively while fostering an inclusive and supportive work environment [22].

Vulnerable workers often have different learning needs, requiring training to be accessible and adaptable. Employers should provide OSH education in multiple formats, such as e-learning modules, interactive workshops, and translated materials for non-native speakers [23].

Special consideration should be given to workers with disabilities, ensuring accessibility features like screen readers, subtitles, and alternative formats for training content [24].

For employees at higher risk of musculoskeletal disorders (MSDs), such as older workers or individuals with disabilities, ergonomic training is essential. Programs should educate employees on proper workstation setup, including the use of adjustable desks, chairs, and monitor stands [25].

Training should also emphasize correct posture, the importance of regular movement breaks, and exercises to alleviate strain. Employers can further support vulnerable workers by providing personalized ergonomic

assessments and adaptive equipment to meet their specific needs [29].

As Industry 4.0 advances toward fostering a more sustainable industrial value, it must carefully weigh the benefits and challenges related to the occupational health and safety of the workforce [30].

To address emerging risks and manage the ethical implications of innovative Industry 4.0 developments, it is essential to implement targeted preventive and protective measures. These measures should prioritize continuous professional development and comprehensive occupational health and safety training [26].

By prioritizing tailored education and training, organizations can enhance workplace safety for vulnerable employees, empowering them to work confidently and sustainably in the evolving digital landscape [27].

Limitations of the study arise from the approach of only one industry (construction) and only one vulnerable group (migrant workers).

Future Directions and Recommendations To enhance OSH training for vulnerable groups, organizations should: develop inclusive policies that consider diverse workforce needs, integrate adaptive learning technologies into OSH training modules, foster collaboration between policymakers, employers, and training providers and conduct regular assessments to update training content in line with technological advancements.

Further Research. Future research will focus on developing a training framework designed to address the unique challenges faced by disabled workers, migrants, young workers, and older workers in Industry 4.0 environments affected by digital transformation, exploring the integration of artificial intelligence to personalize training modules dynamically and longitudinal studies to assess the long-term impact of OSH training on workplace safety and worker adaptability of vulnerable workers.

4. CONCLUSION

The I 4.0 transformation of the workplace will create new opportunities for workers, but these advancements also will bring unique challenges that must be addressed to ensure their safety, inclusion, and well-being. Employers must implement targeted strategies that protect both the physical and mental health of these workers in an increasingly digitalized work environment.

This study highlights the critical need for specialized OSH training for vulnerable groups in the era of Industry 4.0 and the need that research provide a structured approach to designing and implementing effective OSH training tailored to Industry 4.0 environments, addressing gaps left by traditional training methodologies.

By prioritizing tailored education and training, ergonomic adaptations, mental health support, and digital literacy programs, organizations can create safer, more inclusive, and sustainable workplaces.

Ensuring accessible training, flexible work arrangements, and clear digital boundaries will help vulnerable employees navigate the evolving work landscape with confidence.

Fostering a culture of digital wellness and inclusivity allows businesses to leverage the benefits of technological advancements while safeguarding the well-being of all employees.

This approach ensures that digital transformation empowers rather than marginalizes vulnerable workers, enabling them to thrive both professionally and personally.

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Instruirea ssm pentru grupurile vulnerabile în contextul Industriei 4.0

Această lucrare evidențiază nevoia critică de instruire specializată în securitatea și sănătatea în muncă pentru grupurile vulnerabile în era Industriei 4.0. În ciuda creșterii semnificative a varietății de studii, roadmap și modele de maturitate legate de identificarea măsurilor necesare pentru a susține procesul de schimbare, în ceea ce privește siguranța ocupațională, există încă o lipsă de concentrare vizibilă asupra grupurilor vulnerabile de lucrători din Industria 4.0. atât la nivel mondial cât și în România. Pentru a aborda acest decalaj, scopul lucrării noastre este de a analiza problematica grupurilor vulnerabile în contextul Industriei 4.0, cu un accent special pe formarea în domeniul siguranței ocupaționale, propunând o revizuire aprofundată a literaturii de specialitate pentru a identifica și propune recomandări pentru asigurarea Siguranței 4.0 - o „călătorie sigură” în această aventură care reprezintă tranziția la Industria 4.0.

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