1ST INTERNATIONAL SAFETY WORKSHOP

IMPACTS OF NEW TECHNOLOGIES ON WORKERS' SAFETY AND HEALTH

Editors
Angelo Bertolazzi, Giulia De Cet, Chiara Vianello, Mariano Angelo Zanini

EdicomEdizioni

Il volume è pubblicato con il patrocinio del Dipartimento di Ingegneria Civile, Edile ed Ambientale
e del Dipartimento di Ingegneria Industriale dell'Università degli Studi di Padova:

e il contributo finanziario dell'Università di Padova - Dipartimento di Ingegneria Civile, Edile ed Ambientale

SPONSOR PLATINUM

1st International Safety Workshop
IMPACTS OF NEW TECHNOLOGIES ON WORKERS' SAFETY AND HEALTH

The Editors would like to express special thanks to the other members of the Scientific Committee – Professors Daniela Boso and Rossana Paparella, and Professors Giorgio Croatto and Carlo Pellegrino – for their invaluable assistance in the event organization and for their commitment to promoting a culture of safety.

EdicomEdizioni
Monfalcone (Gorizia)
info@edicomedizioni.com
www.edicomedizioni.com
www.edicomstore.it

ISBN 979-12-81229-19-8

Prima edizione aprile 2025 / First edition April 2025

1ST INTERNATIONAL SAFETY WORKSHOP

IMPACTS OF NEW TECHNOLOGIES ON WORKERS' SAFETY AND HEALTH

Editors
Angelo Bertolazzi, Giulia De Cet, Chiara Vianello, Mariano Angelo Zanini

28th April 2025
Padua – Italy

EdicomEdizioni

Contents

Workers' Safety: Societal and Academic Perspectives – Challenges and Future Directions 7
Angelo Bertolazzi, Giulia De Cet, Chiara Vianello and Mariano Angelo Zanini (Eds.)

Self-Evolving Machines and Risk Assessment According to EN ISO 12100 and Regulation (EU) 2023/1230. An Example of a First Application Approach 11
Ugo Fonzar, Lorenzo Baraldo and Enrico Savio

Wearable Technology: Intersections Between Health and Safety and Privacy Protection 27
Davide Tardivo

The Silent Introduction of People Counting Systems Based on Video Camera Image Analysis in Free Entertainment Events in Large-Capacity Public Open Spaces: Opportunities and Risks 41
Vincenzo Puccia

Safety Coordination of Clashing Activities with Total Float Allocation for the Covered Market of Forlì Case study 55
Marco Alvise Bragadin and Benedetta Balzani

Risk Assessment, Human Variability and the Possible New Frontiers of Artificial Intelligence 69
Rita Somma

New Digital Resources at the University of Trento for the Advancement of Health and Safety 85
Matteo Brunelli and Riccardo Ceccato

The Future of Industrial Safety: Remote-Controlled Robots in High-Risk Environments 95
Alessandro Gerotto, Alberto Feletto, Edoardo Marangoni and Lorenzo Baraldo

Building Information Modeling for Advancing Occupant's Health through Green Certifications and Indoor Environmental Quality 113
Giuliana Parisi, Stefano Cascone and Rosa Caponetto

Risk Assessment and Management at Health Authority of South Tyrol: a Sustainable Approach 129
Peter Auer, Francesco Organai and Michele De Stefani

Implementation of Construction Site Management Software with Digital Checklists for Quality Control 139
Eleonora Laurini, Chiara Marchionni and Marianna Rotilio

The Power of Digital Portals in Supplier Management: Transforming Safety Compliance through a Case Study 153
Giovanni Pegoraro, Giampaolo Mardegan, Massimo Moro and Giovanni Costantini

Towards a Safer Future: Integrating Technology and Safety Practices **165**
Chiara Vianello and Giuseppe Maschio

Digital Assistants and Robotic Interfaces: Opportunities for Integration and Social Well-Being **175**
Guglielmo Frare

Smart Solutions for Fire Emergencies: how Digital Tech is Revolutionizing Evacuations **185**
Giulia De Cet, Andrea Liviero, Marco Muraro, Chiara Vianello and Rossana Paparella, Daniela Boso, Fabio Dattilo

The Adoption of a P-Connect Gateway Together with a System of Electromechanical and Electronic Safety Devices: Advanced Safety Accompanied by Network Protection from External threats **195**
Francesco Lo Giudice, Stefano Matterazzo and Lorenzo Baraldo

Optimization of Construction Site Safety: An Ontological Approach through the Integration of Time and Costs **207**
Jacopo Cassandro, Claudio Mirarchi and Alberto Pavan

Revolutionizing Workplace Safety with Computer Vision AI: The Intenseye Solution **221**
Deniz Karakaş, Funda Sayın and Riccardo Borghetto

Digitizing Construction Site Safety Documentation: Benefits, Limitations, and Challenges **237**
Giulia De Cet, Alberto Vicentin, Carlo Zanchetta and Rossana Paparella

The IMPACT Methodology for the Protection of Industrial Facilities and Tertiary Sector **247**
Roberto Barro, Fabio Zorzini, Andrea Dusso and Matteo Sanavia

Industrial Pavements Skid Resistance Evaluations for Workers Safety Check and Improvement **257**
Marco Pasetto and Giovanni Giacomello

Artificial Intelligence in Machine Safety Functions **267**
Batoul Kalout and Dainese Diego

Enhancing Safety in Construction Sites Through Digitalisation and Technological Innovation **283**
Giulia De Cet, Leonardo Rabbi, Carlo Pellegrino and Daniela Boso

The Impact of New Technologies in Collision Avoidance: an Applied Experience of Speed Control and Impact Detection in Material Handling with Forklift Trucks **293**
Alberto Vicentin, Paola Visciano and Edoardo Tovo

Workers' Safety: Societal and Academic Perspectives – Challenges and Future Directions

Angelo Bertolazzi, Giulia De Cet, Chiara Vianello and Mariano Angelo Zanini (Eds.)

In 2003, the International Labour Organization (ILO) set the 28th of April as the "World Day for Safety and Health at Work", a global initiative aimed at raising awareness among both public and private sectors while emphasizing the importance of prevention. This annual celebration became a key component of the ILO's Global Strategy on Occupational Safety and Health, as documented in the Conclusions of the International Labour Conference in June 2003. Over the past two decades, this initiative has become "a significant tool to raise awareness of how to make work safe and healthy and of the need to raise the political profile of occupational safety and health"[1].

The initiative was also designed to analyse the connection among the workers' safety and some of the most challenging topics in modern society, particularly the relationship between new technologies and the emerging hazards associated with them. The International Organization for Standardization (ISO) highlighted that new and emerging occupational risks may arise from technological innovation or social and organizational changes. These include new technologies and production processes (e.g., nanotechnology, biotechnology), new working conditions (e.g., higher workloads, work intensification due to downsizing, poor conditions associated to labour migration, jobs in the informal economy) or emerging forms of employment (e.g., self-employment, outsourcing, temporary contracts).

To address these issues, each year is dedicated to a specific theme, encouraging multidisciplinary and cross-disciplinary research approaches as a basis for both public and private sector actions. The 2024 edition focused on climate change and workers' safety and health, highlighting its serious impact on planetary health, human well-being and the world of work. The challenge was to raise awareness of the increasing risk of exposure to hazards that workers face globally, including ex-

1 United Nations, World Day for Safety and Health at Work, https://www.un.org/en/observances/work-safety-day [accessed on 27/03/2025].

cessive heat, ultraviolet radiation, extreme weather events, air pollution, vector-borne diseases and agrochemicals exposure.

The 2025 edition promotes the topic "Revolutionizing health and safety: the role of AI and digitalization at work". The aim is to highlight the transformative impact of technological advancements in shaping safer and healthier work environments, while also addressing the emerging risks that need to be managed in an increasingly digitalized world. Digitalization is permeating every aspect of society, shaping a growing part of our social, organizational, and economic activities. This process is one of the most critical challenges of our time, as it is evolving at an unprecedented rate, making its medium- and long-term consequences difficult to predict. Digital devices, tools, practices and online interaction flood a large part of our daily life. In many ways, this digital transformation is even more far-reaching and rapid than previous technological revolutions. Its scope, scale, and speed make it difficult to understand, and its consequences for our society, business and everyday life remain complex and unpredictable[2].

Digitalization brings both significant opportunities and great challenges in today's job market and working conditions. The "1st International safety workshop: impacts of new technologies on workers' safety and health" aims to explore the theme proposed by ILO through a conference organized at the University of Padova by the Department of Industrial Engineering and the Department of Civil, Architectural and Environmental Engineering.

The workshop is part of the ongoing activities within the Master Degree in "Civil And Industrial Safety Engineering" and the Bachelor's Degree in "Digital Technologies for Building and Land". The Master Degree aims to train safety engineers who, besides a solid technical knowledge, develop in-depth skills and competence concerning the risk analysis in civil buildings, infrastructures and industrial plants, and the safety in civil buildings and infrastructures and industrial processes and in work environments. The Bachelor Degree aims to train modern, versatile, and independent professionals capable of overseeing the entire construction process – from design to execution – while managing the digital transformation of the built environment. The primary goal is to equip experts with the skills needed to tackle the challenges of contemporary design by leveraging cutting-edge digital technologies.

The multidisciplinary and cross-sectoral approach of both educational programs inspired the workshop's organization, to provide a stimulating and insightful overview of the 2025 ILO theme. Digital tools and practices have been declined following through various theoretical and practical perspectives, showing how AI, BIM and other smart technologies can contribute to improving workplace

2 Callen Anthony, Beth A. Bechky, Anne-Laure Fayard (2023) "Collaborating" with AI: Taking a System View to Explore the Future of Work. Organization Science 34(5):1672-1694.

quality and safety. The participation of academic researchers, public officials and industry professionals is crucial in defining the technological horizon and understanding the implications of new technologies in the workplace.

Ensuring high-quality and safe working conditions is a shared responsibility that involves society as a whole. Public institutions play a key role by establishing laws and services that safeguard workers' rights and business prosperity, implementing national policies, programs, and inspections to align occupational safety and health with legal and regulatory frameworks. Employers must take concrete and effective measures to ensure a safe and healthy work environment, while workers are responsible for following safety guidelines, protecting themselves without endangering others, and knowing their rights. Both parties must actively contribute to preventive measures implementation.

Universities and research institutions also play a crucial role in bridging the gap between theory and practice, addressing critical issues in occupational safety and health, and fostering collaboration among key stakeholders. In the context of the 2025 ILO topic, academic research must clarify uncertainties concerning emerging technologies and their impact on work environment. This includes assessing how digital transformation can enhance occupational safety and health, while identifying strategies for governments, employers, workers and other stakeholders to mitigate potential risks.

This book aims to be a tangible contribution to this effort, offering insights and practical perspectives on the intersection between digitalization and workplace safety.

Self-Evolving Machines and Risk Assessment According to EN ISO 12100 and Regulation (EU) 2023/1230. An Example of a First Application Approach

Ugo Fonzar[1*], Lorenzo Baraldo[2,3] and Enrico Savio[3]
[1] Eng. Ugo Fonzar (Italy)
[2] Sustain Tech Hub S.p.a. SB (Italy)
[3] University of Padua, Department of Industrial Engineering (Italy)

* E-mail: ing@fonzar.com

Abstract. The introduction of machines with self-evolving behaviour poses critical safety challenges. Currently, there are no self-evolving safety components equipped with machine learning that can guarantee reliable safety functions; moreover, risk assessment must consider both current and future hazards arising from the autonomous evolution of machinery. Ignoring these aspects could lead to unintended consequences, especially as artificial intelligence becomes more prevalent in industry. To mitigate these risks, it is crucial to take a precautionary approach that considers the "worst-case scenario" and provides "augmented" safety measures compared to those taken for traditional machinery. This involves rigorously defining safe operating limits and implementing appropriate protections with current technologies. The article proposes a path forward to ensure the safe use of self-evolving machines, pending the integration of artificial intelligence into safety systems to reach levels of reliability that can be considered a certified safety component.

Keywords: Machinery, Self-Evolving, Risk Assessment, Artificial Intelligence

1. Introduction

An imporant new feature introduced by Regulation (EU) 2023/1230 of June 14, 2023 on machinery and repealing Directive 2006/42/EC of the European Parliament is the inclusion of specific requirements for machinery with even partially self-evolving behaviour. This regulation will be applicable as of January 20, 2027, pending which the current Machinery Directive 2006/42/EC should be used.

2. Self-evolutionary behaviour

"Self-evolving behaviour" refers to the ability of machinery to autonomously change its operation through learning and adaptation, using artificial intelligence techniques such as "machine learning", which is based on analyzing data and learning identified patterns so that the system can make predictions or make decisions based on that information. This allows the machinery to improve its performance over time, adapting to new situations or environments without direct human intervention. This feature introduces new challenges in terms of safety, as machinery can develop behaviours not originally anticipated by designers. For this reason, Regulation (EU) 2023/1230 requires risk assessment to consider hazards associated with the evolution of machine behaviour throughout the life cycle, taking into account possible self-evolving changes. In fact, Annex III, Part B "General Principles" provides that "*The risk assessment and risk reduction shall include hazards that might arise during the lifecycle of the machinery or related product that are foreseeable at the time of placing the machinery or related product on the market as an intended evolution of its fully or partially self-evolving behaviour or logic as a result of the machinery or related product designed to operate with varying levels of autonomy*."

2.1. The state of the art today

Currently, EN ISO 12100 defines general principles for risk assessment and risk reduction in machinery. It is under revision and its 2010 edition, which is currently in force, does not contain specific guidance for the case of machinery with self-evolving behaviour. In anticipation of the revision of EN ISO 12100 (expected in 2026) and the applicability of Regulation (EU) 2023/1230, as of January 20, 2027, this article aims to address the risk assessment of such machinery, assuming that to date there are still no "*safety components with fully or partially self-evolving behaviour using machine learning approaches that provide safety functions*" on the market. In fact, various studies to date implemented[1] show that:

- to date, "*specifications for the design of safety-related parts of control systems are given in standards ISO 13849-1 and EN 62061 but the applicability of this standard to AI algorithms has not been demonstrated, so it makes necessary to adapt the recommended test methods and Performance Levels (PLs) to AI.*"
- and that "*machinery that embeds AI systems is considered high risk and will have to conform to both Regulation 2023/1230 and the forthcoming proposal of regulation of AI (systems[2]. At the moment, safety standards for machinery do not adequately address these new developments, revealing a significant gap that exists between the development of safe Level 4 (highly automated) off-road machines and achieving the legislative compliance required for positioning in the EU market.*"

Also of note, the harmonized standards for this type of machine currently are EN ISO 10218-1:2011 *Robots and robot equipment – Safety requirements for industrial robots – Part 1: Robots* (ISO 10218-1:2011) and EN ISO 10218-2:2011 *Robots and robot equipment – Safety requirements for industrial robots – Robot systems and integration* (ISO 10218-2:2011)[3].

---

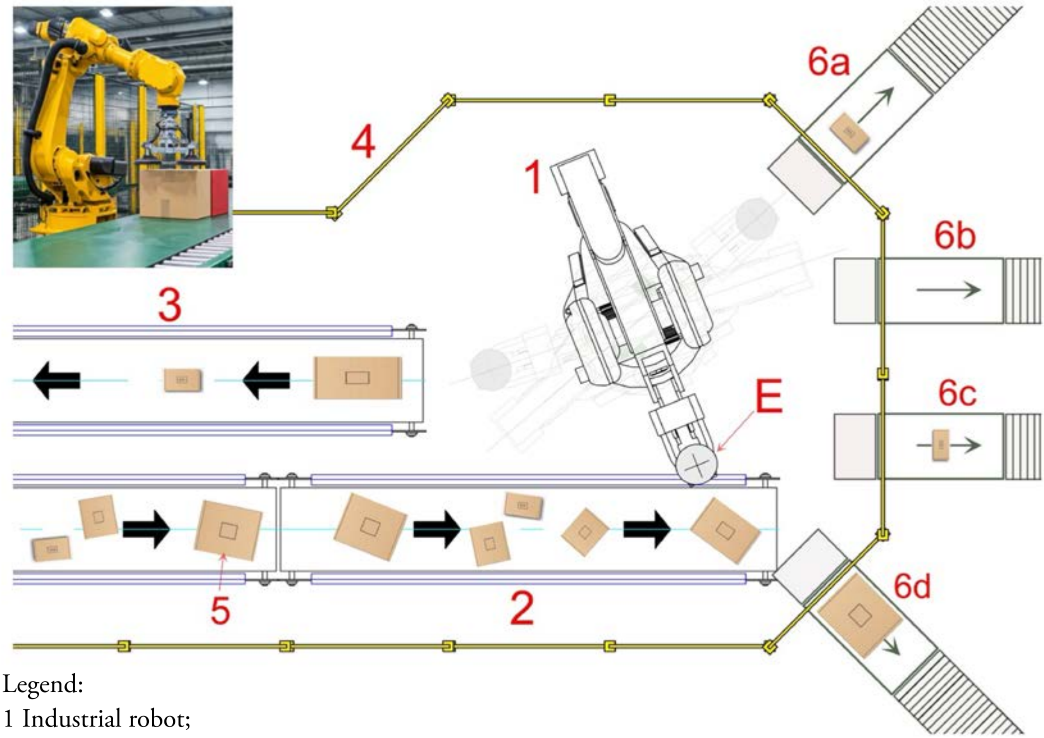
1 See publications [1] and [2] in the bibliography.

2 Regulation (EU) 2024/1689.

3 At time of writing, the new versions were just published in march 2025 as ISO 10218-1:2025 *Robotics – Safety requirements – Part 1: Industrial robots* and ISO 10218-2:2025 *Robotics – Safety requirements – Part 2: Industrial robot applications and robot cells.*

3. The case

An example of an island with a self-evolving robot working in an automated warehouse is proposed as a first approach: see Figure 1. which schematizes the case. The island is still to be considered a machine in that it is composed of multiple machines with an integral operation.[4]



Legend:
1 Industrial robot;
E End-effector of the suction cup robot;
2 Feeding conveyor belt;
3 Return conveyor belt (boxes not in shipment or damaged/non-conforming boxes);
4 Perimeter protections (shelters);
5 Boxes of different sizes, color and weight;
6a, 6b, 6c, 6d Four tunnels1 with idler-roller chutes directing boxes to truck loading bays for shipping.

Figure 1. Example layout of island with a self-evolving robot.

3.1. Brief description of the operating logic

The industrial robot (1), through its end-effector (E) picks up the various boxes (5) arriving from the arrival conveyor belt (2). The vision system installed on the robot and machine-learning decides the following:

- Is the box compliant or not

[4] See the definition in both Directive 2006/42/EC and Regulation (EU) 2023/1230

- Does the box fall within the shipping list of one of the four designated loading bays or not
- Based on the answers to the above two conditions place the boxes on:
  - the return tape (3), for nonconforming boxes or boxes that are not on the shipping list of one of the four loading bays, oriented so that the long side of the rectangle of boxes is in the direction of the tape's movement;
  - one of the four slides (6a 6b 6c 6d), oriented so that they can pass through the slides (some boxes have a larger size).

3.2. Brief description of the objectives of the implementation of AI

Traditionally, robots require lengthy training processes by skilled technicians to optimize their operations. One imagines that with the integration of a self-learning system, the robot no longer needs precise and punctual instructions, but after cursory training can gradually improve its performance in complete autonomy. Using artificial intelligence, the robot analyzes data from environmental sensors, the vision system and predictive algorithms, adapting in real time to changes in the workflow. One of its functions is trajectory optimization: through continuous monitoring and analysis of previous operations, the robot identifies the most efficient paths, reducing handling time. An additional benefit of the self-evolving function is the intelligent selection of boxes to be handled. The AI evaluates criteria such as the weight, size, destination, and urgency of the shipment to determine the optimal order of picking and sorting to the four chutes provided. This not only reduces processing time, but also optimizes space within the warehouse and shipping vehicles, improving inventory and delivery management. Self-learning also enables the robot to autonomously recognize and correct any anomalies in the process, such as an incorrectly placed item or a damaged box. This reduces the need for human intervention and ensures continuous and efficient operation of the logistics system. In summary, the integration of an industrial robot with self-evolving capabilities could radically transform the management of automated warehouses. The elimination of the need for frequent training, coupled with autonomous optimization of operations, reduces operational costs, improves productivity, and makes the system more resilient and adaptable to the changing needs of the logistics industry.

4. Machinery safety and the state of the art today

The above is a feasible application and brings with it new challenges and uncertainties regarding machine safety. In fact, the machine-learning system is designed to optimize pick and place times at the next step of the boxes, i.e., optimizing the movement trajectories of the robotic arm (both in trajectories and in maximum speeds and acceleration), but it does not have sufficient reliability to prevent or avoid accidents. In fact, nowadays the state of the art does not yet provide safety components that use machine learning approaches and provide safety functions, so that we still have to resort to the traditional safety measures available in the market.

The new Regulation (EU) 2023/1230 includes in Annex I under 6. "Machines that integrate systems with fully or partially self-evolving behaviour using machine learning ap-

proaches that provide safety functions that have not been independently placed on the market, only with regard to such systems" which will be to be subject to certification through the intervention of a Notified Body.
The current Annex IV of Directive 2006/42/EC, does not include any such requirement, and therefore one possible way forward is to provide for a precautionary increase in the estimated risk value and consequently an increase in safety measures related to design, safeguards and operating instructions given the uncertainty related to the self-evolution of machinery.

4.1. Risk assessment.

Risk assessment must therefore consider the self-evolving machine and its behaviour and how this may evolve over time due to machine learning. This involves evaluating situations that may not always be predictable. In these cases, the only way forward is related to the worst-cases philosophy of various scenarios in that:

- much information is lacking, e.g., it is not possible to predict all conditions, only the extreme (worst) ones;
- there are insufficient experiences for an exhaustive analysis;
- adoptable security measures are those currently available on the market, typically designed for machines that are not self-evolving, even partially.

The selection of safety measures and risk assessment was performed in accordance with EN ISO 12100 and applicable standards (see bibliography), which should be referred to for more details.
The variables to be considered for risk assessment were as follows:

- **Limits** of the machine (of use, space and time);
- **Life** stages of the machine (considering all life stages, i.e., from "cradle to grave," including reasonably foreseeable misuse);
- **Exposed personnel** (understood as all those who may for any reason interact with the machinery);
- **All hazards** potentially present and associated with the machinery (e.g., mechanical, electrical, thermal, noise, vibration, radiation, materials and substances, ergonomic, environmental, related to machinery states and combinations of these hazards)[5]
- **Hazardous zones** (understood as all zones into which to divide the machinery in order to imagine the generation of individual hazards, starting with the potential hazards present);
- **Risk scenario** (i.e., the description of the hazardous situation and possible consequences).

For each risk scenario imagined, the risk **R** was sized: the adoption of safety measures against these risks[6] in order to reach an acceptable level of risk and the state of the art ex-

[5] See Annex A of EN ISO 10218-2.

[6] According to RES 1.1.2(b), design type, protections and operating instructions.

pected at the time of the machine's construction and, as far as possible to date, also taking into account its self-evolution. This uncertainty related to the self-evolution of the machinery was evaluated by increasing where necessary the assessed risk and adopting safety measures beyond what is required by the applicable harmonized technical standards. As a result of the safety measures adopted, it is followed by a new sizing of the risk **R'** which is compared with its acceptable value (see 4.2).

R-risk sizing can be based on the following formula[7]

[1] R=G x F x P x E

Where:
G is the severity of the damage, sized according to the table below, which is also constructed according to current legislative provisions;[8]
F is the frequency with which people expose themselves to danger (1 = rare or infrequent; 2 = frequent and continuous);
P is the probability that the conditions capable of producing the feared damage will occur with the following values (1 = low; 2 = medium; 3 = high);
And it is the relative weight of whether the harm itself can be avoided or not (1 = YES, it is avoidable; 2 = NO, it is not avoidable).

Value of G	Definition	Meaning
1	**Mild damage**	Very minor or mild injury, ranging from on-farm dressing to injury with healing time up to 40 days
2	**Average damage**	Severe or very severe injury, ranging from injury with recovery time exceeding 40 days, to permanent impairment of a sense or organ
4	**High damage**	Most serious injury, i.e., a disease that is certainly incurable, loss of a sense, loss of a limb, or mutilation that renders the limb useless, or loss of the use of an organ or the ability to procreate, or permanent and severe difficulty of speech, deformation, or permanent disfigurement of the face, up to and including fatal injury.

Table 1. Definition of severity G

[7] See also ISO/TR 14121-2 Safety of machinery – Risk assessment – Part 2: Practical guidance and examples of methods.

[8] Articles 582 and 583 of the Italian Penal Code.

The pattern derived from formula [1] and the values of the four variables is shown below.

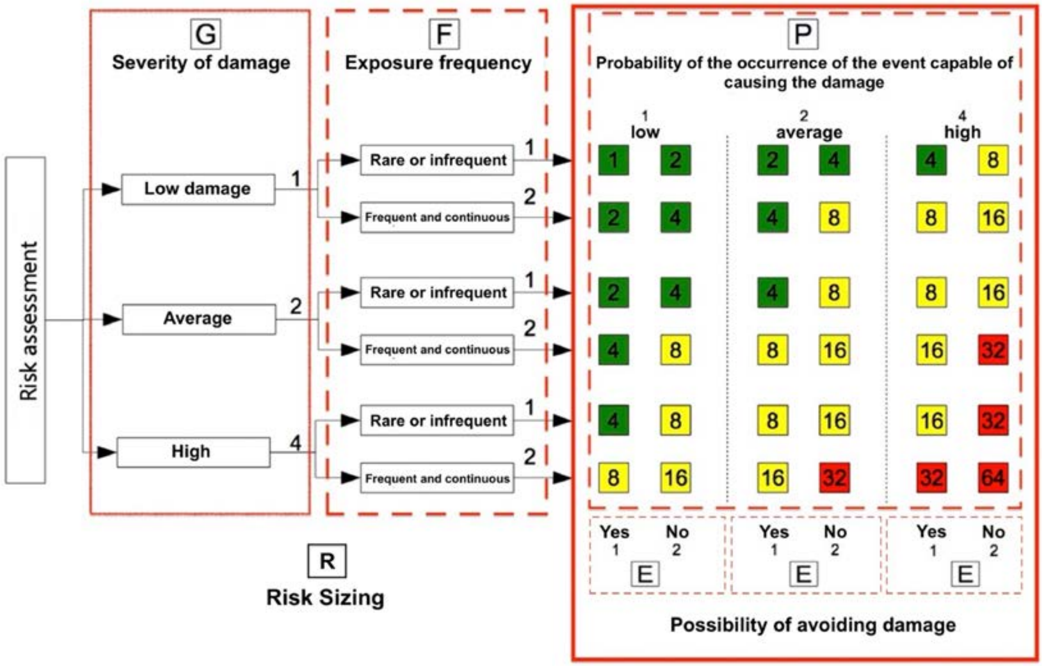


Figure 2. Diagram of risk sizing.

4.2. The acceptable risk

The level of acceptable risk is determined by (in order of importance):

- from legal obligations (in our case and to date, Directive 2006/42/EC and the laws and regulations transposing product directives, and national occupational safety and health standardization);[9]
- By the harmonized technical standards;
- From the state of the art/state of the art in the field;
- From established practices in the industry/activity analyzed;
- By company policy.

While it is intuitive to think that we can always accept a low risk (e.g., for R ≤ 4), interventions under legal provisions and standards may not lower the risk, since they typically intervene only on probability-related parameters, with our aforementioned criteria F, P and E. An acceptable risk could also be a high R risk given that "the state of the art," consisting of technology[10] as well as work procedures, will not be able to affect the severity of the risk

[9] In Italy, Legislative Decree 81/08 and smei.

[10] In our case, we mean the machine guards and safety systems available in the market.

(think for example, electrical risk, fall from height, etc.). As for the case analyzed in this paper, to date the "state of the art" does not provide for components of safety using machine learning approaches that guarantee safety functions for which "traditional" safety systems related to current technical standards are intervened, pending the evolution of technologies. In spite of this, already nowadays, as far as possible, the provisions of Recital (32) of Regulation (EU) 2023/1230 can be taken into account, which is the objective, as far as possible, of the present work.

4.3. Assumptions and limitations of the work

We proceed by defining criteria for identifying scenarios (focusing the analysis on the most dangerous cases by identifying scenarios of maximum credible risk) then an evaluation of the safety measures provided is carried out using the essential health and safety requirements of the Machinery Directive 2006/42/EC and the harmonized technical standards, increasing where necessary the requirements provided or the relative performance, since even these standards do not deal with machines with self-evolving behaviour.
For simplicity's sake, the work will go to consider only the ordinary use of the machinery, excluding the life phases related to training functions, maintenance, access in case of anomalies/ strandings, etc.

4.4. Risk scenarios

In this paper, with the aforementioned assumptions and limitations, only the following risk scenarios are considered:

1. **access from the outside** by a worker through and over the perimeter guards of the island to reach hazardous locations;
2. **Accidental release of the load** during a full-speed approach to the perimeter guards: the load is **"thrown" outward**;
3. **accidental release of the load** during a full-speed approach to the perimeter guards: the load is **"thrown" inside the exit tunnels**;
4. **Accidental release of the load** during an approach at full speed toward the perimeter **guards against the same guards**;
5. **Collision of the robot** with **other work equipment** in the robotic cell;
6. **Collision of the robot** with the **perimeter** spacer **guards**.

The assumptions that are made (pro-safety) for the above scenarios are:

- the maximum speed[11] of the robot end-effector is $\mathbf{v_0 = 2\ m/s}$;
- the weight of a cardboard box is from a minimum value of **m = 1 kg**, up to **m = 10 kg**;
- the danger point created by the robot toward the box exit chutes has a horizontal distance of **c = 0.25 m** and height of **a = 1.8 m**.

[11] Linked to travel distances and maximum predictable accelerations, as well as inertias assessed after a protective stop.

4.5. I RES[12] of Directive 2006/42/EC applicable and relevant

The following RES that are applicable and relevant for the above-mentioned risk scenarios are highlighted below.

Scenario	Essential health and safety requirements of Directive 2006/42/EC
1 Access to the protected area	***1.3.7. Risks related to moving parts*** *The moving parts of machinery must be designed and constructed in such a way as to prevent risks of contact which could lead to accidents or must, where risks persist, be fitted with guards or protective devices.* ***1.4.1. General requirements*** *Guards and protective devices must: ...* *- be located at an adequate distance from the danger zone;* *...*
2 Load release over perimeter guards	***1.2.1. Safety and reliability of control systems*** *Control systems must be designed and constructed in such a way as to prevent hazardous situations from arising. Above all, they must be designed and constructed in such a way that: …* *– no moving part of the machinery or piece held by the machinery must fall or be ejected, …* ***1.4.1. General requirements*** *... In addition, guards must, where possible, protect against the ejection or falling of materials or objects and against emissions generated by the machinery...*
3 Load release through exit tunnel	***1.2.1. Safety and reliability of control systems*** *Control systems must be designed and constructed in such a way as to prevent hazardous situations from arising. Above all, they must be designed and constructed in such a way that: …* *– no moving part of the machinery or piece held by the machinery must fall or be ejected, …* ***1.4.1. General requirements*** *... In addition, guards must, where possible, protect against the ejection or falling of materials or objects and against emissions generated by the machinery.*

[12] Essential health and safety requirements relating to the design and construction of machinery set out in Annex I of Directive 2006/42/EC, which are very similar to those in Regulation (EU) 2023/1230.

Scenario	Essential health and safety requirements of Directive 2006/42/EC
4 Load release against perimeter guards	***1.2.1. Safety and reliability of control systems*** *Control systems must be designed and constructed in such a way as to prevent hazardous situations from arising. Above all, they must be designed and constructed in such a way that: ...* *- a fault in the hardware or the software of the control system does not lead to hazardous situations;* *...* *- the safety-related parts of the control system must apply in a coherent way to the whole of an assembly of machinery and/or partly completed machinery.* ***1.4.1. General requirements*** *Guards and protective devices must: ...* *In addition, guards must, where possible, protect against the ejection or falling of materials or objects and against emissions generated by the machinery.*
5 Robot collision against other machines	***1.2.1. Safety and reliability of control systems*** *Control systems must be designed and constructed in such a way as to prevent hazardous situations from arising. ...* *- the safety-related parts of the control system must apply in a coherent way to the whole of an assembly of machinery and/or partly completed machinery.* ***1.3.9. Risks of uncontrolled movements*** *When a part of the machinery has been stopped, any drift away from the stopping position, for whatever reason other than action on the control devices, must be prevented or must be such that it does not present a hazard …*
6 Robot collision against perimeter guards	***1.2.1. Safety and reliability of control systems*** *Control systems must be designed and constructed in such a way as to prevent hazardous situations from arising.* *...* *- the safety-related parts of the control system must apply in a coherent way to the whole of an assembly of machinery and/or partly completed machinery.* ***1.3.9. Risks of uncontrolled movements*** *When a part of the machinery has been stopped, any drift away from the stopping position, for whatever reason other than action on the control devices, must be prevented or must be such that it does not present a hazard...*

Table 2. Applicable and relevant risk scenarios and essential health and safety requirements.

4.6. The harmonized technical standards considered for the risk scenarios and the related RES

The above RES must be complied with through the technical solutions specified in the applicable harmonized technical standards. Specifically, the following applicable standards have been identified:

- EN ISO 13857 for sizing the height of perimeter guards and their openings, if any, to avoid reaching danger points with the upper limbs (Scenario 1 and 2);
- EN ISO 14120 for evaluating the robustness of perimeter guards when impacted by boxes released from the handling robot (Scenario 3);
- EN ISO 10218-1 and EN ISO 10218-2 for safety measures aimed at avoiding collisions against other machinery or perimeter guards (Scenario 4 and 5 and 6).

4.7. Management of risk scenarios

Scenario 1 is handled by the following security measures:

- The height b of guards according to EN ISO 13857 table 2 for high risk is b = 2,200 mm;
- The maximum size of the square-shaped opening "e" of the guards according to EN ISO 13857 prospectus 4 equal to **e ≤ 40 mm**.

Load release (**scenarios 2, 3** and **4**) is marked by the following characteristics in the worst case scenario:

- **scenario 2** – the load thrown upward reaches a maximum height h_{max} of:

$$h_{max} = \frac{v_0^2}{2g} \approx 0.20 \text{ m} = \mathbf{200\ mm}$$

- **scenario 3** – the load launched toward the exit tunnels, with a maximum range[13] of:

$$x_{G,max} = \frac{v_0^2}{g} \approx 0.41 \text{ m} = \mathbf{410\ mm}$$

- and a maximum displacement speed box on the output idler rollers such that the kinetic energy K ≤ 4 J[14], i.e., at maximum displacement speed

$$v = \sqrt{\frac{2k}{m}} \quad \text{For mass m = 10 kg, } \mathbf{v \leq 0.89\ m/s} \quad \text{For mass m = 1 kg, } \mathbf{v \leq 2.83\ m/s}$$

- **scenario 4** – the load thrown against the guards has a maximum kinetic energy $E_{c,max}$ of:

$$E_{c,max} = \frac{1}{2} m v_0^2 = 20 \text{ J}$$

Scenario 2 is handled by the following security measures:

- height of the fence already identified by scenario 1 (b = 2,200 mm), increased by hmax

[13] Consider the worst case of a 45-degree tilt.

[14] See Section 5.2.5.4 of EN ISO 14120.

of 200 mm, starting at 1.8 m (maximum robot height), thus equal to at least 2,000 mm, but for safety's sake we adopt **a = 2,400 mm**
- in addition to this safety measure, the end-effector is equipped with side restraints that hold the box in case of "failure" of the suction cup gripping system.

Scenario 3 is handled by the following security measures:
- the length of the tunnel is at least **1250 mm** (to which should be added the inner distance of the dangerous point of box support of 0.25 m, at the height of 1.8 m);
- the idler roller system for box exit has friction braking rollers along the path in order to limit the energy to 4 J;
- the end-effector is equipped with side restraints that hold the box in case of "failure" of the suction cup gripping system.

Scenario 4 is handled by the following security measures:
- the end-effector is equipped with side restraints that hold the box in case of "failure" of the suction cup gripping system;
- EN ISO 14120 in Annex C provides for a test of the protection's resistance to an impact of a pendulum simulating a human body with a minimum total weight of 90 kg colliding unconsciously on the protection, resulting in impact energy up toE = 115 J;
- the maximum kinetic energy of a box released by the robot is at most **20 J << 115 J**;
- then perimeter guards are adequate to absorb the energy of a box released during handling, and no perimeter protection reinforcement systems are needed.

Scenarios 5 and 6 are handled by the following security measures:
- EN ISO 10218-1 is expected to take the measures contained in the points:
  - *5.6.4 Safety-rated monitored speed*
  - *5.12.2 Mechanical and electro-mechanical axis limiting devices*
  - *5.12.3 Safety-rated soft axis and space limiting*

with the reliability provided in *5.4.2 Performance requirement*, but increased[15] up to **PL=e**, in order to realize a protective stop of the robot before any collision against other machinery or structures, and keep under control the maximum axis speed by limiting the inertia in case of a stop;
- EN ISO 10218-2 stipulates to take the measures contained in the section:
  - *5.4.3 Means for limiting motion*, with identification of areas inhibited from robot movement to other work equipment and perimeter fences,

  with the reliability provided in *5.2.2 Performance requirement*, but increased[16] to PL=e;
- EN ISO 10218-2 stipulates to take the measures contained in the section:
  - *5.10.5.2 Sensitive protective equipment used to initiate a protective stop*, with the installation of an additional safety system, such as a laser scanner positioned with a horizontal

[15] Section 5.4.2 provides a PL=d.

[16] Section 5.2.2 provides a PL=d.

protective beam, in the high side of the guards, in order to monitor any "trespassing" of the robot's movement (using CLC/TS 62046),

with the reliability provided in *5.2.2 Performance requirement*, PL=d.

It should be noted that all solutions adopted are always equal to or greater than the normative reference provisions, this is in order to consider the worst-case scenario each time and still contain even a possible increase in risk for the self-evolution of the AI-equipped robot.

5. The risks assessed and the safety measures taken

Considering the identified risk scenarios, the applicable RES, and the parts of the harmonized technical standards that provide relevant solutions, together with the R (and R') risk sizing, it is possible to summarize the procedure carried out for the study example in the following summary table, which will be included in the risk assessment document and in the Construction Technical File of the considered machinery assembly. The last column concerns the validation of the safety measures taken, in order to verify whether they were actually adopted in the construction of the set of machines put into service.

Risk Scenario	RES	Harmonized technical standard	R	Safety measures identified	R'	Validation
1 Access to the protected area	1.3.7 1.4.1	EN ISO 13857	G = 2 F = 1 P = 2 E = 2 **8**	Slit opening and ≤ 40 mm Protection height 2.4 m	G = 2 F = 1 P = 1 E = 1 **2**	Visual inspection and dimensional measurements
2 Load release over perimeter guards	1.2.1 1.4.1	EN ISO 13857	G = 4 F = 2 P = 2 E = 2 **32**	Slit opening and ≤ 40 mm Protection height 2.4 m End-effector equipped with lateral restraint systems	G = 4 F = 1 P = 1 E = 1 **4**	Visual inspection and dimensional measurements
3 Load release over perimeter guards	1.2.1 1.4.1	EN ISO 13857 EN ISO 14120	G = 4 F = 2 P = 2 E = 2 **32**	Tunnel length at least 1250 mm with idle braking rollers at box exit End-effector equipped with lateral restraint systems	G = 2 F = 1 P = 1 E = 1 **2**	Visual inspection and dimensional measurements Speed measurements boxes on roller conveyor

Risk Scenario	RES	Harmonized technical standard	R	Safety measures identified	R'	Validation
4 Load release against perimeter guards	1.2.1 1.4.1	EN ISO 14120	G = 2 F = 2 P = 2 E = 2 **16**	End-effector equipped with restraint systems Perimeter shelter robustness already adjusted according to the standard	G = 2 F = 1 P = 1 E = 1 **2**	Visual examination
5 Robot collision against other machines	1.2.1 1.3.9	EN ISO 10218-1 EN ISO 10218-2 EN ISO 13849-1 or EN 62061 EN ISO 13849-2	G = 2 F = 2 P = 2 E = 2 **16**	Hardware limitation of robot axes with PL = e Limitation by safety software of robot axes Limiting robot speed with PL = e Identification of areas inhibited from robot movement with PL = e Installation of laser scanner area above the robotic cell with PL = d	G = 2 F = 2 P = 1 E = 1 **4**	Validation with the EN ISO 13849-2 and with the EN ISO 10218-1 Annex and the EN ISO 10218-2 Annex G
6 Robot collision against perimeter guards	1.2.1 1.3.9	EN ISO 10218-1 EN ISO 10218-2 EN ISO 13849-1 or EN 62061 EN ISO 13849-2	G = 4 F = 2 P = 2 E = 2 **32**	Hardware limitation of robot axes with PL = e Limitation by safety software of robot axes Limiting robot speed with PL = e Identification of areas inhibited from robot movement with PL = e Installation of laser scanner area above the robotic cell with PL = d	G = 4 F = 1 P = 1 E = 1 **4**	Validation with the EN ISO 13849-2 and with the EN ISO 10218-1 Annex and the EN ISO 10218-2 Annex G

Table 3. Risk assessment summary table for the scenarios considered.

6. Conclusions

In conclusion, the deployment of machines with self-evolving behaviour is a major challenge for industrial safety. Currently, there are no safety components that have fully or partially self-evolving behaviour that can use machine learning approaches to ensure protective functions. Consequently, the safety system of self-evolving machines must be designed on "traditional systems," adopting "augmented" measures than those provided for machines without such evolutionary capabilities, while waiting for the integration of artificial intelligence into safety functions to become an established reality.
Risk assessment will need to take into account not only current hazards, but also those potentially emerging during the evolution of machinery behaviour. This dynamic approach requires precautionary estimation, augmented to consider the "worst-case scenario," in order to anticipate possible hazardous situations that could occur as the self-evolving system learns and modifies its behaviour. This approach is critical to preventing unintended harm in a context where the massive use of artificial intelligence in industry is set to grow exponentially. Indeed, while the adoption of self-evolving machines promises to reduce the need for frequent training and direct intervention by technicians, it also introduces new variables in terms of risk, as adaptive behaviour can generate unforeseen situations if not appropriately constrained. Therefore, while waiting for safety systems embedded in artificial intelligences to reach levels of reliability comparable to traditional systems, it is necessary to implement increased safety measures in both hardware and software.
This precautionary strategy is the most prudent way to deal with the coming industrial revolution. Adopting an approach that considers the estimated risk in an augmented manner-to cover worst-case scenarios-is critical to ensuring a safe working environment in the presence of self-evolving machinery. The example discussed in this article points to a possible way forward, highlighting the need for further research and regulatory developments that will reliably and comprehensively integrate AI-based safety systems in the future.

References

Publications

[1] Sara Anastasi, Marianna Madonna, Luigi Monica – Implications of embedded artificial intelligence – machine learning on safety of machinery – International Conference on Industry 4.0 and Smart Manufacturing – Procedia Computer Science 180 (2021) 338-343.

[2] Marea de Koninga, Tyrone Machadoa, Andrei Ahonena, Nataliya Strokinac, Morteza Dianatfar, Franxesco De Rosa, Tatiana Minava, Reza Ghabchelooa – A comprehensive approach to safety for highly automated off-road machinery under Regulation 2023/1230 – Safety Science 175 (2024) 106517.

Harmonized technical standards

EN 62061 Safety of machinery – Functional safety of safety-related electrical, electronic and programmable electronic control systems.

EN ISO 10218-1:2011 Robots and robotic devices – Safety requirements for industrial robots – Part 1: Robots

EN ISO 10218-2:2011 Robots and robotic devices – Safety requirements for industrial robots – Part 2: Robot systems and integration

EN ISO 12100 Safety of machinery – General principles for design – Risk assessment and risk reduction

EN ISO 13849-1 Safety of machinery – Safety-related parts of control systems – Part 1: General principles for design

EN ISO 13849-2 Safety of machinery – Safety-related parts of control systems – Part 2: Validation

EN ISO 13857 Safety of machinery – Safety distances to prevent hazard zones being reached by upper and lower limbs

EN ISO 14120 Safety of machinery – Guards – General requirements for the design and construction of fixed and movable guards.

ISO/TS 14121-2 Safety of machinery – Risk assessment – Part 2: Practical guidance and examples of methods

CLC/TS 62046 Safety of machinery – Application of protective equipment to detect the presence of persons

Wearable Technology: Intersections Between Health and Safety and Privacy Protection

Davide Tardivo[1*]
[1] School of Law, University of Padova, Italy

* E-mail: davide.tardivo@unipd.it

Abstract. The paper explores the potential of wearable devices in the field of occupational health and safety, particularly in light of the European regulatory framework, including the GDPR and the AI Act. It highlights the multiple significant benefits of these technologies in enhancing workplace safety, which can prevent accidents and improve the overall well-being of employees. The analysis suggests that wearable devices, when used for safety purposes, align with the European Union's regulations on data protection and AI, allowing employers to collect and process employees' health-related data. However, the paper also identifies several risks associated with using wearable devices, including concerns over data privacy and potential discrimination as a result of the misuse of health data. While the GDPR's strict provisions on data protection ensure that employers must carefully process workers' personal data (especially data on physical conditions or biometric data), the possible aggregation of such information may expose workers to discriminatory practices. To contrast this risk and avoid unfair use of employees' data, the paper conclusively proposes potential safeguards, such as involving independent professionals (like the occupational physician) as intermediaries in health data processing.

Keywords: Occupational Health and Safety, Digitalization, Artificial Intelligence, Privacy

1. Introduction

Digitalization is arguably the most transformative evolutionary process humanity has experienced so far, reshaping every aspect of our social reality, including the world of work.
Its most distinctive effect is undoubtedly the advent of the so-called "*infosphere*" [1]. This term highlights the 'hybrid nature' of the dimension where we live our daily lives. The infosphere, in fact, simultaneously encompasses features of two dimensions that previously were starkly separated: on the one hand, the "analog" reality, rooted in the empirical experience; on the other, the "virtual" reality, imperceptible to human senses and accessible only through the mediation of digital devices.
While previously, these two dimensions were clearly distinct, their current irreversible merger has been brought about by the extraordinary evolution of ICTs, combined with factors such as the growing digitalization of information, the expansion of interconnected

networks, the development of cloud computing, and advancements in AI and automation. The result has been the gradual disappearance of the remaining boundaries "between *here* (*analog*, *carbon-based*, and *offline*) and *there* (*digital, silicon-based*, and *online*)" [2], leading humans into a new dimension (the infosphere), where they are constantly "online". This is evidenced by the fact that, in modern societies, a vast portion of social interactions (ranging from interpersonal relationships to shopping and travel, but also individuals' interactions with public authorities, for instance, for tax payments or official notifications) are now mediated by digital tools.

As mentioned, the advent of the infosphere has not spared workplaces, which, on the contrary, represent one of the most fertile grounds for its development: today it is rare to find organizations – whether large or small – where the productive process does not rely, at least partially, on digital infrastructures and on the functional interaction between humans, information, and machines.

In this perspective, the rapid advancement of wearable technologies (in the form of smart-watches, rings, armbands, exoskeletons, smart glasses, protective helmets, smart insoles, etc.) is set to further intensify the hybrid nature of the infosphere in the workplace, fostering the integration of the analog and virtual dimensions and bringing worker-information-machine interaction to unprecedented levels.

There are at least three reasons for this.

The first reason is that making the devices wearable enables the continuous transmission of information between the worker and the machine, keeping him constantly "online" without the need to be physically near the machine to interact with the digital infrastructure.

The second reason is that information transfer becomes independent of the worker's will, as the wearable device can transmit data automatically.

The third reason, and perhaps the most critical, is that significantly increasing is not only the "quantity" of information transmitted from the worker to the machine, but also the "quality" of them. This is particularly true when wearable devices are used in the field of occupational health and safety, as the data collected no longer pertain solely to the worker's tasks but also to the worker themselves – more specifically, to their health condition and their biological sphere.

This raises the crucial question of how the employer's obligation to protect the worker's health and safety (interpreted in the light of the duty to ensure the highest possible level of technology outlined in Article 2087 of the Civil Code and Article 15, par. 1, lett. c) of the Legislative Decree No. 81/2008 [3]) interacts with the worker's right to privacy and personal data protection.

The following analysis will therefore focus on the provisions of the EU Regulation 679/2016 (hereinafter "GDPR") [4], and, given that many of the wearable devices are integrated with AI systems that process personal data, also on the provisions of the EU Regulation 2024/1689 (hereinafter "AI Act").

The paper, therefore, will focus exclusively on wearable devices used for health and safety, and not for the different purpose of monitoring workers' performance and productivity [5] by their continuous monitoring (including geolocation). In this case, in fact, the specific provisions and limits established by Article 4 of Law No. 300/1970 should be applied.

2. Wearable Devices Applied to OSH: An Overview Between "Prevention" and "Reaction"

In the first stage, wearable technologies were mainly deployed in the medical field [6]. In recent years, however, their use has significantly expanded into the field of occupational safety and health (OSH) [7].

Wearable devices are part of the broader category of technologies that integrate new forms of OSH monitoring systems, defined by EU-OSHA as systems that "use digital technology to collect and analyze data to identify and assess risks, prevent and/or minimize harm, and promote occupational safety and health" [8].

The analysis of the multiple types of wearable devices currently available on the market has shown that these can be classified into two distinct purposes (although the distinction is not rigid, and in some cases the purposes can overlap): a preventive (or "proactive") purpose, and a "reactive" purpose.

The first category encompasses devices aimed primarily at preventing harmful events and, more broadly, enhancing the process of risk assessment and workplace environment control. These devices help to make this process more efficient, faster, cost-effective, continuous (24/7), and accurate, as they are not subject to human error or negligence.

For example, portable multi-gas detectors connected to a cloud infrastructure assess all atmospheric conditions in confined environments and immediately alert workers in case of threshold exceedances. Simultaneously, they notify the employer by sending the real-time geolocated positions of the workers, making rescue and recovery efforts more effective [9]. Similar considerations can be made for other types of wearable devices, such as armbands, which can also monitor other environmental parameters, like noise levels or air pressure [10].

The first category also includes tools that allow for targeted interventions or provide real-time feedback and support to workers, both concerning non-compliant behaviors with employer's OSH directives (for example, encouraging self-correction of non-ergonomic postures [11]) and exposure to specific risks, enabling an immediate adjustment of preventive measures. An example of this is the devices produced by a Scottish company that aim to prevent hand-arm vibration syndrome (HAVS) by providing workers with real-time information about their exposure to HAV. The devices calculate and display workers' exposure levels when they become excessive. Data collected includes information on the location of remote or lone workers, slips/trips, fall detection, the level of noise entering the ear, the level of harmful particulates, and the level of exposure to vibration [12].

There are also wearable devices, such as smart headbands produced by an Australian company, that continuously monitor a worker's electroencephalogram (EEG) signals to detect fatigue alert thresholds [13]. When the device identifies excessive fatigue levels, it immediately sends an alert via an app to both the worker and the employer, helping to prevent accidents – particularly in sectors where fatigue plays a critical role, such as long-haul transportation or construction.

Similarly, there are also wearable devices designed to promote a healthier and more active lifestyle, aligning the employer's duty of safety with the broader concept of "health" as defined by Article 2, par. 1, lett. o) of the Legislative Decree No. 81/2008: "a state of complete physical, mental, and social well-being, not merely the absence of disease or infirmity". This is the case of a U.S. company that provided its 335,000 employees with a Fitbit smartwatch to encourage physical activity by monitoring daily step count, calories burned, and other health metrics. The initiative aimed to promote a healthier workforce while also reducing the direct and indirect costs associated with poor employee health [14]. In this case, the employer had the opportunity to monitor employees' physical activity through a dedicated dashboard.

This is particularly interesting for our purposes because, depending on the specific device, similar smartwatches can also track and display various health parameters, including the number of hours spent in a sedentary position, sleep quality and duration, heart rate and the presence of arrhythmias, blood sugar levels, blood pressure, hydration levels, etc. [15]

The second category of devices, those which pursue a "reactive" purpose, includes technologies designed to minimize the consequences of accidents or respond promptly to emergencies that have occurred despite the preventive measures in place. These devices enable, for example, the automatic and instantaneous reporting of incidents or facilitate detailed investigations into past accidents, allowing for the implementation of more effective preventive measures in the future.

A notable example is a French company that produces smart insoles specifically designed for lone workers or employees working in large industrial facilities [16]. Thanks to an integrated sensor, these insoles detect when a worker is in a non-conventional (i.e., horizontal) position. They immediately trigger a pre-alarm vibration to alert the worker, and if the worker does not return to a normal position within 30 seconds, the device automatically sends a geolocated emergency signal to the employer or the supervisor via app notification, SMS, or email. Additionally, the employer can also send an alarm signal to the worker through a vibration alert.

Another noteworthy example is the case of devices that facilitate "near-miss" reporting by allowing workers to press a button on the device and record a voice memo describing any workplace hazards they observe [17]. Near-miss reporting captures situations that, while not resulting in damage or injury, had the potential to do so. Typically, reporting such incidents requires paperwork, which can be time-consuming for workers. As a result, traditional near-miss reporting remains relatively infrequent in the workplace. The voice memo function streamlines this process, making it more accessible and immediate. The data collected by the wearable is transmitted to a cloud-based software platform, where it undergoes analysis and is organized into trends and patterns. This analytical process leverages multiple sensors embedded in various devices worn over time, generating a comprehensive dataset across individuals rather than relying on a single device. Based on these insights, managers and safety professionals can implement control measures to mitigate potential hazards and prevent accidents.

From this brief analysis, it is undeniable that wearable devices represent an extraordinary opportunity to develop truly effective prevention systems, free from human error or negligence. These devices have the potential to bridge numerous gaps that human monitoring cannot fully address.

From the employer's perspective, it is quite impossible for even the most diligent companies with rigorous (human) surveillance systems to ensure continuous monitoring of workers as wearable devices can do. Moreover, employers often struggle to fully comply with the obligation outlined in Article 18, par. 1, lett. c) of the Legislative Decree No. 81/2008, which requires them, when assigning tasks to workers, to "take into account their capabilities and their health and safety conditions". Wearable devices, on the contrary, would allow employers to obtain an objective and real-time overview of their workers' physical conditions, preventing the assignment of tasks that could pose a risk to their well-being.
From the workers' perspective, these devices enable them to contribute actively to the shared goal of workplace safety. For example, they can alert workers to fatigue levels they might otherwise underestimate, non-ergonomic postures, or ongoing emergencies, allowing them to react promptly following their assigned duties. More in general, such technologies facilitate the employees' compliance with their general obligation of care established under Article 20, par. 1, of the Legislative Decree No. 81/2008.

3. How do "health" and "privacy" in the workplace dialogue in the European legal framework?

The undeniable benefits of these technologies should not overshadow the serious potential risks associated with processing the "personal data" necessary for their functioning.
Setting aside devices that process environmental information (such as gas presence, air pressure, or noise levels), the situation changes when the data being processed pertains, in various ways, to the worker and his biological sphere (e.g., electroencephalogram readings, heart rate, etc.). When such information can be directly or indirectly linked to the worker, it qualifies as "personal data" under Article 4, par. 1, no. 1 of the GDPR [18].
This makes applicable the rules introduced by the GDPR.
For our purposes, the GDPR conditions the lawfulness of any data processing (including those carried out through wearable devices in the OSH field) on compliance with both the general principles set out in Article 5 [19] and the existence of a valid legal basis among those exhaustively listed in Article 6 [20] – while, in the case of "special categories of data", also adhering to the stricter requirements of Article 9.
Among the general principles of Article 5, par. 1 of the GDPR [21] that the employer must observe are the principles of lawfulness, fairness, and transparency (lett. a) [22]; accuracy (lett. d) [23]; and integrity and confidentiality (lett. f) [24]. Additionally, the employer must comply with the principles of purpose limitation (lett. b) [25], data minimisation (lett. c) [26], and storage limitation (lett. e) [27].
Regarding the legal basis, Article 6 of the GDPR requires that at least one of the conditions listed in par. 1 be met. Given the structural imbalance of power between employer and employee, reliance on the most traditional basis – the data subject's consent (Article 6, par. 1, lett. a) [28] – is generally discouraged. Instead, other legal bases may come into play. Among them, the basis under Article 6, par. 1, lett. b) could be relevant, as it allows processing when "necessary for the performance of a contract to which the data subject is party" – a condition that could apply in our case because of the contractual nature of the employer's

duty to ensure employees' OSH. Similarly, Article 6, par. 1, lett. c) may be invoked when processing is necessary "for compliance with a legal obligation to which the controller is subject", such as the employer's OSH obligations under Article 2087 of the Civil Code and Legislative Decree No. 81/2008.

However, since the data collected by wearable devices often fall within the "special categories of personal data" – including "genetic data, biometric data for the purpose of uniquely identifying a natural person, or data concerning health" [29] – Article 9 of the GDPR also applies.

Article 9, par. 1, establishes a general prohibition on processing such special categories of data, with the exceptions listed in par. 2.

Among the exceptions admitted, excluding the data subject's explicit consent (Article 9, par. 2, lett. a) for the reasons already mentioned, two alternative justifications may be relevant. Article 9, par. 2, lett. b), which allows processing when "necessary for the purposes of carrying out the obligations and exercising specific rights of the controller or of the data subject in the field of employment"; or Article 9, par. 2, lett. h), which permits processing "when necessary for the purposes of preventive or occupational medicine, for the assessment of the working capacity of the employee".

The GDPR, therefore, seems to allow employers to process the health-related data of workers to prevent accidents and, more broadly, ensure workplace health and safety, even without the workers' consent, as long as it complies with the general principles laid out in Article 5. This suggests that the employer could rely on legal bases such as necessity for contract performance (Article 6, par. 1, lett. b) or compliance with legal obligations (Article 6, par. 1, lett. c), even for sensitive health data, provided the processing adheres to the principles of lawfulness, fairness, transparency, data minimization, and purpose limitation.

However, since many wearable devices are integrated with AI systems, the question arises as to whether this conclusion is compatible with the more recent AI Act, which regulates AI systems based on the level of risk they present and categorizes them into three groups: unacceptable risk, high risk, and non-high risk.

For systems considered presenting "unacceptable risks", the AI Act prohibits their market introduction or use (Article 5). High-risk AI systems, on the other hand, must comply with certain requirements and obligations (set in Chapter III), while non-high-risk systems may adopt guarantees voluntarily, such as through codes of conduct (Article 95) [30]. Additionally, regardless of high-risk system qualification, transparency requirements apply to AI providers and deployers, particularly for systems interacting directly with individuals or those that generate contents (Article 50).

For our purpose, the category of AI systems presenting an unacceptable risk is of particular interest. According to Article 5, par. 1, lett. f), the AI Act leads to this category and thus bans the introduction on the market or use of AI systems designed to infer emotions from a natural person in the workplace or educational institutions, except where the use is intended for medical or safety reasons.

At first glance, a restrictive interpretation of the exception "for medical or safety reasons" could lead to the conclusion that the AI Act prohibits the use of wearable devices capable

of measuring workers' emotional states (e.g., work-related stress or fear before an accident occurring). Similarly, it could be argued that systems that monitor worker behaviour or physiological parameters (such as EEG) to assess mental conditions (e.g., levels of attention) could also be prohibited [31].
On closer analysis, however, a different and broader interpretation of the exception in Article 5, par. 1, lett. f) is supported by Recital 18 of the AI Act, which states: "the notion of 'emotion recognition system' referred to in this Regulation should be defined as an AI system for the purpose of identifying or inferring emotions or intentions of natural persons on the basis of their biometric data. The notion refers to emotions or intentions such as happiness, sadness, anger, surprise, disgust, embarrassment, excitement, shame, contempt, satisfaction and amusement. It does not include physical states, such as pain or fatigue, including, for example, systems used in detecting the state of fatigue of professional pilots or drivers for the purpose of preventing accidents".
Although part of the literature argues that the AI Act has a gap on this specific point [32], the literal wording of Recital 18 suggests that the more preferable interpretation is that, under the AI Act, AI systems are permissible for safety reasons, specifically to detect potential states of fatigue, stress, distraction, or pain. As a consequence, such systems may capture and process data from sensors regarding pupil position and diameter, gaze vector and point, posture, gait, head position, heart rate and respiratory rate, sweating, body temperature, voice tone, facial expressions, verbal or written language, and keystroke patterns [33].
This interpretation has also been recently confirmed by the European Commission in its "*Guidelines on the definition of an artificial intelligence system established by Regulation (EU) 2024/1689*" of February 4, 2025. In pt. 43 of the Guidelines, the Commission clarifies that "the AI Act does not affect prohibitions that apply where an AI practice falls within other Union law. Thus, even where an AI system is not prohibited by the AI Act, its use could still be prohibited or unlawful based on other primary or secondary Union law (e.g., because of the failure to respect fundamental rights in a given case, such as the lack of a legal basis for the processing of personal data required under data protection law, discrimination prohibited by Union law, etc.)". To clarify this concept, the Commission gives an example in the field of occupational health and safety protection and states that: "AI-enabled emotion recognition systems used in the workplace that are exempted from the prohibition in Article 5(1)(f) AI Act, because they are used for medical or safety reasons, remain subject to data protection law and Union and national law on employment and working conditions, including health and safety at work, which may foresee other restrictions and safeguards in relation to the use of such systems".
Excluding, therefore, that these technologies can be affected by the prohibition in Article 5, the question arises as to whether they can be categorized as high risk, as defined in Article 6, par. 2 of the AI Act [34], which refers to those included in Annex III.
On this specific question, a potential "gap" in the AI Act could be found.
No. 4 of Annex III is dedicated to AI systems used in the area of "employment, workers' management, and access to self-employment". It provides that AI systems are classified as such, on one hand, as "AI systems intended to be used for the recruitment or selection of

natural persons, in particular to place targeted job advertisements, to analyse and filter job applications, and to evaluate candidates" (lett. a); and on the other hand, as "AI systems intended to be used to make decisions affecting terms of work-related relationships, the promotion or termination of work-related contractual relationships, to allocate tasks based on individual behaviour or personal traits or characteristics, or to monitor and evaluate the performance and behaviour of persons in such relationships" (lett. b).

The qualification as "high-risk" systems of this kind of technologies – many of which have already proven to result in significant violations of workers' rights [35] – is without doubt positive in terms of workers' protection.

The absence of an explicit reference to the protection of workers' health and safety in purpose No. 4 could, however, "liberalize" the use of high-risk AI systems in the OSH field [36]. This would make their implementation in the workplace significantly easier, at least regarding the requirements the AI system must meet and the obligations imposed on deployers and employers. At the same time, it could expose workers to fewer protections in the face of "high risk" system.

Two "corrections" could address this "gap".

The first concerns the fact that certain types of wearable technologies, such as certain exoskeletons and smart individual protective devices, could still fall under the "high-risk" AI systems outlined in Article 6, par. 1, and Annex I of the AI Act, which, in No. 1, refers to the Machinery Directive 2006/42/EC (recently repealed by Regulation 2023/1230) and Regulation 2016/425 on personal protective equipment (which replaced Directive 89/686/EEC).

The second arises from the concrete overlap which can happen between wearable devices with integrated AI used for safety purposes (not included in Annex III, No. 4) that, to achieve this goal, also impact the "allocation of tasks" (a purpose, on the contrary, included in Annex III, No. 4). This is the case of those devices that, to protect OSH, assign new tasks that better align with the actual worker's physical condition (in compliance with Article 18, par. 1, letter c) of the Legislative Decree no. 81/2008), or instruct the worker to stop their activity, which will then be reassigned to another worker. Consider wearable devices mentioned earlier aimed at preventing hand-arm vibration syndrome (HAVS), or those devices which measure body temperature to avoid injuries, particularly in high-risk sectors such as construction (especially considering the effects of climate change) [37], based on the algorithmic analysis of various physiological parameters (e.g., skin temperature, heart rate, etc.). In these cases, the AI system integrated into wearable devices does not appear to aim at "managing" the employment relationship in the strict sense, such as continuously assigning micro-tasks to workers, as observed in companies like Amazon or Leroy Merlin [38]. On the contrary, here the assignment of a task is instrumental not to achieving the productive goal of that organization, but to safeguarding the worker's health and safety.

Should this "instrumental" connection still lead to including these AI systems among those considered "high-risk" under Annex III, No. 4, lett. b)? On this point, the AI Act does not seem to offer a definitive answer [39], leaving it to deployers and, soon, to the judges to clarify this issue.

4. The hidden risk and a proposal for the future

As seen, the potential of wearable devices in health and safety is extraordinary, with these devices potentially representing a key factor in making the prevention system defined by Directive EC 391/89 fully effective.

The brief analysis conducted here would also suggest that the European regulatory framework, particularly the GDPR and the AI Act, allows the employer to use these devices for health and safety protection purposes.

However, it is important to recognize that along with the many unquestionable advantages, there are also risks, including in the specific area of OSH, which are in addition to those related to the security of the large amounts of data processed by these devices. In this regard, the GDPR imposes on the employer specific duties and, in the case of violations, provides significant sanctions.

With regard to risks directly impacting occupational health and safety, the most common and tangible concerns stem from the physical design of these devices, including the presence of electronic components and the potential hazards associated with their function (e.g. explosion or burst).

A different risk is that associated with any failure in their operation, which should prompt the employer to ensure a rigorous and constant (human) control over the AI systems. These devices, in fact, should be considered as complementary tools – not complete substitutes – for human presence and intervention in the OSH field. This approach is supported by the 'legal nature' of AI systems, which does not allow the employer to completely "delegate" to them his supervisory obligations under Article 18, par. 3 *bis* of the Legislative Decree no. 81/2008. Because of the lacking legal personality, AI systems cannot be "delegated" under Article 16 of the Legislative Decree No. 81/2008, and therefore the responsibility remains with the employer, which, in order to avoid its own liability, must prove the adoption of a control system on the proper functioning of the IA System.

The same applies to the supervisors: the employer cannot avoid appointing them under Article 18, par. 1, lett. b-bis) [40], claiming to have assigned the related supervisory task to AI systems. Since the appointment is mandatory, when it occurs, the tasks outlined in Article 19 must be carried out by the supervisor, certainly with the help of AI systems, but not by fully delegating this responsibility to them.

Such an interpretation is not surprising if we consider that the primacy of humans over artificial intelligence is one of the cornerstones of the entire AI Act.

Then, there is another risk, less perceptible and only indirectly linked to the protection of workers' health and safety: the risk of "discrimination".

As known, Article 1 of Directive EC 2000/78 prohibits all forms of discrimination in employment – whether direct [41] or indirect [42] – based on religion or personal beliefs, disability, age, or sexual orientation. Directive EC 2006/54, on the other hand, extends the prohibition of any discrimination to gender.

For our purposes, the "disability" factor is particularly relevant.

The Court of Justice of the European Union has interpreted expansively such factor, including in this notion not only individuals with a physical and/or mental impairment – as is

the case at the national level – but also those who are 'simply' affected by a long-term [43] illness [44], including chronic conditions, resulting from a physical, mental, or psychological impairment [45], which impacts work capacity [46], thereby creating even just an obstacle, and not necessarily a complete inability to perform the job [47].
Given that definition, an "illness" integrating "handicap" for the purpose of the Directive could be, for example, a heart disease or a neurological disorder, a broken leg, or a back disease, if long-lasting and affecting the ability to perform work activities.
So, should the employer decide to secretly aggregate the data collected through wearable devices and thus obtain an overview of the overall physical condition of the employee, avoiding, for example, promoting him because of his heart condition, such conduct proves unlawful under two profiles. First, this could constitute discrimination based on "disability", as defined by the Court of Justice. Secondly, the employer would violate the GDPR by using the data for purposes other than (and indeed unlawful) those initially declared.
Moving from the "disability" to the "gender" forbidden factor of discrimination, the case of data aggregation that reveals workers' pregnancy condition is also particularly risky [48]. Here, there are two violations. The first stems from anti-discrimination law: the pregnant worker could face discrimination, for example, if the employer, knowing about her pregnancy, prefers a male colleague for a promotion to a position of responsibility. The second arises from OSH legislation, as Article 41, par. 3, lett. b) of the Legislative Decree no. 81/2008 would be violated, which prohibits even the occupational physician from carrying out checks to ascertain the worker's pregnancy status.
As seen, the availability for the employer of personal data relating to the worker's "health" and biological condition presents considerable risks.
Even though, according to the GDPR and AI Act, the employer may legitimately process these data, it is worth questioning whether it would be necessary to introduce corrective measures, especially since it is nearly impossible for the worker to prove the employer's unlawful conduct in secretly aggregating data he legitimately process.
A possible solution could be to encourage greater involvement from actors other than the employer, particularly professionals bound by confidentiality regarding these data. One such professional could be the occupational physician, who could act as a "filter" for the data processed by AI systems.
This could help solve what now appears to be a paradox.
On the one hand, as the rules of the worker's illness illustrate, the employer is prohibited from accessing any diagnostic data and may only be informed of the prognosis. On the other hand, however, the use of wearable devices allows the employer to process data which, when aggregated, effectively reveals precisely the health information they are not permitted to know.

References

[1] L. Floridi, *La quarta rivoluzione. Come l'infosfera sta trasformando il mondo*, Milano, Raffaello Cortina Editore, p. 47; see also C. Accoto, *Il mondo in sintesi. Cinque brevi lezioni di filosofia della simulazione*, Milano, Egea, 2022.

[2] L. Floridi, *La quarta rivoluzione. Come l'infosfera sta trasformando il mondo*, cit., p. 47; see also C. Accoto, *Il mondo in sintesi. Cinque brevi lezioni di filosofia della simulazione*, Milano, Egea, 2022.

[3] See also art. 131, co. 5, art. 182, art. 232 of the Legislative Decree no. 81/2008.

[4] In Italy supplemented by Legislative Decree No. 196/2003, as amended by Legislative Decree 101/2018.

[5] On this topic see A. Ingrao, *Il braccialetto elettronico tra privacy e sicurezza del lavoratore*, in *Diritto delle relazioni industriali*, 2019, 3, p. 895.

[6] The World Health Organization has defined "mHealth" as "medical and public health practice supported by mobile devices such as mobile phones, patient monitoring devices, personal digital assistants (PDAs) and other wireless devices", WHO Global Observatory for eHealth, *MHealth: New Horizons for Health through mobile technologies*, 2011, p. 6.

[7] C. B. Olsen, *To track or not to track? Employees' data privacy in the age of corporate wellness, mobile health, and GDPR, in International Data Privacy Law*, 2020, vo. 10, n. 3, p. 238.

[8] European Agency for Safety and Health at Work (EU-OSHA), *Smart digital monitoring systems for occupational safety and health: uses and challenges*, 2022. accessible at www.osha.europa.eu/sites/default/files/Smart-digital-monitoring-systems-useschallenges_en.pdf.

[9] European Agency for Safety and Health at Work (EU-OSHA), *Smart sensors for hazardous gases: smart digital systems for improving workers' safety and health*, 5 December 2024, accessible at, www.osha.europa.eu/en/publications/smart-sensors-hazardous-gases-smart-digital-systems-improving-workers-safety-and-health.

[10] European Agency for Safety and Health at Work (EU-OSHA), *Smart armband for real-time data analysis for health and safety: smart digital systems for improving workers' safety and health*, 5 December 2024, accessible at www.osha.europa.eu/en/publications/smart-armband-real-time-data-analysis-health-and-safety-smart-digital-systems-improving-workers-safety-and-health.

[11] European Agency for Safety and Health at Work (EU-OSHA), *Wearables to monitor and improve posture ergonomics: smart digital systems for improving workers' safety and health*, 5 December 2024, accessible at www.osha.europa.eu/en/publications/wearables-monitor-and-improve-posture-ergonomics-smart-digital-systems-improving-workers-safety-and-health.

[12] European Agency for Safety and Health at Work (EU-OSHA), *Preventing hand-arm vibration syndrome (HAVS): smart digital systems for improving workers' safety and health*, 5 December 2024, accessible at www.osha.europa.eu/en/publications/preventing-hand-arm-vibration-syndrome-havs-smart-digital-systems-improving-workers-safety-and-health.

[13] European Agency for Safety and Health at Work (EU-OSHA), *Smart headband for fatigue risk-monitoring: smart digital systems for improving workers' safety and health*, 5 December 2024, accessible at www.osha.europa.eu/en/publications/smart-headband-fatigue-risk-monitoring-smart-digital-systems-improving-workers-safety-and-health.

[14] See C. Chen, S. Pettypiece, *Target to Offer Fitbits to 335,000 Employees*, Bloomberg, 16 September 2015, accessible at www.bloomberg.com/news/articles/2015-09-15/target-to-offer-health-tracking-fitbits-to-335-000-employees.

[15] A. Troiano, *Wearables and Personal Health Data: Putting a Premium on Your Privacy, in Brooklyn Law Review*, vol 82, 2017, p. 1715, accessible at www.brooklynworks.brooklaw.edu/blr/vol82/iss4/6

[16] European Agency for Safety and Health at Work (EU-OSHA), *Smart insoles for lone worker protection: smart digital systems for improving workers' safety and health*, 5 December 2024, accessible at www.osha.europa.eu/en/publications/smart-insoles-lone-worker-protection-smart-digital-systems-improving-workers-safety-and-health.

[17] European Agency for Safety and Health at Work (EU-OSHA), *Smart armband for real-time data analysis for health and safety: smart digital systems for improving workers' safety and health*, cit.

[18] Personal data are defined as "any information relating to an identified or identifiable natural person ('data subject'); an identifiable natural person is one who can be identified, directly or indirectly, in particular by reference to an identifier such as a name, an identification number, location data, an online identifier or to one or more factors specific to the physical, physiological, genetic, mental, economic, cultural or social identity of that natural person".

[19] To be read in the light of Recitals 39 and 74. These principles are largely consistent with those already laid down in Article 5 of the Strasbourg Convention No. 108/1981, in Article 8 of the Charter of Fundamental Rights of the Union and in Article 6 of EC Directive 95/46, as well as in Articles 3 and 11 of Legislative Decree No. 196/2003, prior to the amendment.

[20] Although not relevant for our purposes, it is worth pointing out that, when processing is based on consent, Article 7 of the GDPR lays down additional conditions in the presence of which consent is deemed to have been lawfully given.

[21] In addition to the principles laid down in Article 5, par. 1, of the GDPR, there is also the further principle laid down in Article 5, par. 2 of the data controller's responsibility (or 'accountability').

[22] While the principles of lawfulness and fairness were already present in Article 6 of EC Directive 95/46, the principle of transparency is a partial innovation introduced by the GDPR. The principle of lawfulness must be read in conjunction with Article 6 GDPR. The principle of fairness which seems to refer to the duty of 'fairness' in processing under Art. 8, par. 2 of the EU Charter of Fundamental Rights, is considered by the Regulation together with the principle of transparency, to accentuate the degree of overall effectiveness of the protections. In implementation of this, for example, the GDPR requires that the information provided by the data controller to the data subject be "easily accessible and understandable, and that clear and plain language be used" (Recitals 39 and 60).

[23] Under which the data controller must update the stored data, taking 'all reasonable steps to delete or rectify promptly data that are inaccurate to the purposes for which they are processed', with the obligation to notify – to the extent possible under Article 19 GDPR – all recipients of any rectification, deletion and restriction.

[24] This is a partial novelty, insofar as it elevates to a general processing principle certain obligations that were previously provided for by EC Directive 95/46, and confirmed by the GDPR, such as, for example, the duty of security of processing (Art. 32 of the GDPR); the responsibility of the data controller (Art. 24 of the GDPR); the principles of data protection by design and by default (Art. 25 of the GDPR); the impact assessment (Art. 35 of the GDPR); the obligations following a data breach (Art. 33 and 34 of the GDPR).

[25] This principle is closely related to the provision of Article 6 of the GDPR, according to which the purposes of processing must be 'specified, explicit and legitimate', also prescribing that processing subsequent to the initial acquisition must take place 'in a way that is not incompatible with those purposes'. This is a principle already present in EC Directive 95/46,

Art. 6. According to Italian Corte di Cassazione No. 5525 of 5 April 2012, this principle constitutes "a real and inherent limitation of the lawful processing of personal data". For the scope of this principle and the notion of 'compatible purpose' see European Data Protection Board (ex WP 29), *Opinion 3/2013 'On purpose limitation'* and more recently Court of Justice 20 October 2022, C-77/21, *Digi Távközlési és Szolgáltató Kft*.

[26] This is also already present in EC Directive 95/46, Art. 6, albeit under the heading of 'non-excessiveness'. Under the principle of minimization, the data to be processed must be only those that are 'adequate, relevant and limited to what is necessary to the purposes for which they are processed'. The general rule, therefore, is that 'personal data should only be processed if the purpose of the processing cannot reasonably be achieved by other means' (Recital 39 of the GDPR).

[27] According to which data must be 'kept in a form which permits identification of data subjects for no longer than the purposes for which they are processed'. It is therefore necessary for the data controller to carry out a periodic check on the actual need to retain the data (Recital 39 of the GDPR), given that – and hence the connection with the principle of minimization under point (c) – the unlawfulness of the processing may also arise at a later point in time than when the data were first acquired.

[28] A. Topo, D. Tardivo, *Hard law e soft law nel Diritto dell'Unione europea in materia di trattamento dei dati personali e di tutela della riservatezza del lavoratore*, in G. Proia, C. Pisani, A. Topo (eds.), *Privacy e lavoro. La circolazione dei dati personali e i controlli nel rapporto di lavoro*, Milano, Giuffré, 2022, pp. 75-109.

[29] Art. 9, par. 1, of the GDPR.

[30] M. Peruzzi, *Sistemi automatizzati e tutela della salute e sicurezza sul lavoro*, in *Diritto della Sicurezza sul lavoro*, 2024, 2, p. 87.

[31] M. Van Vlugt, *Using Biometric Sensors to Measure Productivity*, in C. Sadowski, T. Zimmermann (eds.), *Rethinking Productivity in Software Engineering*, Apress, 2019, pp. 159-167; S. Marassi, *Intelligenza Artificiale e sicurezza sul Lavoro, in Lavoro Diritti Europa*, 2024, 4, p. 9

[32] A. Ponce Del Castillo, *The AI Act: deregulation in disguise, Social Europe*, 11 dicembre 2023, accessible at www.socialeurope.eu/the-ai-actderegulation-in-disguise; see also S. Marassi, *Intelligenza Artificiale e sicurezza sul Lavoro*, cit., p. 10.

[33] This is the interpretation of M. Peruzzi, *Sistemi automatizzati e tutela della salute e sicurezza sul lavoro*, cit., p. 87.

[34] In addition, AI systems that meet both of the conditions set out in Article 6(1) of the GDPR can also be qualified as 'high risk', i.e. "(a) the AI system is intended to be used as a safety component of a product, or the AI system is itself a product, covered by the Union harmonisation legislation listed in Annex I; (b) the product whose safety component pursuant to point a) is the AI system, or the AI system itself as a product, is required to undergo a third-party conformity assessment, with a view to the placing on the market or the putting into service of that product pursuant to the Union harmonisation legislation listed in Annex I".

[35] On recruitment, see A. Topo, *Essay on New Technology and Discrimination*, Cleup, 2025, forthcoming.

[36] See also Recital no. 57 of the AI Act.

[37] On this subject see Ispettorato Nazionale del Lavoro, nota n. 5056 del 13 July 2023 "*Tutela dei lavoratori sul rischio legato ai danni da calore*".

[38] A. Ingrao, *Il braccialetto elettronico tra privacy e sicurezza del lavoratore*, cit.

[39] S. Marassi, *Intelligenza Artificiale e sicurezza sul Lavoro*, cit., p. 13.

[40] Article 18, par. 1, lett. b-bis) provides that one of the employer's obligations is to "identify the supervisor or supervisors to carry out the supervisory activities referred to in Article 19. Collective labour contracts and agreements may establish the remuneration due to the supervisor for carrying out the activities referred to in the preceding sentence. The person in charge may not suffer any prejudice as a result of the performance of his or her activities'. This is an obligation introduced by Law No. 215/2021, converting Decree Law No. 146/2021.

[41] Article 2, par. 2, lett. a) of EC Directive 2000/78 provides that "direct discrimination exists where, on any of the grounds referred to in Article 1, one person is treated less favourably than another is, has been or would be treated in a comparable situation".

[42] Article 2, par. 2, lett. b) of EC Directive 2000/78 provides that "indirect discrimination exists where an apparently neutral provision, criterion or practice would put persons professing a particular religion or belief at a particular disadvantage. b) of EC Directive 2000/78 provides that "indirect discrimination exists where an apparently neutral provision, criterion or practice would put persons professing a particular religion or other ideology, persons with a particular disability, persons of a particular age or sexual orientation at a particular disadvantage compared with other persons, unless: (i) that provision, criterion or practice is objectively justified by a legitimate aim and the means of achieving that aim are appropriate and necessary; or (ii) in the case of persons with a particular disability, the employer or any person or organisation to whom this Directive applies is obliged by national legislation to take appropriate measures, in accordance with the principles set out in Article 5, to redress any disadvantage caused by that provision, criterion or practice".

[43] See European Court of Justice 11 April 2013, C-335 and 337/2011, *HK Danmark*; 18 December 2014, C-354/13, FOA; 1 December 2016, C-395/15, *Daouidi*; 9 March 2017, C-406/15, *Milkova*; 18 January 2018, C-270/2016, *Conejero*.

[44] The ratification of the UN Convention by the Union led the Court of Justice to overcome the initial contrary approach expressed in European Court of Justice, 11 July 2006, C-13/05, *Chacón Navas*, see in this regard 11 April 2013, C-335 and 337/2011, *HK Danmark*.

[45] Of which it does not matter whether they are 'congenital or the result of an accident' or whether they were 'caused by a disease', as stated by European Court of Justice 11 aprile 2013, C-335 e 337/2011, *HK Danmark*.

[46] On the exclusion of infertility due to the absence of a uterus from the concept of 'disability', see European Court of Justice 18 marzo 2014, C-363/12, Z.; on the condition of obesity 18 dicembre 2014, C-354/13, FOA; 18 gennaio 2018, C-270/2016, *Conejero*.

[47] See already C. C-335 and 337/2011, *HK Danmark*.

[48] See V. Mone, F. Shakhlo, *Health Data on the Go: Navigating Privacy Concerns with Wearable Technologies, in Legal Information Management*, 2023, vol. 23, 3, pp. 179-188 reported that "The Washington Post conducted an investigation in 2019 that found that popular fitness tracking apps were disclosing menstrual cycles, pregnancy status and mental health information of users to third-party advertisers. It's possible that this data will be used for malicious purposes like targeted advertising".

The Silent Introduction of People Counting Systems Based on Video Camera Image Analysis in Free Entertainment Events in Large-Capacity Public Open Spaces: Opportunities and Risks

Vincenzo Puccia[1*]
[1] Comando Vigili del Fuoco di Verona, Corpo Nazionale Vigili del Fuoco, Verona, Italy

* E-mail: vincenzo.puccia@vigilfuoco.it

Abstract. The growing utilization of public spaces for free entertainment events with large crowds presents significant challenges in safety management, particularly as crowd flows often continue dynamically throughout the event. Effective area management becomes a critical factor in ensuring the safety of occupants, with specific attention to monitoring the total number of attendees present simultaneously. This complex task is increasingly supported by people counting systems that rely on video camera networks and image analysis so ware powered by artificial intelligence algorithms. These tools assist public officers responsible for safety and security management. However, while their adoption is becoming widespread, the reliability of these systems, particularly in terms of the accuracy of the data they produce, remains under evaluation. The reliability of such a system is another element that needs to be investigated. The performance of automated counting systems can be influenced by several factors, including the presence of hoods or other clothing items, the density of large groups, and the reliance on facial recognition to identify individuals. The acceptance and integra on of these systems in open public events could provide real-me monitoring of attendance but are subject to various critical concerns, including reliability both in term of components functionality and of whole system measures in compromised environment conditions, validation and certification, data privacy and GDPR compliance.

Keywords: Crowd Measurement, Public Entertainment, Crowd Management, Artificial Intelligence Applications

1. Introduction

Large-scale public events demand real-time, reliable monitoring systems to ensure both efficient crowd management and public safety. Automated people counting systems based on video image analysis have emerged as crucial tools for tracking crowd density and flow. This paper investigates the technical architecture and operational challenges of such systems, focusing on a case study from the December 31, 2024 event in Verona. The integrated system relies on cutting-edge hardware and software solutions to process high-definition video data under diverse environmental conditions. Additionally, the study considers the administrative perspective – particularly the legal and ethical implications associated with data privacy under the EU's GDPR framework. Recent technological advancements, such as those embodied in the most recent workstation and network camera, have significantly enhanced system performance, yet they introduce complexities regarding reliability and regulatory compliance. Here, we explore the interplay between advanced hardware capabilities, real-time data processing, and stringent privacy requirements, providing a comprehensive overview of both the opportunities and risks inherent in deploying these systems in dynamic public environments.

2. A short review of the state of the art on automatic crowd counting (and control) systems

Artificial intelligence has made huge progress in crowds processing, especially in advanced dynamic and open environments like public squares having various entrances and exits [1][2][4][7][8].Based on high-resolution video cameras, AI-based techniques offer accurate and real-time analysis of the behaviour of crowds. The Crowd surveillance is notoriously the original goal of those system, also with the aim to associate an identity (adopting a mass collection of data on facial recognition) to each people entering in the field of the high-resolution cameras, for police monitoring and public order management, obviously with heavy implications with regard to citizen personal freedoms and privacy, as understood in the Western world and particularly in the EU [5][11]. The public acceptance (or perhaps imposition) of those AI applications did a leap forward in the context of the pandemic emergency connected to COVID-2019 and the consequent very strict covid-zero policies applied in the country epicentrum of the virus spill over. On the other hand these systems can also have a different use, limiting the threshold of information acquisition, without associating them with databases on the identity of citizens, with the aim of counting the people who pass through an access point. and of monitoring the overall crowding in an area for safety purposes.

2.1. Detection Techniques for Crowd Counting [6][7][8][9][10][13][14][15][16]

Recent advances in crowd counting have brought in advanced techniques to solve issues in dynamic scenes. in particular, the main AI technologies and methodologies applied to this purpose are:

- Deep Learning-Based Methods: Convolutional Neural Networks (CNNs) have been widely used for crowd counting because they can learn hierarchical features from the data. CNNs can deal with the changes in crowd density and perspective distortion efficiently.
- Density Map Estimation: In this, a density map is created where the value of each pixel is the estimated number of individuals in that area. Summing these values over the map gives the count of the crowd. High-resolution images improve the quality of such estimates by providing finer details.

- Regression-Based Methods: These methods directly learn the mapping from image features to crowd count without intermediate representation such as density maps. Though efficient, these might not contain spatial information regarding the crowd distribution.
- Detection-Based Methods: These methods favour the detection of single persons in the frame and perform well under low-density conditions but fail in situations of occlusions and overlapping people in high-density crowds.

2.2. Anomaly Detection in Crowd Surveillance [10][11][13][16]

It is difficult to detect abnormalities like hooded figures, blinking intervals, insufficient lighting or smoke curtains. Anyway, with regard to the poor lighting conditions, the advancements in visible field camera sensors both in the definition and in the noise filtering algorithms coupled with infrared sensitive sensors produced to efficient solutions, once unthinkable. In particular the anomaly detection includes:

- Behavioural Analytics: AI algorithms learn normal patterns of activity within a scene so that anomalies such as unauthorized access or unusual movement can be detected [14]. For example, a person wearing a hood in a situation where it's not normal would be highlighted as an anomaly.
- 2 Robust Anomaly Detection [13]: Researchers have developed techniques for Low-Light anomaly detection in surveillance videos with challenging conditions, including low resolution, dynamic backgrounds, changing illumination, and occlusions. This makes anomaly detection systems more robust for real-world scenarios.

2.3. Challenges and Future Directions

Despite advancements, there remain difficulties in accurately counting and monitoring crowds within dynamic open areas when disturbing factors occur or/and huge amount of data overflowing computing power, as:

- Occlusions and Dense Crowds: Crowds with high density and large occlusions are challenging for individual detection approaches. This affects the overall results in counting applications.
- Lighting Variations: Variable or low lighting conditions can hamper the functioning of vision-based systems, e.g. flashing or strobe lights use badly affects the video cameras, altering the detection results.
- Real-Time Processing: Real-time analysis is accomplished by using algorithms that can process high-resolution video streams, so a huge amount of data. The overall computing is related to the number of gates, to the people flowing through them or to the people doing action inside the monitored area. When a contemporary movement, or a contemporary high transit in all gates, occurs the data analysis process could suffer overflow errors if the computing power isn't enough for a real-time management of the registered data flow.

Current research concentrates on the design of stronger models that can adapt to such difficulties in providing proper and effective crowd monitoring and anomaly detection in complicated circumstances. In particular adopting cameras with field variable optics aiming to the crowd in the area, the goal is the capability to identify the behaviour of groups or isolated people, at various levels of detail, for an early detection of illegal or dangerous actions (this area of research is a part of the much wider Behavioural Analytics Field.).Although this activity is nowadays done by human operators, e.g. the monitoring of football teams supporters inside a stadium, with regard to crimes prevention, checking and repression, anyway at first an AI based monitoring system could be an useful tool on very large areas, with limited human operators. The same algorithms could be applied for behavioural analysis aimed at preventing accidents in the workplace. Clearly the extension of these potentialities to the monitoring of the actions of citizens or workers has very profound legal and ethics implications on fundamental issues of personal freedoms, the foundation of our Western societies.

3. Materials and Methods

This case study focuses the potential connected with Artificial Intelligence applied to crowd management, particularly with regard to the dynamic count of total amount of attenders to the event and the decision support provided to civil servants charged of the security and safety. The area open to the public is close to 18.000 square meters and the maximum required audience capacity was 30,000 people, for an open musical show celebrating the new year. The hardware implemented for public spaces control, as Bra square in front of the famous roman age Arena, is quite light, simply and quickly installable and removable, based on high resolution video cameras, a workstation and few other elements, to operate a real time count of the attenders, limiting the access to the space. Clearly the core of such a system is the A.I. based software, and the data analysis. Anyway, a relevant number of stewards is necessary for the gates control, and the data should be evaluated by public officers with a large experience in crowd management. The methodological approach to the use of data it's also an issue, as per national privacy regulation and UE General Data Protection Regulation (GDPR). Last but not least, a reflection must be made in the common acceptance of these control methodologies, which if not limited by law and strict rules, could lead to the use of the same technologies already in place in countries with a different vision of democracy and individual freedoms compared to Western Europe. The purposes of the plan for maintaining safety conditions are:

- the safety of human life;
- the safety of people;
- the protection of property and heritage

Particularly the heritage was represented from the Roman Arena and the monuments of Gran Guardia directly limiting the area of the musical event.
The measures to pursue these objectives are, in relation to the type of emergency:

- measures, provisions and operational measures intended to reduce the probability of a fire or other emergency and/or to limit its consequences;
- measures, provisions and operational measures to provide the people present, through appropriately trained personnel (with a percentage of stewards formed as per Italian

regulation on football stadium), and with the coordinated assistance of the police, fire brigade and healthcare personnel and facilities, with the necessary assistance to move away unharmed to safe places and to receive any first aid.

The main concern of public authority was represented from the formation of crowd gatherings with the risk of sudden mass movements, induced from capsicum spray or other irritant products such in other tragic events, or brawls among people altered from alcohol or psychotropic substances, considering the number of 30000 attenders required from the organization of the event.

3.1. Study Design and Case Selection

This research employs a mixed-methods approach, combining quantitative performance metrics with qualitative assessments of regulatory compliance and operational control. The December 31, 2024 music show event at the Verona Arena, characterized by high crowd and dynamic environmental conditions, was selected as the case study to evaluate system performance, with approximately 18000 square meters of available space and 30000 maximum authorized attenders fixed by public authorities. The Bra square was accessible by four main gaps, and the other public roads leading to the event zone were used exclusively as escape routes for a possible mass evacuation of the public. Nevertheless, it is appropriate to highlight that the correlations used for the dimensioning of the escape routes remain based on the hypothesis of a reasonably orderly and disciplined movement of the occupants. The occurrence of a sudden movement of the crowd in fact raises legitimate doubts about the effectiveness of the "hydraulic" dimensioning of the exodus in the face of a wave of people

Figure 1. The Crowd on Piazza Bra, Verona, on night of 31th December 2024.

who want to leave the area. In these cases, all the obstacles potentially in the exit path, but it would be more correct to say of escape route, of the crowd, must also be carefully evaluated.

3.2. System Architecture and Hardware Integration

The technical backbone of the people counting system is constituted by two principal hardware components, based on a Detection-Based Methods as above described:

- Workstation Platform:
  The CENTER337-V2 workstation, certified for Dahua's surveillance software platforms (e.g., DSS Pro, DSS Express) and operating on Windows 11 Pro, forms the central processing unit. It is equipped with an Intel Core i7-13700T processor (operating between 2.4–4.8 GHz), 16 GB DDR5 memory, and a 512 GB SSD for rapid data storage. The NVIDIA RTX T400 graphics card, with its multiple mini Display Port outputs, ensures robust real-time image decoding and processing. These specifications are critical for handling high-resolution video streams and implementing advanced AI algorithms with minimal latency.
- Network Camera:
  The DH-IPC-HDW8341X-3D-S2 network camera, featuring a 3MP CMOS sensor and dual-lens architecture, delivers high-quality video under low illumination conditions (as low as 0.005 Lux in color mode) and is equipped with infrared illumination for complete darkness scenarios. In addition to its people counting capabilities – including queue management and area occupancy reports – the camera incorporates advanced cybersecurity features such as encrypted transmission (HTTPS, firmware encryption), secure authentication, and IP/MAC filtering.

A robust environmental design (IP67, IK10) further supports reliability if the components are exposed to adverse weather conditions.

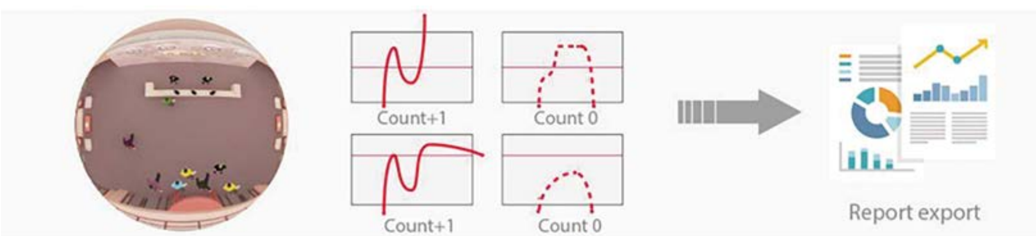


Figure 2. One of rules for the training of the artificial intelligence algorithm used to evaluate transits at the gates, a detection method application.

3.3. Counting Mode [6][7][8][9][10]

Virtual lines are drawn in the camera's field of vision that delimit the flow of people, the crossing line is drawn in frame centre with the relative direction of the flows of attenders (entry/exit). The camera perceives the image of the people's heads creating a metadata that is

processed on board the camera, passing the counting data to the software which is processed together with all the other data coming from the other cameras to maintain the count of those present.
All the cameras work in Stand Alone mode, therefore, if there is a loss of connection between the camera and the operating system, the data will not be lost as the camera and the operating system will synchronize again once the connection is restored, updating the database.
At the end of the event, the data can be extracted from the system to process the statistical data of the
flows detected hour by hour for each Gate. Clearly, this is the application of mass surveillance tools created for a very different purpose.

3.4. Data Collection and Analysis

Data were continuously captured during the event, with performance metrics including counting accuracy, system downtime, error rates, and the activation times of backup systems. Manual counts performed by civil servants on duty for the event served as the ground truth and a backup of the automatic counting. The data analysis provided a real time attenders balance in the area, considering the flows going in and out of the public event. The resulting people number in the area was displayed in the control room, for a continuous evaluation of the safe. Also an overall evaluation on local risk was conducted by stewards surveillance, to prevent any dangerous scenario.

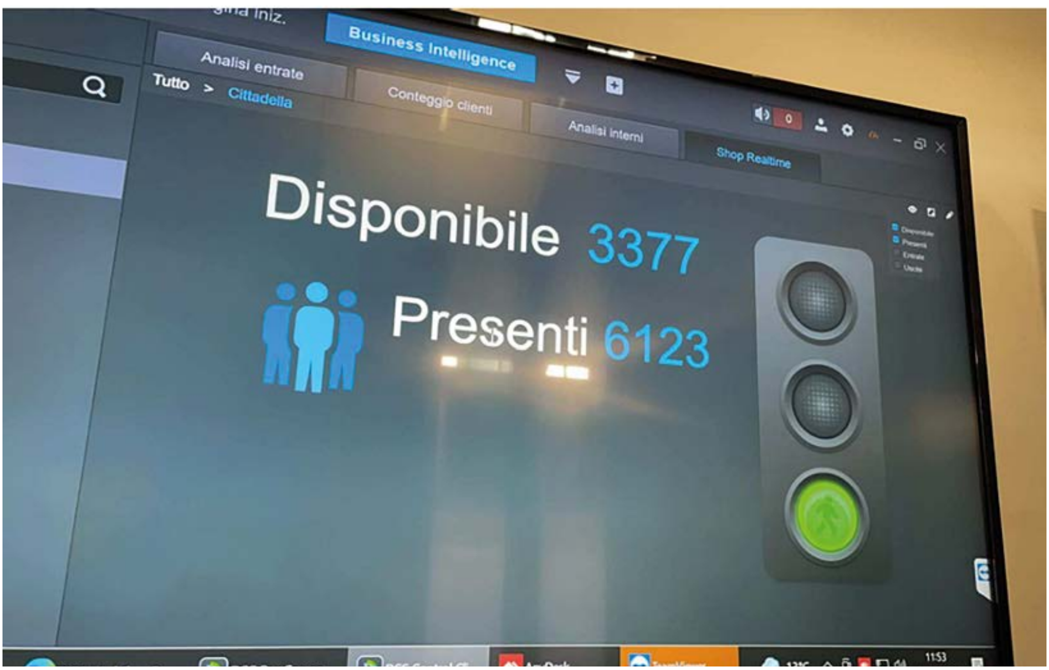


Figure 3. The predicted attenders in the area with the availables.

3.5. Environmental and Operational Testing

In consideration of the huge number of people estimated to attend the music show, various concerns have been raised by public officials with competence in the authorisations on the levels of confidence of the count produced by the automatic system based on AI algorithms. Among documentation transmitted, a document illustrated the system implemented was previously tested under varying operational conditions, such as:

- **Optimal Conditions:** High illumination and minimal interference.
- **Adverse Conditions:** Low light, presence of smoke, and deliberate camera obstructions.

These tests transmitted to the public commission describe insights into the robustness of the image analysis algorithms and the efficacy of the backup protocols in ensuring uninterrupted operation. Anyway, in other events in the past, a similar system resulted affected by a critical crash in the mid of the show, charging on the civil servants the entire responsibility to allow or stop the access to the area. In particular, this system evidenced on the night of 31th December 2024 a vulnerability in the effectiveness in the spectators counting when grouped in large parties, sometimes overestimating their number.

3.6. Privacy and Data Protection Measures

In compliance with the EU's GDPR and other data protection regulations, all captured facial data were anonymized immediately upon acquisition. The system integrates multiple layers of encryption – from secure boot protocols in the workstation to HTTPS transmission and configuration encryption in the camera. Detailed logs of data access and system interventions were maintained to ensure accountability and traceability. This dual approach not only safeguards individual privacy but also fortifies the system against potential cybersecurity threats.

4. Results

4.1. System Performance Under Optimal Conditions, referred by the producer/supplier

During periods of optimal lighting and minimal environmental disruption, the integrated system demonstrated outstanding performance:

- **Accuracy:** The system achieved a counting accuracy exceeding 95%, with deviations below 2% when compared to manual headcounts.
- **Processing Speed:** Real-time processing was achieved with negligible latency, thanks in part to the high-performance specifications of the CENTER337-V2 workstation.
- **Cybersecurity:** Encryption and secure transmission protocols operated as intended, ensuring that all transmitted data adhered to GDPR and EU data protection guidelines.

4.2. Impact of Adverse Conditions, referred by the producer/supplier

Under challenging environmental conditions, system performance exhibited measurable degradation:

- **Low Illumination:** The accuracy dropped to approximately 88% during low-light conditions, highlighting limitations even in advanced low-light imaging provided by the Dahua camera.

- **Environmental Interference:** artificial or geometric interference (e.g., smoke or physical obstructions) resulted in further reductions in accuracy, with error margins increasing to an average of 10–15% in densely populated areas.
- **Backup Activation:** In simulated hardware malfunctions, the redundant backup systems were activated within 3–5 seconds, preserving data continuity but causing a temporary accuracy reduction of around 5%.

4.3. Data Overestimation and System Calibration

Notably, overestimation errors were frequently observed in scenarios characterized by extreme crowd density and rapid movements. These inaccuracies were attributed to the misclassification of overlapping figures as multiple individuals. Continuous calibration, cross-referencing with alternative sensor data, and periodic manual validation were necessary to mitigate these errors. The feedback with the ground assessment at the end of the event evidenced that the value still produced on the control room, close to 6000 attenders, was overestimated with regard to a visual assessment from an expert judgment from public officers on duty.

4.4. Cybersecurity and Privacy Compliance

Throughout the event, the system's cybersecurity features – including encrypted video streams, secure boot, and access control protocols – proved effective in safeguarding sensitive data. No unauthorized access or data breaches were detected. However, the reliance on AI algorithms necessitates ongoing vigilance; any malfunctions or misconfigurations could potentially expose personal data, thereby violating GDPR and EU privacy regulations.

5. Discussion

The integration of advanced hardware components has markedly enhanced the operationa efficiency and reliability of people counting systems [1][2][4]. The network camera's advanced low-light imaging, robust environmental design, and built-in cybersecurity features collectively contribute to the system's resilience in adverse conditions. Despite that, a large steward number (more than 150) was necessary to the gates management and the area control. Furthermore, a team of twelve fire service personnel was in charge for the entire duration of the event. In fact, despite the high processing power and rapid image decoding capabilities of the workstation ensures that complex AI algorithms can be executed in real time, even during peak crowd conditions, the use of the system as a decisional support for civil servants requires a large contribution from operators for the safety control of the area for this specific use on open access shows.

5.1. Risks of Malfunctions and Their Implications [3][6][11][13][16]

Despite these technological advancements, several risks remain. Adverse environmental factors – such as poor lighting, flashing or strobe lights, smoke, and deliberate camera obstructions – can lead to significant data underestimations and counting errors. Such malfunctions are particularly concerning in high-density scenarios where even minor inaccuracies may result in misinformed decisions regarding public safety. The activation of backup systems, although effective in maintaining continuity, introduces a brief period of reduced

accuracy that could have critical implications during emergencies.
Furthermore, the potential for unauthorized manipulation of system controls by event organizers raises administrative concerns. Inadequate oversight or deliberate interference could allow crowd limits to be bypassed, posing serious risks to public order. These technical and administrative vulnerabilities necessitate rigorous control protocols, frequent system audits, and independent verification to ensure that the system remains both reliable and compliant with regulatory standards.
Moreover, the approval of these systems places the authorities having jurisdiction in the condition of depending on a system in fact controlled by the organization of the entertainment event. This aspect is considered by the author to be particularly problematic, and a potential source of public overfilling in the case of paid shows, where one wishes to maximize the profit from ticket sales, fraudulently exceeding the legal constraints and the requirements of the commissions having jurisdiction for the authorization to perform the show, according to the current Italian legislation.

5.2. Privacy Regulation and EU Data Protection [5][11]

In the current European regulatory climate, compliance with the EU's GDPR (Regulation (EU) 2016/679 of the European Parliament and of the Council of 27 April 2016) is non-negotiable. The integration of strong encryption, anonymization of facial data, and secure access protocols is essential to protect personal data. Also the data storage is a fundamental issue on the European policy on personal data protection. The Dahua camera's cybersecurity features – such as HTTPS transmission, firmware encryption, and secure authentication – play a pivotal role in ensuring that data handling practices meet EU standards. Nonetheless, the risk of malfunction – be it through software glitches or hardware failures – remains a critical concern. Any deviation from expected performance could inadvertently result in privacy breaches, especially if data streams become accessible to unauthorized parties. This underscores the importance of not only adhering to existing privacy regulations but also continuously updating system protocols to mitigate emerging cybersecurity threats.

5.3. Interdisciplinary Approach for Future Enhancements

The findings of this study advocate for a holistic, interdisciplinary approach to system design and operational management. On the technical side, future improvements should focus on enhancing the robustness of AI algorithms against environmental disruptions and refining calibration techniques to reduce counting errors [12][13][14][15][16]. On the administrative front, establishing an independent regulatory framework and mandatory certification processes for people counting systems will help prevent misuse and ensure compliance with public safety and privacy standards.
Collaboration between engineers, data scientists, and regulatory bodies is critical to achieving a balance between operational efficiency and stringent data protection. By integrating technical innovation with rigorous oversight, it is possible to develop systems that not only deliver precise, real-time crowd analytics but also uphold the highest standards of cybersecurity and privacy protection.

6. Conclusions

This case study has demonstrated that the integration of advanced hardware components significantly enhance the performance of people counting systems in large-capacity public events, providing a valuable support to civil servants. While high processing power and robust image analysis algorithms enable reliable operation under optimal conditions, challenges remain under adverse environmental conditions, where data overestimations and temporary malfunctions may occur. Moreover, the necessity to comply with GDPR and other EU data protection regulations requires that stringent cybersecurity measures be maintained at all times.

in this particular event, real-time awareness of the degree of filling of the area allowed for dynamic filtering of the entrances, admitting spectators up to the maximum admissible value, which in any case was not reached, thus allowing all those who wanted to attend the show.

Ultimately, ensuring system reliability demands a dual approach: technological innovation combined with rigorous administrative oversight. Future research should focus on further refining AI algorithms, integrating additional sensor modalities, and establishing independent certification processes to secure both operational performance and data privacy. In doing so, public safety can be maintained without compromising the privacy and rights of event participants.

Also, from precedent experience, a backup counting system should be present, because a system crash was previously experienced in a precedent event in Padua. Another concern is that this system and the others similar AI products, based on surveillance technology products, are under the control of the event organizer, and in the case of paid shows it could lead the organization to carry out controlled blackouts, aimed at increasing the number of tickets that can be sold, placing public officials in front of the dilemma of managing public order in the event of an interruption of the show by authority. So an human backup is a necessary measure to manage the event, even in presence of a critical crash of the automatic counter, and in the use for public shows those system don't are a way to implement a crowd control with a reduced number of operators, as they do in other application of mass surveillance, in which the resolution of the video cameras, even in low-light conditions, also allows facial identification. This kind of application, anyway, are associated to security and police uses.

It must also be reiterated that for use in monitoring crowds in areas where a public show takes place, a high number of operators at the entrances and inside the event area is essential, as well as a manual backup system, also based on a smartphone network app, in the event of a critical system crash.

The aspects of this technology with implications in terms of privacy and ethics of the invasiveness of the control of the state entity escape the purely technical purposes of this article. In particular, the use of high-resolution video surveillance systems based on AI algorithms would theoretically allow the monitoring of individual activities carried out by workers, may be also evaluating their job performance. However, Italian legislation prohibits this type of use. With the necessary guarantees regarding the above mentioned national and

UE regulations, nevertheless, the system could have uses in terms of occupational safety by providing an early warning in case of accidents, e.g. for lone workers.

References

[1] Doe, J., Smith, A., & Brown, L. (2018). Video Image Analysis for Crowd Monitoring in Large-Scale Events. *Journal of Safety and Security Technology, 12*, 145-162.

[2] Smith, A., Jones, M., & Williams, R. (2020). Artificial Intelligence Applications in Public Event Management. *International Journal of Crowd Science, 8*, 87-104.

[3] Brown, L., Patel, S., & Miller, P. (2017). Reliability and Redundancy in Automated People Counting Systems. *IEEE Transactions on Intelligent Transportation Systems, 18*, 2345-2353.

[4] Miller, P. (2019). The Impact of Environmental Factors on Image Analysis Systems. *Journal of Applied Computer Vision, 15*, 321-338.

[5] Rossi, M., & Bianchi, G. (2021). Regulatory Challenges in the Adoption of AI-Based Surveillance Systems. *European Journal of Public Administration, 19*, 56-73.

[6] Chidananda, K., Kumar, A.P.S. An Efficient Real Time Anomaly Detection in Surveillance Videos Using PRU-DPCN Classifier. *SN COMPUT. SCI.* 6, 31 (2025). https://doi.org/10.1007/s42979-024-03443-7

[7] Hossain, Mohammad & Cannons, Kevin & Jang, Daesik & Cuzzolin, Fabio & Xu, Zhan. (2021). Video-Based Crowd Counting Using a Multi-scale Optical Flow Pyramid Network. 10.1007/978-3-030-69541-5_1.

[8] R. Wang, Y. Hao, Y. Miao, L. Hu and M. Chen, "RT3C: Real-Time Crowd Counting in Multi-Scene Video Streams via Cloud-Edge-Device Collaboration," in *IEEE Transactions on Services Computing*, vol. 17, no. 4, pp. 1739-1752, July-Aug. 2024, doi: 10.1109/TSC.2024.3377156

[9] Li, B., Huang, H., Zhang, A. *et al.* Approaches on crowd counting and density estimation: a review. *Pattern Anal Applic* 24, 853–874 (2021). https://doi.org/10.1007/s10044-021-00959-z

[10] Sharif, M.H., Jiao, L. & Omlin, C.W. Deep crowd anomaly detection: state-of-the-art, challenges, and future research directions. *Artif Intell Rev* 58, 139 (2025). https://doi.org/10.1007/s10462-024-11092-8

[11] Rahul Kumar, S., Jayakrishnan, K., Ramesh, P., Krishnamurthy, V. (2025). Real-Time Anomaly Detection in Low-Light Environments for Enhanced Cybercrime Mitigation. In: Chawki, M., Abraham, A. (eds) Cybercrime Unveiled: Technologies for Analysing Legal Complexity. Studies in Computational Intelligence, vol 1181. Springer, Cham. https://doi.org/10.1007/978-3-031-80557-8_15

[12] Hossain, M.S., Sultana, S., Chakraborty, C. and Andersson, K., 2020. Video-based crowd counting using a multi-scale optical flow pyramid network. *Asian Conference on Computer Vision (ACCV)*. Available at: https://openaccess.thecvf.com/content/ACCV2020/papers/Hossain_Video-Based_Crowd_Counting_Using_a_Multiscale_Optical_Flow_Pyramid_Network_ACCV_2020_paper.pdf

[13] Sun, L., Li, Y., Luo, C., Wang, Y., Huang, L. and Chen, M., 2024. Robust anomaly detection in adverse surveillance conditions. *SN Computer Science*, 5(1), pp. 1-12. Available at: https://link.springer.com/article/10.1007/s42979-024-03443-7.

[14] Li, X., Zhang, J., Wang, Q., Lei, X. and Su, Y., 2021. Deep learning for crowd counting: A survey. *Pattern Analysis and Applications*, 24(3), pp. 1-20. Available at: https://link.springer.com/article/10.1007/s10044-021-00959-z

[15] Zhang, Y., Li, H., Lin, L., Huang, Y., Liu, H. and Zhang, T., 2024. Artificial intelligence for video surveillance: Challenges and future directions. *Artificial Intelligence Review*, 57(2), pp. 1-24. Available at: https://link.springer.com/article/10.1007/s10462-024-11092-8

[16] Ramesh, S., Gupta, P. and Sharma, R., 2024. Anomaly detection in low-light surveillance environments. In: *Advances in Computer Vision and Artificial Intelligence: Proceedings of ICVIP 2024*, Springer, Cham, pp. 255-270. Available at: https://link.springer.com/chapter/10.1007/978-3-031-80557-8_15

Safety Coordination of Clashing Activities with Total Float Allocation for the Covered Market of Forlì Case study

Marco Alvise Bragadin[*1] **and Benedetta Balzani**[1]
[1] Department of Architecture, University of Bologna, Bologna, Italy

* E-mail: marcoalvise.bragadin@unibo.it

Abstract. Construction Industry is a high hazard industry, therefore occupational health and safety investments can provide large benefits. The 92/57/EEC Directive on temporary or mobile construction sites aims at preventing safety risks by the implementation of the Health and Safety Plan (HSP). Construction Scheduling is a key component of the HSP, as indicates the sequence of construction activities and related safety provisions, including the installation of scaffoldings and other protective equipment. Organizational or system safety can be also tackled by the construction schedule as it can be used to detect and mitigate safety risks interactions among overlapping activities, i.e. time-space safety clashes between activities. Time-space overlapping activities can create new hazards for construction operations, as hazards can be transferred from an activity to another contemporary one, because of space overlapping or proximity. Critical Path Method and corresponding software applications, are most used tools to develop a construction project schedule and perform project control. As the project schedule is the basis for project control, construction schedules are also the basic tools for detecting safety organizational issues of construction activities. Time- space clashes can be avoided by activity sequencing and time shifts of overlapping activities. Therefore, they can be avoided by application of CPM network scheduling and Total Float usage. Total Float is the maximum admissible delay of a sub-critical activity without delaying project total duration. As known, critical activities do not have total float as any delay will be transferred to a delay in project completion. Delaying sub – critical activities to avoid time-space conflicts allows project manager of avoiding interference hazards without affecting project efficiency. The proposed approach was tested with the data of an actual case study, the renovation project of the Cover Market of Forli.

Keywords: Safety Management, Construction, Project Scheduling, Precedence Diagramming, Total Float

1. Introduction

Construction Industry contributes significantly to world economy, but is a high hazard industry, therefore occupational health and safety investments can provide large benefits.

Safety design indeed, should be part of project management of construction projects since the very first preliminary design stage. The 92/57/EEC Directive on temporary or mobile construction sites aims at preventing safety risks by improving project co-ordination between the various parties concerned at the project preparation and during the execution stage with the Health and Safety Plan (HSP). According to the EU directive, the HSP in Italy is a mandatory component of Detailed Design, together with the Construction Schedule. Construction Scheduling is a key component of the HSP, as indicates the sequence of construction activities and related safety provisions, including the installation of scaffoldings and other protective equipment.
Critical Path Method (CPM) is a powerful scheduling techniques, that is implemented in Precedence Diagramming Method (PDM) and its many computer applications. Precedence Diagramming is an activity network that creates a construction schedule indicating also a sub-set of critical activities that form the Critical Path that cannot be delayed without delaying the total project duration. Sub critical activities are the rest of network activities that do not belong to the Critical Path. Sub-critical activities can be delayed inside the Total Available Time window, as indicated by Total Float time.
Project Safety management has the task of implementing HSP strategies during the construction stage to ensure that construction operations will be performed following safety policies and with safety provisions to ensure that no accidents will occur thus preventing personal injuries and even fatalities. The Safety Specialist, or Health and Safety Co-ordinator as defined by the well-known 92/57/EU directive, should develop a safety-oriented project schedule, also evaluating the contractor's schedule, to assure that the provisions of the HSP are correctly implemented and planned in actual construction operations. Hazard protection indeed, can be delivered analysing safety constraints between activities and their logical dependencies. Time – space clashes detection between activities are of capital importance, as they can generate new hazards for working crews, or transfer an hazard from an activity to another. Time-space conflicts can be caused by errors in workflow management or congested spaces. In fact, some construction activities can have no technical interdependencies, but due to the proximity of work zones, or crowded workspace, or other safety issues, may cause risks to the crews [1].
Therefore, safety performance of construction projects depends on actual implementation of safety devices and procedures, but the relationship between project scheduling and safety performance is tight, as an improvement in scheduling generally result in an improvement in construction safety [2].
Many research works focused on the relationship between construction project scheduling and safety, as the project schedule has to address health and safety requirements of construction operations both in the preliminary design and detailed design. In addition to this, the contractor's schedule should adhere to the safety – oriented schedule requirements of both when planning and programming construction activities. The schedule model should demonstrate that the scheduled process creates a safe workflow of activities and crews thorough the project, and provides a safe working environment concerning time – space clashes of activities, workspace requirements, hazard protection and temporary facilities. The

research work under this paper has the aim of demonstrating the potential of total float allocation in terms of evaluating and improving safety of project operations with project scheduling with Precedence Diagramming.

2. Safety-oriented project scheduling

The 92/57/EU directive concerning temporary and mobiles construction sites requires Health and Safety plan for public and private construction projects that can include a safety oriented project schedule, as for instance it is requested in Italy by the Consolidated Act addressing Occupational Heath and Safety (D.lgs. 81/08). Suraj et al. [3] found that accidents in construction sites in the UK are mostly related to planning and control failures related to safety and production.

Veteto [2] indicated that safety performance is related to five project schedule -based factors: a) the use of computer-based planning and programming applications including activity networks and resource loaded-schedules; b) the frequency in updating the project schedules; c) the frequent holding of co-ordination meetings to maintain good communication with subcontractors; d) the holding of coordination meetings with subcontractors before the commencement of construction; e) maintaining the project on-schedule.

Saurin, Formoso and Guimares [4] presented a safety-oriented implementation of the Last Planner system by Ballard [5]. There are three hierarchical levels of the construction planning and control process, safety-based: long-term planning, look-ahead planning and short-term planning. Long-term safety plans should be improved with hazard description and should be systematically updated.

Daewood and Mallasi [6] observed that lack of schedule workflow planning may disrupt construction operations, especially if the pace of construction processess (i.e. the takt time) is not addressed, and they proposed to model and quantify workspace congestion.

The most effective approach to workspace management and modelling suggested by researchers and practictioners is a project schedule made by flowlines, or linear planning, integrated with an activity network [7] [8].

Sulankivi, Kahkonen, Makela and Kiviniemi [9] explored 4D BIM for construction safety planning, that can result in improved safety management performance because of the connection between safety planning and site layouts. Later Alaloul et alii [10] found that construction industry stakeholders believe that BIM in Malaysian construction projects can improve health and safety and reduce accidents rate.

Bragadin and Kahkonen [11] addressed the schedule quality problem in construction focusing on space requirements concerning safety management. The application of the well-known 3 “S” rule of thumb for construction scheduling, meaning safety, space and structure is believed to be fully implemented when displaying the flow-line view of the activity network.

Zhang, Teizer, Pradhananga and Eastman [12] highlighted construction safety and productivity problems due to congested site conditions, and proposed a method for automated visualization of workspace with BIM. Workspace modelling is based on five workspace sets and a conflict taxonomy.

Tao, Wu, Hu and Xu [13], observed that PDM forward scheduling can generate workspace interference and safety problems., therefore they proposed a genetic algorithm to develop safer construction scenarios. For modeling convenience a workspace interference matrix is also proposed.
Zarghami [14], while addressing the prioritization of construction activities of a CPM – based schedule, observed that total float of sub-critical activities is crucial, but it needs to be connected to the total network topological organization.
Akinci, Fisher, Levitt and Carlson [15] investigated the time-space conflicts of construction projects, and detected six types of spaces required by construction activities: a) building component; b) labor crew; c) equipment; d) hazard; e) protected; f) temporary structure. Each construction activity requires at least one of these spaces, and if they have time overlaps time-space clashes may happen. The problem is how to load these space requirements to a construction schedule in a quick and easy way, without creating a BIM model or a flowline chart, and then use total float of subcritical activities to mitigate time-space clashes.

3. Time – Space clash mitigation with total float allocation: the case study of the Cover Market of Forlì (Italy)

3.1. Time – space clashes and safety hazards of construction activities

Construction project safety management has the objective of mitigating hazard for construction workers during construction operations. Common hazards in construction activities can be categorized in many ways. Hazard classification can be connected with energy sources as gravity, mechanical, thermal, electrical, chemical, biological and physical [16]. Typical hazards of construction projects are the followings [17]: a) hazards that may cause occupational accidents; b) hazards that may cause occupational illness. The most frequent accident hazards are the following:

- falls from height;
- caught in / caught between;
- cave in;
- electrocution;
- slips, trips, falls
- fire / explosion;
- struck by.

The most frequent occupational illness hazards are:

- respiratory diseases from inhaling dust, asbestos, fumes, atmospheric contaminants;
- back injuries and musculoskeletal disorders from material and manual handling;
- hand-arm vibration syndrome;
- hearing losses, noise;
- skin diseases from manipulation of dangerous materials.

Time – space conflicts may create interference hazards. Interferences are hazards that are created by a construction activity and can be transferred to other contemporary and nearby activities. In the proposed method, three types of conflicts are identified for the safety evaluation of a project schedule:

- Time / space clashes due to activities' time-space overlapping and consequent contemporary space usage that creates a congested space due to crowded labor space. The increase of labor density can lead to safety hazards and productivity loss.
- Safety hazards due to hazard transfer by an activity to other nearby activities.
- Time / space clashes due to labor crew spaces, equipment space, temporary structure space, hazard space and protected space required by an activity that conflicts with a space of another nearby activity.

The main tool suggested for time – space conflict resolution is the Precedence Diagramming Method, and Total float of sub-critical activities, integrated with a Location Breakdown Structure [7]. The detection of time / space conflicts of a construction schedule can be facilitated plotting workspaces on a interference matrix. The use of Total Float is aimed at preventing time delays of the project completion.

3.2. Case Study: the Covered Market of Forlì renovation project

The Covered Market of Forlì is an historic building dating back to the eighteenth century in the northern part of Italy. The building has two symmetric wings, with an H shape plan, each of two floors, which flank the former Annonarius Forum. Since 1924, a high school has been located in the northern wing of the building (Figure 1).
The actual functions of the Covered Market building are divided as follows:

- ground floor square side: shops, bars and small restaurants overlooking the square;
- ground floor exedra side: at the back there is a semicircular exedra supported by columns that houses the fish market;
- first floor: construction site.

At the first floor there is the planned and actual construction site of the Covered Market. This is a renovation project that aims at the transformation of the former high school premises into municipality offices. The renovation project activities and their locations can be acknowledged by the detailed renovation project plans that portrays the Location Breakdown Structure (LBS) (Fig. 2a and 2b). From the point of view of hazard interference, the main problem is the contemporaneity between the renovation project at the first floor of the building and the existing food market shops at the ground floor, that need to operate during the construction project. This situation constitutes a large interference problem as construction operations are on the top of commercial premises, the shops that are open to the public. In addition to this, in some cases the time-space conflict is at the highest level, because construction operations need to be performed even in the same spaces of commercial activities. Because of this, construction operations have been planned to be the least invasive as possible for the open market and its users. Despite this, sometimes it was needed to request the interruption of market activities, closing the market to the public for safety reasons, for the time of development of the most dangerous operations, such as demolitions.

Figure 1. Covered Market of Forlì (Google Earth®).

Figure 2a (left), **2b** (right). Location Breakdown Structure of the Covered Market Renovation Project, Fig. 2a (left) Ground floor. Fig. 2b (right) First floor.

3.3. Proposed approach

The proposed approach is aimed at detecting time-space clashes of construction activities and proceeding to clash resolution for safety management purposes. The proposed approach can be performed in the following eight steps.

1. Context and activity analysis
2. LBS – Location Breakdown Structure
3. WBS – Work Breakdown Structure
4. Estimate of activity duration
5. PDM network plotted with locations
6. Interference matrix
7. Identification of time – space clashes of interfering activities
8. Optimization with total float

Step 1: Context analysis and activity analysis
In this initial step, the specific characteristics of the project site are analyzed, with the aim of identifying potential risks and interferences due to the external environment that could compromise the achievement of the set objectives. In parallel to this, an activity list is defined.

Step 2: LBS – Location Breakdown Structure (LBS)
The Location Breakdown Structure for the considered construction phase is developed. Note that since in different phases different types of working operations can be performed, the LBS can change. LBS is therefore phase specific. This breakdown facilitates the recognition of the construction process zones and of the job site layout, the path of trades and, above all, the work flow passing through locations.
The LBS provides not only a map of the workspace, but allows to assess the impact of each individual activity on the surrounding area. It also allows to identify possible hazard transfer, and interferences or overlaps between different activities. Therefore, LBS codes are assigned to recognize the areas. In this case, the ground floor (0) of the Covered Market (MC) is divided into areas B, C and E, while the first floor (1) is divided into areas A, C, D, E and B which is in turn divided into two subunits (fig. 2a and 2b). The LBS is can be presented also as an outline table (fig.3).

PROGETTO	PIANO	AREA	UNITÀ	CODICE
MERCATO COPERTO - MC	PIANO TERRA (0)	Area B	-	***MC.0.B***
		Area C	-	***MC.0.C***
		Area E	-	***MC.0.E***
	PIANO PRIMO (1)	Area A	-	***MC.1.A***
		Area B	1	***MC.1.B.1***
			2	***MC.1.B.2***
		Area C	-	***MC.1.C***
		Area D	-	***MC.1.D***
		Area E	-	***MC.1.E***

Figure 3. LBS of the renovation project of the Covered Market of Forlì.

Step 3: WBS – Work Breakdown Structure

Depending on the activity list to be carried out and the LBS, a Work Breakdown Structure is created. The Work Breakdown Structure (WBS) is a fundamental tool in the management of complex projects that organizes hierarchically all project activities and Work Packages (WP), allocating tasks to specific locations. The WBS ensures a clear and detailed view of each individual task, facilitating the allocation of resources and the definition of timelines.

Step 4: Estimate of activity duration

The estimate of activity duration is performed with an indirect method, thus through computation of the effort in labor days of each activity. Effort data can be extracted from WP cost analysis. As a first estimate, each crew was consisting of 3 laborers.

Step 5: PDM network plotted with locations

A PDM network was created plotting also location of activities. This allows the planner to better detect the complex relationships between activities, their spatial location and the use of resources. Therefore, the PDM network was structured in such a way that each row was corresponding to a specific LBS zone of the project, thus providing a clear and immediate representation of the distribution of activities in space. Inside the network, first the technological links between the activities were defined, i.e. the dependency relationships that regulate the sequence of execution. Then, the resource allocation was performed, i.e. the work crews were assigned to activities and their movement between workspaces was defined. In Figure 4, PDM tasks are the network nodes and the logical relationships are identified with arrows (Figure 4 and Figure 5).

Step 6: Interference matrix

An interference matrix is created to detect the spatial relationships between the different project locations and to identify the zones where time-space conflicts could occur. The matrix has a double-entry table in which both rows and columns represent the project locations, cells. Possible interferences are established between locations, selecting one of the following three possible proximity relationship (Figure 6):

- adjacent, without possibility of interference (yellow);
- adjacent, with the possibility of interference (orange);
- they are not adjacent (green).

Step 7: Identification of time – space clashes of interfering activities

This step is the one that focuses on identifying time-space clashes. In this case the PDM network is created again with MS Project software. In this way it is possible to take advantage of the MS project automatic creation of both activity network and Gantt Chart, a fundamental tool for viewing and analyzing time scheduling of project activities. Therefore, with the analysis of the Gantt chart, of the space and resource loaded network and the clash matrix, it is possible to determine the activities that take place at the same time and in the same place or in contiguous areas, i.e. all those that present a risk of interference due to time-space conflict (Fig. 4, Fig. 5, Fig. 6 and 7a). Simultaneous operations and operations carried out in areas with potential interference are identified with a specific alphanumeric *i-x* code. An over allocation of some construction phases is detected, because of lack of available human resources, as the limit number of personnel is of 15 units, and the construction site storage area is very small. This type of criticality is identified with the *s-x* code.

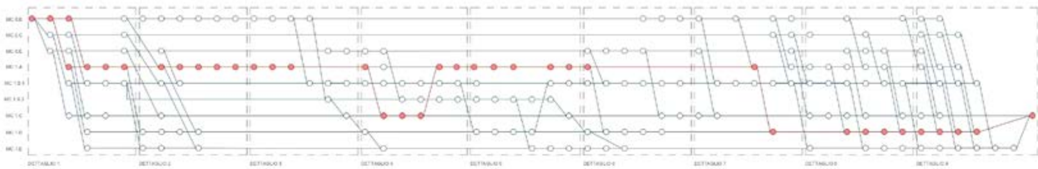


Figure 4. PDM network of the renovation project of the Covered Market of Forli.

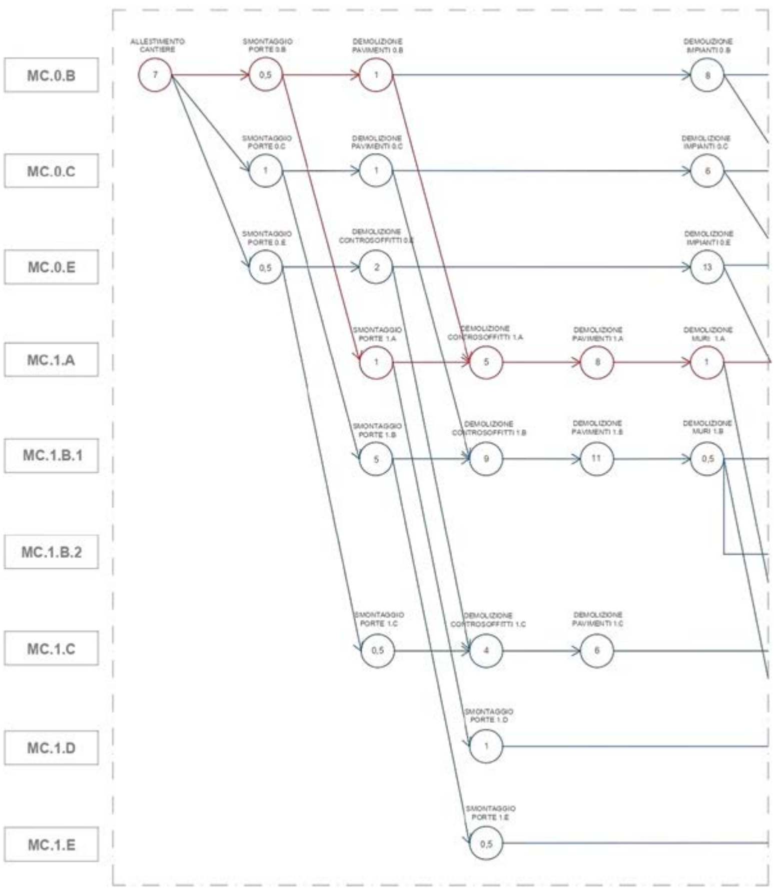


Figure 5. Excerpt of the detailed PDM network of the renovation project of the Covered Market of Forli.

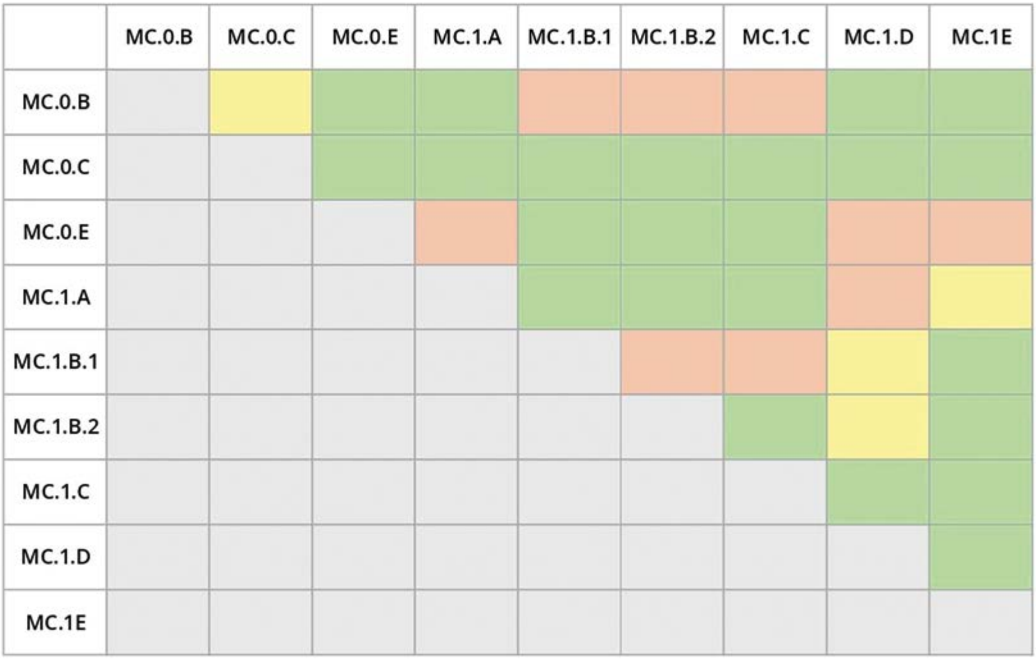


Figure 6. Activity interference matrix of the renovation project of the Covered Market of Forli.

Step 8: Optimization with total float

The last step of the method is the one that leads to the optimization of the production process. To achieve this goal, the automatic calculation of the Total Float of MS Project was used. Total Float of an activity is defined as the possible time delay of an activity without delaying project completion. The Total Float (TF) can be found subtracting Early Start ES (or Early Finish EF) from Late Start LS (or Late Finish LF), that is, for each activity J:

$$TF\ j = LFj - EFj = LSj - ESj$$

Zero Total Float defines critical activities and critical path; that are all those activities that, if delayed lead to a same delay in the overall duration of the works. Target Start and Finish are the postponed time allocation of interfering activities that avoids time-space clashes, and can be set only for sub-critical activities. The Target Start of interfering activities can be set by adding manually a lag time in the preceding Finish-To-Start logic link. This procedure can be applied iteratively, activity by activity by going through the entire project network (Figure 7a and Figure 7b). When possible, the time delay of activities is kept inside the TF, thus limiting as much as possible a major delay of the project completion.

4. Discussion and conclusions

The proposed approach applied to the Covered Market of Forli case study has proved to be an effective and reliable tool for time-space clash detection of interfering activities, thus al-

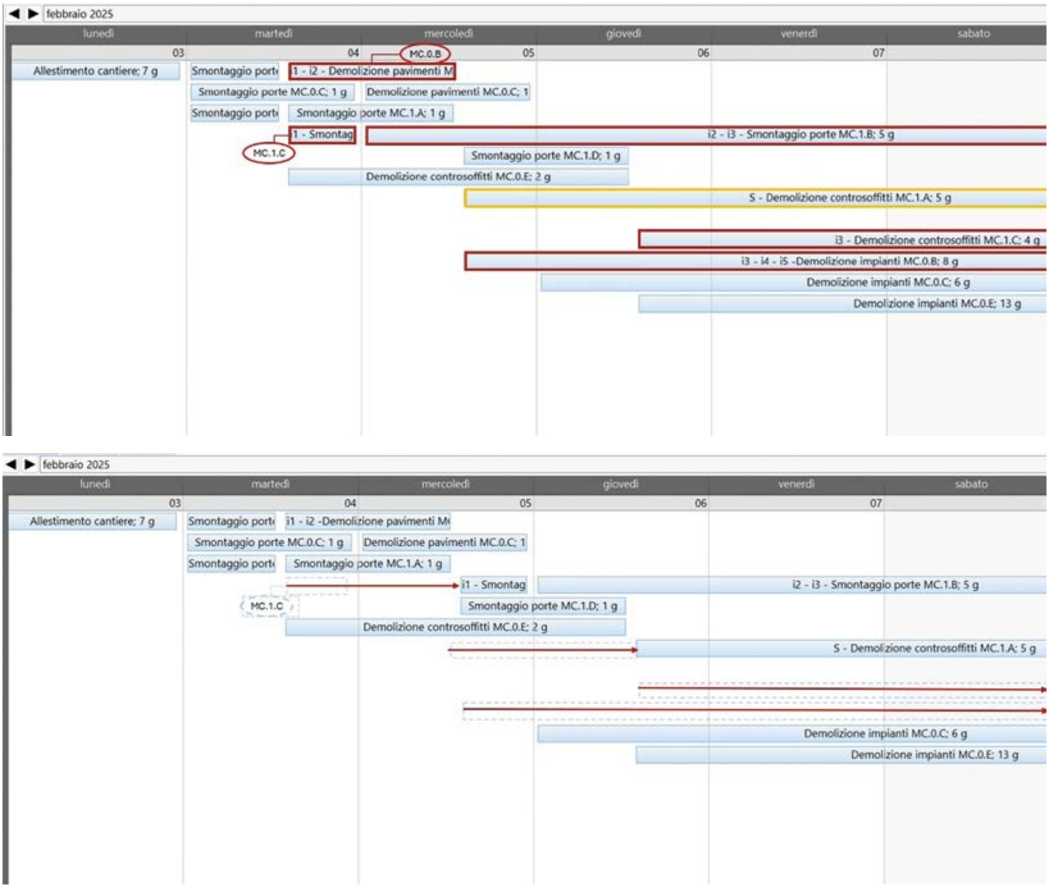


Figure 7a (top), **7b** (down). **7a** Identification of time – space clashes; **7b** Optimization with total float.

lowing safety specialists to mitigate interference hazards without delaying the project completion. Its main strength lies in its ability to provide global control over the entire project, allowing a clear and detailed overview, but also a specific and timely analysis of each individual operation. The adopted manual approach, while time consuming especially in the very first steps, proved to be crucial for its ability to adapt to the specificities of the project. Unlike an automated system, human based schedule management allows to carefully evaluate each activity and the context in which it takes place, considering the peculiarities of the workplace and the potential interactions. Therefore, this method allows for active monitoring and control actions, ensuring that each phase is carefully supervised and that any critical issues are immediately identified and addressed. The solution of time-space conflicts by delaying activities creates a final delay in the project completion date, or an increase in the project total duration. This depends on shifting activities to avoid clashes. A strength point of the proposed project method is limiting the final delay because of massive usage of Total Float.

However, it must be recognized that the method also has some limitations. Applying it in

highly complex projects could be time-consuming and resource-intensive, as each change requires manual updating and an assessment of the impact on all other tasks. Anyway; while the initial planning phase can be more time consuming, the output is a clear and detailed project schedule, portraying a complete and up-to-date view of project's progress during execution, with a limit in the unavoidable delay of project completion.
In summary, the proposed approach has made possible to combine safety and efficiency on site, reducing risks for workers, time-space conflicts, optimizing resources, avoiding waiting times and meeting deadlines. The concrete benefits for the construction site outweigh the initial challenges.

References

[1] Project Management Institute PMI (2007). Construction Extension to A Guide to the Project Management Body of Knowledge. Project Management Institute, Inc. USA.

[2] Veteto, C. E. (1994). The relationship beteween planning and safety. Cost Engineering, Apr. 1994, vol. 36, No. 4, pages 23-26.

[3] Suraji A., Duff R., Peckitt S., 2001. Development of casual model of construction accident causation. Journal of Construction Engineering and Management, 127 (4), 337-44

[4] Saurin T.A., Formoso C.T. Guimaraes L.B.M., 2004. Safety and production: an integrated planning and control model. Construction Management and Economics vol. 22, issue 2, pages 159-169.

[5] Ballard G. (2000). The Last Planner System of Production Control. PhD thesis, School of Civil Engineering, University of Birmingham.

[6] Dawood N., Mallasi Z. (2006) "Construction Workspace Planning: Assignment and Analysis Utilizing 4D Visualization Technologies", Computer-Aided Civil and Infrastructure Engineering vol. 21, 498-513.

[7] Kenley R., Seppänen O. (2010) Location-Based Management for Construction: planning, scheduling and control, Routledge, U.K., Spon Press, U.K.

[8] Russell A., Tran N., Staub-French S. (2014) "Searching for value: construction strategy exploration and linear planning", Construction Management and Economics, vol. 32, issue 6, pages 519-546.

[9] Sulankivi, K, Kähkönen K., Mäkelä, T. Kiviniemi, M. (2010). 4D-BIM for Construction Safety Planning. Proceedings of W099-special track 18th CIB world building congress, 2010.

[10] Alaloul,W.S.; Qureshi, A.H.; En, Y.P.; Khan, S.A.; Musarat, M.A.; Alzubi, K.M.; Salaheen, M.A. (2023) Survey Evaluation of Building Information Modelling (BIM) for Health and Safety in Building Construction Projects in Malaysia. Sustainability 2023, 15, 4899

[11] Bragadin, M. A., & Kähkönen, K. (2015). Safety, space and structure quality requirements in construction scheduling. *Procedia Economics and Finance*, *21*, 407–414

[12] Zhang S. Teizer, J., Pradhananga N., Eastman C.M. (2015) "Workforce location tracking to model, visualize and analyze workspace requirements in building information models for construction safety planning", Automation in Construction, 60 (2015) 74-86.

[13] Tao S., Wu C., Hu S. and Xu F. (2023) Construction project scheduling under workspace interference *Comput Aided Civ Inf.* 2020;35:923–946.

[14] Zarghami S. A. (2022) Prioritizing Construction Activities: Addressing the Flaws of Schedule-Based Indexes. Journal of Construction Engineering and Management, 2022, 148(8): 04022069.

[15] Akinci B., Fischer M., Levitt R., Carlson R. (2002). Formalization and Automation of time-space conflict analysis, Journal of Computing in Civil Engineering, 16 (2) pages 124-134. ASCE USA.

[16] Siddika A., Lu M. (2023) Project Schedule Acceleration Optimization Integrated with Energy Source–Based Assessment of Occupational Health and Safety Risks. J. Constr. Eng. Manage., 2023, 149(12): 04023120

[17] Dias, L. A. (2009). Inspecting Occupational Safety and Health in the Construction Industry. International Training Centre of the International Labour Organization (ILO), Tourin, Italy

Risk Assessment, Human Variability and the Possible New Frontiers of Artificial Intelligence

Rita Somma
Department of Neuroscience, University of Padua, Italy

E-mail: rita.somma@unipd.it

Abstract. The contribution starts from the consideration that the assessment of risks to the health and safety of workers present within an organisation where they perform their activities, aimed at identifying the appropriate prevention and protection measures, is necessarily an instrumental operation of calculating the risk generally based on a modelling of homogeneous groups (classified as such by tasks, activities, types of risk exposure, etc.). Therefore, it must be borne in mind that the result should be read as a first approximation of a much more complex reality. Indeed, those homogeneous groups are composed of a heterogeneity of workers with distinctive physical, cognitive and psycho-social characteristics. The variability inherent in human beings also has an inescapable impact on exposure and the level of risk assessed and, thus, cannot be disregarded but must be reintroduced into the application phase by looking at the actual beneficiaries of the preventive action.
Hence, there is a need for an operational proposal that can take advantage of the new frontiers opened by using Artificial Intelligence to reintroduce those variants given for constants on the "human factor" issue. A guiding approach that could direct towards a substantial health and safety protection and help overcome the flattening processes produced by the current safety management system, putting the real person back at the centre.

Keywords: Artificial Intelligence, Risk assessment, Human factor, Human variability, Adaptability

1. Premise

Workers are not always exposed to the same level of risk to their health and safety; some specific groups of workers may be exposed to greater risks (or subject to special requirements). This is crystallised, in black and white, in the EU Framework Directive 89/391/EEC and Legislative Decree 9 April 2008, no. 81, Consolidation Act on the protection of health and safety in the workplace (G.U. no. 101 of 30 April 2008, as amended). In fact, both regulations explicitly provide that to guarantee uniformity of preventive protection in the workplace, when assessing risks and defining protective measures, employers must consider the presence of groups of workers exposed to particular risks, such as those related to gender differences, age, origins from other countries and those related to the specific type of contract through which the work is performed (Articles 1 and 28 of Legislative Decree 81/08). The legislator's direction seems particularly clear: to achieve the same result in the essential level of the right to occupational health and safety protection, it is necessary to consider the different initial exposure conditions, looking not only at absolute risk concepts but also at the variables relating to specific characteristics of the beneficiaries of the preventive action, the actual population of workers present within the organisation, in synergy with each other.

However, this remains an aspect of the legislative provision that, even being conceptually relevant, too often lacks the attention it deserves, if not forgotten, flattened by the need for probabilistic calculability of the risk, which often requires eliminating that entropy, as well as by the need to necessarily move towards the risk assessment that consider generalising "Homogeneous groups of workers" subdivided by tasks, activities, exposure risks, etc.

This is all well and good, but one must be fully aware of the fact that the result of such risk assessment should be read as a first approximation of a much more complex reality. Indeed, those homogeneous groups, are composed of a heterogeneity of categories of workers with distinctive physical, cognitive and psycho-social characteristics. The variability inherent in human beings also has an inescapable impact on exposure and the level of risk assessed and, thus, cannot be disregarded but must be reintroduced into the application phase by looking at the actual beneficiaries of the preventive action.

Courageously raising the bar, the picture that considers human variability in the construction of a prevention framework becomes even more complex if we bypass the categorising framework, broadening the horizons, to look at the individual (the worker) beyond the categorisation into defined categories to touch upon the capacities and limitations characterising each individual. Moreover, it is almost pleonastic to say it, but beyond that, there are other differences which may impact on the initial conditions and, hence, on the exposure to risk, such as cultural, language, social, psychic, anthropometric, biomechanical, educational, power, generational, economic, lifestyle, family context differences, all of those to be considered in an evolutionary perspective over time, even intra-individual in relation to ageing processes.

And it is precisely this variability inherent in the human being, in the worker, that is the specificity, which, all too often, seems to be absent from the construction of prevention practices. In fact, the preferred preventive modelling stops at the stereotyped image of a "standard worker", generally reproduced as a middle-aged male, of average build, psycho-physically fit, native speaker, who yet represents only a very low percentile of the variety of the working population[1]. However, real people present that extreme variability highlighted above, which impacts the level of risk and affects their safe behaviour, which cannot be disregarded for effective and substantial protection.

The accounting calculation of risk, which unites physics, engineering and social sciences,

---

1 https://aifos.org/home/news/int/nostre_attivita/diversity-e-valutazione-dei-rischi

precisely because it can be applied to disparate phenomena: from smoke to nuclear energy, road accidents or monetary investment, i.e. the risk which claims to be rational but cannot be the one (Beck, 1992), as it is an essential assumption from which to start, but cannot therefore be considered as the point of arrival.

The preventive approach cannot be neutral, but must be attentive to subjectivity, in an inclusive mindset (ed. of the person), which requires preserving the awareness that the impersonal abstraction of the risk assessment is an instrumental operation. Accordingly, in the application phase, it is essential to introduce into the system the variables that have been taken for constants, forcing us to think about the protection of the real person including all its facets. If this does not occur, the result either does not solve the problem or the problem was not the one that had been faced initially, with human variability, almost inevitably, tending to turn into inequalities, i.e. into advantages and disadvantages for the people and groups that bear these differences.

Nevertheless, the approach of homogenising standardisation in the risk assessment and definition of protective measures, sometimes being distant from the actuality of the contexts on the ground, appears difficult to overcome, given the implementation difficulties due to the lack of tools, as well as standardised and shared methodologies.

In the same way, there are still some difficulties of assessment related to the need to further investigate the variability of certain risks for certain categories, leaving de facto expositional uncertainty, despite the awareness of diversity. Let us think, for example, of the new knowledge brought about by the studies of Gender Medicine[2], which have highlighted precisely how the determinants of sex and gender differences are not only linked to physical strength or reproduction, but involve a wide range of aspects, such as genetic, epigenetic, hormonal, environmental and behavioural ones, constituting a complex of biological and socio-cultural factors that can affect the level of risk, regardless of the degree of exposure, which may be the same for males and females.

From these considerations, let me start my analysis proposal, trying to solicit some reflections, as well as an operational proposal that can make use of new frontiers by exploiting the potential of Artificial Intelligence, to overcome flattening processes produced by the current safety management system.

In this perspective, I believe it is necessary to critically search for other concrete possibilities, to make an epistemological leap to introduce new cognitive parameters in the management of occupational health and safety, which also consider other factors in order to build coherent images, as well as concrete and feasible alternatives.

2. The human factor in occupational health and safety protection

Looking into the Human Factor means approaching the issue of safety and health in an integrated manner, necessarily focusing on the adequacy of the human resources and work

---

[2] [1] Gender medicine (MoG) introduces the concept of gender in medicine into healthcare (Law 3/2018). Gender medicine is not the women's medicine, but it is the study of the influence of biological (defined by sex) and socio-economic and cultural (defined by gender) differences on each person's state of health and illness.

organisation in relation to the tasks assigned but also, as well as analysing the social dimension[3] ('man-context-situated variable of action').
Therefore, the aspects to be included in the risk assessment are as follows: the task nature, task preparation, workload, procedures, verification and control tools and methods, the environment, organisational structure, leadership, policies, communication methods, shared values, etc.
In this contribution, we will focus on the aspect related to the characteristics, capabilities and psycho-physical limitations of the human element that impact on risk, which includes:

- the PHYSICAL HUMAN FACTOR (person-work-appearance),
- the COGNITIVE HUMAN FACTOR (person-work-cognitive system, including the emotional sphere).

On this last point, new frontiers have recently been opened by neuroscience studies that have shown how, at the human level, certain mental mechanisms, inherent in cognitive functioning (bias, attention, heuristics, memory, frames, scripts, etc.), often unconsciously, trigger the chain of events that can lead to an accident, influence decisions and cause behavioural errors that must be prevented. Disregarding human limitations lends itself to accidents/incidents. Thus, individual errors hide conditions of latent organisational errors, which have taken these aspects into account[4].
In the aviation sector, perhaps being the most interesting error-free one in the world, human factor professionals work alongside the technicians to support them on the people and task organisation aspects, outlining an approach to the prevention system as a "jigsaw puzzle to build", where each single specialist piece becomes essential to construct the whole and, with the image represented in the box of all the pieces of the game at hand.

2.1. The human variability

However, the concept of Human Factor is broader and more complex, since every person is different from another: it is the result of a certain form of resonance, which must consider the individual, in his or her psycho-physical variability, skills, technical and non-technical abilities, personal experience, culture, motivations, etc.
In fact, very human resource is different from another in terms of sex and gender, age, weight, pre-existence of diseases, physiological and anthropometric characteristics, strength, mobility, etc., but also in the personality or cognitive characteristics, as well as considering their evolution (e.g. the physiological ageing of each worker) (see Figure 1).
In fact, people can show extreme variability, and some systems must also be used by individuals who are at the age extremes of the population (very young people, workers over 60), who show high variability in relation to both growth and ageing processes.

---

[3] Somma R. Servadio M. "The Social Dimension, A Cornerstone of ISO 45001". An in-depth study published in the magazine 'Soluzioni tecniche per la sicurezza' (Technical solutions for safety), semi-annual attachment 2/2022 'ISL – Igiene & Sicurezza del Lavoro' by IPSOA – Wolters Kluver Italia.

[4] As revealed by the information campaign Learn About Errors by ATS Monza Brianza.

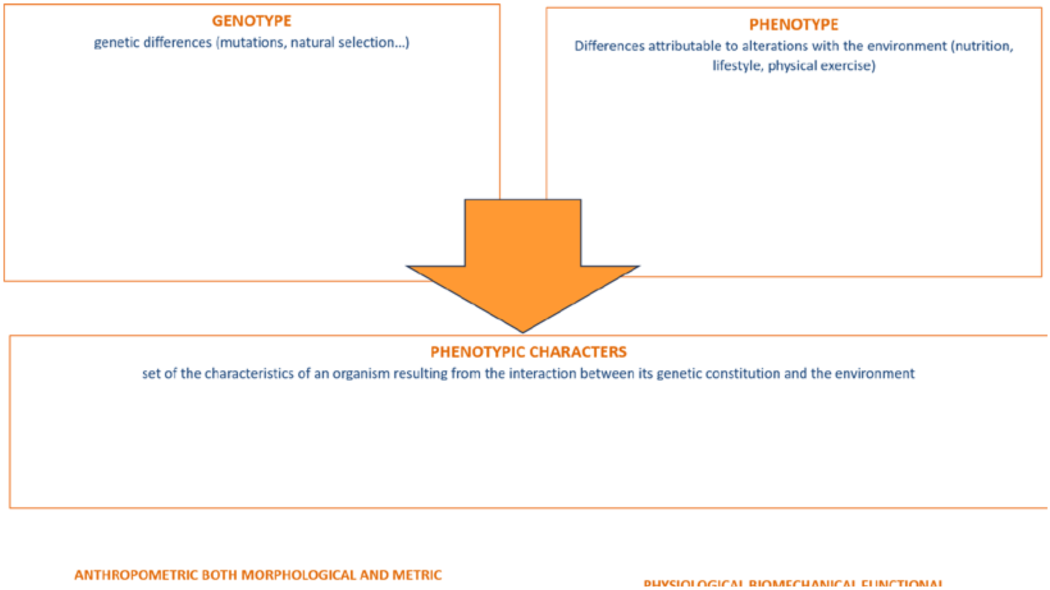


Figure 1. Relationship between genotype, phenotype, and phenotypic characters.

This inclusive dimension includes:
- Intra-individual variability – same individual at different stages (it covers all dimensional, sensory, cognitive and behavioural changes that impact on the level of risk individuals undergo in relation to age during the various stages of life). This includes slow but also temporary and transient changes (nutrition, age, medical treatment, physical activities, asymmetries, occupation, movement, clothing, posture, breathing).
- Inter-individual variability – between groups (it concerns differences between individuals, in relation to large geographical and ethnic groups, and differences between the sexes and genders, which may include differences in psycho-physical traits, but also social differences).
- Secular variability (secular trend) – between generations (concerns differences in lifestyle, environment, stature[5], weight[6], between different generations).
  It has been observed that, particularly in the last decade, there has been a progressive increase in stature and weight in the most developed countries.

Therefore, variability and diversity require going beyond standards (see Figure 2). The standardisation of tasks, in the context of risk assessment of those tasks, is to be considered correct, but we must be aware that when we say "the person is" we are leaving other equally important aspects out of the analysis. Reducing the complexity of the human being to standard models is almost impossible. And the ineffectiveness of prevention measures is often caused by the lack of attribution of this qualification of "the system component" to subjec-

[5] From what is going on now, it can be assumed that we can generalise a secular process of the stature increase of about 10 mm per decade.

[6] For the weight, the increase is about 2 kg per decade.

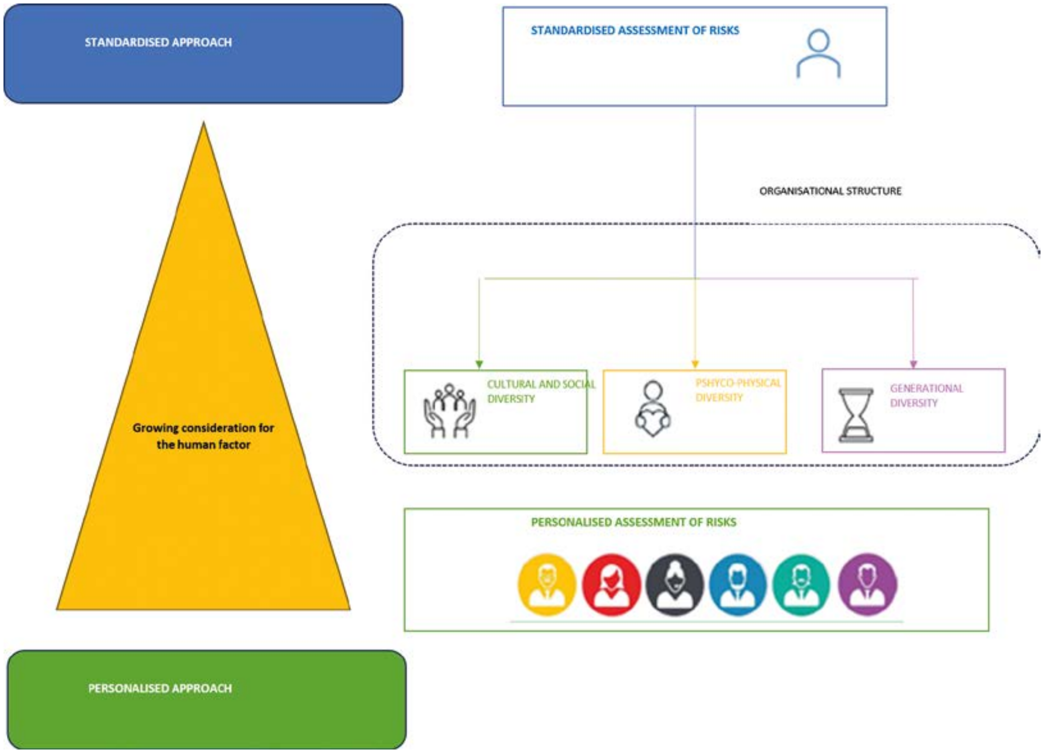


Figure 2. The evolution from a standardized to a personalized approach in risk assessment, emphasizing the growing consideration of human factors.

tive risk factors, which instead requires an increasingly "tailor-made" assessment, i.e. without pre-packaged solutions.

In this perspective, not all tasks can be fulfilled by workers automatically. The preventive structure of an OSH system must ineluctably be tailor-made. Recalling the theatrical metaphor of the American sociologist Goffman, the safety planner cannot enter the scene with a pre-printed script but must interpret it according to the actors and the story to be played, letting himself be contaminated by the setting (the palimpsest is everything, including the specific population of workers). Of course, to do so, one must have the competence and a mental attitude consistent with the epistemological paradigm of reference. Common sense is not enough.
Moreover, a preventive interpretation that follows the ratio of the EU framework directive 89/391/EEC, as well as Article 28 of Legislative Decree 81/08. In fact, both regulations expressly provide that, in order to ensure uniformity of protection in the workplace, in assessing risks and defining protection measures, employers must consider the presence of groups of workers exposed to particular risks, such as those related to gender differences, age, origins from other countries and those related to the specific type of contract through which the work is performed.

In this perspective, risk assessment must be inclusive of the person, by which we do not mean that an ad personam risk assessment must be carried out, but that human variability and diversity must be visualised and emphasised, be it social, cultural or psycho-physical, which impacts on interaction and hence on risk exposure. And taking precisely the human variable as a factor of analysis, risk prevention appears to be one of the most difficult and complex problems to tackle, due to the multiplicity of aspects it involves, but we must not fall into the theoretical evanescence that may ensue.

2.2. Ergonomics or Human Factor science

The concepts such as those just outlined are advanced by Ergonomics (or Human Factor Science[7]), which is the scientific discipline concerned with understanding the interactions between human beings, other elements of a system and the profession that applies theory, principles, data and methods to design and optimise human well-being and overall system performance (definition given by the International Ergonomics Association).
In a nutshell, the principle of ergonomics is to adapt work to the psycho-physiological nature of the individual, as opposed to Taylorism, which aimed to adapt the person to the characteristics of machines. The historical context can give us a clear idea of how conceptually "revolutionary" the paradigm shift brought about by ergonomic science was, that of finding optimal solutions suited to the man's psycho-physiological capabilities and limitations.
Over the time, the subject of Ergonomics has expanded with three specific but complementary fields of study:

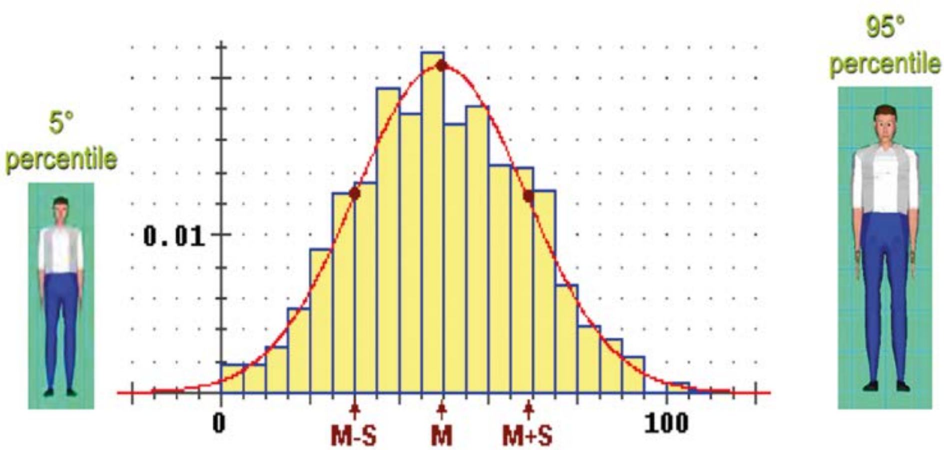


Figure 3. Normal distribution curve illustrating height variation in a population, with 5th and 95th percentile representations. The graph shows the mean (M) and standard deviations (S), demonstrating the range of human height from shorter individuals at the 5th percentile to taller ones at the 95th percentile.emphasizing the growing consideration of human factors.

7 The two terms are essentially synonyms.

Physical ergonomics (human anatomy, anthropometry, physiology and biomechanics[8] and how they relate to physical activity).
Cognitive ergonomics (mental processes such as perception, memory, reasoning and motor response – but also emotional – and how they influence interactions between humans and other elements of the system).[9]
Social and organisational ergonomics (optimisation of socio-technical systems, including organisational structures, rules and processes).[10]
The primary objective of the "HUMAN FACTOR" approach is to improve the level of reliability of the operator and more generally of the system within which the individual worker operates, considering the complexity of all the elements with which he or she must interface. This translates into design, training, policies or procedures to support workers.
Human factors are concerned with what people are asked to do:
The task and its characteristics – Is it a sustainable (psycho-physical) task?
The individual – Is the person in charge competent and does he/she have the personal characteristics to do it?
The organisation – Where are they working?
The study of human factors is about human performance and understanding behaviour. It starts from the consideration that the human element is fundamental to enable safe work operations.
Basic principles:

1. Performance is influenced by the psycho-physical capabilities and limitations of INDIVIDUALS.
2. Individuals interpret situations differently and behave in ways that make sense to them (PERCEPTION AND PROPENSION TO RISK).
3. People's performance is influenced by relationships with other people, technology and the complex and dynamic work environment (THE CONTEXT).
4. People evaluate and make trade-offs.

In conclusion, we can therefore state that taking an ergonomic approach to work design means adapting work systems to the needs, abilities and limitations of workers, so that people can work safely, comfortably and effectively. This forces one to look at the variability of the relevant human resource.
Over time, ergonomics and the technical reference standards have developed a solid scientific ribbing to which reference can be made, both for analysis and for work design that

[8] Biomechanics is the application of the principles of mechanics to living organisms. Human biomechanics deals with the mechanical aspects of the body (bones, muscles, joints) and thus makes it possible to translate the human body itself into a set of mechanical elements.

[9] SOMMA R. SERVADIO M. "Cognitive Ergonomics And Safety at Work: The Usability of Interfaces". Scientific article in the ISL magazine Technical solutions for safety issue dedicated to 'New frontiers for ergonomics', semi-annual attachment 2/2023 'ISL – Igiene & Sicurezza del Lavoro' by IPSOA – Wolters Kluver Italia.

[10] Somma R. Buratti G. "Organisational Ergonomics". Scientific article in the ISL magazine Technical solutions for safety issue dedicated to 'New frontiers for ergonomics', semi-annual attachment 2/2023 'ISL – Igiene & Sicurezza del Lavoro' by IPSOA – Wolters Kluver Italia.

examine both physical and cognitive aspects, which are less well attended to. A design that must consider both absolute concepts of risk, respecting the limits and general capacities of the human being, and the specific target population, i.e. the people whom the project is intended for, specified on the basis of relevant characteristics (which include, for example, the level of ability, intelligence or physical characteristics – such as anthropometric dimensions – of these individuals. Gender and age may be related to variations in these characteristics. In addition to these intrinsic characteristics, extrinsic factors (e.g. cultural differences) may also be relevant.

Hence, in designing the work one must reflect in terms of:

The EXTERNAL LOAD, i.e. the external conditions and demands in a system that influence a person's internal physical and/or mental load;

The INTERNAL LOAD, i.e. a person's internal response to exposure to the external load, depending on his or her individual characteristics (e.g. body size, age, abilities, skills, etc.)[11].

3. Artificial Intelligence, risk assessment and management

AI has long been used to support both occupational safety and health protection: in real-time monitoring through sensors and video cameras (analysis of images and data from sensors to identify risky behaviours, dangerous environmental conditions, to prevent collisions, for example), by wearable devices (smartwatches and smart wristbands to monitor workers' vital parameters, to identify physical overload conditions, monitor drivers' fatigue status and report any anomalies), as well as in predictive maintenance, training, assistance to workers (chatbots and virtual assistants), intelligent monitoring of access to construction sites, etc. Although considerable work is yet to be done, several research activities have already been started and are still ongoing.

On the other hand, less followed has been the path of using AI to contribute to risk analysis, and I would like to start precisely from here, arguing the need for an instrumental epistemological approach of AI to risk assessment, in particular, to support a risk assessment that considers not only the absolute risk level, but also the variability characteristics of the real population of workers, which affects the risk exposure level. An AI-based system could thus help to manage one of the least standardisable pieces of the prevention system: the human factor, to which most accidents are blamed today.

The idea could be that of an AI-based system that allows the absolute risk level assessed in the risk assessment document to be matched with the characteristics, capacities and heterogeneous limitations of the reference population of workers in order to assess any possible exposure discrepancies, also with the aim of adapting prevention measures to the peculiarities of the individual worker, improving the work environment and working methods to make them compatible with health and safety requirements.

In particular, AI, by allowing large amounts of data to be analysed, can greatly aid the identification of less common, more complex risk factors related to differences that may impact

[11] Here is the link where I am talking about this topic: https://www.puntosicuro.it/informazione-formazione-addestramento-C-56/formazione-per-la-sicurezza-un-abito-prevenzionistico-su-misura-AR-22007/

on initial conditions and, therefore, on risk exposure. The idea is to act in prevention with the support of AI, incorporating the elements of variability linked to human beings that impact on the level of risk[12].

In this perspective, the current need is to elaborate an operational tool that can match the data related to the task or to the characteristics of the single activities included (competences, capacities, required psycho-physical characteristics) and those related to the worker, going to identify what each individual can or cannot really sustain, as well as possible subjective prevention and protection measures. Therein, health surveillance also has a decisive role, which must be strengthened and enhanced, with a view to assessing suitability for the task that can really match the specific activities to be performed with the worker's capabilities and limitations, and not just in general terms.

From this point of view, AI could be used precisely to achieve this goal, by interweaving the complex data of the "objective" assessment of risks, those of the absolute risk macro-negativity, with the variables related to specific characteristics of the real population of workers, i.e. the micro-negativity closer to the work operations.

Therefore, a system using AI could incorporate, into risk management, the ergonomic variability (physical, cognitive, organisational)[13] of the worker population to provide, as follows:

- Adaptive versus 'subjective' risk assessment (see next chapter).
- Data on the suitability of the resource with respect to the work organisation (nature of the task, task preparation, workload, procedures, tools and methods, environment, etc.).
- (For example, based on the results of health surveillance and other defined variables, it could provide, which exact ergonomic movements can or cannot be performed by that worker with respect to the task to be performed. A path already taken in large organisations).
- Indications for any variables of the health protocol defined by the Competent Doctor with respect to the human factor.
- Indications for any specific characteristics of PPE (based on anthropometric characteristics, gender, age, for example, etc.).
- The specific subjective additional training needs (based on learning ability, language, education, skills, experience, etc.). This is a fundamental point of support for AI (**assessment of individual, person-inclusive training needs**), which should be pursued[14].
- And identify any further corrective action necessary for subjective risk management.

The primary objective of the hypothesised project is to improve the level of reliability of the

[12] Ien the proposal I am going to discuss below, I am recalling my studies and my numerous contributions, both popular and editorial, written on the human factor in the protection of health and safety at work, as well as my final thesis of the Master's degree in Prevention and Safety in the Workplace at the Alma Mater Studiorum University of Bologna entitled "Inclusive risk assessment by gender, age, origin from other countries and those related to the specific type of contract through which the work is performed".

[13] 11228-3:2009: Ergonomics – Manual handling – Part 3 – Handling of low loads at high frequency (repetitive upper limb movements)

[14] Here is the link where I am talking about this topic: https://www.puntosicuro.it/informazione-formazione-addestramento-C-56/formazione-per-la-sicurezza-un-abito-prevenzionistico-su-misura-AR-22007/

operator and, more generally, of the system within which the individual worker operates, taking into account the complexity of all the elements with which he or she must interface, which requires going beyond standards, moving towards an (increasingly) "tailor-made" risk assessment, but also design, training, policies or procedures to support workers.
The system using A.I. should therefore be able to:

- analyse the work organisation, the task and its characteristics (psycho-physical sustainability);
- analyse the individual who has to perform it (competence and personal characteristics);
- identify any critical aspects and corrective measures (e.g. provision of more 'ergonomic' equipment, targeted training, introduction of specific health checkups, etc.).

4. A methodological proposal for subjective risk assessment

For the "subjective" Risk Assessment one could use the A.I. starting from the results of the 'objective' Risk Assessment, carried out with the classic R=PxD matrix, with which the risk is defined with the simple correlation between the probability of occurrence of the negative event and the severity of the injuries caused by it, and add a risk aggravator given by the given diversity (of gender, age, anthropometric, etc.), represented by a K factor.
In this way, the same risk factor will be declined by pointing not only to absolute risk concepts but also to variables relating to particular characteristics of the actual population of workers.

$$R = P*D$$

Thus, the K factor reproduces a corrective coefficient of the risk magnitude, which can represent the different human variabilities.
By assigning a score of 1 to 4 to probability, 1 to 4 to severity, and applying the aggravating corrective factor K, one can derive R as a product of these and obtain a progressive degree of risk.
In addition to representing all the individual variables (language, culture, generation gap, health, physical and cognitive limitations, learning ability, mobility, etc.), the factor K also considers the possible simultaneous presence of the variables themselves, with a consequent increase in Risk, as shown below:

		Corrective coefficient K					
		Gender	**Age**	**Contract**	**Language**	**Learning ability**	**Etc.**
	R	**R^1**	**R^2**	**R^3**	**R^4**	**R^5**	**R^i**
R= PxD	**4**	**K= 1,2**					
		4,8	**K= 1,3**				
			6,24	**K= 1,5**			
				9,36	**K= 1,7**		
					15,912	**…**	
						…	**…**
							…

Therefore, by means of AI, a risk assessment could also consider how human variability factors intersect and influence risk. On the basis of the risk assessment, the system based on AI could support the organisation in identifying what specific competencies, skills and psycho-physical characteristics are required to perform that particular task in order to guarantee health and safety. The hypothesis is therefore to start from the risk assessment and incorporate the real characteristics of the worker, detecting criticalities and needs in order to adapt the Prevention and Protection measures.

This is in line with the 'Industry 5.0' paradigm, which points towards research and innovation that can lead the transition to a sustainable, human-centred environment and resilient European industry with the aim of putting human needs and interests at the centre of the production process, but also of a technology used in the production adapted to the needs and diversity of individuals and of more inclusive working environments. The path outlined is that of workers' participation: more involved in the design and realisation of new technological industries, including robotics and AI.

This perspective is already underway in some sectors, where design is directed towards workstations that are more suited and flexible to the needs of line workers, allowing them to perform their tasks not only in safety but also in comfortable conditions, promoting well-being and improving performance. We are thinking of the self-adaptive platforms in the automotive industry, which has introduced workstations that adapt to workers' anthropometric measurements: the system reads and identifies the worker's anthropometric data by means of a personal badge adjacent to the workstation and modifies the height of the workstation according to the worker's reference percentile.

5. Application examples

One of the examples are some large industrial realities beginning to adopt the use of Artificial Intelligence to accelerate the OCRA (Occupational Repetitive Actions) analysis[15], by performing an assessment starting from one or more videos of the workstation in order to express the judgement of suitability to the task by referring to subjective health limitations to the task, expressed by the competent doctor and related to the various districts of the upper limb with the colours dictated by the OCRA analysis. Obviously, the input data includes the mapping of all workstations (operations/work tasks) analysed with the complete OCRA method, since the risk analysis includes each individual area (hand, wrist, elbow and shoulder), and the suitability judgments made by the competent doctor with a precise indication of the limitation (an example of a limitation is "suitable for the task of .... with the exclusion of .... (one or more stages of disengagement from the task)". Thus, the AI-based system should be able to match work operations/tasks with the subjective limitation of workers on shift, organising the work by assigning each worker to the operational phase according to the results, while respecting the limitations to the task expressed in the suitability judgement. Obviously, the result must be reviewed and possibly corrected by an ergonomist who monitors it. This speeds up the analysis significantly.

[15] 11228-3:2009: Ergonomics – Manual handling – Part 3 – Handling of low loads at high frequency (repetitive upper limb movements)

Task:	Assembly line operator (mechanical engineering)		
Analysed risk factor:	Postural risk and manual handling of loads (assumption of incongruous postures during work: prolonged standing, squatting or kneeling, arms held above shoulder height, etc., lifting loads > 3 kg, repetitive assembly line movements, push-pull pallet trucks. etc.)	R= PxD = 2x2	**4**

Age diversity:	- Decreased physical strength and ability to move (e.g. chronic inflammation of the arch of the foot, back, knees, elbows and wrists) and/or increased musculoskeletal disorders – often damage. - Decreased resistance to physically hard or stressful activities (need for longer recovery time). NOTE: The damage sustained is often more serious and requires longer recovery time.	K = 1,5 (ages: 50-55 years old) K = 2 (ages: 55-60 years old)	
R' (aggravated)	PxDxK = 2x2x1,5		**6**
	PxDxK = 2x2x2		**8**

Diversità di genere:	- Increased exhaustion and risk of injury resulting from physical limitations (e.g. body size and height) conflicting with the activity (weights to be moved, heights to be reached, etc.). - Decreased capacity for movement resulting from prolonged standing (e.g. varicose veins).	K = 1,8 (presence of women)	
R' (aggravated)	PxDxK = 2x2x1,8		**7,2**

Aggravating factor for contractual diversity:	- Increased physical exhaustion and accident risk due to labour activities diverted to "less" protected workers and/or lack of knowledge about correct work procedures. - Increased risk of accidents due to "more uncomfortable" activities diverted to "weaker" contracted workers and/or lack of knowledge about correct working procedures.	K = 1,5 (temporary contracts)	
R' (aggravated)	PxDxK = 2x2x1,5		**6**

Table 1. The example.

The same principle could be adopted for the other factors of human variability that impact risk by including the K factor illustrated in the previous section (Table 1).

Based on this corrective assessment of the individual variability, the organisation could then define any further prevention and protection measures tailored to the beneficiary of the preventive action.

References

[1] Beck U. (Ed. 2013), La società del rischio. Verso una seconda modernità, Feltrinelli

[2] Benini, Sorcioni (2006), Il fattore umano, Donzelli

[3] Chialastri (2012), Human Factor. Sicurezza & Errore Umano, IBN Editore

[4] Bisio (2003) fattore umano e sicurezza sul lavoro, Edizioni Unicopli

[5] D'Avenia (2018), Le vere cause degli incidenti, www.puntosicuro.it

[6] Federici M.C., Romeo A. (2017), Sociologia della Sicurezza, Mondadori Università

[7] Hawkins Franck (1987), Human factor in Flight, Aldershot Hampshire

[8] Helmreich R.L. (1996), Safety and Error Management: The Role of Crew Resource Management, University of Texas

[9] ICAO (1998), Human Factor Training Manual, Doc 9683-AN/950

[10] Koonce J.M. (2002), Human Factor in the Training of Pilots, Taylor & Francis

[11] Orlady H.W e Orlady L.M. (1999), Human Factor in Multi-Crew Flight Operations, Ashgate Publishing Limited

[12] Ralli Marcello (1993), Fattore umano e operazioni di volo, Libreria dell'Orologio

[13] Reason J.T., (1990), "Human error", Cambridge university press, trad. it. "L'errore umano", Il Mulino

[14] Salas E., Maurino D. (2010), Human Factors in Aviation, Academic Press, Elsevier

[15] Turner e Pidgeon, 2001 Disastri: la responsabilità dell'uomo nelle catastrofi, Einaudi

[16] Vecchione E, Viola M. (2008), Fattore umano in aviazione, IBN Editore

[17] Woods D., Dekker S., Cook R., Johannesen L., Sarter N. (2010), Behind Human Error, Ashgate

[18] Zamponi (2022), l'ergonomia e il benessere organizzativo: Le fasi e i processi di adattamento, 78Edizioni

Other academic and specialist contributions

[19] Angelini, Flexible work and safety in the workplace: a critical issue to be governed, in Olympus, entry Insights, 2007

[20] D'Avenia R. (2018), Investigating accidents with causal models, Environment & Safety, no. 2

[21] Gherardi S., Nicolini D. and Odella F., «From risk to safety: the sociological contribution to the construction of trustworthy organisations», Quaderni di Sociologia

[22] Gherardi S., Nicolini D. (2000), The Organizational Learning of Safety in Communities of Practice. Journal of Management Inquiry

[23] Spadoni Daniele, Human factor and non-technical skills: how to build a culture of safe behaviour, Puntosicuro of 31/01/2017

New Digital Resources at the University of Trento for the Advancement of Health and Safety

Matteo Brunelli[1] and Riccardo Ceccato[1*]
[1] Department of Industrial Engineering, University of Trento, Trento, Italy

* E-mail: riccardo.ceccato@unitn.it

Abstract. We consider the problems of choosing (i) the best combination of learning modules necessary to have a sufficient awareness of the risks inherent with a given work environment and (ii) the minimum combinations of personal protective equipments that are necessary in the presence of a set of risks. Albeit different, both problems can be modeled as set covering problems, a special family of combinatorial optimization problems. More specifically, in (i) we minimize the effort of the worker in terms of time and resources dedicated to learning modules, also keeping in mind the temporal validity of some modules requiring the necessity to update his/her knowledge of some specific risks. In (ii) the goal is to minimize the total amount and the cost of the personal protective equipments (PPE). For both problems we show a possible implementation in an academic environment through common spreadsheets. We consider that the models proposed in this manuscript could have a use in making explicit tacit knowledge as well as in being training tools.

Keywords: Safety at the Workplaces, Training Plan, Personal Protective Equipment, Combinatorial Optimization Process

1. Introduction

In the world of work, the health and safety at the workplaces management becomes more and more relevant, with the demanding goal of a constant lowering of occurring injuries or occupational diseases [1].
According to the Italian Law [2], regarding the health and the safety at the workplaces, even universities are considered as specific workplaces and university students are recognized as workers when they participate to laboratory activities [3].
Therefore, an extremely high number of participants to the demanding training courses is registered, with an increasing request of specific learning modules on health and safety, compliant to the existing specific risks. These learning issues regard the general and specific training courses, together with the refresher programs, according to the guidelines in force [4].
At the same level, such a variety of activities requires a meticulous examination of all the connected risks, with the subsequent identification of the suitable personal protective equipment (PPE).
The starting point of this work is the possibility of optimizing the choice of the training

plan or the individuation of the best PPE, based on combinatorial models; in such a way, the tasks for the activity supervisors or the persons in charge will be simplified.
Among these models, our interests are focused on set covering problems, a special set of combinatorial optimization problems [5]. At a first glance, the choice of specific PPE falls quite completely in a so called "experience-based" procedure, with a high degree of uncertainty, due to the acquired experience and knowledge of the responsible of the entire process. The same limitations, actually, were present also in many models adopted in industry for the development of the risk analysis, risk evaluation and risk assessment procedures; as it is now well known, the development of similar combinatorial models found applicable solutions in this field [6]. In fact, some experience-based models, like Preliminary Hazard Analysis or What-if Analysis, were improved and substituted by "step-by-step" models, like Hazard and Operability Analysis (HAZOP).
Along the next paragraphs the model guidelines, with some preliminary examples, will be developed.

2. Two optimal selection problems

2.1. Optimal selection of courses

We consider the problem of choosing the set of modules, belonging to the specific training courses, that can cover a predefined set of families of risks at the minimum cost. In our specific case the cost could be monetary or non-monetary (for example the total number of hours, as provided by the regulations in force).
This problem can be formulated as a minimum set covering problem with a set of *m* risks and *n* courses. The input of the problem consists of a matrix $A=(a_{ij})_{m\times n}$ where each entry is defined as

$$a_{ij} = \begin{cases} 1, \text{ if the risk covered by the j th course} \\ 0, \text{ otherwise} \end{cases}$$

Furthermore, each course is associated with a cost $c_j>0$ for all j=1...,n. Such costs can be collected into a list $c=(c_1,\ldots,c_n)$. With the information contained i A and c, it is possible to write the minimum cost selection problem in the form of a set covering problem [5].
That is, it is sufficient to solve the problem

$$\text{minimize} \sum_{j=1}^{n} c_j x_j$$
$$\text{subject to} \sum_{j=1}^{n} a_{ij} x_j \geq 1 \forall i \in \{1,\ldots,m\}$$
$$x_j \in \{0,1\} \forall j \in \{1,\ldots,n\}$$

In matrix notation it can be written, more compactly, as

$$\text{minimize } c_T$$
$$\text{xsubject to } Ax \geq 1 x \in \{0,1\}^n$$

It is therefore a binary linear optimization problem that can be solved with common solvers. In our application to make it more user friendly we used the Excel Solver, that can be

found also on open source Spreadsheets.
We note that, so far we considered that the requirements in terms of risks to be covered by modules were binary. That is, a course could either cover or not cover a risk, regardless to the time that the module dedicates to the given risk. A more sensible approach could consider the extent to which a risk is discussed in a given course. We could use the number of minutes dedicated to a risk as a proxy measure of the depth of the discussion of the risk in the module. It is relatively simple to modify the previous optimization problem to make it suitable to this new approach. If the previous binary parameter A_{ij} is replaced by

$$b_{ij} = \text{number of minutes that the j th course devotes to the i th risk}$$

then, the optimization problem becomes

$$\text{minimize} \sum_{j=1}^{n} c_j x_j$$
$$\text{subject to} \sum_{j=1}^{n} b_{ij} x_j \geq l_1 \, \forall i \in \{1,\ldots,m\} x_j \in \{0,1\} \forall j \in \{1,\ldots,n\}$$

where $l_i > 0$ is the minimum number of minutes that must be allocated to the i th risk.

2.2. Optimal selection of PPE

We consider the problem of finding the minimum cost set of PPE that are necessary to be employed to guarantee safety presence of some risks. That is, if we call R the set of risks and D the set of PPE, and 2^R and 2^D their power sets, then we want to define a function $f{:}2^R \rightarrow 2^D$ such that for each set of risk $R' \subseteq R$ is finds an associated set $D' \subseteq D$ that is minimum as it represents the « lightest » set of PPEs required for the risks R'.

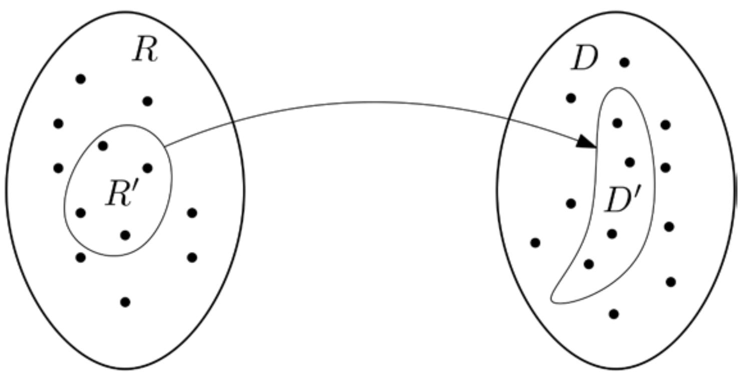


Figure 1. A mapping between the subset of risks R' and the optimal subset of PPEs D'.

Unlike for the previous problem, that required to solve an optimization problem, this problem can be modeled and solved as a rule-based system. This is done by using a multi-stage approach.

1. The required *input* of the system is a list of risk levels expressed on the components of the «inventory for risks» according to the Annex VIII, present inside the Italian Law in force

[2]. Using this taxonomy, there are 21 different risks, ranging from the risk of free falls to possible expositions to viruses or bacteria. For the sake of simplicity, we can gather them in three categories: physical, chemical and biological risks, as developed in Table 1.

Risks		
Physical	Mechanical	**Falls (1)**
		Impacts (2)
		Cuts (3)
		Vibrations (4)
		Slips (5)
	Thermal	**Heat (6)**
		Criogenic (7)
	Electrical (8)	
	Radiations	**Non-ionizing (9)**
		Ionizing (10)
	Noise (11)	
Chemical	Aerosols	**Powders, fibers (12)**
		Smokes (13)
		Mists (14)
	Liquids	**Immersions (15)**
		Spills, streams (16)
	Gases (17)	
Biological		**Bacteria (18)**
		Viruses (19)
		Fungi (20)
		Antigenes (21)

Table 1. Classes of risks. Quantifiable and tangible risks are in boldface, next to a sequential number.

Hence the input is a list, that we can call r, with 21 entries. For example, if we consider the physical risk associated with noise, then its corresponding input could be an estimation of the decibels that are present in the working environment and therefore the component of the list regarding noise levels would simply be a positive number.

The same approach can be used for the identification of the body parts that should be protected by the suitable PPE. Again, according to the above mentioned Annex VIII, it is possible to identify them, as reported in Table 2. Note that, to minimize the probability of mistakes in the list **r**, we implemented drop down menus that can be used to input values out of predefined sets to ensure that the chosen value is considered valid.

Body parts	Head	Cranium
		Hearing
		Eyes
		Breathing apparatus
		Face
		Head
	Upper limbs	Hands
		Arms
	Lower limbs	Feet
		Legs
	Others	Skin
		Trunk
		Gastrointestinal apparatus
		Entire body

Table 2. Body parts that must be protected.

2. Next, a Table «Risk levels vs. Body parts» is built. Each cell of such a Table should be empty if the risk does not trigger the adoption of any PPE for that part of the body, or it should contain the name of the device that is needed.
   A simple example of an always empty table cell is the one matching «noise» with «feet» as no conceivable level of noise shall trigger the adoption of particular protection of the feet. On the contrary, the cell matching «noise» with «ears» will contain the name of the required device. Formally, entries of such table are dependent on the input r, so that we can state that the table **T** is a function of the input levels **r**. That is **T(r)**. More precisely each cell on the jth column of the table **T** is an «if-then» function of the jth component of the vector **r**. A representative, but simplified, instance is the cell describing the PPE to protect «ears» from «noise», that is defined by means of the following «if» function

   If($0 \le$ noise ≤ 40 Db) $\Rightarrow$ cell(ears, noise) := «no PPE»
   If($40 <$ noise ≤ 70 Db) $\Rightarrow$ cell(ears, noise) := «Earplugs»
   If($70 <$ noise ≤ 110 Db) $\Rightarrow$ cell(ears, noise) := «Headset»

3. Clearly, it may happen that different risks can trigger different protection devices for body parts. For example, both chemical and biological risks can demand the use of different and conflicting PPEs to protect the breathing apparatus, or the presence of chemical risk can affect both eyes and the breathing apparatus again. In all cases, such conflicts must be reconciled. It is usually done by prioritizing the most protective device. In our model, we assume the existence or a partial order relation $\gtrsim_k$ such that $d_i \gtrsim_k d_j$ if and only if the PPE d_i is at least as protective as d_j for the body part k. This new action of if-then rules, coupled with order relations $\gtrsim_k$ acts as a function that maps a given table **T** into a list of recommended devices **d** so that, in turn, d = f(T). Figure 2 represents an example: both « inert dusts » and « mists », due to their levels trigger the use of protective masks. In the former case, the required mask is an FPP1 whereas in the latter case the requirement is an FPP2. Since FPP2 is more protective than FFP1, i.e., FFP2 $\gtrsim$ FFP1, the final recommendation is FFP2, since it can cover for FFP1.

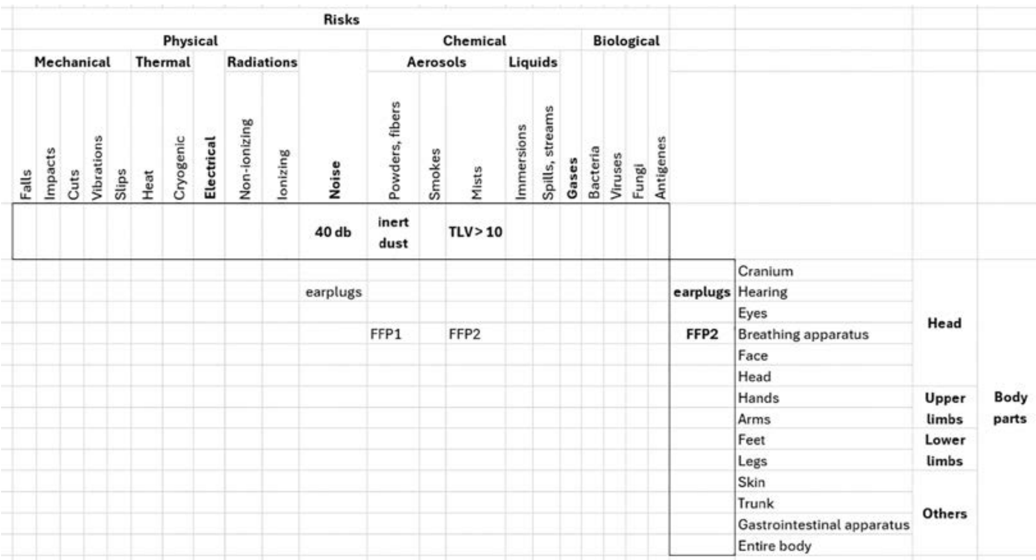


Figure 2. The pivot table T mapping risk levels contained in the list r into recommended PPE in the list d.

4. This approach can be used again in a depth-in-depth procedure, with the aim to select the «best» choice of a set of PPE. As an example, for the selection of a suitable equipment for the breathing apparatus, the European technical guidelines provide the classification of PPE (facial masks, filtering masks) into three categories. The suitable choice involves: (i) the nature of powders (inert, harmful, toxic); (ii) its load percentage in the environmental air; (iii) its size distribution (granulometry). Thus, the above reported if-then rules allow to make a final suitable choice, after some steps of the entire procedure. At the same time, we can also put some other constraints that «force» the procedure to a mandatory PPE; as an example, the

protection of hands from the exposure to chemical substances requires gloves with the high level device, formally Class 3 device, independently from the nature of the substances itself.

3. Preliminary tests

3.1. Optimal selection of courses

The first procedure applied to the above described model has been developed taking into account the requirements of the training courses, according to the national guidelines: in particular, the identification of a refresher course for all workers, considering the level of risk of their activity (low, medium, high risk).

As refresher courses, at the moment, are characterized by a minimum number of hours (6) for all the specific sources of risk, the model can help the persons in charge to find out the best pattern among all the available modules of training, taking into account the minimum number of hours, as provided by the technical guidelines.

As a first attempt, a set of modules has been identified; each module is also connected to a relative cost (number of hours).

In Table 3, the available modules are reported with the relative number of hours:

Module, specific risk	Number of hours
Organizational chart	1
Safety signs, emergencies	0.5
Chemical	1
Biological	1
Mechanical, machines	1
Mechanical, manual handling of loads	0.5
Mechanical, falls and slips	0.5
Thermal, heat	0.5
Thermal, cryogenic	0.5
Electric	1
Radiations, non-ionizing	0.5
Radiations, ionizing	1
Noise	0.5
Electromagnetic fields	0.5
Computers	0.5
Social risks	0.5
...	...

(Note: number of hours can be modified according to specific requirements of the working activity)

Table 3. Available training modules.

Starting from this set, the person in charge who has the responsibility of the workers can apply the model, finding out the «optimum» solution among the modules.
As an improvement of the model, some constraints can be inserted giving rise to a priority level for some modules; for instance, the module regarding the organizational chart, or dealing with the safety signs, could be considered as modules with an high level of priority; in this case the two modules are demanding for all the possible combinations among the choices. As another possibility, according to the personal working activity and the identification of possible sources of risk, some modules (for instance, mechanical) could be divided into several sub-modules.
With this new configuration, it is always possible to identify the «best» training or refresher pattern among the available modules, selecting ones that are more appropriate for the workers who need very specific long-learning activities. As an example, for the workers subjected to «mechanical risk» it will be possible to select only the modules for the real exposure to the specific source of risk (crushing or cutting) among all the mechanical risk modules available.

3.2. Optimal selection of safety devices

As suggested in the previous paragraph, once the set of if-then rules have been chosen, the entire procedure can be enlarged, taking into account several requirements given by the technical regulations and guidelines, specific for each part of body that requires protective equipment and the specific source of risk, together with its intensity.
Few representative examples are reported:

(i) *PPE for hearing*: in this case, all the devices belong to Class III of protection (maximum protection). There are two sets of devices: ear inserts and protective earphones. The choice of the recommended device is ruled by the following relation:

   $$dB(A)r = dB(A)m - SNR + 7 \text{ with } 70 \leq dB(A)r \leq 80$$

   where dB(A)r is the level of noise (in absolute decibels) really heard by the worker with specific PPE; dB(A)m is the level of noise measured in the environment (workplace); SNR is the attenuation factor offered by the device. In this case, some other parameters can be adopted for the final choice, once the SNR value is obtained. In fact, ear inserts could be adopted when the workplace is wet and warm, avoiding an extensive sweating, or when the worker has to move frequently his or her head. On the other hand, when the worker has to wear off the device frequently, the earphones should be preferred.

(ii) *Eyes protection*: the technical guidelines provides three different classes for the optical quality of the lenses. A first if-then step regards the amount of time the glasses (or goggles, as explained later) must be worn: for long period of times, class 1 is preferable. Together to this classification, glasses and goggles are classified in terms of mechanical protection; in its turn, this quality can be expressed in terms of basic robustness (two classes: minimum and augmented robustness) and impact energy protection (three classes: low, medium and high energy of impact). Each entry (if entry) can lead to a specific class of protection (then result). As a final step, the protection against chemicals, especially towards vapors, gases or mists, can be considered; in this case the required PPE belongs to the set of goggles.

(iii) *Brething apparatus*: as already mentioned, the choice of the suitable PPE for the breathing apparatus requires several if-then steps. The first step is related to the physical state of the contaminants present in the environment: solids (dusts or powders), liquids or aerosols, gases and vapors. This parameter should lead to the first selection: facial masks or filter masks. Inside each set of devices, the chemical nature of the contaminants should lead to a second choice: inert dusts or powders probably requires facial mask of class FFP1. FFP2 and FFP3 devices are mandatory if the threshold limit value (TLV) of the chemical substances detected belongs to a medium or a high level of protection required (harmful or toxic substances). As an tentative assignment, substances with TLV ranging between 0.1 and 10 mg/m^3 require FFP2 devices, whereas FFP3 is recommended for TLV < 0.1 mg/m^3. Thus, an estimation of the concentration of substances present in the air, or the measured value in the workplace during the monitoring campaign, can give a specific indication that has to be reported in the Table **T**. Furtherly, among the filters, the choice is strictly related to the substance, or substances, detected; each class of chemicals, organic vapors with low or high boiling points, acid or basic substances, mercury and etc., requires a specific filter that has to be used on the mask. In this case, the connection between two (or more) specific risks can lead to more complex PPE, as in the case of protection of the complete face (eyes, nose and mouth), or by the need of a more complex kind of filters (combined filters).

(iv) *Gloves*: this device probably represents the most used PPE inside the university laboratories. Several technical guidelines rule the choice of the suitable gloves for the working activity, specific for each source of risk: chemical and biological, mechanical, electric, exposure to heat or cryogenic liquids. Again, some steps can be performed by the model, taking into account selected if-then steps. Against chemical (or biological) exposure, only class 3 of gloves can be considered; in their turn, gloves are classified in terms of substances that must be blocked by them. On the other hand, the gloves against other sources of risk can belong again to three different classes and levels of protection (low, medium and high level). For specific activities, the choice is ruled by the requirement of protecting the upper limbs from more than one source of risk (for instance, protection from chemicals and heat, mechanical and heat, etc.).

(v) *Shoes*: even for the protection of the lower limbs some choices are necessary; again, these requirements can be expressed in terms of if-then steps. The first step is the need to protect feet and legs from the chemical risk: in this case the protective shoes must be made of resistant materials against the specific chemical substances. The second step regards the presence of the mechanical risk and, more precisely, the presence of the fall of heavy objects (risk of crushing) and/or the presence of cutting surfaces or objects (risk of injuries form cutting edges). In this case, the choice will regard the level of protection assured by specific devices, like protective rod against crushing or anti-puncture sole. Specific signs and symbols (S for safety and P for protection) together with an integer number representing the level of protection (from 1 to 5) identify the recommended the PPE.

4. Conclusions and future perspectives

The possibility to develop specific tools for the choice of training programs or protective devices regarding the health and safety management in particular workplaces, like universities, represents a noticeable aid for the responsible of these «decision-making» procedures.
In this work, we applied a special family of combinatorial optimization problems, the set covering problems, with the effort to begin and to solve these two topics, that involve a large number of workers, employed in working activities with a high degree of qualification that requires rapid refresher modules, also because in the same workplace (laboratory) a continuous turnover of workers is registered and expected.
Our attempts, especially the second one, mapping sets of risk factors to suitable PPE can be interpreted as a knowledge management tool, that makes knowledge (that is often only available for experts) explicit and reusable instead of tacit [7]. Furthermore, we envision their use also as training tools.
As a final remark, we think that this optimization tool could be applied also to other procedures in the field of management of health and safety at the workplaces, like the procedure regarding the risk assessment.

References

[1] "Relazione Annuale 2023", Rivista degli infortuni e delle malattie professionali, 1/2024, INAIL, 30-54.

[2] "Testo Unico sulla Salute e Sicurezza sul Lavoro" D.Lgs. 9 aprile 2008, n.81 (rev. settembre 2024).

[3] "Regolamento recante norme per l'individuazione delle particolari esigenze dell'Università e degli Istituti di Istruzione Universitaria", D.M. 5 agosto 1998, n. 363.

[4] "Accordo tra il Ministro del lavoro e delle politiche sociali, il Ministro della salute, le Regioni e le Province autonome di Trento e Bolzano per la formazione dei lavoratori ai sensi dell'articolo 37, comma 2 del decreto legislativo 9 aprile 2008, n.81" n. 221/CSR, 21 dicembre 2011,

[5] Hillier, F. S., & Lieberman, G. J. "Introduction to Operations Research", McGraw-Hill (Seventh edition), p. 599, 2015.

[6] "Guidelines for Process Hazards Analysis, Hazards Identification & Risk Analysis", Dyadem, pp. 5-1, 5-10 (2003).

[7] Venkitachalam, K., & Busch, P. "Tacit knowledge: review and possible research directions". Journal of Knowledge Management, 16(2), 357-372, 2012.

The Future of Industrial Safety: Remote-Controlled Robots in High-Risk Environments

Alessandro Gerotto[1], Alberto Feletto[1], Edoardo Marangoni[1] and Lorenzo Baraldo[2,3]

[1] Gerotto Federico Srl (Italy)
[2] Sustain Tech Hub S.p.a. SB (Italy)
[3] University of Padua, Department of Industrial Engineering (Italy)

* E-mail: info@gerotto.it

Abstract. This paper examines the ongoing transition from manual to automated industrial maintenance and cleaning methodologies, particularly within confined and hazardous (ATEX) environments. While acknowledging the increasing deployment of remotely controlled robots, the study highlights the limitations of full automation, while arguing for the continued necessity of human intervention for certain tasks. Looking forward, the paper proposes a comprehensive framework for the integration of wireless sensor networks – robot-mounted in the work environment, and incorporated into wearable devices for operators – with a central Artificial Intelligence (AI) system. This interconnectedness opens the way to the creation of synergistic relationships between humans, robots, and the environment, ultimately enhancing safety for both personnel and the industrial plant.

Keywords: No-Man Entry Robot, Remotely Operated Robot (ROV), ATEX, Tank Cleaning, Safety, Confined Spaces, Sensors, Artificial Intelligence

1. Data on safety and health in confined and explosion-risk spaces.

Maintenance operations – both routine and emergency – are critical for ensuring industrial plant productivity and safety. Malfunctions can impair operational efficiency, leading to damage and wear to machinery, pipelines and structures. Critically, malfunctioning plants pose increased safety risks. While maintenance enhances safety, the operations themselves can be hazardous, particularly within confined spaces such as tanks, reservoirs, silos and ducts.
Confined spaces, as defined by U.S. OSHA 1910.146[1], are areas that:

- Are large enough for a worker to enter and perform tasks;
- Have limited entry and exit options; and
- Are not designed for continuous human occupancy.

Italian regulations governing confined spaces are integrated into various legal and technical standards, notably Legislative Decree 81/2008 (Consolidated Law on Health and Safety

at Work). Articles 66 and 121, along with Annex IV, point 3, address safety measures for work in potentially hazardous or confined environments. Article 66 in particular restricts access to environments such as wells and sewers without prior verification of atmospheric safety or appropriate remediation. Presidential Decree 177/2011 further outlines qualification requirements for companies and workers operating in these environments. The UNI 11958:2024 technical standard, effective from 14 November 2024, specifies hazard identification and risk assessment criteria for confined and/or potentially polluted spaces.
A critical subcategory is ATEX explosion-risk spaces. These are subject to product mandatory certification throughout Europe and a social compliance directive. Two directives apply: Directive 99/92/EC focuses on worker health and safety in potentially explosive atmospheres, mandating proper equipment selection, installation, inspection, and maintenance. Directive 2014/34/EU addresses trade regulations, with provisions both for equipment for use in hazardous areas and the production and sale of ATEX-compliant equipment.
Data from the INAIL "National Surveillance System for Serious and Fatal Accidents" (InforMO)[2], covering 2002-2014, highlight the dangers of these environments in Italy. During this period, 69 accidents in confined and explosion-risk spaces resulted in 90 fatalities. Asphyxiation accounted for 64.4% of deaths, followed by drowning at 17.7%. Tragically, 41% of cases involved multiple fatalities during rescue attempts. Accidents occurred mainly in tanks/reservoirs and autoclaves (28.8%), basins (22.2%), and wells/sumps (12.5%). These data indicate that 63.5% of accidents occurred within these three environments, resulting primarily in asphyxiation. These statistics underscore the urgent need for preventive measures to limit human entry into confined spaces, even for trained personnel. This need is amplified in ATEX explosion-risk environments.

2. European and international regulations on explosive atmospheres.

The term ATEX comes from the French ATmosphère EXplosibles, which describes the equipment and use of a product to be placed in an explosive atmosphere. ATEX certification is mandatory throughout Europe and applies to all use phases, from production up to installation and application of the equipment. IECEx is the acronym for International Electrotechnical Commission Explosive. While ATEX is mandatory only in Europe, IECEx is an international certification accepted in several countries to help build confidence in the safety of Ex equipment. It also facilitates international trade in equipment and services to be used in explosive atmospheres. The ATEX nomenclature identifies two substances whose presence, measured over time, determines the degree of danger: gases and dust. This gives rise to a classification that has become a reference standard: ATEX zones for gases (classification according to ATEX Directive 2014/34/EU [3]):

- Zone 0 → Continuous presence of explosive atmosphere (air-gas mixture, vapour or mist). Examples: inside tanks, fuel lines.
- Zone 1 → Occasional presence of explosive atmosphere during normal operation. Examples: areas around vents, near pumps or valves.
- Zone 2 → Rare and short-term presence of explosive atmosphere during normal operation. Examples: areas close to accidental gas leaks.

ATEX zones for dust (classification according to ATEX Directive 1999/92/EC):

- Zone 20 → Continuous or frequent presence of combustible dust in the air. Examples: inside silos, mills or industrial filters.
- Zone 21 → Occasional presence of combustible dust under normal operating conditions. Examples: areas around dust conveying systems.
- Zone 22 → Rare and short-term presence of combustible dust in the air. Examples: areas where dust may accumulate near machinery.

3. Taxonomy of risks in relation to confined spaces and spaces at risk of explosion

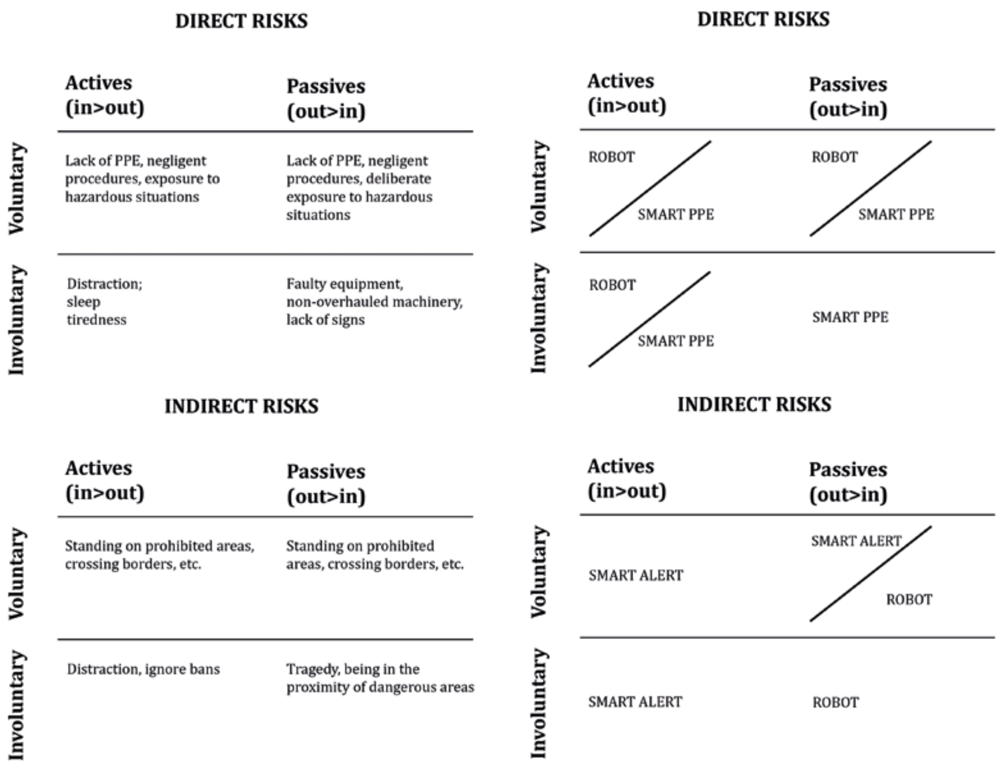
This paper proceeds by examining the multifaceted nature of workplace safety and health, emphasising the interconnectedness of individuals, systems and the broader community. The 2007 Viareggio train accident, resulting in 32 fatalities due to an LPG train explosion [4], serves as a stark reminder of the devastating consequences that can extend beyond those directly involved. This paper argues that effective safety and health management hinges on both individual behavioural factors and the broader operational context, including technological advancements. While regulatory frameworks establish a baseline for compliance [5], the onus lies with employers and the manufacturing sector to cultivate a robust safety culture, driven by innovative technologies and proactive solutions. Prioritising safety requires a systematic approach to risk reduction, and must address both inherent workplace hazards and risks stemming from human behaviour.

This paper further categorises risks in order to provide a comprehensive analysis framework:

- **Active and Passive Risks:** Active risks originate from individual actions (or inactions), encompassing both voluntary and involuntary behaviours such as deviations from procedure or failure to use personal protective equipment (PPE). Passive risks instead arise from external factors, such as defective equipment, inadequate procedures or hazardous environmental conditions.
- **Direct and Indirect Risks:** Direct risks impact individuals directly engaged in specific tasks, whereas indirect risks affect those in proximity to the workplace, including individuals who may be potentially unaware of the hazards (often termed "interfering risks"). These indirect risks may affect personnel from separate companies operating within the same shared space.
- **Risk Targets:** Risks can impact individuals or the plant itself and its associated equipment and infrastructure.

This paper shall also consider the concept of risk mitigation thresholds, ranging from complete risk elimination to risk mitigation. Complete elimination is the highest level of risk control, exemplified by the use of "no-man entry" robotic technologies in confined and explosion-risk spaces. These technologies inherently exclude human presence from hazardous areas. Other risk control measures, such as the use of PPE and technological innovations, focus on mitigating rather than fully eliminating risk. This paper argues that in scenarios involving confined and explosion-risk spaces, the primary objective should be complete risk elimination, through the application of robotic solutions.

In summary, the taxonomy for analysing the issue of safety and health in confined and explosion-risk spaces can be represented with the following diagram:



Three categories of product designed to mitigate risks, particularly in hazardous environments, are:

1. **No-man entry robotic solutions:** These robots are designed to operate in confined spaces. They eliminate the need for human entry. This approach aims to remove all direct risks (both active and passive, voluntary and involuntary) to human workers. Additionally, under the certifications required for operation in potentially explosive atmospheres (ATEX), these robots are designed to minimise additional risks and protect personnel and equipment from indirect risks.
2. **SMART PPE (Personal Protective Equipment):** These are tools designed to help operators mitigate direct risks and encompass active and passive risks, whether voluntary or involuntary. This effectively includes advanced PPE that goes beyond basic protection and incorporates safety enhancement technology.
3. **SMART ALERT:** These are sensors deployed on-site to detect faults or unexpected events. Described as a kind of "Industrial IoT (Internet of Things)", their purpose is to enhance safety for workers and machinery by providing real-time monitoring and alert.

4. Health and Safety AI: an integrated approach to safety

Based on the preceding taxonomy, it is crucial to envision a future of integrated technological development. This development should take the form of a digital ecosystem harmonising machines, people, and the work environment.

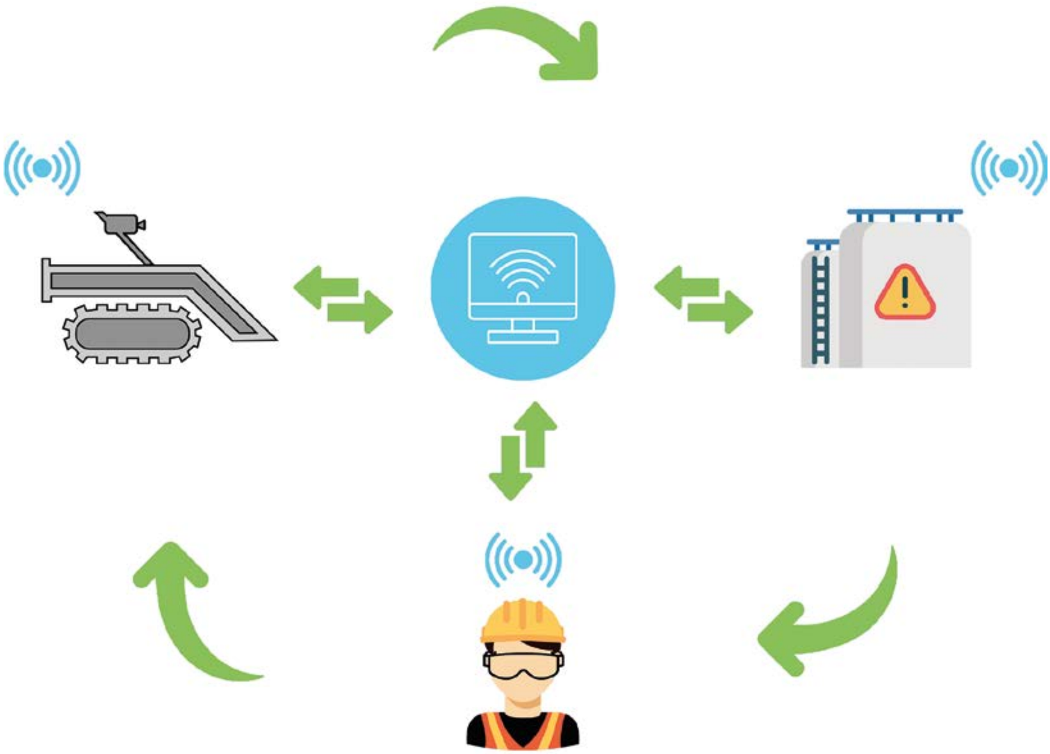


Figure 1. The Health and Safety Ecosystem that integrates no-man entry robots, workers and the work environment.

In the industrial and productive world, and especially in Italy, the term 4.0 connotes an approach encompassing the digitalisation of companies in a broad sense. In this process, the notion of machines – including manufacturing, transportation and operational equipment – interfacing with PLC software was a paradigm shift. This paradigm shift must however be expanded to increase the safety of work within confined spaces: each element of the system (machines-people-environment) must be equipped with sensors that allow a constant, continuous and punctual transmission of data to and from the works site.

4.1. Robots

Activities within confined spaces often prevent the direct (visual) monitoring of potentially dangerous situations. This necessitates remote monitoring capabilities through sensor networks mounted on robots. These sensors (wireless sensors) provide real-time data on the robot's operational status. This data can then be processed by an artificial intelligence (AI) system to generate outputs that can identify emerging risks or anomalies, or that suggest appropriate remedial actions.

4.2. People

While automation reduces certain risks for personnel, some processes within confined spaces still require human intervention. These would be tasks that demand the specific skills and professionalism of human workers, on account of the nature of the works site or the intervention itself. In this context, the individual becomes the first line of defence against risks. However, despite extensive safety regulations at various levels (supranational, national, and company-specific), this "first barrier" role is challenging to consistently fulfil. Workers engaged in complex tasks within confined spaces are focused primarily on maintaining high levels of professional performance. As in the case of high-risk sports or extreme activities, proper performance management demands that safety is not left to merely individual or procedural measures. Instead, it can be augmented by a network of wearable sensors (SMART PPE) that monitor workers, provide continuous feedback and enable constant and bidirectional communication between personnel and a central, AI-managed software system. The ability to transform and transmit field information (from sensors and operator input) into digital data that is then processed by the software is a necessity in order to:

- Obtain disintermediated data directly from the field
- Enhance the operator's Health and Safety performance, because they will be a 4.0 operator equipped with means that can increase the ability to anticipate and prevent risky events.

At the same time, the capability for constant and continuous communication with operators allows for:

- Constant engagement with people in the field.
- Provision of remote assistance to the operator on procedures to follow, checklists, preparatory activities for work, and, in the event of unforeseen events, "guiding" them via remote assistance systems (with voice assistant or smart glasses).

4.3. Environment

Robots and people interact with work environments that often house industrial infrastructure, plants, and other companies operating on the same works site and performing a diverse range of tasks. Mapping potential environmental risks is usually a preliminary activity at the start of operations (via Risk Assessment, Safety and Health Plan, etc.). However, it is important to recognise the potential for installing wireless sensors (SMART ALERTS) on valves, pipelines, gates and manholes. They can provide continuous information on the state of the environment in which robots and people operate. These technologies have seen significant development in domestic environments through IoT and home automation solutions that digitise various aspects of daily life.

5. No-Man entry robotic solutions

Increased concern for worker safety together with stringent regulations governing ATEX (Atmosphères Explosibles) environments, specifically Zone 0 classifications, have resulted in significant market demand for solutions that eliminate human presence in high-risk areas. This demand has been particularly evident in the oil and gas sector, which makes abundant use of storage tanks in refineries and hydrocarbon depots. In 2023, 825 active refineries were recorded globally, with a projected 15% capacity growth between 2023 and 2027 (source: GlobalData's refinery database). Europe alone has approximately 90 refineries. Augmenting this figure are the numerous tank terminals; according to the 2023 "Tank Terminals in Europe – Key Figures" report published by FETSA (Federation of European Tank Storage Associations) [6], there are 768 terminals across Europe. Historically, tank cleaning, vacuuming operations and remediation of hydrocarbon-contaminated land have been manual activities. While subject to international confined space regulations, these tasks carry a substantial degree of risk, which is exacerbated in potentially explosive atmospheres. Consequently, remotely operated vehicles (ROVs), commonly termed "no-man entry robots," emerged in the mid-2000s as a viable solution, allowing human workers to be replaced for the performance of tasks such as liquid and soil removal in hazardous zones.

5.1. No-Man Entry Robots

No-Man Entry Robots, also known as Remotely Operated Vehicles (ROVs), are robotic and remotely controllable machines designed for the removal of material in confined and hazardous spaces, including ATEX environments. These robots, used with external suction units (vacuum trucks or suction excavators) [7] or equipped with on-board or external pumps (volumetric, lobe, dredging, etc.), enable the suction, pumping or transportation of accumulated materials and debris from tanks, ducts, and other confined spaces. Applications include remediation of industrial environments, such as sludge removal, remediation of land contaminated by oil spills or leached liquids, and removal of dust and ash from industrial processes.

Depending on the nature, consistency and density of the material, the robots can be fitted with specialised accessories to optimise cleaning operations. Frontal augers with rotating blades can be attached to break up compacted or calcified materials. High-pressure jets (exceeding 200 bar) can be mounted on the robot's front to fluidise materials, to facilitate suction or pumping. Robots can be configured for suction via connection to a pneumatically equipped vehicle (vacuum truck or suction excavator) or utilise on-board or external pumps (volumetric, lobe, single screw) depending on site and client needs.

The system comprises three distinct units:

- The Robot: operating within the confined and/or ATEX space (tank, basin, duct), the robot is equipped with cameras, LED lights, and sensors for remote visual monitoring of operations.
- The Control Unit: positioned away from the hazardous areas, this unit allows a qualified

Figure 2. Example of a no-man entry robot ATEX Zone Zero certified for tank cleaning. (Model: Lombrico S EX0 manufactured by Gerotto Federico Srl).

operator to monitor and control the robot's movements. Equipped with screens and hydraulic controls, it provides real-time video and telemetry feedback. Depending on the site's ATEX classification, the control unit can be mounted on mobile trolleys (skid frames) or housed within certified ATEX Zone 1 containers.

- The Power Unit: provides power to the entire system.

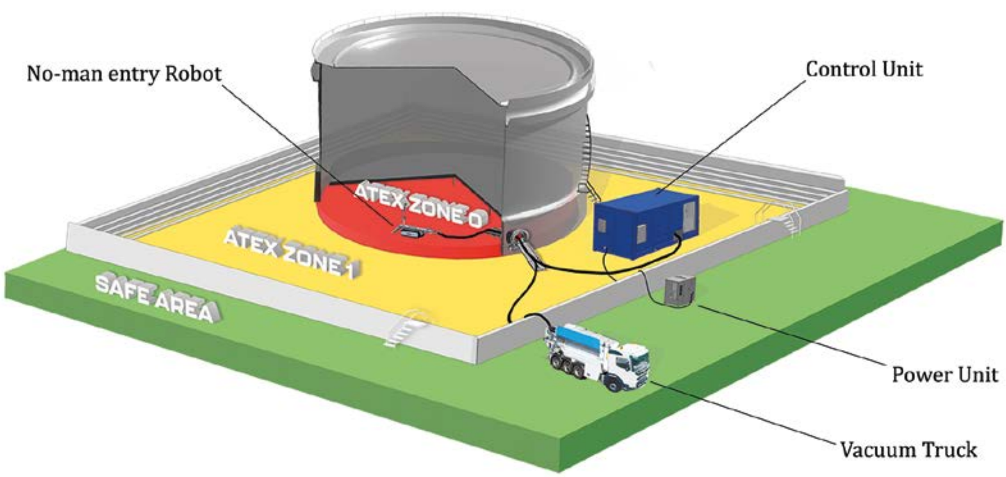


Figure 3. An example of a tank cleaning system with: no-man entry robot, control unit, power unit and vacuum truck.

The different types of robots on the market can be grouped into four families:
- Atex Robots for the suction of material in environments at risk of explosion.
- Vacuum robots that suck up material but do not have ATEX constraints.
- Underwater robots for cleaning collection basins containing plant-cooling water.
- Robot Diggers designed for the suction of solid material such as rubble or debris.

Then there are robots designed for specific functions such as materials handling (dozer) or video inspection of pipelines, pipes and tanks. The current state of the art imposes regulatory constraints and design constraints:
- Regulatory constraints:
  - ATEX Directive
  - Machinery Directive
- Design constraints:
  - Size of the manhole through which the robot enters the tank (typically Ø600 [mm]).
  - Type of tank: flat bottom, with internal pipes, with columns.
  - Works site logistics: distance between robot, suction system (vacuum truck) and control unit.

Currently, the connection between the operator and the machine (HMI) is managed by a programmable logic controller (PLC) for communication with the robot. The PLC transmits a video signal that is captured by on-board cameras and sent to the operator's control unit. In addition to the video feed, sensor data, such as inclinometer readings and gas detection measurements, can be transmitted depending on the sensors installed. This combined visual and sensor data enables the operator to remotely manoeuvre the robot and enable specific functions, such as deploying frontal augers or high-pressure jets.

5.2. Robot 4.0: future developments

Future developments for no-man entry robots will focus on equipping these machines with more advanced sensors to collect highly specific data and monitor a wider range of information. These enhancements are designed to expand the robots' functionalities beyond those currently available (suction and material removal), to include:
- Thickness Measurement: monitoring the structural integrity of tank, silo, and basin surfaces to detect corrosion risks and prevent potential spills, thereby mitigating environmental and health hazards.
- Weld Analysis: assessing the condition of welds to ensure structural integrity and prevent faults.
- Geolocators: enabling precise location tracking of robots – a crucial function in post-accident recovery scenarios.
- Work Mapping: monitoring robot operations to analyse performance through Key Performance Indicators (KPIs) for predictive maintenance management.
- Alert Systems: Implementing alert systems to notify operators of malfunctions or critical events.

While these advanced sensors do enhance robot functionality, their primary purpose is to address environmental and operational safety. For optimal operator safety, however, robots

must be integrated into a comprehensive ecosystem that also includes personnel and the work environment. For automation levels to be increased, robots need to be able to perceive their surroundings, just as domestic robot vacuum cleaners do. This requires equipping both the robot and the environment with sensors, infra red barriers or magnetic guides to define workspaces and access points.
An effective safety monitoring system in hazardous industrial environments must be designed to ensure reliable operation under challenging conditions without introducing additional risks. For example, the equipment used in refinery tank cleaning operations must ensure worker safety by adhering to stringent environmental and operational rules [8]. This points to a need for a holistic approach to safety that considers all aspects of the working environment and the interplay between humans and machines.

5.2.1. Environmental Resistance and Durability

To maintain functionality and reliability, technical devices deployed in refinery tank cleaning operations must withstand the following conditions:

- Extreme temperatures: operating reliably in ambient temperatures ranging from -20°C to +60°C.
- Exposure to moisture and chemicals.
- High-pressure cleaning resistance: withstanding regular cleaning using high-pressure washers.
- Mechanical vibrations: enduring continuous exposure to mechanical shocks and vibrations.
- UV radiation: operating effectively despite prolonged exposure to ultraviolet light.
- Impact resistance: withstanding accidental mechanical shocks without malfunctions.

5.2.2. Operational Efficiency and Reliability

An ideal monitoring system should function seamlessly in the background, with user intervention needed only in cases of genuine risk. To achieve this, the system must:

- Minimise false alarms: too many false alarms can lead to operator desensitisation and reduced trust in the system, with more chance of real hazards being ignored.
- Optimise power consumption: devices should require minimal recharging or battery replacements to ensure uninterrupted operation.
- Streamline system maintenance: routine inspections and software updates should be infrequent and non-disruptive to ongoing operations.

By meeting these stringent requirements, safety monitoring systems can effectively protect workers while ensuring cost-effective deployment and long-term sustainability in industrial environments.

5.2.3. Layered Architecture of an Industrial Safety Monitoring System

To ensure effective safety monitoring in hazardous industrial environments, the system should be divided into multiple functional layers, each responsible for a specific aspect of data collection, transmission, analysis, and presentation.

a) Data Acquisition Layer

This layer of the system comprises measurement sensors responsible for collecting the physical parameters needed to create analytical models that generate warnings and alarms. In the context of Industry 4.0, some of this data may already be produced by industrial machines, allowing for integration via standardised interfaces [9]. However, external sensors are often still required to capture a full range of parameters.

Considering the environmental and operational constraints previously discussed, wireless sensors are a preferred solution for data acquisition. Their key advantages include:

- Ease of Deployment: the absence of extensive cabling infrastructure simplifies installation and reduces maintenance requirements.
- Non-Intrusive Integration: many wireless sensors can be magnetically attached to monitored equipment without requiring design modifications.

The main drawback of wireless sensors is their reliance on battery power. However, recent advancements have significantly mitigated this issue through several key technologies:

- MEMS Technology: Micro-Electro-Mechanical Systems (MEMS) [10] enable ultra-low-power sensor operation, which dramatically reduces energy consumption.
- Energy Harvesting: energy harvesting techniques allow sensors to recharge using residual energy from industrial processes [11], [12], thus providing a sustainable power source.
- Ultra-Low-Power Microcontrollers: the use of ultra-low-power microcontrollers with wireless communication interfaces further extends battery life.
- Optimised Power Management: power management strategies, such as sleep-wake cycles, minimises energy consumption while maintaining data accuracy.

Through these combined optimisations, modern wireless sensors can operate on battery power for over a year at a sampling rate of once per second. This extended operational lifespan makes wireless sensors a practical and reliable solution for long-term industrial monitoring.

b) Transmission Layer

This layer is responsible for wirelessly transmitting collected data to a centralised database. Industrial environments present unique challenges for radio communication, such as:

- Structural obstacles (e.g., steel walls and machinery).
- High levels of electromagnetic interference.
- The need for coexistence with other wireless systems.

Various wireless communication standards can be used, including Bluetooth [13], ZigBee [14], [15], Z-Wave [16], Wi-Fi (802.11) [17], and LoRa [18], as well as proprietary short-range radio solutions. These technologies operate within frequency bands regulated by CEPT and ETSI, ensuring compatibility with industrial IoT applications.

(c) Analytical Layer

When sensor data reaches the system's central database, it undergoes processing and analysis. This analytical layer performs several key functions:

- Detection of anomalies: identification of abnormal conditions based on real-time sensor readings.
- Generation of alerts: triggering alerts when unsafe or critical situations are detected.
- Predictive Maintenance: implementing predictive maintenance models to assess machine health and forecast potential failures.

Key Parameters for Analysis

The analysis utilises several key parameters, including:

- Vibration Levels (Accelerometers): vibration data indicates machine status (idle, operational, overloaded) and can reveal imbalances, misalignments, or other mechanical issues.
- Temperature Readings: temperature measurements give insights into machine conditions and potential overheating risks, which can be indicative of various malfunctions.

By integrating these real-time measurements with expert knowledge and historical data, the system can accurately assess machine health, allowing it to determine whether a machine is operating correctly, experiencing performance degradation, or likely to fail in the near future [19], [20]. In the case of mobile machinery, movement patterns can be monitored and analysed to optimise operations and identify potential safety hazards. Of course, it should be noted that safety functions must comply with applicable regulatory requirements. In particular, the starting point is the IEC 61508 standard (IEC 61508 is "Functional safety of electrical, electronic and programmable electronic (E/E/PE) safety-related systems"). IEC 61508 is the basic functional safety benchmark that establishes the minimum safety requirements for safety-related systems to be applied in each specific industrial sector. The standards for safety instrumented systems for the process sector refer to IEC 61511. Even if IEC 61508 is the basic functional safety benchmark, any declaration of conformity with the Machinery Directive 2006/42/EC requires the application of additional requirements for the specific machinery sector under harmonised standards, which for functional safety are:

- IEC 62061: Safety of machinery – Functional safety of safety-related control systems.
- ISO 13849: Safety of machinery – Safety-related parts of control systems.

Both are harmonised for the Machinery Directive 2006/42/EC

6. SMART PPE: enhancing workers' safety

As previously discussed, no-man entry robots play a crucial role in enhancing safety within confined spaces. However, human operators remain key to ensuring safe operations. Operators are both active and passive actors in safety matters. They are subject to direct and indirect influences, which may involve both voluntary and involuntary actions (as defined in the above taxonomy). Operators must be equipped with wearable sensors in order to effectively function as key nodes within the Health and Safety network. These sensors not only enhance their safety but also support the execution of high-level professional performance.

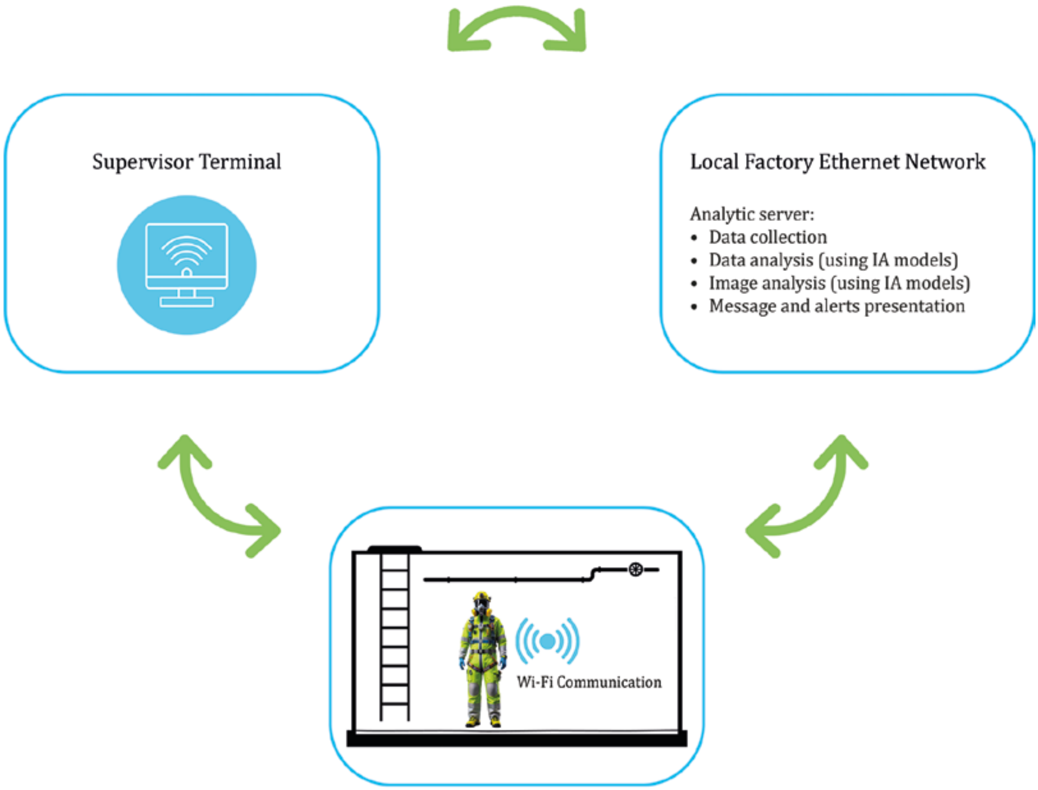


Figure 4. Connection between worker in a confined space and the IT Network.

a) Lone Worker System

Lone Worker Systems are safety solutions designed to protect employees who work alone without direct supervision [21], [22]. These systems are used across various industries and environments that may pose risks to workers, including refineries, technical services, security, forestry, and maintenance operations.

A typical Lone Worker System provides the following core functionalities:

- Worker Monitoring: real-time tracking of the worker's location and activity.
- Automated Alerts: automatic alerts to supervisors or emergency services if the worker becomes unresponsive within a predefined time.
- GPS and Geofencing: location detection and alerts if the worker leaves a designated safe zone.
- Panic Button: a dedicated button with which the worker can send an immediate distress signal in case of danger.
- Fall and Motion Detection: automatic alarm triggers based on sensors that detect falls or prolonged inactivity.

Lone Worker Systems can be implemented through various devices, including mobile apps, GPS devices, smart watches or dedicated telemetry systems. The system supports the above functionalities regardless of the platform chosen. These capabilities are enabled by equipping employees with portable devices containing appropriate sensors and communication technologies.

b) Smart Watches
Smart watches cified for use in potentially explosive atmospheres are commercially available [23] and comwith a range of functionalities that can improve worker safety. When coupled with appropriate software, these devices can provide the following key features:
- SOS Key: dedicated emergency button for lone worker protection.
- Motion Sensors: integrated accelerometer, gyroscope and magnetic sensor for activity tracking and fall detection.
- Environmental Monitoring: barometric pressure sensor for detecting changes in atmospheric pressure.
- Information Display: clear display of alarms, messages, and relevant information.
- Location Tracking: GPS or other positioning technology to pinpoint worker location.
- Physiological Monitoring: heart rate measurement to identify potential cardiovascular risks in supervised personnel.

These devices' unique capabilities, particularly the ability to monitor physiological data like heart rate, allows for the identification of health risks affecting the circulatory system. This provides an additional layer of safety for workers in hazardous environments.

c) Smart PPE
Workers cabe supplied with a new generation of Personal Protective Equipment (PPE). Known as "Smart PPE," this equipment is based on traditional PPE fitted with wireless sensors that connect with centralised software. This technology enables a continuous data flow from the work site, providing valuable insights into worker safety and well-being.

This text describes the supervisor's terminal designed to enhance safety for refinery kers. There follows an improved version with enhanced clarity, flow, and academic tone:
A supervisor's terminal used with refinery workers is a critical tool for ensuring workplace safety by enabling real-time monitoring, rapid communication and immediate response to potential hazards. This system provides supervisors with comprehensive situational awareness and facilitates proactive risk mitigation.
The supervisory terminal has the following key features:
- Interactive Dashboards: web-accessible dashboards display real-time safety data, including worker locations, hazardous conditions and compliance with safety protocols. This allows supervisors to effectively monitor risks across the refinery.
- Ongoing Work Parameter Evaluation: continuous tracking of key safety parameters, such as exposure to hazardous substances, equipment conditions and adoption of protective mea-

sures. This ensures a safer working environment by providing proactive alerts and insights.
- Alarms and Warnings: supervisors receive immediate alerts regarding dangerous situations, including gas leaks, excessive heat or worker inactivity. This enables rapid emergency response and facilitates injury prevention.
- Statistical Data Sharing: collection and sharing of safety-related statistics, including incident reports, near-miss events and compliance trends. This data allows refinery management to improve safety policies and prevent future accidents.
- Broadcast Messaging: rapid dissemination of safety alerts, evacuation orders or hazard warnings to all workers, ensuring clear communication during emergencies.
- Individual Messaging and Commands: direct communication with individual workers in high-risk areas, allowing supervisors to provide immediate instructions, check workers' well-being, or dispatch emergency assistance as needed.

Figure 5. Worker with wearable sensors (Smart PPE).

7. SMART ALERT: enhancing workers' safety

Having examined how robotic technologies and sensor-integrated Personal Protective Equipment (PPE) can improve work site safety, this paper shall now explore the role of Human-Machine Interface (HMI) technology applied to the operating environment. It shall investigate in particular how such technology can further protect personnel and systems from accidents. Work sites typically involve the use of a variety of machinery. Our approach involves monitoring the work environment with pre-existing or strategically placed sensors interfaced with a centralised system. This entails a retrofit system adaptable to existing machines and industrial infrastructure, enabling communication with the centralised system to ensure worker safety.

The proposed system offers the following functionalities:

- Environmental Monitoring and Alerts: the system can detect suspicious temperature increases via heat-sensitive wireless sensors and subsequently notify workers of potential hazards.
- Access Control based on Safety Checks: worker access to the site is contingent upon

verification of safe environmental and machinery conditions.
- Hazard Identification and Notification: the system can be configured to recognise specific hazards, such as closed and blinded pipes, and communicate this information to relevant parties.

These machines and the environment must be monitored by a system capable of continuous communication with the centralised portal. If safe conditions are not maintained, activities must be immediately halted, and workers evacuated. To ensure rapid and feasible implementation, systems must be developed to receive input from various machine types and convert this data into wireless output. This output should dynamically communicate with both workers and robots, providing real-time updates on the stability of safe conditions.

8. Conclusions: emerging risks

Confined spaces and hazardous environments represent a significant challenge in industrial environments. Methodologies for the clearance and cleaning of such spaces are changing radically. The shift is from operations performed by people to operations using remotely controlled automated systems (ROVs). The spread of this type of technology has been boosted by the ATEX Directives and a growing awareness of operator health and safety issues. The ATEX standards were specifically created to mitigate the risks associated with the use of machines in confined and explosive environments. They regulate the use of electrical and electronic components as well as mechanical components. Currently, the robots used for industrial cleaning are automated with remote control via a PLC. On-board sensors allow the control of certain machine functional parameters, mechanical anomalies or other telemetric indicators that give real-time information on the machine's status.

In the future, more sophisticated sensors may become available, allowing access to new functions beyond those already on the market. Most no-man entry robots are currently used for video-inspection, material suction or high-pressure jet cleaning. In the near future, robots may also be able to check the thickness of surfaces or the soundness of welds, etc. These functions are, however, only indirectly related to safety issues. Operations within confined spaces still in fact require a human presence. Some tasks require specific human skills and expertise that cannot currently be fully automated. The potential of these robots – especially in terms of safety – is inextricably linked to their functioning as a node in a wider network that includes people and the working environment. The robot/people/environment triad is at the core of this paper's argument: thanks to the sensors installed (on robots and in the work environment) or worn (on people), each of the three elements can communicate bidirectionally with the other elements and with a centralised system.

Information gathered from the field – and from other sources, such as technical documents, protocols, policies, etc. – can feed into a central system. By leveraging Artificial Intelligence, the system can provide task support for operators and command robot use autonomously. The introduction of advanced sensors in robots, people (SMART PPE) and work environments (SMART ALERT) entails a need for improved cybersecurity or privacy compliance for sensors worn by operators. These two issues are, however, common to many other sec-

tors where digital technologies and artificial intelligence are spreading, and it is from these sectors that best practices can be borrowed and used to manage related risks.
Implementing this solution is a complex undertaking that requires the cooperation of regulators, practitioners and asset owners. But the main objective remains clear: to prioritise safety and save human lives.

References

[1] '1910.146 – Permit-required confined spaces | Occupational Safety and Health Administration'. Accessed: Feb. 25, 2025. [Online]. Available: https://www.osha.gov/laws-regs/regulations/standardnumber/1910/1910.146

[2] 'Sistema di sorveglianza degli infortuni mortali sul lavoro'. [Online]. Available: https://www.inail.it/content/dam/inail-hub-site/documenti/2017/06/Scheda11-InforMO.pdf

[3] 'Directive – 2014/34 – EN – ATEX directive – EUR-Lex'. Accessed: Feb. 25, 2025. [Online]. Available: https://eur-lex.europa.eu/eli/dir/2014/34/oj/eng

[4] 'La strage di Viareggio dall'archivio ANSA – Notizie – Ansa.it'. Accessed: Feb. 25, 2025. [Online]. Available: https://www.ansa.it/sito/notizie/cronaca/2024/06/29/la-strage-di-viareggio-dallarchivio-ansa_d7db8705-e296-4df7-9d57-680dc617e820.html

[5] Bird & Bird – Giulia Brambilla, 'Legislative Decree No. 81/2008', Lexology. Accessed: Feb. 25, 2025. [Online]. Available: https://www.lexology.com/library/detail.aspx?g=38af885f-8f8b-4844-ad0a-577b56cea043

[6] 'Tank Terminals in Europe – Key Figures'. FETSA Federation of European Tank Storage Associations. [Online]. Available: https://fetsa.eu/wp-content/uploads/2023/05/FETSA-TT-Key-Figures-2022.pdf

[7] 'UNI/PdR 97:2020 – UNI Ente Italiano di Normazione'. Accessed: Feb. 26, 2025. [Online]. Available: https://store.uni.com/uni-pdr-97-2020

[8] M. Y. Aalsalem, W. Z. Khan, W. Gharibi, M. K. Khan, and Q. Arshad, 'Wireless Sensor Networks in oil and gas industry: Recent advances, taxonomy, requirements, and open challenges', *Journal of Network and Computer Applications*, vol. 113, pp. 87–97, Jul. 2018, doi: 10.1016/j.jnca.2018.04.004.

[9] H. Lasi, P. Fettke, H.-G. Kemper, T. Feld, and M. Hoffmann, 'Industry 4.0', *Bus Inf Syst Eng*, vol. 6, no. 4, pp. 239–242, Aug. 2014, doi: 10.1007/s12599-014-0334-4.

[10] M. Varanis, A. Silva, A. Mereles, and R. Pederiva, 'MEMS accelerometers for mechanical vibrations analysis: a comprehensive review with applications', *J Braz. Soc. Mech. Sci. Eng.*, vol. 40, no. 11, p. 527, Oct. 2018, doi: 10.1007/s40430-018-1445-5.

[11] V. Marsic, M. Zhu, and S. Williams, 'Design and implementation of a wireless sensor communication system with low power consumption for energy harvesting technology', in *2011 19th Telecommunications Forum (TELFOR) Proceedings of Papers*, Nov. 2011, pp. 607–610. doi: 10.1109/TELFOR.2011.6143621.

[12] Y. Han, Y. Feng, Z. Yu, W. Lou, and H. Liu, 'A Study on Piezoelectric Energy-Harvesting Wireless Sensor Networks Deployed in a Weak Vibration Environment', *IEEE Sensors Journal*, vol. 17, no. 20, pp. 6770–6777, Oct. 2017, doi: 10.1109/JSEN.2017.2747122.

[13] C. Bisdikian, 'An overview of the Bluetooth wireless technology', *IEEE Communictions Magazine*, vol. 39, no. 12, pp. 86–94, Dec. 2001, doi: 10.1109/35.968817.

[14] Manpreet and J. Malhotra, 'ZigBee technology: Current status and future scope', in *2015 International Conference on Computer and Computational Sciences (ICCCS)*, Jan. 2015, pp. 163–169. doi: 10.1109/ICCACS.2015.7361343.

[15] C. M. Ramya, M. Shanmugaraj, and R. Prabakaran, 'Study on ZigBee technology', in *2011 3rd International Conference on Electronics Computer Technology*, Apr. 2011, pp. 297–301. doi: 10.1109/ICECTECH.2011.5942102.

[16] C. Paetz, *Z-Wave Essentials*. eBook Partnership, 2017.

[17] N. P. Reid and R. Seide, *Wi-Fi (802.11) Network Handbook*, 1st ed. McGraw-Hill Osborne Media, 2002.

[18] S. Devalal and A. Karthikeyan, 'LoRa Technology – An Overview', in *2018 Second International Conference on Electronics, Communication and Aerospace Technology (ICECA)*, Mar. 2018, pp. 284–290. doi: 10.1109/ICECA.2018.8474715.

[19] K. Szczyrba, M. Sikora, and \Lukasz Wróbel, 'Monitoring and diagnostics of a belt conveyor based on a wireless system for measurement and analysis of the vibrations level', *Studia Informatica*, vol. 39, 2018.

[20] M. Hermansa, M. Kozielski, M. Michalak, K. Szczyrba, \Lukasz Wróbel, and M. Sikora, 'Sensor-based predictive maintenance with reduction of false alarms – A case study in heavy industry', *Sensors*, vol. 22, no. 1, p. 226, 2021.

[21] N. Mohankumar, K. K. Manivannan, A. Ramesh Babu, M. M. Sampoornam, R. Kambattan Kovarasan, and C. Srinivasan, 'Cloud-Connected Wearable Devices for Lone Worker Protection With Wireless Sensor Networks', in *2024 4th International Conference on Sustainable Expert Systems (ICSES)*, Oct. 2024, pp. 351–356. doi: 10.1109/ICSES63445.2024.10763014.

[22] 'Rail Lone Worker Safety Solution with Deep Learning'. Accessed: Feb. 25, 2025. [Online]. Available: https://ieeexplore.ieee.org/abstract/document/9767482

[23] G. Ondrey, 'Focus on Mobile Devices. | EBSCOhost'. Accessed: Feb. 25, 2025. [Online]. Available: https://openurl.ebsco.com/contentitem/gcd:159460822?sid=ebsco:plink:crawler&id=ebsco:gcd:159460822

Building Information Modeling for Advancing Occupant's Health through Green Certifications and Indoor Environmental Quality

Giuliana Parisi[1], Stefano Cascone[2*] and Rosa Caponetto[1]
[1] Department of Civil Engineering and Architecture – University of Catania, Catania, Italy
[2] Department of Architecture and Territory – Mediterranea University of Reggio Calabria, Reggio Calabria, Italy

* E-mail: stefano.cascone@unirc.it

Abstract. The integration of advanced digital technologies, particularly Building Information Modeling (BIM), is transforming the design, construction, and operation of buildings aiming to create more sustainable, comfortable, high performing and safer built environments. This study investigates the intersection of BIM, sustainability certification frameworks (e.g., LEED, BREEAM, WELL, etc.), and Indoor Environmental Quality (IEQ) categories, emphasizing their combined role in advancing health-focused sustainability standards in work environments. Through a synthesis of previous studies, this research examines how BIM streamlines the processes associated with green building certifications by automating evaluations of key IEQ categories. The analysis categorizes results into four subcategories of IEQ: Indoor Air Quality (IAQ), Thermal Comfort, Visual Comfort, and Acoustic Comfort. IAQ focuses on pollutant reduction, ventilation, and air quality monitoring for occupant health. Thermal Comfort ensures optimal temperature and humidity through HVAC design and passive strategies. Visual Comfort optimizes natural and artificial lighting to enhance well-being and reduce energy consumption. Acoustic Comfort minimizes noise through insulation and absorption materials. These subcategories enhance "Healthy Building" while advancing sustainability goals, which align with both IEQ-related certifications and European Union policies (Agenda 2030). Their implementation highlights BIM's potential to mitigate risks linked to poor air quality, inadequate lighting, and thermal and acoustic discomfort, directly impacting occupant well-being. Despite its significant potential, challenges remain in standardizing BIM workflows to incorporate diverse IEQ parameters across certification systems. The absence of comprehensive frameworks for aligning advanced BIM models with health-focused certification requirements highlights the need for further research and interdisciplinary collaboration. By bridging the gap between sustainability frameworks, digitalization, and IEQ improvements, this study provides actionable insights into how BIM can transform workplace health and sustainability standards. It emphasizes the importance of leveraging BIM as a tool to achieve compliance with green

building certifications while advancing occupant well-being and health in work environments.

Keywords: Digital Tools, Data-Driven Optimization, Environmental Monitoring, Smart Building Technologies, BIM

1. Introduction

Nowadays, people spend most of their time indoors, making indoor environmental conditions a key factor in occupants' well-being [1]. Indoor environmental quality (IEQ) significantly affects health and comfort in both residential and workplace settings, directly influencing living and working conditions [2]. In particular, research has focused on assessing IEQ to prevent issues such as Sick Building Syndrome (SBS), a condition associated with poor air quality, inadequate ventilation, and exposure to pollutants, all of which negatively impact occupants' health. Research on this topic continues to support the development of the "Healthy Buildings" concept, which is grounded in a broad set of scientific studies [2]. The World Health Organization (WHO) recognizes the influence of the built environment on public health, with particular attention to densely built-up contexts [3]. Moreover, workplace regulations have progressively incorporated requirements aimed at ensuring healthy indoor environments, aligning with the United Nations' Sustainable Development Goals (SDGs), particularly SDG 3, SDG 8, and SDG 11, which promote health, safe working conditions, and sustainable urban development [4].

This framework reflects a growing awareness of the relationship between IEQ and well-being, emphasizing the importance of appropriate design and management strategies to safeguard occupants' health. As outlined, the certification schemes include categories focused on optimizing health and well-being in the indoor built environment. Rating systems are structured as point-based frameworks, with categories that encompass various credits, which collectively determine the final sustainability score attributed to the building [5]. The most widely recognized international systems include WELL Building Standard, Leadership in Energy and Environmental Design (LEED), and Building Research Establishment Environmental Assessment Method (BREEAM). These rating systems feature categories, such as "Indoor Environmental Quality" (IEQ) in LEED [6] and "Health and Well-being" in BREEAM [7], which primarily focus on improving IEQ by implementing strategies like minimizing air pollutants and reducing other sources of indoor environmental distress [8]. Such findings further highlight the importance of healthy indoor environments in improving both the physical and mental well-being of building occupants.

Ensuring high IEQ requires an integrated approach that considers multiple design, construction, and operational strategies [9]. In this regard, digital methodologies such as Building Information Modeling (BIM) offer advanced tools to support decision-making processes aimed at enhancing IEQ.

BIM enables the creation of an information-rich model that facilitates the analysis and management of key environmental parameters, including air quality, thermal comfort, acoustic performance, and lighting conditions. Within the framework of the European Union's digital transition agenda, the adoption of BIM represents a crucial step toward more effective and data-driven strategies for improving indoor environmental conditions [10]. When integrated with advanced digital tools, such as Visual Programming Languages and Textual Programming Languages, BIM enables the execution of sustainability analyses and ensures the management of comfort and well-being throughout the entire building lifecycle, from the design phase to the operational phase [11]. By enabling detailed modelling and the integration of multidisciplinary data, BIM enhances informed decision-making, improves coordination among designers, engineers, and contractors, and optimizes resource efficiency. This approach facilitates buildings performance and supports IEQ control, ultimately contributing to the sustainability and well-being of building occupants.

Previous studies examine the integration of BIM methodology with green building certification systems, with a particular focus on the "IEQ" category. This underscores the growing relevance of the topic and the need to consolidate existing knowledge to enable future developments in sustainability. Existing review articles, such Jayasanka et al. [12] discusses the role of various digital approaches, such as BIM with plug-in software, BIM ontology, and cloud-BIM, in supporting the "IEQ" credit category. It highlights the growing role of automation in sustainability assessments, particularly in evaluating IEQ impacts, and calls for further exploration and standardization. Olanrewaju et al. [13] analysed articles from 2009 to 2020 on BIM-based tools for Green Building Certification Systems (GBCS), focusing on Green Star. They found that 35% of the articles addressed the "IEQ" category and identified 85 software packages, including Autodesk Revit, Tally, IES-VE, and Dynamo, used to evaluate indoor environmental distress. Caravalho et al. [14] reviewed the integration of building sustainability assessment (BSA) during the design process, particularly focusing on LEED, BREEAM, and SBTool. They found that BIM, particularly Autodesk Revit, was widely applied in assessing "IEQ" criteria, often in combination with external tools like Athena Impact Estimator, Ecotect, and IES-VE. Finally, Ansah et al. [15] provided an overview of the integration between BIM and Green Building Assessment Systems (GBAS), emphasizing the "IEQ" category. They categorized the identified tools into BIM modelling tools, performance assessment tools, and auxiliary tools, and stressed the importance of automating sustainability indicator calculations and addressing interoperability issues to reduce manual errors.

These previous review studies examine the integration of BIM with various digital tools to automate and enhance sustainability evaluations. They highlight the diversity of available tools, with Autodesk Revit being particularly prevalent due to its capacity to manage BIM models [16]. However, despite the growing adoption of BIM in sustainability assessments, none of the reviewed studies specifically address the integration of BIM with rating systems for credit validation and verification concerning key aspects of IEQ. Addressing this gap could facilitate the development of more precise and automated tools for "IEQ" credit validation and verification, thereby improving the accuracy and efficiency of sustainability assessments and ensuring a more reliable integration of BIM with rating systems throughout the project lifecycle.

This review adopts the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) methodology [17] to systematically assess the current state of digital approaches for "IEQ" category evaluations. Specifically, it aims to:

- Analyse the credits within the "IEQ" category, grouping studies that address similar indicators into broader "IEQ" subcategories to facilitate the analysis process.
- Conduct an in-depth examination of the current state of automation in "IEQ" credit validation and verification across different rating systems, outlining the BIM-based strategy proposed in each study.
- Provide a comprehensive overview of the key limitations, advantages, and potential future developments in the digital integration of BIM frameworks for automating "IEQ" credit validation and verification.
- Propose optimization strategies to enhance existing frameworks, addressing their limitations and advancing toward a fully automated process.

The proposed study is aimed at stakeholders involved in building design, construction, and operation, as it explores how the integration of BIM with rating systems can enhance IEQ. By leveraging BIM-based approaches, the findings contribute to the development of more effective assessment tools that support healthier and safer indoor environments. This perspective aligns with the broader discussion on the impact of digital technologies in mitigating occupational risks and improving well-being in increasingly digitalized workspaces.

2. Methodology

This review used the PRISMA methodology to analyse data management for sustainability evaluations in the built environment, with a focus on BIM and its integration with rating systems. The review specifically examines the "IEQ" category as key tools for assessing sustainability.
To identify relevant literature, the Scopus database was searched using Boolean operators applied to the "Title, Abstract, and Keywords" fields. The selection process was limited to peer-reviewed journal articles, yielding an initial set of 47 publications, of which 8 were ultimately deemed relevant to this review.
Among these, 4 articles presented BIM-based frameworks directly related to the "IEQ" category, while the remaining 4 articles proposed BIM methodologies that, although not specifically designed for "IEQ", indicated that they could also be applied to the validation and verification of "IEQ" category credits. The research process is outlined in Figure 1.
To facilitate the analysis process, the results were categorized into four IEQ subcategories based on key factors influencing IEQ: Indoor Air Quality, Visual Comfort, Thermal Comfort and Acoustic Comfort.
In the next section (Section 3), a distribution of the contents from the analyzed papers was proposed into the four IEQ subcategories. In sub-sections 3.1 to 3.4, each of the IEQ subcategories and the associated "IEQ" category credits were analyzed by investigating the workflows proposed in the articles identified during the systematic literature review (SLR). Finally, in Section 4, a proposal for further exploration is presented, where the limitations of the analyzed frameworks are examined, and optimization strategies are outlined that could enable the full automation of the validation and verification process for the "IEQ" category credits.

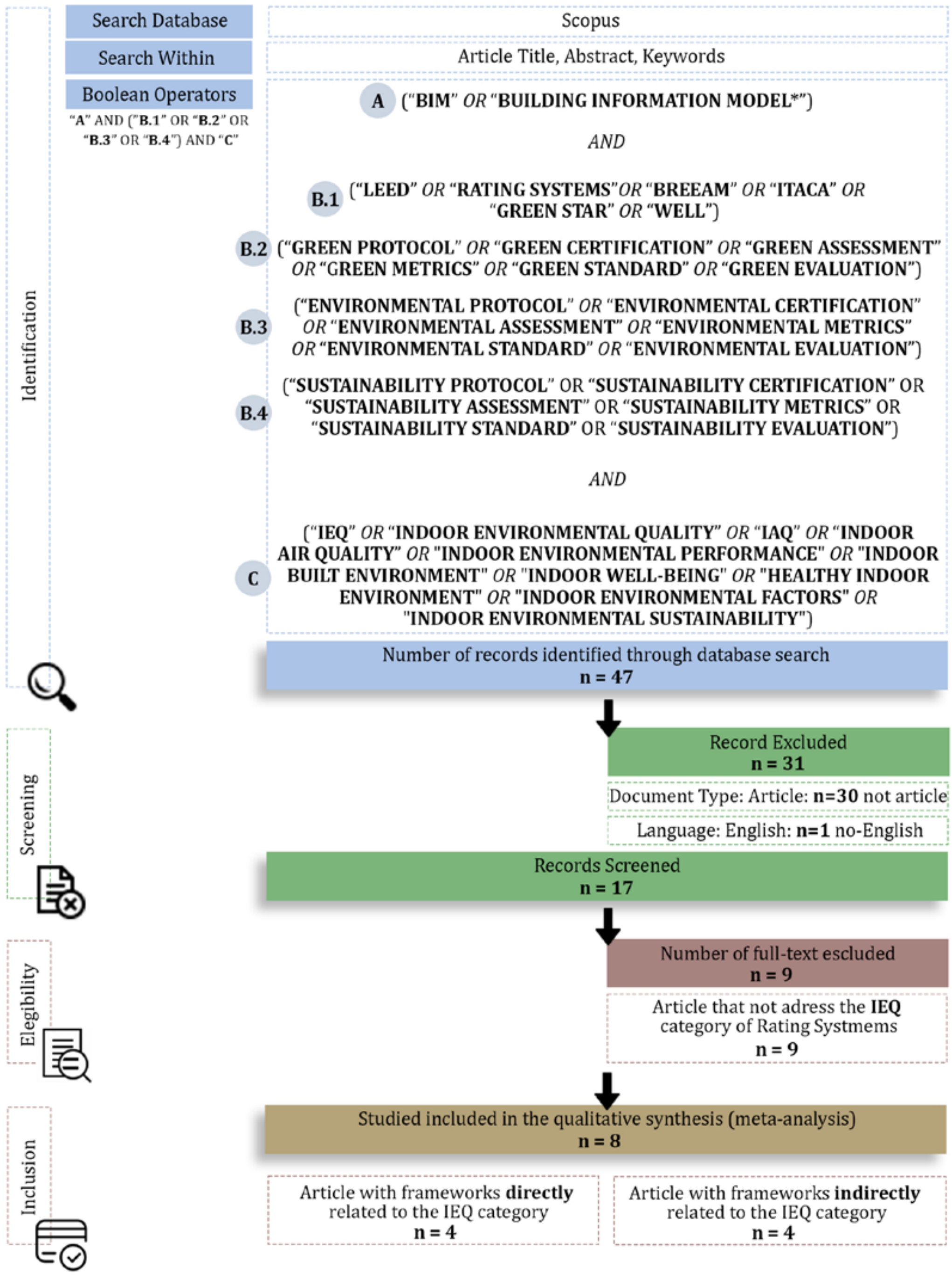


Figure 1. Methodology flowchart

3. Analysis of the IEQ subcategories

Table 1 provides a structured analysis of the subcategories of IEQ addressed in the various articles, highlighting both the topics discussed and the and the tools used for the BIM-based framework.

Ref.	IEQ subcategories				Tools
	Indoor Air Quality (IAQ)	Thermal Comfort	Visual Comfort	Acoustic Comfort	
[18]	x				BIM, CFD, GA, ML
[19]	x	x	x	x	BIM
[20]	x	x			WSN, BIM, MS Access
[21]	x				BIM, Dynamo, Google Spreadsheet, Autodesk Model Checker
[22]		x			WSN, BIM, MS Excel, C# Software, MS Access
[23]		x	x		BIM, Design Builder, External Software
[24]			x		BIM, Dynamo, External Software
[25]			x		BIM, Dynamo

BIM = Building Information Modeling, CFD = Computational Fluid Dynamics, GA = Genetic Algorithms, ML = Machine Learning, WSN = Wireless Sensor Network

Table 1. Distribution of studies across the subcategories of IEQ category credits.

It was observed that the distribution of the subcategories varied significantly across the reviewed articles. In fact, the Indoor Air Quality (IAQ) category was examined in four articles [18], [19], [20], [21], suggesting a widespread interest in IAQ, likely linked to the increasing focus on the healthiness of indoor environments and the reduction of indoor pollutants, as also evidenced rating systems specific to both indoor and outdoor comfort, such as the WELL Building Standard. Thermal Comfort was addressed in five articles [18], [19], [20], [22], [23] suggesting that the evaluation of thermal comfort is a key aspect in the design and management of buildings. Visual Comfort was analyzed in four articles [19],

[23], [24], [25], and was a subject of research, often supported by digital tools for modeling and simulation. Lastly, Acoustic Comfort was the least addressed subcategory, with only one article [19], highlighting a potential gap in research and a lower application of BIM-based strategies for environmental acoustics analysis.

Regarding the tools used in the BIM-based framework, the BIM methodology, common to all the references, was frequently combined with other digital tools. For Thermal Comfort, the use of Computational Fluid Dynamics (CFD) was highlighted, and, as in the case of IAQ, methodologies based on Machine Learning (ML), Genetic Algorithms (GA), and the use of Wireless Sensor Networks (WSN) were also found, combined with BIM and data management software (MS Access, MS Excel, C# Software). Acoustic Comfort was addressed exclusively through the BIM methodology. Lastly, Visual Comfort mostly involved the intersection of the BIM methodology and visual programming tools such as Dynamo. Overall, digitalization played a key role in analyzing the various subcategories of environmental comfort, with methodologies varying depending on the specific topics addressed.

Figure 2 presents a graphical representation of the workflows used by the analyzed articles for the validation and verification of the IEQ subcategories. This visualization offers a comprehensive overview of how BIM-based framework enhance integration with rating systems, helping to identify efficient practices and optimize the validation process for IEQ category.

3.1. Indoor Air Quality (IAQ)

The IAQ subcategory aims to ensure healthy indoor air by minimizing pollutant concentrations and enhancing ventilation. IAQ is crucial for occupant health and well-being, as poor air quality could lead to respiratory issues, fatigue, and reduced productivity. To improve IAQ, rating systems incorporates strategies such as proper filtration and ventilation to mitigate pollutants like VOCs, PM2.5, and CO_2, source control (e.g., low-emission materials, tobacco smoke reduction), and air quality monitoring through sensors to maintain optimal comfort and safety in both residential and workplace environments.

A multi-zone IAQ optimization framework was developed by Cheng et. al [18], considering variable environmental conditions such as seasonal changes, MVAC (Mechanical Ventilation and Air Conditioning) system settings, limited access to certain areas within occupied buildings and the distribution of heat and CO_2 emission sources. The authors proposed an approach based on BIM, CFD, GA, and ML to optimize sensor placement for IAQ monitoring. The methodology was tested against the IEQ credit requirements of LEEDv4, achieving a coverage of over 70% of areas with significant CO_2 variations. The BIM model provided data for CFD simulations and based on the validated model, scenario analyses were conducted to estimate the distribution of temperature and CO_2. Using Value Encoding strategies, GA-based ML algorithms optimized sensor placement. The verification process included coverage assessment to evaluate compliance with LEED sensor distribution criteria and accuracy assessment to determine the sensors' ability to detect significant variations. The optimized sensor placement provided significantly more effective coverage in areas with substantial variations in temperature and CO_2 compared to random or uniform distributions. However, the study only considered CO_2 concentration for sensor placement, excluding other common air pollutants, such as particulate matter (PM), which could have impacted overall occupant comfort.

Indeed, assuming that the assessment IAQ considers several factors, including the building's ventilation system, construction materials, and activities that may affect the healthiness of indoor environments, Larsen et al. [19] proposed an analysis that took into account the concentration of PM in outdoor air, the efficiency of mechanical or natural ventilation, and the presence of certified low-emission materials. The proposed framework, based on data derived from the BIM model and on-site investigations, suggested manually evaluating technical solutions for controlling internal pollution sources, such as additional ventilation systems and exhaust hoods. It also considered the possibility for occupants to improve air quality by opening windows, activating mechanical ventilation, or using automated systems based on CO_2 sensors. However, this was a completely manual process: data extraction, processing, and analysis were carried out manually, without the use of automated procedures, leading to extended timelines and increased costs due to a high probability of errors. Marzouk et al. [20] also proposed a framework in which the comparison of measured values with threshold indicators was performed manually. Within this framework for monitoring IAQ, field measurements were conducted using the Aerocet-51 device, which is designed for accurate monitoring of PM, a key indicator of IAQ. The data related to PM measurements were transmitted via a wired connection to a central computer and stored in Comma Separated Values (CSV) format. These data were subsequently transferred to an Access database and eventually exported to Autodesk Revit using an import/export tool. In the BIM environment, a manual comparison was carried out against threshold indicators defined by the relevant rating systems to validate the IAQ parameter verification. This approach, though effective for small-scale validation, is limited in terms of scalability and automation, as it relies heavily on manual processes for data comparison and integration within the BIM framework. To overcome these limitations, it was useful to develop workflows where data processing was either semi-automated or fully automated. D'Amico et al. [21], for instance, proposed a BIM-based workflow for controlling and verifying the emissions of volatile organic compounds (VOCs) from building materials and their concentration in indoor environments to improve IAQ. The proposed methodology consisted of four main phases. The first phase involved defining IAQ parameters using the IFC standard to ensure compatibility across different software. The second phase focused on developing an automated process to apply the parameters to BIM elements, with tools such as ParaManager and Google Spreadsheet used to manage and share the data. Parameter control was conducted through Model Checker for Revit, which allowed saving and sharing the workflow in XML format, thus enabling the sharing of results with the scientific community. The third phase integrated a VOC concentration prediction model into the BIM model, utilizing Dynamo scripts to calculate and transfer material emission values into Revit. Finally, the fourth phase involved developing a model checker to verify the concentration of TVOCs in the model's indoor environments, comparing emission values with predefined thresholds in an automated manner using Autodesk Model Checker. This approach allowed for the monitoring and optimization of IAQ while ensuring compliance with environmental sustainability standards,

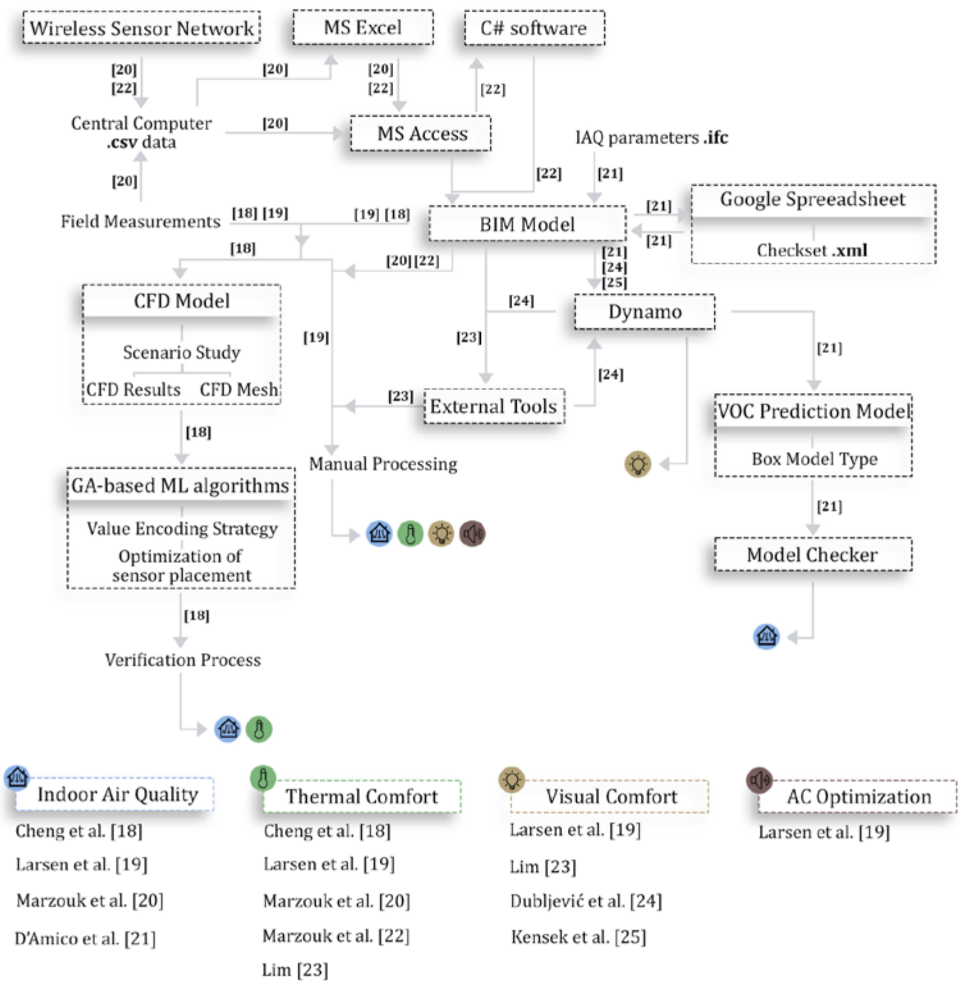


Figure 2. Workflow visualization for the optimization of IEQ subcategories in the analysed articles.

such as BREEAM and the Italian CAMs. However, it presented some limitations, such as the lack of complete information in IFC formats and the difficulty in integrating complex variables into IAQ simulations.

3.2. Thermal Comfort

The Thermal Comfort subcategory focuses on creating thermally comfortable indoor environments to enhance well-being and productivity. Inadequate temperature and humidity levels could cause discomfort, reduced concentration, and energy inefficiencies. To ensure optimal thermal comfort, rating systems includes criteria such as HVAC system design to maintain appropriate temperature and humidity levels, monitoring and controlling indoor temperatures, and integrating passive design strategies such as radiant surfaces and natural ventilation. In particular, the LEED certification assesses thermal comfort based on ASHRAE standards.

The IEQ subcategory of thermal comfort was addressed in five articles, three of which [18], [19] [20] had already been discussed in Section 3.1 on IAQ. However, it was possible to outline some fundamental methodological differences proposed by the authors.

In the workflow proposed by Cheng et al. [18], scenario studies were conducted for the verification and validation of Thermal Comfort, considering different seasons, various HVAC system settings, and different occupancy scenarios to assess temperature and humidity variations under changing boundary conditions. Additionally, heatmaps were generated to verify whether the sensors could detect significant temperature changes. In the certification tool developed by Larsen et al. [19] (Figure 2), the manual analysis of thermal comfort considered both winter and summer temperature conditions, air currents, and the occupants' ability to regulate these factors. The assessment involved manual calculations of temperature control, ventilation, and shading, evaluating their influence on indoor thermal comfort. The semi-automatic process developed by Marzouk et al. [20] required the implementation of a Wireless Sensor Network (WSN) connected to a BIM model for collecting thermal comfort values. The temperature and humidity data measured by the WSN were transmitted to a central computer via a wireless module and stored in Comma Separated Values (CSV) format. The data were then transferred to an Access database, exported to Autodesk Revit, and analyzed. The same authors also proposed a framework exclusively for the validation of Thermal Comfort indicators [22]. In this second workflow, the BIM model included a virtual element called the "Thermal Comfort Monitor," which stored the data collected from the WSN. The temperature and humidity sensors sent data to a receiver node, connected to a computer that imported the readings into the BIM model. Zigbee technology was used for data transmission due to its low energy consumption and wide coverage range. The sensors were connected to an Arduino Uno board, which sent the data to an Excel file via the Gobetwino software. The collected data were then recorded in Excel and associated with a Microsoft Access database for further processing and analysis. Interaction between the BIM model and the database occurred through the Revit Database Link, a C# module that automatically calculated the average of the readings and stored the data in the database. Finally, through manual assessments, the acceptability of the values was determined based on predefined thresholds. This systematic data collection allowed for more precise control over environmental conditions and enabled prompt interventions to ensure occupant well-being. However, there were some limitations to consider: the system depended on the quality and reliability of the WSN sensors, which could have issues compromising data accuracy. Furthermore, scalability posed a challenge, as implementing such a system on a large scale could present difficulties in terms of cost and data management, especially in environments with numerous sensors and complexities in their management.

The validation and verification of thermal comfort indicators included in the LEED and BREEAM rating systems were also carried out in the workflow proposed by Lim [23]. This workflow began with the modeling of the building in BIM software such as Autodesk Revit, Graphisoft Archicad, and Bentley Systems. Once the modeling was completed, the model could be exported in various formats, depending on the type of analysis to be performed. The main formats included IFC (Industry Foundation Classes), used to ensure interoperability between different software and gbXML (Green Building Extensible Markup Language), designed for sustainability analysis tools. The exported model was then imported into specific sustainability analysis software, which allowed the environmental performance of the building to be evaluated. For Thermal Comfort indicators, the external software Design Builder was used, which offers features with a particular focus on Thermal Comfort assessment according to the BREEAM system. In this workflow, the need for manual operations and the export of the BIM model to third-party sustainability simulation tools resulted in a non-dynamic BIM model. Indeed, after obtaining the results from the simulations, any changes made to optimize performance could not be automatically translated back into the BIM model.

3.3. Visual Comfort

The Visual Comfort subcategory aims to optimize both natural and artificial lighting, as inadequate lighting conditions could lead to eye strain, headaches, and sleep-wake cycle disruptions. Rating systems promotes the use of optimized natural lighting to reduce energy consumption while enhancing comfort, along with high-quality artificial lighting that ensures appropriate illumination levels, glare control, and color rendering. Notably, the WELL certification includes advanced criteria such as circadian lighting design, which adjusts the color temperature of light to support occupants' biological rhythms.

The visual comfort subcategory was explored in four articles, with two [19], [23] already covered in Sections 3.1 and 3.2. Nonetheless, it was possible to identify key methodological distinctions put forward by the authors.

In the analysis of indicators related to Visual Comfort, Larsen et al. [19] evaluated natural light, direct sunlight, view quality, and occupant control. Using a 3D BIM model, they performed manual calculations considering factors such as glazed area, glass type, and orientation. They assessed view quality both in terms of visual benefits for occupants and privacy, as well as the control of solar shading, distinguishing between fixed and adjustable systems. Occupant control was less emphasized, given its limited impact during the design phase. In the methodological workflow developed by Lim [23], for the evaluation of Visual Comfort indicators, data extracted from BIM models in various formats were imported, in most cases, into the external software IES <VE>. This software allowed simulations of both natural and artificial lighting, analyzing parameters such as illuminance, luminance, daylight factor, and glare. It also included a specific analysis for visual comfort credits according to the LEED protocol.

The automation of the Daylighting section within the Hea01 Visual Comfort category of the BREEAM rating system was addressed by Dubljević et al. [24]. BREEAM provided users with a manual calculator in Excel format for calculating the Hea01 credit. One of the main challenges in using this calculator was the time and effort required to prepare the input data, which could be significant. To overcome these limitations, the authors developed a methodology for creating a workflow capable of providing an automated analysis of BREE-

AM credit achievement within a BIM environment. By analyzing the Hea01 Calculator, the relevant data for the analysis were selected and identified. The selected requirements were parameterized, and the corresponding data were made available within the BIM model elements so that, upon activation of the algorithm developed in Dynamo, these data could be extracted from the three-dimensional model. To automate the credit evaluation, additional scripts in Dynamo were developed, processing the geometric and informational data of the BIM model and providing the real-time output "Credits achieved." The developed framework enabled the verification of all credit-related options, though with some differences: some options were validated through the extraction and analysis of BIM data via the designed algorithm, whereas others required the integration of the framework with external simulations, such as Autodesk Revit Insight. The reliance on simulation tools thus represented a significant limitation of the framework, as it required external software to ensure a complete verification. Moreover, another limitation of the framework was that the script did not provide suggestions for alternative design solutions to maximize the achievable credit score, thereby restricting the designer's ability to proactively optimize the project.

The BIM methodology and the Visual Programming Language (VPL) Dynamo were also implemented in the workflow developed by Kensek et al. [25]. Specifically, the authors proposed a framework that utilized Dynamo integrated with Revit to automate the analysis of interior lighting, assessing the control of emitted light during nighttime hours. The workflow required the designer to create the building model in Revit using customized families containing parameters related to the data required by visual comfort credits. These parameters were either inserted as type parameters within the family, applicable to all instances of that component, or as material properties. Subsequently, through a Dynamo script designed by the user, the data were extracted from the BIM model and processed by the script. In Dynamo, the final result was calculated using Boolean operators to verify compliance with the conditions. If all criteria were met, the system generated a "Pass"; otherwise, it returned a "Fail," indicating whether the project met the LEED requirements. The integration of Dynamo with Revit offered several advantages, such as automating the calculation of lighting requirements, reducing manual work, and improving the efficiency of the design process. It allowed designers to quickly assess their choices concerning LEED requirements on existing BIM models. However, the system had certain limitations, including the lack of an updated external database, which restricted automation, and the absence of suggestions for alternative solutions to improve the design.

3.4. Acoustic Comfort

The Acoustic Comfort subcategory focuses on minimizing unwanted noise and enhancing indoor acoustics to support concentration and well-being. This is achieved through criteria that addressed sound insulation, control of mechanical noise from HVAC systems and technological equipment, and the use of acoustic absorption materials to reduce reverberation and improve sound clarity in enclosed.

This subcategory was examined in only one article, partially covered in Sections 3.1, 3.2, and 3.3. However, the analysis revealed key methodological differences proposed by the authors.

The evaluation of acoustic comfort in the workflow proposed by Larsen et al. [19] considered various factors, including noise from external sources and building technical systems, as well as the ability of occupants to regulate the acoustic environment. The analysis was based on parameters related to the construction characteristics, such as wall insulation and window type, and used normative criteria to determine the acoustic quality of the internal spaces. Additionally, the reverberation time was considered, calculated based on standardized furnishing assumptions to ensure an objective assessment. Since acoustics mainly depended on the building design, the potential interventions by occupants had a limited impact on the overall assessment. Each credit in this category was assigned a weight relative to the total score. One of the main limitations of the tool was that the entire calculation and evaluation process was completely manual. This meant that data extraction, processing, and analysis were performed without the aid of automated tools, which brought several disadvantages. The manual process was time-consuming and prone to human errors, increasing the risk of inaccuracies in the results. Moreover, it required significant effort from users, limiting the efficiency and accuracy of the process, especially in complex or large-scale scenarios. Finally, the manual analysis constrained the tool's ability to integrate with other digital systems and automated processes, reducing its versatility and making it difficult to adapt to a more modern and scalable implementation.

4. Discussion and Conclusion

This study explored the role of IEQ in sustainability assessment frameworks (LEED, WELL, BREEAM) and emphasized the importance of integrating BIM to support the large-scale data processing required for IEQ assessments.

The findings demonstrated that BIM, when combined with other digital tools such as Computational Fluid Dynamics (CFD), Wireless Sensor Networks (WSN), Visual Programming Languages (VPLs) like Dynamo, and Textual Programming Languages (e.g., C#), improved the accuracy and efficiency of IEQ assessments. However, several methodological limitations remained, particularly regarding automation, optimization capabilities, and integration with certification workflows.

A key limitation across the reviewed frameworks was the lack of automated design optimization. The proposed methodologies did not offer alternative design solutions to maximize credit scores, thereby restricting the designer's ability to proactively enhance project performance. Another critical challenge was the limited level of automation, which resulted in manual data processing dependencies. While some workflows incorporated semi-automation, such as collecting sensor data and supporting simulations, final validation still required manual intervention. This made the process time-consuming, error-prone, and difficult to scale. The lack of fully automated data exchange between BIM models and certification platforms further reduced efficiency, especially in large or complex projects. Manual validation increased the risk of human error and inefficiency, particularly in systems dependent on CSV-based data exchanges and manual comparisons, which were prone to data inconsistencies and processing delays. Furthermore, the high level of user effort required for manual analysis limited the scalability of these workflows in larger projects.

Additionally, interoperability between BIM-based tools and rating systems remained insufficient. Most of the workflows relied on third-party simulation tools (e.g., IES-VE, Design Builder, Autodesk Revit Insight) that operated outside the BIM environment, creating disconnected workflows where modifications required manual reprocessing. This limitation prevented real-time design adjustments and reduced the potential for iterative optimization. The restricted automation in sustainability analyses also limited BIM's ability to integrate real-time monitoring data, which could have supported continuous validation throughout the building lifecycle.

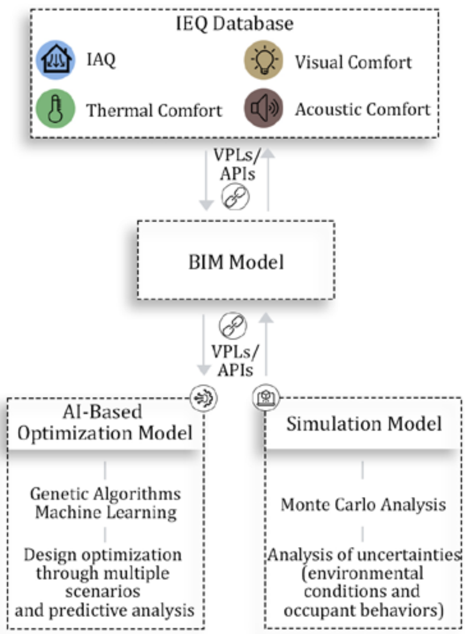


Figure 3. Hypothetical methodology for automated flow optimization for the validation and verification of the IEQ category.

To address these limitations, an optimization-based approach integrating BIM, simulation techniques, and automated evaluation models could improve the verification and validation of IEQ credits within sustainability rating systems (Figure 3). A BIM model, developed in platforms like Autodesk Revit, would serve as a centralized data repository, collecting information on IAQ, thermal comfort, visual comfort, and acoustic comfort. By linking this data to an AI-based optimization model leveraging GA and ML techniques, multiple design scenarios could be evaluated to identify optimal configurations that enhance IEQ [26], [27]. Additionally, simulation models such as Monte Carlo analysis could be employed to assess uncertainties in environmental conditions and occupant behaviors ensuring more resilient and adaptable design solutions. Furthermore, integrating APIs and plug-ins with BIM could streamline the assessment process by automating the retrieval of relevant IEQ data from external relational databases [28], [29]. This would enable seamless integration of data on factors such as ventilation, lighting, and pollutant control, enhancing the overall efficiency of IEQ evaluations and ensuring that the system remains flexible and scalable for diverse sustainability assessments. These approaches would address key limitations in current IEQ assessment methods by automating design optimization, generating alternative solutions to maximize IEQ credits and enabling proactive design improvements. They would also reduce manual verification, improving efficiency, scalability, and accuracy in certification workflows. Additionally, enhanced interoperability between BIM models and sustainability rating systems would allow for real-time compliance checks and dynamic performance adjustments, streamlining workflows and eliminating inefficiencies.

References

[1] N. Çobanoğlu, Z. H. Karadeniz, S. C. Sofuoglu, and M. Toksoy, "Sleep quality: Design of bedroom ventilation and evaluation within the scope of current standards," *Energy Build*, vol. 327, Jan. 2025, doi: 10.1016/j.enbuild.2024.115073.

[2] S. Capolongo *et al.*, "Healthy design and urban planning strategies, actions, and policy to achieve salutogenic cities," *Int J Environ Res Public Health*, vol. 15, no. 12, Dec. 2018, doi: 10.3390/ijerph15122698.

[3] World Health Organization (WHO), "Health as the Pulse of the New Urban Agenda: United Nations conference on Housing and Sustainable Urban Development," Quito, Ecuador, 2016.

[4] United Nations, "Transforming our world: The 2030 Agenda for Sustainable Development." Accessed: Jan. 22, 2025. [Online]. Available: https://sustainabledevelopment.un.org/post2015/transformingourworld/publication

[5] G. H. B. Polli, A. M. V. D. Oliveira E Sá, and B. P. Biju, "Qualitative Analysis of Sustainability Certification Systems Based on ISO 21929-1," *U.Porto Journal of Engineering*, vol. 8, no. 4 Special Issue, pp. 47–64, Jul. 2022, doi: 10.24840/2183-6493_008.004_0006.

[6] J. Herzing Jessica Baker and S. Ours HGA, "ASHRAE 90.1 and LEED v4".

[7] "About BREEAM." Accessed: Jan. 03, 2025. [Online]. Available: https://breeam.com/about/

[8] Y. He, N. H. Wong, T. Kvan, M. Liu, and S. Tong, "How green building rating systems affect indoor thermal comfort environments design," *Build Environ*, vol. 224, Oct. 2022, doi: 10.1016/j.buildenv.2022.109514.

[9] Epa, "Healthy Buildings, Healthy People," 2001. [Online]. Available: www.HealthyIndoors.com

[10] S. Habibi, "The promise of BIM for improving building performance," *Energy Build*, vol. 153, pp. 525–548, Oct. 2017, doi: 10.1016/j.enbuild.2017.08.009.

[11] S. Cascone, G. Parisi, and R. Caponetto, "BIM-Based Strategies for the Revitalization and Automated Management of Buildings: A Case Study," *Sustainability (Switzerland)*, vol. 16, no. 16, Aug. 2024, doi: 10.3390/su16166720.

[12] T. A. D. K. Jayasanka, A. Darko, D. J. Edwards, A. P. C. Chan, and F. Jalaei, "Automating building environmental assessment: A systematic review and future research directions," *Environ Impact Assess Rev*, vol. 106, May 2024, doi: 10.1016/j.eiar.2024.107465.

[13] O. I. Olanrewaju, W. I. Enegbuma, M. Donn, and N. Chileshe, "Building information modelling and green building certification systems: A systematic literature review and gap spotting," *Sustain Cities Soc*, vol. 81, Jun. 2022, doi: 10.1016/j.scs.2022.103865.

[14] J. P. Carvalho, L. Bragança, and R. Mateus, "A systematic review of the role of BIM in building sustainability assessment methods," *Applied Sciences (Switzerland)*, vol. 10, no. 13, Jul. 2020, doi: 10.3390/app10134444.

[15] M. K. Ansah, X. Chen, H. Yang, L. Lu, and P. T. I. Lam, "A review and outlook for integrated BIM application in green building assessment," *Sustain Cities Soc*, vol. 48, Jul. 2019, doi: 10.1016/j.scs.2019.101576.

[16] S. Cascone, "Digital Technologies and Sustainability Assessment: A Critical Review on the Integration Methods between BIM and LEED," Mar. 01, 2023, *MDPI*. doi: 10.3390/su15065548.

[17] D. Moher, A. Liberati, J. Tetzlaff, and D. G. Altman, “Preferred reporting items for systematic reviews and meta-analyses: The PRISMA statement,” Aug. 08, 2009. doi: 10.1136/bmj.b2535.

[18] J. C. P. Cheng, H. H. L. Kwok, A. T. Y. Li, J. C. K. Tong, and A. K. H. Lau, “BIM-supported sensor placement optimization based on genetic algorithm for multi-zone thermal comfort and IAQ monitoring,” *Build Environ*, vol. 216, May 2022, doi: 10.1016/j.buildenv.2022.108997.

[19] T. S. Larsen *et al.*, “IEQ-Compass – A tool for holistic evaluation of potential indoor environmental quality,” *Build Environ*, vol. 172, Apr. 2020, doi: 10.1016/j.buildenv.2020.106707.

[20] M. Marzouk and A. Abdelaty, “BIM-based framework for managing performance of subway stations,” *Autom Constr*, vol. 41, pp. 70–77, May 2014, doi: 10.1016/j.autcon.2014.02.004.

[21] A. D’Amico, G. Bergonzoni, A. Pini, and E. Currà, “BIM for healthy buildings: An integrated approach of architectural design based on IAQ prediction,” *Sustainability (Switzerland)*, vol. 12, no. 24, pp. 1–31, Dec. 2020, doi: 10.3390/su122410417.

[22] M. Marzouk and A. Abdelaty, “Monitoring thermal comfort in subways using building information modeling,” *Energy Build*, vol. 84, pp. 252–257, 2014, doi: 10.1016/j.enbuild.2014.08.006.

[23] Y. W. Lim, “Building information modeling for indoor environmental performance analysis,” *Am J Environ Sci*, vol. 11, no. 2, pp. 55–61, Apr. 2015, doi: 10.3844/ajessp.2015.55.61.

[24] S. Dubljević, B. Tepavčević, A. Stefanović, and A. S. Anđelković, “BIM to BREEAM: A workflow for automated daylighting assessment of existing buildings,” *Energy Build*, vol. 312, Jun. 2024, doi: 10.1016/j.enbuild.2024.114208.

[25] K. Kensek, Y. Ding, and T. Longcore, “Green BuildinG and Biodiversity: FacilitatinG Bird Friendly desiGn With BuildinG inFormation models”, [Online]. Available: http://meridian.allenpress.com/jgb/article-pdf/11/2/116/1768022/jgb_11_2_116_1.pdf

[26] M. Marzouk, S. Azab, and M. Metawie, “BIM-based approach for optimizing life cycle costs of sustainable buildings,” *J Clean Prod*, vol. 188, pp. 217–226, Jul. 2018, doi: 10.1016/j.jclepro.2018.03.280.

[27] M. Marzouk, S. Azab, and M. Metawie, “Framework for sustainable low-income housing projects using building information modeling,” *Journal of Environmental Informatics*, vol. 28, no. 1, pp. 25–38, Sep. 2016, doi: 10.3808/jei.201600332.

[28] F. Jalaei and A. Jrade, “Integrating building information modeling (BIM) and LEED system at the conceptual design stage of sustainable buildings,” *Sustain Cities Soc*, vol. 18, pp. 95–107, Nov. 2015, doi: 10.1016/j.scs.2015.06.007.

[29] F. Jalaei and A. Jrade, “Integrating Building Information Modeling (BIM) and energy analysis tools with green building certification system to conceptually design sustainable buildings,” *Journal of Information Technology in Construction*, vol. 19, pp. 494–519, Nov. 2014, doi: 10.1007/s12273-013-0120-0.

Risk Assessment and Management at Health Authority of South Tyrol: a Sustainable Approach

Peter Auer[1], Francesco Organai[2] and Michele De Stefani[2]

[1] Azienda Sanitaria Dell'Alto Adige
[2] Projit Srl

* E-mail: peter.auer@sabes.it

Abstract. The Health Authority of South Tyrol (in Italian Azienda Sanitaria Dell'Alto Adige – ASDAA) is a public entity in the province of Bolzano. It is divided into four health districts (Bolzano, Bressanone, Brunico, and Merano) and manages seven hospitals. Local healthcare services ("territory") are provided through 20 health districts and 14 centres across the province. The organization employs approximately 11,000 workers. In compliance with the obligations established by Legislative Decree 81/08, the Employer decided to develop a strategy to assess and subsequently manage health and safety risks across the organization, as described in the previous section. Due to the organizational complexity, a key requirement identified during the analysis phase was the need to digitize the assessment to manage the consequent actions.
The project was developed based on the definition of specific objectives: (1) risk assessment by actively involving the relevant functions, (2) Enhance the effectiveness and efficiency of the monitoring and control process carried out by fire safety personnel, (3) Measure work-related stress and provide the Employer with an analysis to assess the risk and define subsequent strategies, (4) Promote the digitalization of processes to facilitate data analysis and organizational changes.
After defining the Project requirements and assembling the work team, the implementation phase began: (1) Risk Assessment, (2) Fire Safety Checklist Management, (3) In-depth work-related stress assessment.
The consequence digital transformation has provided ASDAA with a comprehensive and dynamic overview of workplace safety management, ensuring continuous improvement and regulatory compliance.

Keywords: Assessment, Digitalization, Sustainability, Value, Efficiency

1. Risk Assessment and Management at Health Authority of South Tyrol: a sustainable approach

1.1. Introduction

The Health Authority of South Tyrol (in Italian Azienda Sanitaria Dell'Alto Adige – AS-

DAA) is a public entity under the Province of Bolzano, founded in 2007 and endowed with public legal personality and managerial autonomy. ASDAA is divided into four healthcare districts (Bolzano, Bressanone, Brunico, and Merano) and manages seven hospitals:

- Bolzano district: Bolzano hospital.
- Bressanone district: Bressanone and Vipiteno hospitals.
- Brunico district: Brunico and San Candido hospitals.
- Merano district: Merano and Silandro hospitals.

Local healthcare services are provided through 20 health districts and 14 centres, which are distributed across the province and fall under one of the four districts. ASDAA employs approximately 11,000 workers.

The General Director, as the Employer under Article 2, paragraph 1, letter b of Legislative Decree (DL) 81/08, has set the following general objectives:

- Assess the risks to which workers are exposed.
- Establish prevention and protection measures to be implemented.
- Pursue continuous improvement by adopting actions to eliminate or reduce risks.
- Implement a monitoring system (e.g., through control checklists) to ensure the organization enforces the measures defined in the risk assessment phase.

To achieve these objectives, the Employer must be supported by the entire organization, particularly by the Head of the Prevention and Protection Service (RSPP) and the Prevention and Protection Office, which was formally established through a specific resolution.

Given the organizational complexity of ASDAA, an interdisciplinary approach was essential to ensure the success and long-term sustainability of the project. The approach was based on three key pillars:

- People: Professionals with both technical and organizational expertise were needed to drive the project forward.
- Processes: Clearly defined and well-structured procedures for project management.
- Technology: Adequate resources to ensure work efficiency and effectiveness.

As support for the project's development, implementation, and monitoring, ASDAA engaged Projit Srl, a consulting company, within the framework of the Consip agreement.

1.2. Objectives

The project was developed based on the definition of specific objectives:

- Risk assessment by actively involving the relevant functions.
- Enhance the effectiveness and efficiency of the monitoring and control process carried out by fire safety personnel.
- Measure work-related stress and provide the Employer with an analysis to assess the risk and define subsequent strategies.
- Promote the digitalization of processes to facilitate data analysis and organizational changes.
- Establish a continuous improvement process for performance enhancement.

1.3. Requirements

The next step was defining the project requirements:

- Identification of the organizational structure.
- Risk assessment documents compliant with regulatory requirements.
- Completion of risk assessment documents for each department/service within the three-year contract period.
- Active participation of Prevention and Protection Service personnel.
- Involvement of responsible functions in the areas where the assessment was conducted, both during inspections and in the sharing of results.
- Digitalization of processes.
- Compliance with privacy regulations;

Note**:** Technical requirements were also defined, including assessment methodologies, deliverable formats, etc.

1.4. Project Team

As previously highlighted, one of the key elements of the project is the people involved. A dedicated team was established, defining roles and responsibilities. In addition to the core team members, other organizational functions participate as needed (e.g., during surveys for the preparation of risk assessment documents).

The Project Team consists of:

- Sponsor (ASDAA);
- Supplier Representative (Projit srl);
- Head of the Prevention and Protection Service (ASDAA);
- Project Manager (Projit srl);
- Digitalization Manager (Projit srl);
- Prevention and Protection Service Officers from (ASDAA);
- Subject Matter Experts, involved as needed (Projit srl);
- Responsible Functions, involved as necessary (ASDAA).

1.5. Digitalization

As previously mentioned, ASDAA's organizational structure is highly complex. Below are some figures that highlight this complexity:

- Approximately 11,000 employees;
- Around 270 workplaces, including hospital departments and territorial offices;
- About 1,246 different job roles;
- Approximately 1,600 types of equipment/machinery.

Note**:** Some figures are approximate as the work is still in progress.

Additionally, there is a high volume of data related to the main services provided by the project, namely:

- **Risk assessment**: For each workplace, a risk assessment document is prepared, including improvement actions and any corrective measures in case of non-compliance. Each action specifies, in addition to the workplace, the responsible function and the closure deadlines. To date, there are approximately 2,000 actions in total, of which 1,600 are still open;

- **Fire safety register management**: For the various workplaces, a specifically trained staff member conducts monthly monitoring (e.g., checking for the presence of fire extinguishers, the adequacy of circulation routes, etc.), reporting any discrepancies. This part of the project started in December 2023 for the Bolzano Hospital and, to date, includes approximately 850 completed checklists;
- **In-depth work-related stress assessment**: This involved administering a questionnaire to all the workers involved; in the past year, the activity was carried out in the districts of Bressanone, Brunico, and Merano, covering a total of approximately 6,600 workers. The results were then analysed to provide strategic insights to top management, which were incorporated into the PIAO (Integrated Plan of Activities and Organization). This tool, with a three-year duration, serves as a unique planning and governance document for public administrations, encompassing performance plans, personnel needs, gender equality, agile work, and anti-corruption measures.

From the very early stages of the project, it became clear that it was necessary to employ IT tools that allow for a comprehensive analysis of the data collected and an effective and efficient management of changes, which, given the complexity, occur very frequently. Therefore, a dedicated software: Q-81 HSE, was chosen to digitize the risk assessment processes, risk management, and management of fire control registers, along with Qualtrics for the work-related stress assessment.

1.6. Work Breakdown Structure definition

1.6.1. Introduction

The WBS (Work Breakdown Structure) is the hierarchical decomposition of the overall scope of work that must be carried out by the project team to achieve the project objectives and deliver the required deliverables (PMBOK Guide, Seventh Edition).

1.6.2. Work package and tasks

In the Table 1, are the Work Breakdown Structure with the project's work packages (WP), the tasks, and the deliverables where foreseen. The underlined tasks are those that have yet to be concluded.

1.7. Responsabilities

For the achievement of the project objectives, it is important to define, for each activity in the WBS, the actors (members of the project team) and their responsibilities. To this end, the RACI methodology has been used, which consists of a resource allocation table that presents the assignment of responsibilities in matrix form according to the activity/task.
The roles defined in the matrix (see an example in Table 2), are:

- **Responsible (R):** The person who executes and assigns the activity;
- **Accountable (A):** The person who is responsible for the outcome of the activity. Unlike the other three roles, each activity must have one and only one Accountable;
- **Consulted (C):** The person who assists and collaborates with the Responsible in executing the activity;
- **Informed (I):** The person who must be kept informed, either during the execution of the activity or upon its completion.

WP	WP Description	Tasks	Deliverables
Definition of the Organizational Structure	The objective of this phase is to define an organization with clearly defined responsibilities that is legally sustainable and consistent with the strategy.	Collection and review of company documents and resolutions	*Corporate act, organizational chart, delegation of functions, and regulations.*
		Assessment of the employer's needs	
		Interviews with the responsible functions to identify the current state of the organizational model	
		Proposal of an organizational structure consistent with the company strategy	
		Official implementation of the new organizational structure;	
		Digitalization of functions;	
Definition of Communication Methods	This involves establishing the communication flows based on the subject matter and the role defined within the project team.	Definition of a communication plan	*Presentation in .ppt format*
Mapping of Master Data	This involves establishing the communication flows based on the subject matter and the role defined within the project team	Mapping workplaces	*Digitalization of the master data in Q-81 HSE*
		Mapping Job roles	
		Mapping types of equipment	
		Mapping employee master data	
		Mapping fire safety checklists	
Risk Assessment	The objective of this work package is to prepare the risk assessment documents (approximately 250, i.e., one for each department/ service) on a digital platform using the Q-81 HSE software. This ensures that the subsequent management of actions (to date, approximately 2,000) is sustainable for the organization and allows for data analysis, and there's efficient management of the frequent organizational changes.	Definition of the risk assessment documents to be prepare	*Digitalization of the methodology, hazards, and documents*
		Definition of the hazards applicable to the organization	
		Definition of the risk matrix and the evaluation logic (actions based on the measured risk level)	
		Definition of the following formats: • Risk assessment document; • List of improvement and corrective actions; • Document containing descriptive information of the workplace (job roles, equipment, etc.). The documents are output from the software in DOC format. The latter two are used when sharing results with the responsible functions.	

WP	WP Description	Tasks	Deliverables
Risk Assessment	The objective of this work package is to prepare the risk assessment documents (approximately 250, i.e., one for each department/ service) on a digital platform using the Q-81 HSE software. This ensures that the subsequent management of actions (to date, approximately 2,000) is sustainable for the organization and allows for data analysis, and there's efficient management of the frequent organizational changes.	Presentation of the work phases to the RLS and MC	*Presentation in .ppt format*
		Sharing of the assessment methods: • Planning • Contact with the department/service representatives • Management of the site visit	*Documentation of decisions in a report (.ppt)*
		Creation of a "pilot" document to assess the efficiency and accuracy of the workflows and results	*Risk assessment digitized in Q-81 HSE, pilot department risk assessment document*
		Training of the Prevention and Protection Service on the use of the IT tool Planning of the assessments and processing (see GANTT chart)	*Risk assessments digitized in Q-81 HSE, risk assessment documents, action reports, informational document*
Management of Control Registers	Before the project began, the monthly control checks (averaging 50 per month) were paper-based, which made it difficult to manage corrective actions and perform a general analysis of the results (e.g., recurring non-compliances). The objective, as defined earlier, was to digitize these checks to ensure timely management of process outputs (corrective actions). The software used is Q-81 HSE.	Presentation of the project to the company managers responsible for managing the fire safety system;	*Checklists and reports on digital support* *Checklists and reports on digital support*
		Digitalization of the checklists in two languages	
		Establishment of the communication flow: the reports generated by the IT tool trigger an email notification system to the relevant functions (internal or external to the organization, based on responsibilities)	
		Training of the personnel on the use of the software	
		Initial testing in some workplaces	
		Evaluation of the effectiveness of the testing system with any necessary adjustments	
		Launch – Step 1: Each staff member begins using the checklist on their personal computer to become familiar with the tool	
		Launch – Step 2: Each staff member is provided with a tablet so that they can complete the checklist and generate any reports directly during the site visit.	
		Setup of the system in the other districts (where necessary).	

WP	WP Description	Tasks	Deliverables
		Definition of the elements to be mapped (location, profile, job role, etc.)	
		Digitalization of the personnel master data with the mapping elements from the previous phase	*Database per piattaforma*
		Identifying the managers of each area so that they can promote the questionnaire to their subordinates to reach a minimum redemption of 20%	
		Definition of the documents to be produced (three, one for each district)	
		Evaluation of the privacy regulations and the subsequent adoption of the necessary measures	*Project start up. ppt*
		Definition of the communication plan	
		Sharing of the questionnaire and translation into German	*Subjective survey in dual language*
Work-Related Stress Assessment	The questionnaire to be administered consists of 44 questions divided into 10 key areas (e.g., Environment and Equipment, Task Design, etc.). Each worker (approximately 5,000 in total) must complete this questionnaire. It is clear that an IT support tool (Qualtrics) is necessary to analyse and manage the data	Configuration of the IT tool: • customization of the layout of communications (via email); • customization of the Business Intelligence that manages the results and of the dashboard for their representation; • preparation for access to the questionnaire from different devices (smartphone, tablet, PC); • setup of automatic email reminders.	*Test*
		Presentation to the Employer and top management of the methodology and project steps	*Project start up. ppt*
		Presentation of the project by the Employer to the entire organization	
		Informative launch: publication on the ASDAA website landing page (landing page text, flyer, booklet, email access guide)	*Booklet – Flyer – email*
		Testing of the tool with IT and the Prevention and Protection Service	*Test*
		Launch of the survey: sending emails to the involved personnel (approximately 6,500) containing the link to the platform	
		Management of reminders for those who have not responded (automatic system)	*Survey closed*
		Closing of the survey	

WP	WP Description	Tasks	Deliverables
Work-Related Stress Assessment	The questionnaire to be administered consists of 44 questions divided into 10 key areas (e.g., Environment and Equipment, Task Design, etc.). Each worker (approximately 5,000 in total) must complete this questionnaire. It is clear that an IT support tool (Qualtrics) is necessary to analyse and manage the data	Presentation to the Employer and the Prevention and Protection Service of the dashboard that allows cross-sectional analysis of the survey data	*Dashboard (access credentials provided to each participant)*
		Initial analysis of the results to identify strategic directions to be included in the PIAO (Integrated Plan of Activities and Organization).	*Integrated Plan of Activities and Organization*
		In-depth analysis of the results, definition of risk levels identifiable for homogeneous groups (filterable based on the mapped elements: location, professional profile, job role, item)	*Risk assessment documents (one for each district), final report with the analysis of the results, and improvement proposals*
		Presentation to the Employer and management of the results and proposals for subsequent steps	

Table 1. The Work Breakdown Structure of the Project.

Activity	R	A	C	I
Definition of the risk matrix and the evaluation logic (actions based on the measured risk level).	RSPP, SME	RSPP	ASPP	PM

Table 2. Example of the RACI matrix representation for an activity.

1.8. GANTT diagram

The final phase of the design involves scheduling the activities defined in the WBS over time, taking into account the necessary precedences (e.g., one activity cannot start until another is completed) and priorities (e.g., one document must be prepared before another). In general, the project has a contractual duration of three years.
Figure 1 shows a portion of the GANTT chart that highlights the planning of assessments, processing, and delivery of the risk assessment documents.

1.9. Monitoring and control

The project presents high complexity and frequent changes, so periodic monitoring and subsequent controls are necessary. To this end, weekly meetings have been systematically scheduled with the following objectives:

- Project Progress Review:
  The KPIs used are:

Figure 1. Example of GANTT diagram.

  - The number of documents completed compared to what was planned;
  - The number of non-conformities and issues reported in the project (which, within the first year, should tend toward zero).
- Analysis of any issues that have emerged;
- Review of changes that result in modifications to the schedule (e.g., the need to prepare a risk assessment document earlier than planned);
- Analysis of the outcomes of the activities carried out.

The meeting agenda is established in the week preceding the meeting. The outcomes of the meetings are recorded in a specific minutes document (Attachment 1) that is updated week by week to capture all decisions made during the project execution.

1.10. Continuous improvement

Continuous improvement is one of the objectives set by the organization and is promoted through the various activities described above. Below is a description of the different types of improvements according to the activity:

- Health and Safety Risk Assessment:
- Where risks are not deemed "low" according to the defined methodology, improvement actions are identified and mapped in the system with the following details:
  - Title of the action;
  - Description of the improvement action;
  - Categorization (e.g., work equipment, repetitive movements, electrical risk, etc.);
  - The workplace to which it refers;
  - Responsible function;
  - Implementation deadlines.
- Management of Fire Safety Control Registers:
  This process leads to the identification of corrective actions and also the improvement of processes following a general data analysis (e.g., identification of actions in case of recurring non-conformities for specific types).
- Work-Related Stress Assessment:
  Similar to the risk assessment, this evaluation identifies improvement actions when risks are not deemed "low." Additionally, digitalization has introduced the possibility of com-

parative analyses (e.g., the same job role in different districts) and in-depth analyses by key area – a risk might be globally low but not low for a specific key area. As mentioned earlier, the improvement actions have been incorporated into the Integrated Plan of Activities and Organization. A more detailed evaluation of the actions is carried out by the project team.

Within the weekly review meetings, other improvement actions aligned with the company's objectives are identified, which may generate additional projects. In the specific case, the following have been defined:

- A project to support the reorganization of the Prevention and Protection Office, which became necessary due to the changes implemented.
- Development of interaction with the software by the Prevention and Protection Service; in the early phase of the project, this interaction was limited because training on the tool was required first. At this point, an alignment activity was planned with clearly defined objectives (what to do and by whom).
- Digitalization of the training process; this essentially consists of managing training deadlines for each individual based on their job role and managing changes (hirings, terminations, job changes, etc.)

References

[1] https://www.asdaa.it/it/home

[2] Azienda Sanitaria dell'Alto Adige Piano integrato di attività e organizzazione 2024

[3] Legislative Decree 81/2008

[4] Decree 01/09/2021

[5] Leavitt's Diamond Model (1960)

[6] PMBOK Guide, Seventh Edition (2021)

[7] PMI_Guide to Business analisys (2017)

[8] https://q-81-hse.it

[9] Consip agreement (2023)

Implementation of Construction Site Management Software with Digital Checklists for Quality Control

Eleonora Laurini[1*], Chiara Marchionni[1] and Marianna Rotilio[1]
[1] Department of Civil, Construction-Architectural and Environmental Engineering, University of L'Aquila, Italy; eleonora.laurini@univaq.it (EL); chiara.marchionni@univaq.it; marianna.rotilio@univaq.it (MR);

* E-mail: eleonora.laurini@univaq.it

Abstract. Accurate planning of construction site activities, integrated with careful safety management, is essential to protect workers and ensure the success of the project. It allows to prevent accidents, reduce risks and ensure a working environment compliant with current regulations. The complexity of construction sites, especially in energy and seismic requalification contexts, requires constant monitoring to ensure compliance with safety standards, correct execution of work and coordination between different professional figures. The integration of project management with digital software in the organization of construction sites allows for process optimization, improved communication, ensuring compliance with time and budget and monitoring safety on the site. A construction site management software can offer features to create detailed schedules, define activities, assign resources, and establish timeframes, checking that all regulatory requirements are met. With digital tools is possible to obtain the centralization of documents in a digital archive, facilitating search and sharing. Workflow features automate document approval and distribution, while integrated communication tools improve collaboration between team members, also thanks to mobile access to project information via dedicated apps that allow remote construction site management. After a literature analysis about digital instruments and apps designed to improve efficiency, communication and safety in construction projects, the research aims to introduce correct software implementation to facilitate the adoption and effectiveness of digital tools on the construction site. The study examines the impact on operational efficiency and project quality through checklists for control and safety on the construction site to guarantee fundamental tools for regulatory compliance, prevent accidents and improve operational efficiency. The research developed a protocol through checklists for the implementation of software and the control of all management activities: checklists are a practical and indispensable tool to guarantee safety, control and efficiency in the complex working context of a construction site.

Keywords: Facility Management, Quality Control, Construction Site, Checklist

1. Introduction

After the construction sector crisis due to the Covid19 epidemic, several important economic initiatives for recovery followed. In July 2020 the European Commission issued the program "Next Generation EU" (NGEU), with the aim of repairing the economic and social damage caused by pandemic in the immediate term; of creating a more ecological, digital, and resilient Europe in the long term [1]. The instrument used in Italy outlined the objectives, reforms and investments to be made with the use of European funds was the "National Recovery and Resilience Plan (PNRR) – Italy tomorrow", approved on 13 July 2021 with a total value of 235 billion euros between European and national resources [2]. The approval of Legislative Decree 34/2020 (so-called Superbonus 110%) was another significant initiative for the relaunch of the construction sector [3], which initially provided for a 110% deduction of expenses relating to energy efficiency and seismic improvement interventions. The statistical observatory National Joint Commission for Housing Edili (CNCE) recorded, in fact, a significant increase in working hours and the monthly average of companies, with growth in 2023 of +4.80% and +4.76% respectively compared to the previous year [4].

This exponential growth has determined the need for a huge coordination activity between the various construction sites and their internal operations, creating the need for operators in the sector to ensure construction quality. Quality control on the construction site translates into a construction quality management system, which goes from the materials used to the installation carried out, but above all from the processes performed. The processing phases are the solid basis on which to build a work that responds to the design activities: for this reason, the quality control activity is fundamental. The control is based on three aspects of the construction that are represented by the project: satisfying the regulatory requirements, using materials corresponding to the required technical characteristics, and construction in a work of art. In this sense, quality control, in addition to guaranteeing safety standards [5, 6] and the functionality of the product, is useful for the mitigation of risks on the construction site, compliance with times and costs. The control is also necessary to ensure compliance with the regulations and the requests of the client [7].

Furthermore, the construction phase must meet various requirements. First, remote controls to reduce travels, business trips and interpersonal contacts. Secondly, ensuring speed of response and greater fluidity of processes using digital technologies, with the possibility of recording each construction site event in a virtual and shared space, to respect the construction times and the expected budget. It is also important to ensure safety on the construction site, applying the correct procedures to allow the activities to be carried out without risks. Finally, responding to the criterion of flexibility, which ensures greater speed in acquiring information and a streamlined workflow. At the same time, digital tools allow tracking documentation and activities on the construction site to constantly evaluate the quality of the activities in progress.

The use of digital tools is also becoming increasingly common in the construction sector and in the construction phase itself. The "Construction Site 4.0" is the result of the transformation in progress in relation to the management and operation of the construction site

thanks to the use of digitalization tools [8]. It has seen the succession of different technologies: the use of SAPR systems (Rapidly Piloted Aircraft Systems), the Internet of Things (IoT) systems, the use of smartphones and applications (Apps). The creation of digital platforms, in fact, allows the recreation of a synergic working environment with all the figures involved and the storage of all the information through cloud storage. It also allows the introduction of innovative and simplification strategies, as also required by the new "Procurement Code" about digitalization (art.19-36 Legislative Decree 36/2023).
This paper illustrates an operational methodology applied to quality control on construction sites, through the implementation of commercial software for its management, which can be accessed with an App from a smartphone, through control checklists developed for each figure on the construction site and for each activity of the construction. Chapter 2 illustrates the state of the art; section 3 explains the developed methodology, while section 4 illustrates the validation on the case study.

2. Background

Technological and digital transformation has become a key topic in the construction sector, which requires simplification and innovative strategies to support process management. The literature review shows how it can well meet the needs of safety, flexibility, reactivity, and remote control of the sustainable construction site.
Cho et al [8] identify the construction site risk zones through digital information with a site information model framework to define digital objects and relationships in the construction site layout and propose methods to automatically identify unsafe spaces considering the risks and visibility of the structure. Larbi et al [9] proposes a digital system characterized by construction risk mitigation guidelines, through a novel IDD-HSM framework to establish a proactive real-time lifecycle approach for construction safety and health management. Zhao et al [10] use digital tools for waste management through building information modelling (BIM), artificial intelligence (AI), geographic information systems (GIS), big data (BD), remote sensing (RS) and radio frequency identification (RFID).
Traditional tools for construction site management have been gradually integrated with digital systems for monitoring activities. The analysis of the state of the art has highlighted the presence on the market of numerous software and computer programs related to the sustainable and digital management of construction sites, tools that have become indispensable for the automation of flows and processes. They allow sharing and exchanging information on the organization of the construction site, facilitating document management, promoting document sharing and cooperation between stakeholders in real time [11]. Jiang et al [12] identify the main obstacle of digital management in the synchronization of these digital elements based on cyber-physical interoperability to optimize multiple objectives without interruption. To overcome this obstacle, they formulated an "Orthogonally Synchronized Digital Twin" (SDT) model with regular expression, based on the proposed roadmap for a remodelled construction management.
One of them is "Mela Works", by the start-up Mela Works Srl [13]: it allows to control costs and times, archive photos and videos, compile and sign the construction site reports

directly from smartphone and process the work journal. In addition, to tracking all the information on the construction site, the digital tool allows to reduce errors and delays thanks to continuous communication between operators who can connect with a dedicated chat to each construction site. The software also allows to interface with other applications and validate the reports through notarization with Blockchain technology [14].
For the Works Management, several pre-filled templates are available, such as the assignment, the start of work, the service orders, the suspension, and resumption of works and the end of works. For the safety coordinator during the execution phase, templates are available for assignment, meeting calls, functional organization chart, minutes of site visits.
The research aims to fill the gap concerning cooperative governance [15] for the management of the construction site, in relation to the identification of the tasks and mandatory procedures to be respected by each figure responsible for the administrative, safety and quality control activities of the construction site.

3. Materials and Methods

The analysis of the state of the art allowed the selection and the analysis of some software related to the optimization of the construction site management phase. Specifically, the proposed methodology made use of the "Mela Works" software.
The first phase consists in carrying out preliminary operations for entering standard data, such as human resources (worker details, working hours, hourly wages) and material resources (quantities and unit prices). In the vehicles section, the vehicles entering the construction site, the hours, and days of use as well as rental equipment are recorded. The tags allow for quick retrieval of all stored data. After entering the standard parameters, the actual actions that were carried out on the construction site were inserted (Figure 1).

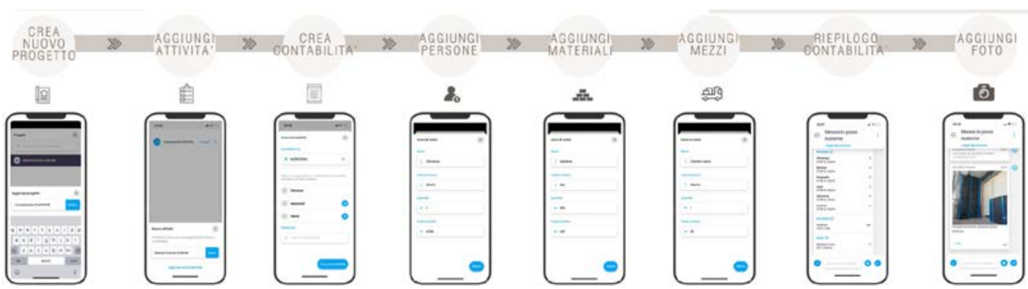


Figure 1. First phase: data entry process for creating a new project.

The second phase was aimed at implementing the section of checklists and reports contained in the device by organizing the process through folders and subfolders. Here the "control checklists" are available and can be activated. This list of mandatory steps and checks allows us to guarantee the correct application of the work procedures and the detection of faults or problems that reduce safety. In this way, on the one hand, the employer can have evidence of the checks performed on equipment, systems, and machines. On the other, the site manager can be sure of proceeding in an optimized manner, having all the tools necessary to perform a particular activity. It is also possible to carry out quality checks and operational checks to reduce the margin of error and to plan the actions to be followed by verifying regulatory compliance.

Some of the checklists have been drawn up according to regulations, others have been implemented according to the need for use: each one is equipped with an identification number that is associated with a layout and specific processing.

The third phase is related to the formulation of control checklists based on specific activities of a construction site. In fact, each control and management area is accompanied by a general checklist containing control subfolders (Figure 2).

Each checklist must be compiled and integrated with the construction site data according to the established deadlines and the obligations to be carried out which regulate both the times foreseen by the construction site schedule, the testing and acceptance of materials, and the updates of the list of subcontractors with the relative documents and the inclusion in the preliminary notification.

At the end of each compilation the software will be able to produce a *"traffic light"* summary:

- incomplete list (blank);
- formal inconsistencies (yellow);
- substantial inconsistencies (red);
- no inconsistencies (green).

The output is a table that summarizes the list ID number, the description of the unresolved issue, and the revisions made to process the review timing with a reminder or a new notice. With the use of tags during the checklist selection process, it is possible to indicate the type of work or the development status. The search can be done in a temporal or selective manner. The first is based on the definition of the layout number (Figure 3) in which the checklists are inserted: the Works Manager will have to identify the development status of the construction site at a given time. The selective type, instead, depends on the type of work.

4. Case study

The proposed methodology was validated on a case study, relating to an energy and seismic efficiency construction site. The building complex is called "Condominio Italposte", and is located in the hamlet of the Municipality of L'Aquila, in Abruzzo Region. It is composed of two buildings built in the 70s (Building A and Building B) (Figure 3), each with three independent entrances, which house a total of 45 real estate units. Building A consists of five floors above ground, while building B has four levels. Between the two buildings there is a common area used as a condominium parking lot. The load-bearing structure is in framed reinforced concrete and the infill walls are made of box masonry composed of double perforated with an interposed air chamber and rock wool insulation. Each real estate unit is equipped with an independent heating system.

The complex is located in a peripheral area of the city easily accessible through a condominium gate. Inside, a large area of relevance has allowed the construction site to be organized, avoiding interference between the operators and the owners of the real estate units.

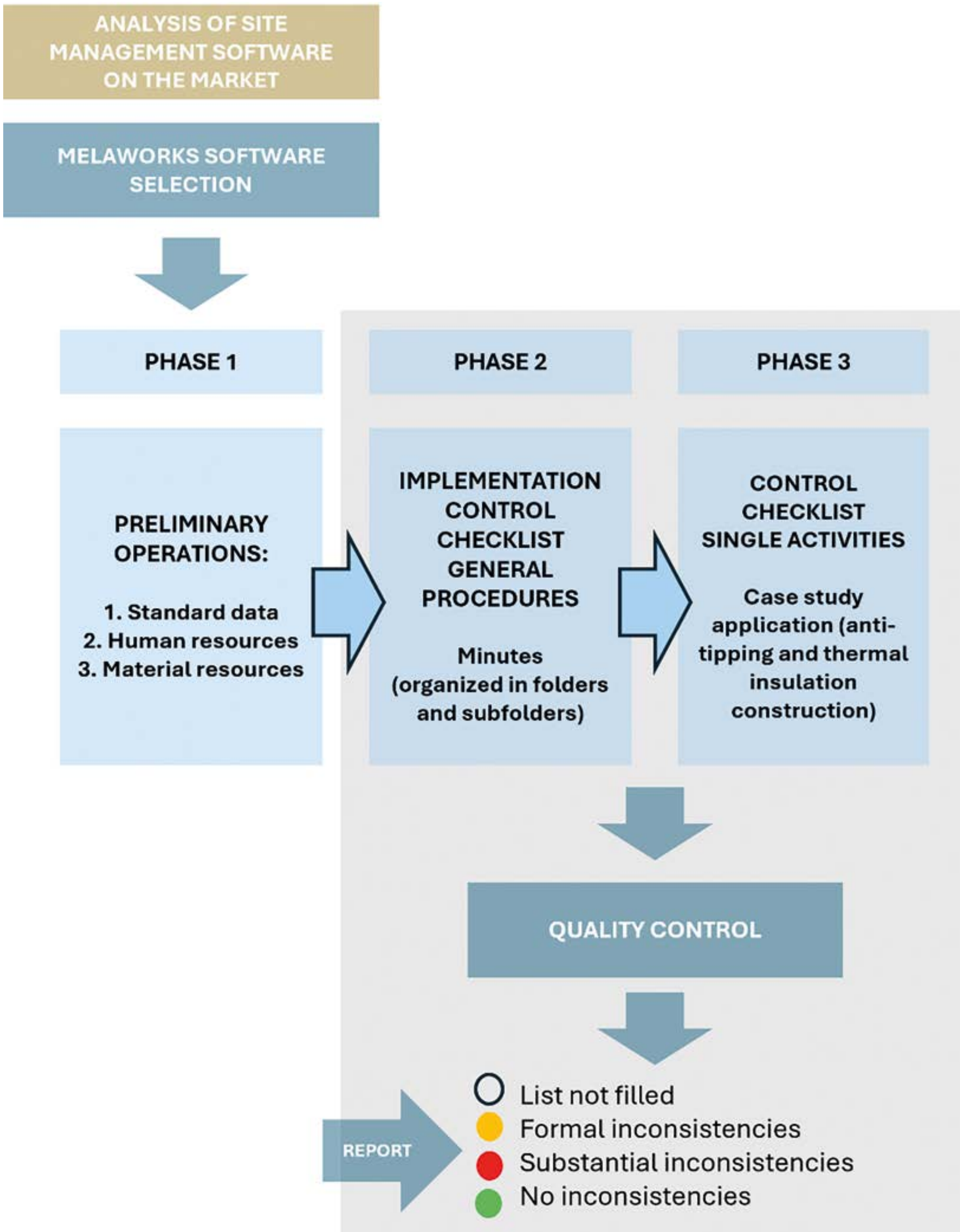


Figure 2. Methodological path: composition of a checklist, checks and controls.

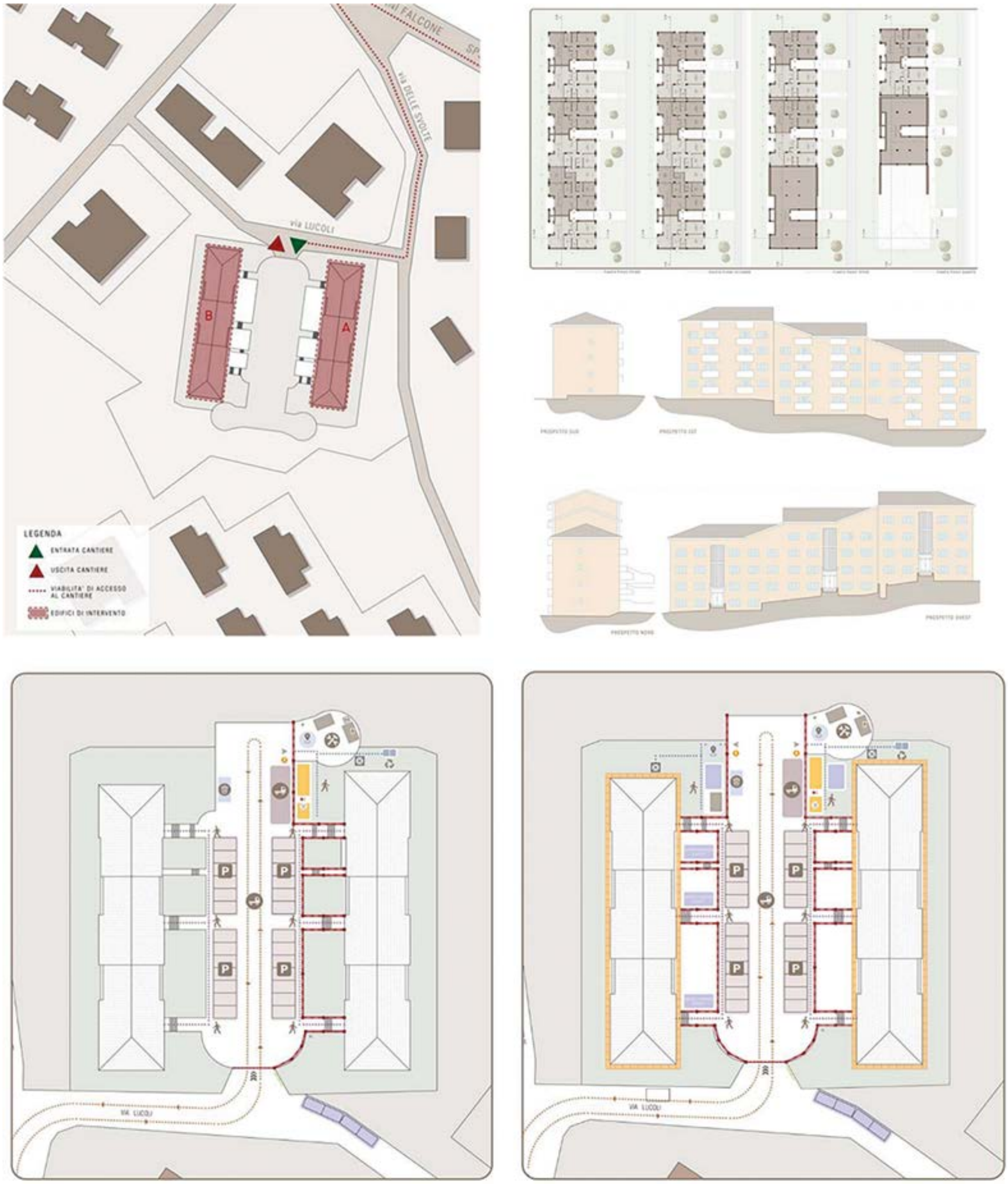


Figure 3. Top: location of buildings on the left, floor plans and elevations on the right. Bottom: construction site layout.

4.1. Description of the interventions and construction site

The project interventions regarded energy and seismic efficiency with interventions referred to Legislative Decree 34/2020 (so-called "Superbonus 110%"). The energy efficiency interventions concerned the opaque envelope insulation with a ventilated facade, the replacement of the window frames, the installation of a photovoltaic system, the replacement

of the condensing boilers and the installation of columns for charging electric cars. The structural interventions, on the other hand, involved the consolidation of the nodes using steel plates, the consolidation of the box masonry with helical bars and the anti-tipping of the external infill walls with carbon fiber mesh.
Particular attention was paid to the construction site operations (Figure 3), as it was necessary to ensure the accessibility and use of the buildings during the works. The site did not present particular problems: there were no active construction sites nearby and it was not necessary to manage interference with them. All the construction site preparations were positioned on the opposite side to the entrance to avoid interference with the users of the complex.

4.2. Monitoring activities with software

To develop the proposed methodology, specific processes were identified that involved the application of heat-reflecting insulation on the facade for the creation of the ventilated facade cladding and the creation of the anti-tipping of the external infill walls.
The insulation placement activity was carried out in three days with a team of six workers on a surface area of 1,598 square meters in building B. The activity was preceded by the placement of the aluminum substructure and followed by the placement of the fiber cement and PVC ventilated facade finishing panels.
The anti-tipping system was achieved by connecting the two perforated brick walls of the external infill walls with helical bars and a carbon fibre mesh extended over the entire external surface.
The data relating to the activity carried out the numbers of workers, the quantity of material used, the means used and the photos of the activities carried out were entered into the software every day. Through these steps, the accounting is automatically processed and implemented by the insertion of the DDT.
The checklist for these activities included (Figure 4):

- control of the activities to be carried out to access 110% Superbonus incentive;
- safety control on construction sites as per Legislative Decree 81/08;
- scaffolding inspection;
- control of employees;
- materials control;
- control of the means;
- control of the processes;
- waste disposal control;
- the control of subcontractors.

Particular attention has been paid to the area of sustainability and production quality. Firstly, it is important to manage waste control by preparing a legislative compliance checklist through the compilation of the FIR (Waste Identification Form) questionnaires and the loading and unloading register. In terms of quality, it is important to verify the Quality Control Plan according to the requirements of the UNI EN ISO 9001 standard. By compiling the list, it will be possible to have a report of compliant and non-compliant activities. The final check was carried out on the anti-tipping processing.

According to the model designed, in a folder called "control 4" all the lists that were taken into consideration for the construction site activities were inserted (Figure 8). In addition to the safety check, the equipment and the acceptance check of the materials were chosen. Each material is equipped with a sub-checklist of conformity to be carried out as in this case the tension test of the carbon fibers and the extraction test of the helical connectors.
The work has been summarized in tables divided by work processes and number of layouts. The work process folders will be different depending on the type of checks to be done: it was enough to select a development status of the construction site and open the folders to obtain the control checklists of all the activities (Figure 5).
The ventilated facade works are included in layout 3 and layout 5 and were carried out between September and December for a duration of approximately four working months.
The control covered safety, materials, the execution of the work and the workers. The checklists associated with safety are of a general nature (administrative, scaffolding and construction site set-ups), and associated to the equipment (hoist, circular saw and drill and workstations.

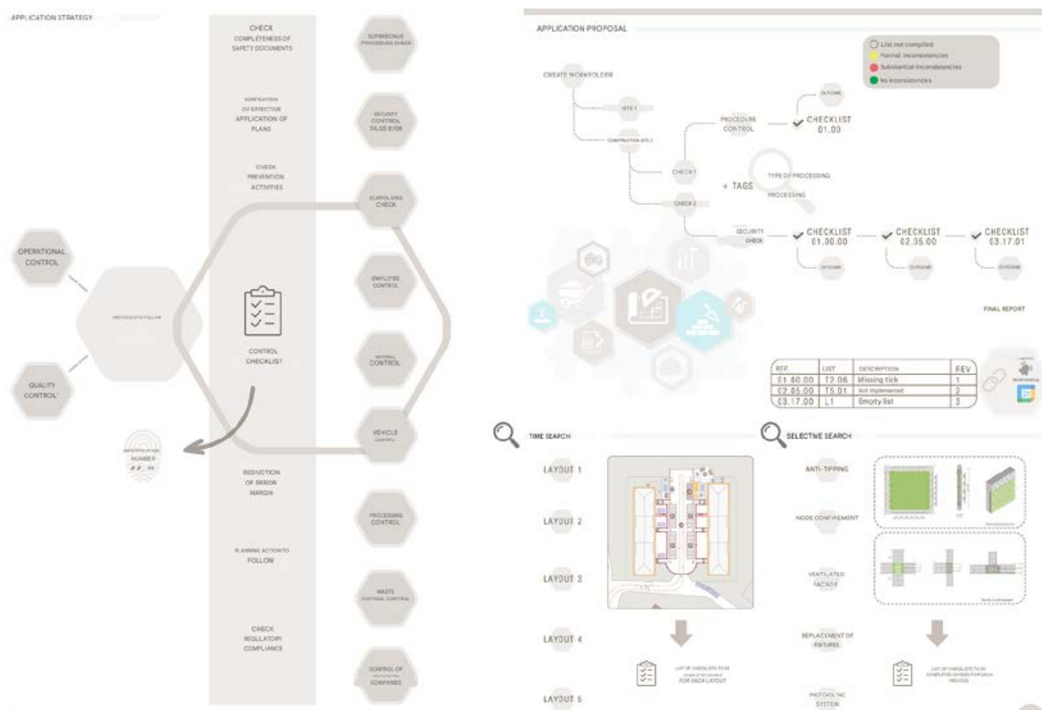


Figure 4. Example of a checklist for controlling safety activities on construction sites.

The control of the materials includes the acceptance of the fibre cement and PVC cladding sheets, the insulation and the related tests, the work includes checks on the installation, waste management and the means, finally the control is carried out on the training of the workers, the working hours and the tasks performed.

The anti-tipping is carried out in September and is planned in layout layout 3 and layout 4. For the work, a general safety check as previously described and of the equipment such as the concrete mixer and drill were planned. The check was carried out on the anti-tipping net, on the lime, on the connectors and on the tests such as the tensile test and the connector extraction test.
For this work, a check of the correct installation of the materials, waste management and use of the means, and the control of the workers were planned too. The selection can be made through the layout that represents all the processes included in the reference period and automatically opens the folders of the control checklists and checks to be carried out. In the case of layout 3, three folders are associated, while four folders are associated with layout 4. The number of folders is strictly connected to the control activities to be carried out to ensure the quality of the realization.

5. Conclusions

The digitalization of built environment sector is an aspect of the construction process for which the data extrapolated from the document assumes a significant importance, providing for a reasoned coordination of information flows, which in turn requires greater supervision also due to numerous compliance schemes relating to regulations, environmental and circularity certifications.
In addition, there is the need for interoperability of sharing platforms that will necessarily have to integrate with other information systems. An ecosystem composed of different actors that create digital value to the physical construction site must be activated, each for their own professional skills. To draw up a quality control plan, therefore, it is essential to have an organizational chart and job description with the tasks and responsibilities of each team member, to optimize work with defined roles. Identifying responsibilities, which includes updating documents, verifying materials, and implementing the plan, allows to immediately identify whether it is necessary to suspend work if a lack of compliance should occur. The inspection and acceptance control phases of the materials can guarantee the required quality, finally the tests and checks define the subsequent checks and frequency of the tests to be carried out.
The designed method for quality control, composed of folders and checklists, allows to the Quality Control Manager to implement all his activities, through a single software containing the protocols to be followed by each figure on the construction site. Within the checklists it will be possible to coordinate the activities [16], verify the execution of the tests, and instantly communicate any problems that arise during the works [17], also through communication between the operators. This also allows better risk management and optimal and centralized management of all documents.
The digitalization of the construction site aims at making everything predictable: the future development of research includes the integration of management systems composed of digital control checklists with artificial intelligence (AI) [18]. In this way, data analysis can be even simpler and faster. AI can also be assigned the task of analysing photos taken on the construction site to identify construction anomalies on large surfaces [19]. Furthermore, the data entered the software during the construction of the building can be processed by

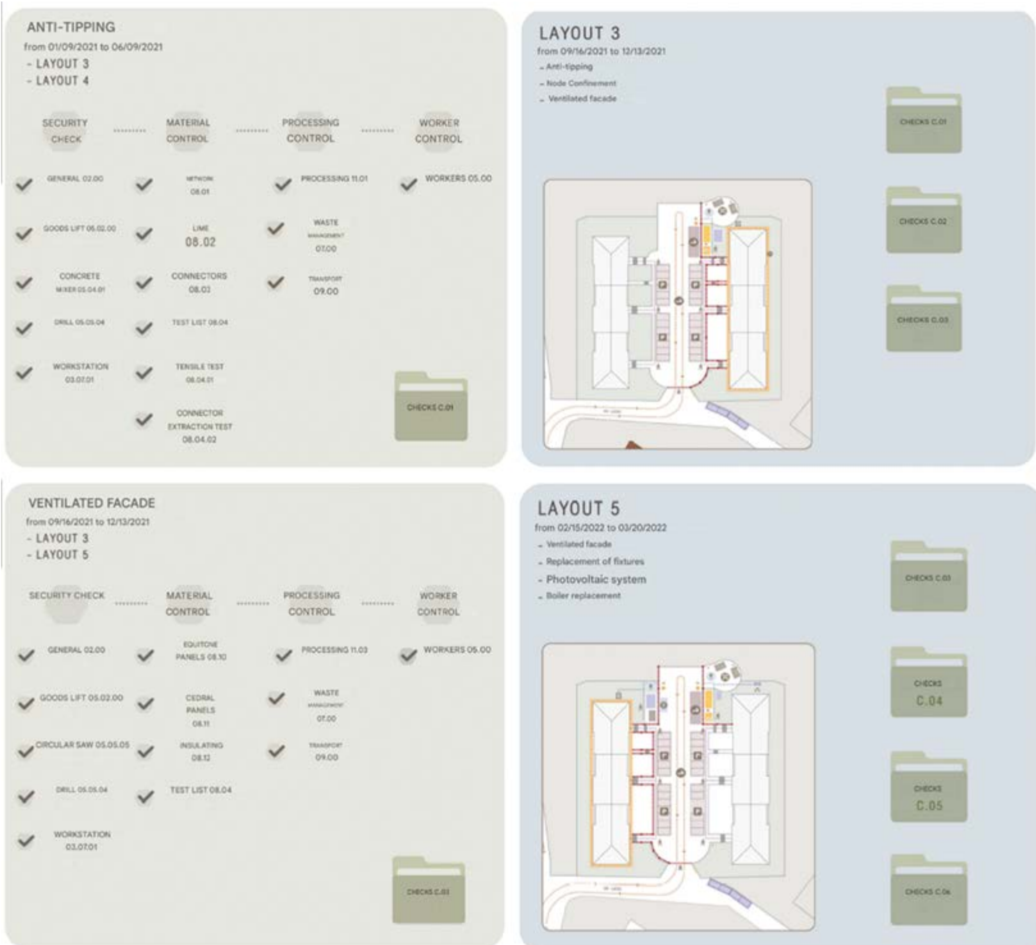


Figure 5. Example of system architecture consisting of folders for control checklists in the processes relating to anti-tipping and the creation of insulation on the facade.

AI to optimize the management and maintenance phase of the buildings, through preventive maintenance activities and optimized management of the systems.

Author Contributions

Conceptualization, EL, CM and MR; methodology, EL; software, EL; validation, all authors; formal analysis and investigation, EL; resources, EL and CM; data curation, all authors; writing–original draft preparation, EL and CM; writing–review and editing all authors.; supervision, MR and EL; project administration, EL, CM and EL is responsible for the research. The study is developed within the framework of the research 'The relationship between the worker and the environment. Strategies and methodologies for the safety, well-being and health of workers', Scientific Responsible MR, Review EL and CM.

The images were created by thesis student Annalisa Trasatti, supervisor Prof. Pierluigi De Berardinis and co-supervisor Ph.D. Eleonora Laurini. All authors have read and agreed to the published version of the manuscript.

References

[1] https://next-generation-eu.europa.eu/index_it (accessed 05/03/2025)

[2] https://www.agenziacoesione.gov.it/dossier_tematici/nextgenerationeu-e-pnrr/ (accessed 05/03/2025)

[3] Legislative Decree 19 May 2020, n.34. Relaunch Decree: Urgent measures on health, support for work and the economy, as well as social policies related to the COVID-19 epidemiological emergency (GU General Series n.128 of 19-05-2020 – Ordinary Supplement n. 21).

[4] https://www.cnce.it/associazione-statistico-cnce/ (accessed 05/03/2025)

[5] Mohamed Elrifaee, Tarek Zayed, Eslam Ali, Ali Hassan Ali, IoT Contributions to The Safety of Construction Sites: A Comprehensive Review of Recent Advances, Limitations, And Suggestions for Future Directions, Internet of Things, 2024, 101387, ISSN 2542-6605, https://doi.org/10.1016/j.iot.2024.101387.

[6] Jeongeun Park, Sojeong Seong, Soyeon Park, Minchae Kim, Ha Young Kim, Multi-label material and human risk factors recognition model for construction site safety management, Journal of Safety Research, Volume 91, 2024, Pages 354-365, ISSN 0022-4375, https://doi.org/10.1016/j.jsr.2024.10.002.

[7] Mihai Iliescu, Remus Ciocan, Modern Technologies Innovation in Use for Quality Control on Construction Site, Procedia Engineering, Volume 181, 2017, Pages 999-1004, ISSN 1877-7058, https://doi.org/10.1016/j.proeng.2017.02.499.

[8] Jongwoo Cho, Jiyu Shin, Junyoung Jang, Tae Wan Kim, Automated identification of hazardous zones on construction sites using a 2D digital information model, Automation in Construction, Volume 170, 2025, 105922, ISSN 0926-5805, https://doi.org/10.1016/j.autcon.2024.105922.

[9] Joshua Amo Larbi, Llewellyn CM Tang, Richard Amo Larbi, Derek A. Abankwa, Richmond Darko Danquah, Developing an integrated digital delivery framework and workflow guideline for construction safety management in a project delivery system, Safety Science, Volume 175, 2024, 106486, ISSN 0925-7535, https://doi.org/10.1016/j.ssci.2024.106486.

[10] Wenbo Zhao, Jian Li Hao, Guobin Gong, Thomas Fischer, Yong Liu, Applying digital technologies in construction waste management for facilitating sustainability, Journal of Environmental Management, Volume 373, 2025, 123560, ISSN 0301-4797, https://doi.org/10.1016/j.jenvman.2024.123560.

[11] Clinton Aigbavboa, Ernest Kissi, 3 – Understanding digital construction management, Editor(s): Clinton Aigbavboa, Ernest Kissi, In Woodhead Publishing Series in Civil and Structural Engineering, Digital Management of Construction Costs,Woodhead Publishing, 2025, Pages 27-38, ISBN 9780443237157, https://doi.org/10.1016/B978-0-443-23715-7.00003-2).

[12] Yishuo Jiang, Shuaiming Su, Shuxuan Zhao, Ray Y. Zhong, Waishan Qiu, Miroslaw J. Skibniewski, Ioannis Brilakis, George Q. Huang, Digital twin-enabled synchronized construction management: A roadmap from construction 4.0 towards future prospect, Develop-

ments in the Built Environment, Volume 19, 2024, 100512, ISSN 2666-1659, https://doi.org/10.1016/j.dibe.2024.100512.

[13] https://www.mela.work/it/ (accessed 05/03/2025)

[14] Yuhan Liu, Xingyu Tao, Moumita Das, https://doi.org/10.1016/j.autcon.2024.105447.

[15] Ahmed Mohammed Shirwa, Abdiqani Muse Hassan, Abdiqani Qorane Hassan, Muslum Kilinc, A cooperative governance framework for sustainable digital transformation in construction: The role of digital enablement and digital strategy, Results in Engineering, Volume 25, 2025, 104139, ISSN 2590-1230, https://doi.org/10.1016/j.rineng.2025.104139.

[16] Syed Muhammad Taimur Shah, Asmat Ullah, A system dynamics approach to plan strategy for managing factors influencing safety hazards on construction sites in developing countries, Journal of Safety and Sustainability, Volume 1, Issue 3, 2024, Pages 141-150, ISSN 2949-9267, https://doi.org/10.1016/j.jsasus.2024.09.003.

[17] Saurabh Gupta, Syam Nair, A review of the emerging role of UAVs in construction site safety monitoring, Materials Today: Proceedings, 2023, ISSN 2214-7853, https://doi.org/10.1016/j.matpr.2023.03.135.

[18] SK Baduge, S. Thilakarathna, JS Perera, M. Arashpour, P. Sharafi, B. Teodosio, A. Shringi, P. Mendis Artificial intelligence and smart vision for building and construction 4.0: machine and deep learning methods and applications Automation in Construction., 141 (2022), Article 104440, 10.1016/j.autcon.2022.104440.

[19] Almo Senja Kulinan, Minsoo Park, Pa Pa Win Aung, Gichun Cha, Seunghee Park, Advancing construction site workforce safety monitoring through BIM and computer vision integration, Automation in Construction, Volume 158, 2024, 105227, ISSN 0926-5805, https://doi.org/10.1016/j.autcon.2023.105227.

The Power of Digital Portals in Supplier Management: Transforming Safety Compliance through a Case Study

Giovanni Pegoraro[1], Giampaolo Mardegan[1], Massimo Moro[1] and Giovanni Costantini[2,1]
[1] PWP s.r.l. (Italy)
[2] Giovanni Costantini – Ingegnere della sicurezza (Italy)

Abstract. In the ever-evolving landscape of workplace safety and compliance, Italy's Decree 81/08, Article 26, mandates the qualification of suppliers for all subcontracted activities. This legal requirement has prompted organisations to seek innovative solutions to streamline the qualification process, ensuring both efficiency and thoroughness. A prime example of this modernisation is the case study of a PWP srl – Centro Assistenza Porsche Livorno's inaugural event in Livorno, where the Management, the marketing department and the Head of Protection and Prevention Services (RSPP) collaborated to implement a cutting-edge digital approach.
The traditional supplier qualification process often involved a cumbersome exchange of physical documents, time-consuming manual verifications, and potential oversights. Recognising these challenges, the company embarked on a digital transformation journey, using and implementing a bespoke online portal to revolutionise their supplier qualification procedures.
This state-of-the-art portal serves as a centralised hub for all supplier-related documentation and qualifications. Upon initial contact from the company's RSPP, suppliers are granted access to this secure platform. The RSPP provides comprehensive guidance on how to navigate the system, ensuring a smooth onboarding process for all parties involved.
The portal's user-friendly interface allows suppliers to effortlessly upload required documents pertaining to their personnel, company credentials, and equipment. This digital repository covers all aspects of qualification, from individual worker certifications to company-wide safety policies and vehicle maintenance records. The system's intelligent architecture ensures that all necessary fields are completed, reducing the risk of incomplete submissions.
One of the portal's most significant advantages is its real-time status tracking feature. This allows the RSPP and other relevant stakeholders to monitor the qualification progress of each supplier at a glance. The system generates automated reminders for missing or expiring documents, proactively maintaining the integrity of the qualification process.
Furthermore, the portal incorporates advanced data analytics capabilities. These tools provide valuable insights into supplier performance, compliance trends, and potential areas for improvement. This data-driven approach not only enhances safety

measures but also informs strategic decision-making regarding supplier relationships. The inaugural event served as a litmus test for this digital qualification system. The results were nothing short of remarkable. Through the streamlined, user-friendly process, the company achieved a 100% supplier qualification rate. This unprecedented success not only ensured full compliance with Decree 81/08, Article 26 but also significantly reduced administrative burdens and minimised the risk of oversight.

The digital transformation of the supplier qualification process yielded numerous benefits beyond mere compliance. It fostered improved communication between the company and its suppliers, enhanced transparency in the qualification process, and dramatically reduced the time and resources required for document management.

Moreover, the system's ability to store and organise data securely provided an invaluable audit trail. In case of inspections or audits, all necessary information can be accessed and presented swiftly, demonstrating the company's safety and regulatory adherence.

As we move further into the digital age, such innovative approaches to compliance and safety management are likely to become the norm rather than the exception. The case study of this inaugural event serves as a testament to the power of digital transformation in enhancing operational efficiency, ensuring regulatory compliance, and ultimately, fostering a safer work environment for all.

Keywords: Safety, Digital Portal, Supplier, Cooperation, Q-81 HSE

1. Introduction

The Italian legislative framework for workplace safety is primarily based on Legislative Decree 81/2008, also known as the Consolidated Act on Occupational Health and Safety [1]. This comprehensive legislation addresses various aspects of workplace safety, including the management of suppliers and contractors. The effective management of suppliers is crucial for maintaining a safe work environment, particularly in complex organizational structures where multiple entities interact within the same workspace.

The Italian regulatory system places significant emphasis on the principle of shared responsibility between the client company and its suppliers. Article 26 of Legislative Decree 81/2008 outlines the specific obligations of employers when engaging external companies or self-employed workers [2]. These obligations include:

1. Verification of technical and professional suitability
2. Provision of detailed information on specific risks in the work environment
3. Cooperation and coordination of prevention and protection measures
4. Elaboration of combined interference risk assessment report (in Italian DUVRI)

Before engaging a supplier, the client company must verify the supplier's technical and professional suitability. This process involves examining various documents, including: (1) Chamber of Commerce registration (2) Self-declaration of compliance with technical and professional requirements (3) Regular payment of social security and insurance contributions.

Masi and Cagno emphasize the importance of this verification process in ensuring that suppliers possess the necessary competencies to operate safely within the client's premises [3].
The client company is obligated to provide comprehensive information about specific risks present in the work environment where supplier activities will take place. This information exchange is crucial for preventing accidents and ensuring that suppliers can adequately prepare their workers for potential hazards. Fabiano et al. highlight the significance of effective communication in reducing workplace accidents, particularly in high-risk industries [4].
Article 26 of Legislative Decree 81/2008 mandates that client companies and suppliers cooperate in implementing prevention and protection measures against work-related risks. This cooperation extends to coordinating interventions to protect workers from the risks of interference between different work activities. Cagno et al. discuss the challenges and benefits of this collaborative approach in their study on safety management in Italian small and medium-sized enterprises [5].
One of the key requirements in supplier management is the preparation of the DUVRI, a document that assesses the risks arising from the interference of activities between the client company and its suppliers.
Battaglia et al. analyze the effectiveness of DUVRI in promoting safety culture and reducing accidents in multi-employer worksites [6].
While the regulatory framework provides a solid foundation for supplier management in workplace safety, implementation can be challenging.
To address these challenges, organizations often adopt best practices that go beyond mere regulatory compliance. Micheli et al. propose a comprehensive framework for supplier safety management that integrates legal requirements with proactive safety measures [7].
One effective approach is the implementation of a Supplier Safety Management System (SSMS).
Gnoni and Saleh discuss the benefits of integrating SSMS with overall organizational safety management systems, highlighting improved safety performance and reduced incidents [8].
Advancements in technology have significantly enhanced the ability of organizations to manage supplier safety effectively. Digital platforms for document management, real-time monitoring, and communication have streamlined the process of supplier oversight. Podgórski explores the potential of ICT-supported systems in improving occupational safety and health management, including supplier-related aspects [9].
Emerging technologies such as Internet of Things (IoT) devices, wearable technology, and artificial intelligence are being increasingly employed to monitor and enhance workplace safety. These technologies offer new possibilities for real-time risk assessment and immediate intervention in supplier activities.
The Italian regulatory framework for supplier management in workplace safety provides a comprehensive foundation for ensuring safe work environments in multi-employer settings. However, effective implementation requires a proactive approach that goes beyond mere compliance.
As organizations continue to rely on complex networks of suppliers and contractors, the importance of effective supplier safety management will only grow. Continuous improve-

ment in this area is essential for creating safer workplaces and reducing occupational risks. In conclusion, while Italian regulations provide a robust framework for supplier management in workplace safety, successful implementation requires a combination of legal compliance, organizational commitment, and innovative approaches. As Bianchini et al. note, a holistic approach that considers both regulatory requirements and organizational factors is crucial for achieving sustainable improvements in workplace safety [10].

2. Case Study: PWP srl – Centro Assistenza Porsche Livorno's Inaugural Event

In the ever-evolving landscape of workplace safety and compliance, regulatory frameworks have emerged as crucial pillars to safeguard the well-being of employees and ensure the integrity of operations. Among these frameworks, Italy's Decree 81/08, Article 26, has mandated the qualification of suppliers for all subcontracted activities. This legal requirement has prompted organizations to seek innovative solutions to streamline the qualification process, ensuring both efficiency and thoroughness.

The inauguration of the Livorno facility marked a significant milestone, following an extensive and meticulous renovation process meticulously overseen by the Facility Manager. This comprehensive overhaul was far from a superficial update; instead, it represented a transformative endeavor that touched every aspect of the building and its surroundings. The Facility Manager orchestrated a massive restructuring that encompassed both the interior and exterior spaces. From the ground up, each element was carefully considered and optimized to meet the highest standards of functionality, aesthetics, and efficiency. The renovation included state-of-the-art upgrades to all systems, including electrical, plumbing, and HVAC, ensuring the facility's long-term sustainability and optimal performance. Special attention was paid to creating an environment that not only met but exceeded modern workplace standards, incorporating ergonomic designs and cutting-edge technology. The exterior underwent a similarly thorough transformation, with landscaping and facade improvements that enhanced the building's visual appeal while aligning with the company's brand identity.

A prime example of this modernization is the case study of PWP srl – Centro Assistenza Porsche Livorno's inaugural event in Livorno, where the Management, the marketing department, and the Head of Protection and Prevention Services (RSPP) collaborated to implement a cutting-edge digital approach.

The traditional supplier qualification process often involved a cumbersome exchange of physical documents, time-consuming manual verifications, and potential oversights. This arduous process not only consumed valuable resources but also posed significant risks of non-compliance and compromised safety standards. Recognizing these challenges, the company embarked on a digital transformation journey, using and implementing a bespoke online portal to revolutionize their supplier qualification procedures.

PWP srl – Centro Assistenza Porsche Livorno, a renowned automotive service center, organized an inaugural event to celebrate the opening of their new facility in Livorno. This high-profile event required the involvement of multiple suppliers, ranging from catering services to entertainment providers and event management companies. With a diverse array of suppliers, each with their own set of qualifications and documentation, the company

faced a daunting challenge in ensuring compliance with Decree 81/08, Article 26.
Faced with the daunting task of qualifying numerous suppliers in accordance with the legal requirements, the company recognized the need for a streamlined and efficient process. The traditional methods of document exchange and manual verification were deemed inadequate, as they were time-consuming, prone to errors, and lacked transparency. Moreover, the sheer volume of documentation and the complexity of the qualification process posed significant risks of oversight and non-compliance.
In response to these challenges, PWP srl embarked on a digital transformation journey by implementing a state-of-the-art online supplier qualification portal. This innovative platform served as a centralized hub for all supplier-related documentation and qualifications, revolutionizing the way the company managed the qualification process.
The portal's user-friendly interface allowed suppliers to effortlessly upload required documents pertaining to their personnel, company credentials, and equipment. This digital repository covered all aspects of qualification, from individual worker certifications to company-wide safety policies and vehicle maintenance records. The system's intelligent architecture ensured that all necessary fields were completed, reducing the risk of incomplete submissions and subsequent non-compliance.
One of the portal's most significant advantages was its real-time status tracking feature. This allowed the RSPP and other relevant stakeholders to monitor the qualification progress of each supplier at a glance. The system generated automated reminders for missing or expiring documents, proactively maintaining the integrity of the qualification process and ensuring timely compliance.
Furthermore, the portal incorporated advanced data analytics capabilities, providing valuable insights into supplier performance, compliance trends, and potential areas for improvement. This data-driven approach not only enhanced safety measures but also informed strategic decision-making regarding supplier relationships and future collaborations.

3. Q-81 HSE: An Innovative Software Solution for Workplace Safety Management

Q-81 HSE is a comprehensive software platform designed to streamline and enhance workplace safety management in compliance with Italian Legislative Decree 81/2008. Developed by a team of experts in occupational safety and health, this cloud-based solution offers a range of features to help organizations effectively manage their safety protocols, documentation, and compliance requirements.
The platform offers a centralized repository for all safety-related documentation. This includes policies, procedures, training records, and incident reports. The system ensures that documents are version-controlled, easily accessible, and can be quickly retrieved during audits or inspections.
The system can also send automated reminders for refresher courses or when certifications are due to expire.
The platform includes features for managing the safety compliance of external suppliers and contractors. It allows for the storage and verification of supplier safety documentation and certifications.

Q-81 HSE represents a significant advancement in workplace safety management software. By offering a comprehensive, user-friendly platform that addresses the specific requirements of Italian safety regulations, it enables organizations to more effectively manage their safety programs, ensure compliance, and ultimately create safer work environments. As workplace safety continues to be a critical concern for businesses across industries, tools like Q-81 HSE play an increasingly important role in supporting organizational safety efforts and promoting a culture of prevention.

Q-81 HSE is a multi-domain software platform for those in companies or on construction sites who wish to manage mandatory and voluntary compliance aspects in occupational health and safety, environmental protection and sustainability, quality assurance, and human resources. The system also allows for the digitization and integration of corporate management systems such as ISO 45001, ISO 14001, ISO 9001, ISO 37001, SA 8000, ISO 27001, ISO 22001, as well as the Organizational Management and Control Model 231.

Q-81 HSE is one of the leading solutions in the Health, Safety and Environment sector, used by thousands of users and managing over 400,000 workers and 25,000 contractors in Italy alone.

Figure 1 presents a comprehensive supplier management interface designed for use by the RSPP. The interface provides a detailed overview of suppliers information, qualification status, and compliance checks.

The Key elements of the interface in Figure 2 include:

1. Header: Displays the current section “Anagrafiche di base > Clienti e Fornitori” (Basic Registry > Clients and Suppliers), indicating the hierarchical navigation within the system.
2. Supplier Details:

- Codice Anagrafica (Registry Code): C_2018_1
- Ragione Sociale (Company Name): AMBivalenza Srl
- Tipo (Type): Cliente/Fornitore (Client/Supplier)
- Stato (Status): Attivo (Active)

3. Verification Notes: A text area for “NOTE VERIFICHE PER CLIENTE / FORNITORE” (Verification Notes for Client/Supplier) allows the RSPP to add important remarks. In this case, it mentions “Rinnovare il caricamento del DURC” (Renew the upload of DURC – Single Insurance Contribution Payment Certificate).
4. Verification Status: “STATO VERIFICHE FORNITORE” (Supplier Verification Status) is set to “Dati rimandati per correzione” (Data returned for correction), suggesting that some information needs to be revised or updated.
5. Verification Checklist: This section forms the core of the supplier qualification process, listing various compliance checks:

a. DURC Verification: Checks if the supplier has a valid DURC, with an expiration date of 14/03/2025.

b. Chamber of Commerce Registration: Verifies the supplier’s registration with the relevant Chamber of Commerce, Industry, Crafts, and Agriculture.

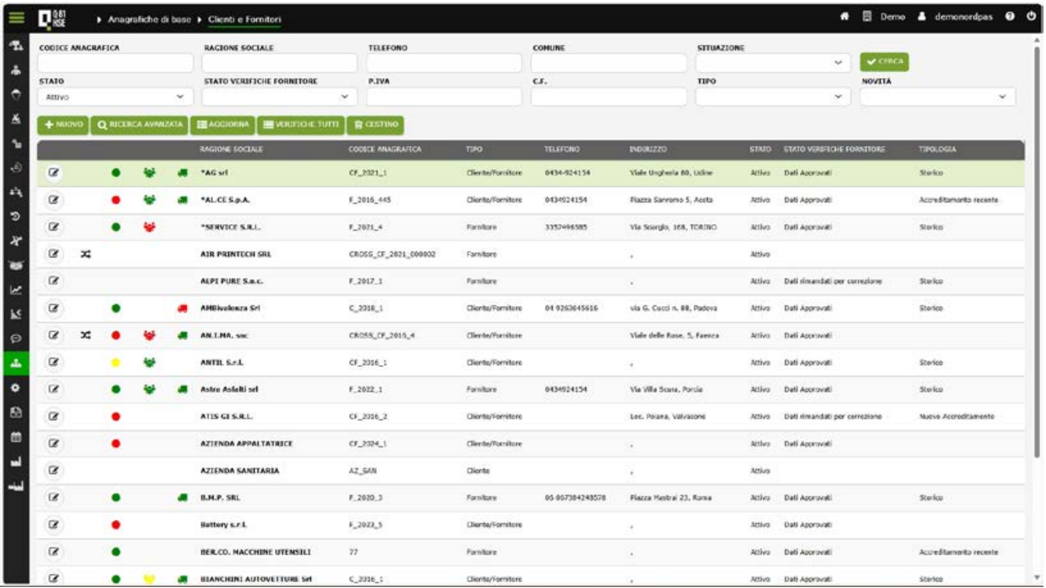


Figure 1. General RSPP Management Interface.

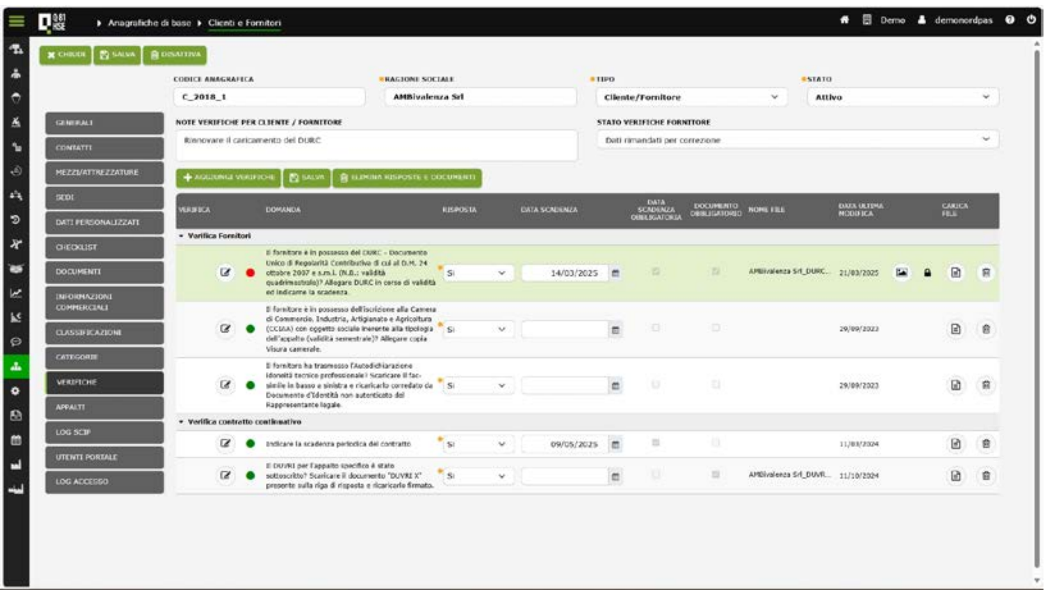


Figure 2. An example of a specific interface.

c. Technical-Professional Suitability: Ensures the supplier has provided necessary documentation to prove their technical and professional competence.
d. Continuous Contract Verification: Checks the periodic expiration of the contract, set to 09/05/2025.

e. DUVRI: Verifies if the DUVRI for the specific contract has been signed and uploaded.
6. Document Management: For each verification item, there are options to upload documents, set expiration dates, and track the last modification date.
7. Navigation Menu: On the left side, a comprehensive menu allows access to various sections such as Contacts, Equipment, Locations, Custom Data, Checklists, Documents, Commercial Information, Classifications, Categories, Verifications, Contracts, and more.

Although not shown in the image, the system includes a separate, simplified interface for suppliers. Key features of this portal include:
1. Secure Access: Suppliers are provided with unique login credentials to access their personalized portal.
2. Customized Document Requests: Based on the supplier type highlighted by the RSPP, the system automatically generates a list of required documents.
3. Document Upload Functionality: An intuitive interface allowing suppliers to easily upload the requested documents.
4. Expiration Date Management: Fields for suppliers to input and update expiration dates for various certifications and documents.
5. Company Information Section: Areas for suppliers to maintain their company details, including contact information, tax codes, and other relevant data.
6. Worker Information: For suppliers providing manpower, a section to manage worker details, qualifications, and certifications.
7. Equipment/Vehicle Management: For suppliers providing equipment or vehicles, a dedicated area to input and update information on these assets, including maintenance records and safety certifications.
8. Notification System: Automated alerts for upcoming document expirations or missing information.

This comprehensive system streamlines the supplier qualification process, ensuring that all necessary information is collected, verified, and maintained in a centralized location.

4. Analysis: Streamlining the Qualification Process

The implementation of the online supplier qualification portal revolutionized the way PWP srl – Centro Assistenza Porsche Livorno managed the qualification process for the inaugural event. The digital platform addressed several key challenges associated with traditional methods, paving the way for a more efficient, transparent, and compliant approach.

- **Efficiency**: The online portal eliminated the need for physical document exchange, reducing the time and resources required for document management. Suppliers could upload their documentation directly to the system, streamlining the entire process and minimizing administrative burdens. This digital approach not only saved valuable time but also reduced the risk of misplaced or lost documents, ensuring a seamless and organized qualification process.
- **Transparency**: The real-time status tracking feature provided complete visibility into the qualification progress of each supplier. This transparency ensured that no supplier was

overlooked and that all necessary documentation was accounted for. Stakeholders could easily monitor the status of each supplier, facilitating effective communication and coordination throughout the qualification process.

- **Compliance**: The portal's intelligent architecture ensured that all required fields were completed, reducing the risk of non-compliance with Decree 81/08, Article 26. Automated reminders for missing or expiring documents further reinforced compliance efforts, ensuring that suppliers remained up-to-date with their qualifications and minimizing the potential for lapses or oversights.
- **Data-driven decision-making:** The advanced data analytics capabilities of the portal provided valuable insights into supplier performance and compliance trends. This data-driven approach enabled informed decision-making regarding supplier relationships and potential areas for improvement. By analyzing historical data and identifying patterns, the company could make strategic decisions about future collaborations, fostering a culture of continuous improvement in safety and compliance practices.
- **Collaboration and coordination:** The centralized nature of the online portal facilitated seamless collaboration and coordination among various stakeholders involved in the qualification process. The Head of Prevention and Protection Service, the Management, and the marketing department could access and share information in real-time, fostering effective communication and ensuring a cohesive approach to supplier management.

5. Results: Achieving Unprecedented Success

The inaugural event served as a litmus test for this digital qualification system, and the results were nothing short of remarkable. Through the streamlined, user-friendly process, the company achieved a 100% supplier qualification rate. This success not only ensured full compliance with Decree 81/08, Article 26 but also significantly reduced administrative burdens and minimized the risk of oversight.

The digital transformation of the supplier qualification process yielded numerous benefits beyond mere compliance. It fostered improved communication between the company and its suppliers, enhanced transparency in the qualification process, and dramatically reduced the time and resources required for document management. Suppliers appreciated the user-friendly interface and the clear guidelines provided by the Head of Prevention and Protection Service, facilitating a smooth onboarding process and fostering a collaborative relationship.

Moreover, the system's ability to store and organize data securely provided an invaluable audit trail. In case of inspections or audits, all necessary information could be accessed and presented swiftly, demonstrating the company's safety and regulatory adherence. This digital repository not only streamlined the qualification process but also served as a comprehensive record-keeping system, ensuring transparency and accountability throughout the entire supplier lifecycle.

6. Conclusions

The case study of PWP srl – Centro Assistenza Porsche Livorno's inaugural event represents a compelling example of the potential of digital transformation in enhancing operational efficiency, ensuring regulatory compliance, and ultimately, fostering a safer work environment. The implementation of the online supplier qualification portal not only streamlined the qualification process but also provided valuable insights into supplier performance and compliance trends. This data-driven approach enabled informed decision-making and continuous improvement in safety measures.

Furthermore, the success of this digital initiative highlights the importance of collaboration between various stakeholders within an organization. The seamless cooperation between the Management, the marketing department, and the Head of Prevention and Protection Service was instrumental in achieving the remarkable results witnessed during the inaugural event. By leveraging the expertise and perspectives of different teams, the company was able to develop a comprehensive and effective solution tailored to their specific needs and challenges.

The digital supplier portal is an excellent tool for safety management professionals, however, it's crucial to remember that this portal is ultimately a tool, not a replacement for human expertise and judgment. While it can automate many tasks and provide valuable insights, the human element remains indispensable in interpreting data, making critical decisions, and fostering a culture of safety. The most effective approach combines the efficiency of digital tools with the irreplaceable skills of experienced safety professionals, ensuring a comprehensive and nuanced approach to workplace safety management.

As organizations continue to navigate the complexities of workplace safety and compliance, embracing digital transformation becomes increasingly crucial. The case study presented here can serve as a blueprint for other companies seeking to optimize their supplier qualification processes, ensuring both efficiency and thoroughness.

7. Future Developments

As we delve further into the digital age, the potential for further innovation in this domain is vast. Emerging technologies such as artificial intelligence, machine learning, and blockchain could offer new avenues for enhancing supplier qualification processes.

For instance, intelligent algorithms could automate document verification and identify potential risks or discrepancies, while blockchain-based systems could provide an immutable and transparent record of supplier qualifications and compliance histories. Additionally, the integration of digital supplier qualification portals with other enterprise systems, such as Enterprise Resource Planning (ERP) and Supplier Relationship Management (SRM) systems, could lead to greater efficiency and a holistic view of operations.

Moreover, the adoption of digital solutions for supplier qualification could be further incentivized by the emergence of new regulations and guidelines at the national and international levels. As regulatory authorities recognize the benefits offered by digital technologies in terms of transparency, traceability, and compliance, we may witness an acceleration in the adoption of such solutions by organizations.

A crucial aspect for the future development of these digital solutions is data security and privacy. With the increasing amount of sensitive information shared through online portals, it will be essential to implement robust cybersecurity measures and adopt best practices for data protection to ensure the confidentiality and integrity of supplier information.

Furthermore, the adoption of digital solutions for supplier qualification could be further incentivized by the emergence of new regulations and guidelines at the national and international levels. As regulatory authorities recognize the benefits offered by digital technologies in terms of transparency, traceability, and compliance, we may witness an acceleration in the adoption of such solutions by organizations.

In conclusion, the case study of PWP srl represents a turning point in supplier qualification and regulatory compliance management. By embracing digital innovation and promoting cross-functional collaboration, organizations can not only meet legal requirements but also cultivate a culture of safety and continuous improvement, ensuring a competitive edge in the rapidly evolving business landscape.

References

[1] Italian Legislative Decree 81/2008, "Attuazione dell'articolo 1 della legge 3 agosto 2007, n. 123, in materia di tutela della salute e della sicurezza nei luoghi di lavoro," Gazzetta Ufficiale, 2008.

[2] M. Tronci, L. Mercadante, P. Ricciardi, Industria 4.0: rischi e opportunità per la tutela e la sicurezza dei lavoratori, in Sfide e cambiamenti per la salute e la sicurezza sul lavoro nell'era digitale – Quaderni della Rivista degli infortuni e delle malattie professionali, 2018, 51 ss.

[3] M. Masi and E. Cagno, "Barriers to OHS interventions in Small and Medium-sized Enterprises," Safety Science, vol. 71, pp. 226-241, 2015.

[4] B. Fabiano, F. Currò, A.P. Reverberi, and R. Pastorino, "A statistical study on temporary work and occupational accidents: Specific risk factors and risk management strategies," Safety Science, vol. 46, no. 3, pp. 535-544, 2008.

[5] E. Cagno, G.J.L. Micheli, and S. Perotti, "Identification of OHS-related factors and interactions among those and OHS performance in SMEs," Safety Science, vol. 65, pp. 49-57, 2014.

[6] M. Battaglia, M. Frey, and E. Passetti, "Accidents at work and costs analysis: A field study in a large Italian company," Industrial Health, vol. 53, no. 6, pp. 562-572, 2015.

[7] G.J.L. Micheli, E. Cagno, and C. Calabrese, "The transition from occupational safety and health (OSH) interventions to OSH outcomes: An empirical analysis of mechanisms and contextual factors within small and medium-sized enterprises," International Journal of Environmental Research and Public Health, vol. 16, no. 12, p. 2180, 2019.

[8] M.G. Gnoni and J.H. Saleh, "Near-miss management systems and observability-in-depth: Handling safety incidents and accident precursors in light of safety principles," Safety Science, vol. 91, pp. 154-167, 2017.

[9] D. Podgórski, "Measuring operational performance of OSH management system – A demonstration of AHP-based selection of leading key performance indicators," Safety Science, vol. 73, pp. 146-166, 2015.

[10] A. Bianchini, F. Donini, M. Pellegrini, and C. Saccani, "An innovative methodology for measuring the effective implementation of an Occupational Health and Safety Management System in the European Union," Safety Science, vol. 92, pp. 26-33, 2017.

Towards a Safer Future: Integrating Technology and Safety Practices

Chiara Vianello[1,2*] and Giuseppe Maschio[1]
[1] Department of Industrial Engineering – University of Padua, Padua, Italy
[2] Department of Civil, Environmental and Architectural Engineering – University of Padua, Padua, Italy

* E-mail: chiara.vianello@unipd.it

Abstract. Workplace safety remains a critical concern globally, with millions of accidents occurring annually, resulting in substantial economic costs. While progress has been made in improving safety conditions, there is still room for improvement, especially with the advent of new technologies introduced by the Fourth Industrial Revolution or Industry 4.0. The evolution of safety concepts has progressed from a mechanistic view focused on human error to a more systemic approach that considers complex socio-technical systems and resilience engineering. This shift aligns with the technological advancements brought about by Industry 4.0, which integrates various enabling technologies through the Internet, leading to innovations in processes, organization, products, and business models. Emerging technologies offer new opportunities and challenges for enhancing workplace safety. Advanced monitoring systems and sensors can continuously track equipment, structures, and industrial environments, detecting anomalies and potential risks before incidents occur. Data analytics can reveal hidden patterns and trends, enabling predictive maintenance and risk forecasting. Automation can reduce the need for human involvement in hazardous activities, while virtual and augmented reality can provide realistic training simulations in a safe environment. Other technologies, such as intelligent alarm systems, wearable devices for worker health monitoring, remote control capabilities, and cybersecurity measures, also contribute to improving safety. However, these technologies also introduce new risk scenarios that must be carefully managed.

While some technological solutions are more effective than others in enhancing safety, their implementation faces challenges such as lack of information, adaptation to specific industry needs, worker training, and effectiveness evaluation.

To fully leverage the potential of these technologies, a comprehensive approach is required, involving incentives for adoption, worker training, and continuous assessment of the measures implemented. By embracing technological advancements while addressing their limitations, industries can create a safer working environment and contribute to the overall well-being of their workforce.

Keywords: Technology, Workplace, Safety

1. Introduction

In the ever-evolving landscape of industrial operations, workplace safety remains a paramount concern that continues to challenge organizations worldwide. Despite significant strides in improving safety conditions over the years, the global statistics on workplace accidents and their associated economic costs remain alarmingly high [1]. This persistent issue underscores the need for innovative approaches to enhance workplace safety, particularly in light of the technological advancements ushered in by the Fourth Industrial Revolution, commonly known as Industry 4.0[2], [3].

The concept of workplace safety has undergone a significant transformation in recent decades. Initially rooted in a mechanistic perspective that primarily focused on human error as the source of accidents, it has evolved into a more comprehensive, systemic approach. This modern understanding recognizes the complexity of socio-technical systems and incorporates principles of resilience engineering [4]. This shift in perspective aligns seamlessly with the technological innovations brought forth by Industry 4.0, which has revolutionized industrial processes, organizational structures, products, and business models through the integration of various enabling technologies via the Internet [5], [6].

The advent of Industry 4.0 has introduced a plethora of emerging technologies that offer both new opportunities and challenges for enhancing workplace safety [7]. These technologies, ranging from advanced monitoring systems and sensors to sophisticated data analytics and automation, have the potential to revolutionize how we approach safety in industrial settings [8]. They promise to provide unprecedented levels of risk detection, prediction, and prevention, potentially marking a new era in workplace safety.

However, the integration of these technologies into existing safety frameworks is not without its challenges. While some technological solutions have proven more effective than others in enhancing safety, their implementation often faces obstacles such as lack of information, the need for adaptation to specific industry needs, worker training requirements, and difficulties in evaluating their effectiveness [9]. Moreover, these new technologies introduce novel risk scenarios that must be carefully managed to ensure that the pursuit of enhanced safety does not inadvertently create new hazards [10].

This paper aims to explore the intersection of Industry 4.0 technologies and workplace safety, examining how these innovations can be leveraged to create safer working environments while addressing the challenges that come with their implementation. We will delve into the various technologies that are reshaping safety practices, analyse their potential impacts and limitations, and discuss the comprehensive approach required to fully harness their benefits.

By examining these aspects, we hope to contribute to the ongoing dialogue on workplace safety in the age of digital transformation. Our goal is to provide insights that can guide industries in embracing technological advancements while addressing their limitations, ultimately contributing to the creation of safer working environments and enhancing the overall well-being of the global workforce.

As we embark on this exploration, it is crucial to recognize that the pursuit of workplace safety in the context of Industry 4.0 is not merely a technological challenge, but a multifaceted endeavour that requires a holistic approach. It involves not only the implementation of new technologies but also the development of new skills, the adaptation of organizational cultures, and the evolution of regulatory frameworks. Only through such a comprehensive approach can we hope to fully realize the potential of these emerging technologies in creating truly safer workplaces for the future.

2. Analysis and Results

The integration of Industry 4.0 technologies into workplace safety practices has yielded a wealth of data and insights. This section will analyse the impact of these technologies on various aspects of workplace safety and present the results of their implementation across different industrial sectors.

2.1. Advanced Monitoring Systems and Sensors

The deployment of advanced monitoring systems and sensors has revolutionized the way industries detect and prevent potential hazards. These technologies enable continuous tracking of equipment, structures, and industrial environments, providing real-time data on various parameters such as temperature, pressure, vibration, and air quality.

The effectiveness of these systems is not uniform across all industries. Smaller businesses, in particular, have reported challenges in implementing and maintaining these advanced monitoring systems due to cost constraints and lack of technical expertise. This highlights the need for scalable solutions that can be adapted to different industry sizes and types.

2.2. Data Analytics and Predictive Maintenance

The application of data analytics to the vast amounts of information gathered by monitoring systems has opened new frontiers in predictive maintenance and risk forecasting. By revealing hidden patterns and trends, these analytics tools enable industries to anticipate potential safety issues before they occur.

The success of these analytics systems heavily depends on the quality and quantity of data available. Industries with longer histories of data collection and more sophisticated sensor networks tend to see better results. This underscores the importance of long-term investment in data infrastructure to fully leverage the benefits of predictive analytics in safety management.

2.3. Automation and Robotics

The increasing use of automation and robotics in industrial settings has significantly reduced the need for human involvement in hazardous activities, thereby enhancing workplace safety. Robots are now routinely employed in tasks involving extreme temperatures, toxic substances, or heavy lifting, minimizing human exposure to these risks.

The introduction of robotics and automation has also created new safety challenges. There have been instances of accidents involving human-robot interactions, highlighting the need for proper safety protocols and training.

2.4. Virtual and Augmented Reality

Virtual Reality (VR) and Augmented Reality (AR) technologies have emerged as powerful tools for safety training, providing realistic simulations of hazardous scenarios in a controlled, safe environment. These technologies allow workers to experience and respond to dangerous situations without actual risk, enhancing their preparedness for real-world incidents.

However, the effectiveness of VR and AR technologies in safety training is not uniform across all age groups and learning styles. Some studies have noted that older workers or those less familiar with technology may find these training methods challenging, emphasizing the need for a balanced approach that combines traditional and technology-based training methods.

2.5. Wearable Devices for Worker Health Monitoring

The advent of wearable technology has opened new avenues for monitoring worker health and safety in real-time. These devices can track vital signs, detect falls, monitor exposure to harmful substances, and alert supervisors to potential health risks.

However, the use of wearable devices for worker monitoring has also raised privacy concerns among some workers.

2.6. Intelligent Alarm Systems

The evolution of alarm systems from simple noise-makers to intelligent, context-aware systems has significantly improved emergency response in industrial settings. These systems can differentiate between different types of emergencies, provide specific instructions, and even guide evacuation processes.

However, the implementation of intelligent alarm systems has also revealed challenges related to system complexity and the potential for information overload. Some studies have noted instances where workers became desensitized to alarms due to frequent non-critical alerts, highlighting the need for careful calibration of these systems to maintain their effectiveness.

2.7. Cybersecurity Measures

As industrial systems become increasingly connected and reliant on digital technologies, cybersecurity has emerged as a critical component of workplace safety. Cyber attacks on industrial systems can lead to equipment malfunctions, data breaches, and even physical harm to workers.

However, the rapidly evolving nature of cyber threats poses ongoing challenges.

2.8. Remote Control and Monitoring Capabilities

The ability to control and monitor industrial processes remotely has significantly enhanced safety in high-risk environments. This technology allows workers to operate equipment and oversee processes from a safe distance, reducing exposure to hazardous conditions.

However, the reliance on remote systems has also introduced new challenges, particularly in terms of maintaining situational awareness and responding to unexpected situations. Some studies have noted instances where over-reliance on remote systems led to delayed responses to emergencies, emphasizing the need for balanced approaches that combine remote capabilities with on-site expertise.

2.9. Challenges in Technology Implementation

While the potential benefits of Industry 4.0 technologies for workplace safety are clear, their implementation is not without challenges.

2.10. Effectiveness Evaluation

Evaluating the effectiveness of new safety technologies has proven to be a complex task. While many studies show promising results, the long-term impacts are still being assessed.

In conclusion, the analysis of various Industry 4.0 technologies in the context of workplace safety reveals a landscape of significant potential benefits coupled with notable challenges. While these technologies have demonstrated impressive capabilities in enhancing safety across various industrial sectors, their effective implementation requires careful consideration of numerous factors, including cost, expertise, integration, and regulatory compliance. The results highlight the need for a nuanced, industry-specific approach to leveraging these technologies for maximum safety benefits.

3. Conclusions

The comprehensive analysis of Industry 4.0 technologies and their impact on workplace safety leads to several key conclusions:

1. Transformative Potential: Industry 4.0 technologies have demonstrated significant potential to transform workplace safety practices across various industrial sectors. From advanced monitoring systems and predictive analytics to automation and virtual reality training, these technologies offer unprecedented capabilities for risk detection, prevention, and management.
2. Measurable Improvements: Numerous case studies and large-scale surveys have shown measurable improvements in safety metrics following the implementation of these technologies. Reductions in accident rates, decreased severity of incidents, and improved emergency response times are among the most commonly reported benefits.
3. Industry-Specific Variations: The effectiveness of these technologies varies considerably across different industries and types of safety risks. While some sectors, such as manufacturing and chemical processing, have seen dramatic improvements, others face unique challenges in implementation and effectiveness.
4. Integration Challenges: Despite their potential, the integration of Industry 4.0 technologies into existing safety frameworks is not without challenges. Issues such as high initial costs, lack of technical expertise, difficulties in system integration, and resistance to change are common obstacles that organizations must overcome.

5. New Risk Scenarios: While these technologies aim to enhance safety, they also introduce new risk scenarios, particularly in areas such as cybersecurity and human-machine interaction. Managing these new risks is crucial to realizing the full safety benefits of Industry 4.0 technologies.
6. Human Factor Remains Critical: Despite the increasing role of automation and AI, the human factor remains critical in workplace safety. The effectiveness of these technologies often depends on proper implementation, interpretation, and response by human operators and managers.
7. Need for Comprehensive Approach: Maximizing the safety benefits of Industry 4.0 technologies requires a comprehensive approach that goes beyond mere technology implementation. This includes adapting organizational cultures, updating regulatory frameworks, and continuously training and upskilling the workforce.
8. Data Quality and Quantity: The success of many safety technologies, particularly those involving predictive analytics and AI, heavily depends on the quality and quantity of available data. Organizations with more mature data collection and management practices tend to see better results from these technologies.
9. Privacy and Ethical Considerations: The use of certain technologies, especially those involving worker monitoring and data collection, raises important privacy and ethical considerations that need to be carefully addressed to ensure worker trust and compliance.
10. Continuous Evolution: The field of workplace safety in the context of Industry 4.0 is rapidly evolving. Continuous research, development, and adaptation of these technologies are necessary to address emerging challenges and capitalize on new opportunities.
11. Cost-Benefit Analysis: While the initial investment in these technologies can be substantial, the long-term benefits in terms of reduced accidents, improved productivity, and potentially lower insurance costs can offer significant returns on investment.
12. Regulatory Adaptation: The rapid pace of technological advancement in workplace safety often outpaces regulatory frameworks. There is a need for more agile and adaptive regulatory approaches that can keep up with technological innovations while ensuring worker protection.
13. Small and Medium Enterprise (SME) Challenges: Smaller businesses often face greater challenges in adopting these technologies due to resource constraints. Developing scalable and affordable solutions for SMEs is crucial for widespread improvement in workplace safety across all industry segments.
14. Interdisciplinary Collaboration: Effective implementation of Industry 4.0 safety technologies requires collaboration across various disciplines, including engineering, data science, human factors, and organizational psychology.
15. Global Disparities: The adoption and effectiveness of these technologies vary significantly across different regions and economic contexts. Addressing these disparities is important for improving global workplace safety standards.

In conclusion, Industry 4.0 technologies offer immense potential for enhancing workplace safety, but realizing this potential requires a nuanced, comprehensive approach. Organiza-

tions must carefully consider the specific needs of their industry, the capabilities and limitations of different technologies, and the broader organizational and human factors that influence safety outcomes.
The successful integration of these technologies into workplace safety practices represents a significant step forward in protecting workers and improving overall operational efficiency. However, it's crucial to recognize that technology alone is not a panacea for all safety challenges. The most effective approaches will likely combine technological innovations with robust safety cultures, ongoing training and education, and a commitment to continuous improvement.
As we move forward, it will be essential to continue monitoring and evaluating the long-term impacts of these technologies on workplace safety. This ongoing assessment will help refine implementation strategies, identify best practices, and address emerging challenges. Moreover, it will be crucial to ensure that the benefits of these safety innovations are accessible to organizations of all sizes and across all industries, promoting a more equitable improvement in global workplace safety standards.
Ultimately, the integration of Industry 4.0 technologies into workplace safety practices represents not just a technological shift, but a fundamental reimagining of how we approach and manage safety in industrial environments. By embracing these innovations while remaining mindful of their limitations and challenges, organizations can create safer, more resilient workplaces that protect their most valuable asset – their workforce.

4. Future Developments

As we look towards the future of workplace safety in the context of Industry 4.0, several key areas of development and potential advancements emerge in Table 1.

In conclusion, the future of workplace safety in the context of Industry 4.0 is likely to be characterized by increasingly sophisticated, interconnected, and adaptive technologies. These advancements promise to make workplaces safer, more efficient, and more responsive to emerging risks. However, as these technologies evolve, it will be crucial to address the ethical, privacy, and human factors implications of their implementation. The challenge will be to harness these technological advancements in a way that enhances human capabilities and decision-making, rather than replacing them, ultimately creating work environments that are not only safer but also more fulfilling for workers. As we move forward, continuous research, interdisciplinary collaboration, and a commitment to ethical implementation will be key to realizing the full potential of these exciting developments in workplace safety.

Artificial Intelligence and Machine Learning	The continued evolution of AI and machine learning algorithms promises to further enhance predictive capabilities in safety management. Future AI systems may be able to analyse complex, multi-factorial data sets to predict potential safety incidents with even greater accuracy. These systems could potentially identify subtle patterns and risk factors that are not apparent to human observers, leading to more proactive and targeted safety interventions.
Internet of Things (IoT) Integration	The proliferation of IoT devices in industrial settings is likely to accelerate, creating increasingly interconnected and responsive work environments. Future developments may include more sophisticated sensor networks that can communicate with each other and central systems in real-time, providing a more comprehensive and nuanced picture of workplace conditions and potential hazards.
Advanced Materials and Smart PPE	Innovations in materials science could lead to the development of more effective and comfortable personal protective equipment (PPE). Future PPE might include smart fabrics that can adapt to environmental conditions, self-repair when damaged, or even actively neutralize hazardous substances. Wearable technology integrated into PPE could provide real-time health monitoring and environmental sensing capabilities.
Autonomous Systems and Advanced Robotics	The next generation of autonomous systems and robots may be capable of more complex decision-making and adaptability in hazardous environments. This could include robots that can independently assess risks and take appropriate actions to maintain safety, potentially replacing human workers in the most dangerous tasks entirely.
Enhanced Virtual and Augmented Reality	Advancements in VR and AR technologies could lead to more immersive and effective safety training experiences. Future systems might be able to create highly realistic simulations of complex, multi-factor accident scenarios, allowing workers to practice responses to rare but critical events. AR systems could provide real-time, context-aware safety information to workers in the field, enhancing situational awareness and decision-making.
Blockchain for Safety Compliance and Reporting	Blockchain technology could be leveraged to create tamper-proof, transparent records of safety compliance, incident reporting, and equipment maintenance. This could enhance accountability, streamline auditing processes, and provide a more reliable basis for safety analytics and decision-making.
Biometric Monitoring and Personalized Risk Assessment	Advanced biometric monitoring systems could provide more comprehensive and individualized assessments of worker health and fatigue levels. This could lead to personalized work schedules and task assignments based on individual risk profiles, optimizing safety at the individual level.
Quantum Computing for Complex Risk Modelling	As quantum computing technology matures, it could be applied to safety risk modelling, potentially allowing for the analysis of vastly more complex scenarios and interactions than is currently possible. This could lead to more accurate risk assessments and more effective preventive strategies.
Nanotechnology in Safety Applications	Nanotechnology could find various applications in workplace safety, from advanced filtration systems for air and water purification to nano-sensors capable of detecting minute levels of hazardous substances. Nanotech could also be incorporated into materials to create stronger, more durable safety equipment.

Table 1. Key areas of development and potential advancements.

Green Technologies and Safety	As industries increasingly focus on sustainability, there will likely be a growing intersection between green technologies and safety innovations. This could include safer, more environmentally friendly alternatives to hazardous materials, or energy-efficient systems that also enhance workplace safety.
Advanced Human-Machine Interfaces	Future developments in human-machine interfaces could lead to more intuitive and seamless interaction between workers and safety systems. This might include brain-computer interfaces for hands-free operation of equipment or advanced haptic feedback systems for improved situational awareness in hazardous environments.
Predictive Maintenance Evolution	The next generation of predictive maintenance systems may incorporate more advanced sensing technologies and AI algorithms, potentially predicting equipment failures with near-perfect accuracy. This could virtually eliminate accidents caused by equipment malfunction.
Adaptive Safety Systems:	Future safety systems might be able to dynamically adapt to changing conditions and emerging risks in real-time. These systems could automatically adjust safety protocols, reconfigure work environments, or redirect resources based on evolving risk assessments.
Integration of Social Sciences	There may be increased integration of insights from social sciences, such as behavioural psychology and organizational theory, into technological safety solutions. This could lead to systems that are better aligned with human behaviour and more effective at promoting safe practices.
Global Safety Networks	The development of global, interconnected safety networks could allow for real-time sharing of safety data, best practices, and incident reports across industries and geographical boundaries. This could lead to more rapid dissemination of safety innovations and quicker responses to emerging global safety challenges.
Ethical AI for Safety Decision-Making	As AI systems take on more significant roles in safety management, there will likely be increased focus on developing ethical AI frameworks specifically for safety-critical decision-making. This could involve creating AI systems that can balance safety considerations with other factors like productivity and cost in a transparent and ethically sound manner.
Advanced Simulation and Digital Twins	The concept of digital twins – virtual replicas of physical systems – could be extended to entire work environments. This would allow for more comprehensive testing of safety measures and could provide a platform for continuous, real-time safety optimization.
Neuroadaptive Systems	Future safety systems might incorporate neuroadaptive elements that can adjust based on a worker's cognitive state. This could include systems that detect fatigue or stress and automatically implement appropriate safety measures or interventions.
Climate Change Adaptation	As climate change continues to impact working conditions in many industries, future safety technologies may need to adapt to more extreme and unpredictable environmental conditions. This could lead to the development of more robust and adaptable safety systems designed to operate effectively in a wider range of environmental scenarios.
Customizable Modular Safety Systems	The future might see the development of highly modular and customizable safety systems that can be easily adapted to different industrial contexts. This could allow for more cost-effective and tailored safety solutions, particularly beneficial for smaller businesses or unique industrial environments.

References

[1] “Safety and health at work | International Labour Organization.” Accessed: Mar. 28, 2025. [Online]. Available: https://www.ilo.org/topics-and-sectors/safety-and-health-work

[2] A. Badri, B. Boudreau-Trudel, and A. S. Souissi, “Occupational health and safety in the industry 4.0 era: A cause for major concern?,” *Saf Sci*, vol. 109, pp. 403–411, Nov. 2018, doi: 10.1016/J.SSCI.2018.06.012.

[3] L. Da Xu, E. L. Xu, and L. Li, “Industry 4.0: state of the art and future trends,” *Int J Prod Res*, vol. 56, no. 8, pp. 2941–2962, 2018, doi: 10.1080/00207543.2018.1444806.

[4] David. Woods and Erik. Hollnagel, *Resilience Engineering*. CRC Press, 2017. Accessed: Mar. 28, 2025. [Online]. Available: https://www.routledge.com/Resilience-Engineering-Concepts-and-Precepts/Hollnagel-Woods/p/book/9780754649045

[5] H. Lasi, P. Fettke, H. G. Kemper, T. Feld, and M. Hoffmann, “Industry 4.0,” *Business and Information Systems Engineering*, vol. 6, no. 4, pp. 239–242, Aug. 2014, doi: 10.1007/S12599-014-0334-4/METRICS.

[6] M. Ghobakhloo, “The future of manufacturing industry: a strategic roadmap toward Industry 4.0,” *Journal of Manufacturing Technology Management*, vol. 29, no. 6, pp. 910–936, Jul. 2018, doi: 10.1108/JMTM-02-2018-0057/FULL/XML.

[7] G. Li, Y. Hou, and A. Wu, “Fourth Industrial Revolution: technological drivers, impacts and coping methods,” *Chin Geogr Sci*, vol. 27, no. 4, pp. 626–637, Aug. 2017, doi: 10.1007/S11769-017-0890-X/METRICS.

[8] G. J. Cheng, L. T. Liu, X. J. Qiang, and Y. Liu, “Industry 4.0 development and application of intelligent manufacturing,” *Proceedings – 2016 International Conference on Information System and Artificial Intelligence, ISAI 2016*, pp. 407–410, Jan. 2017, doi: 10.1109/ISAI.2016.0092.

[9] J. Lee, B. Bagheri, and H. A. Kao, “A Cyber-Physical Systems architecture for Industry 4.0-based manufacturing systems,” *Manuf Lett*, vol. 3, pp. 18–23, Jan. 2015, doi: 10.1016/J.MFGLET.2014.12.001.

[10] N. Tuptuk and S. Hailes, “Security of smart manufacturing systems,” *J Manuf Syst*, vol. 47, pp. 93–106, Apr. 2018, doi: 10.1016/J.JMSY.2018.04.007.

Digital Assistants and Robotic Interfaces: Opportunities for Integration and Social Well-Being

Guglielmo Frare[1*]
[1] Contec AQS | A Bureau Veritas Company

[*] E-mail: guglielmo.frare@hotmail.it _ guglielmo.frare@contecaqs.it

Abstract. The introduction of new technologies such as digital assistants and robotic interfaces represents a revolution for all work environments. These tools are redefining the way technical, operational and support tasks are handled. However, their social and cultural impact goes far beyond efficiency and productivity.
The humanisation of interfaces – through the use of natural voices, realistic visual and physicality appearance, and empathetic behaviour – introduces new challenges. Elements such as gender, skin tone and body language can unintentionally amplify social and cultural prejudices. On this issue, the first example can be associated with characteristic female voices to virtual assistants. A 2019 Unesco report pointed out that this use of that technology (voice assistants) may perpetuate gender stereotypes. Likewise, a lack of visual diversity in interfaces may lead to the alienation of certain categories of workers. Conversely, excessive customisation may favour the creation of 'self-referential bubbles' amplifying social separation. These phenomena have significant repercussions on occupational health and safety, not only in physical but also in psychosocial terms. A design that does not consider these aspects could compromise inclusivity and a sense of belonging in the workplace. Adopting an ethical and inclusive approach in the design of robotic and digital interfaces can turn these tools into catalysts for a more equitable and respectful environment, improving not only safety but also collective well-being.
Workplace design in the last century stopped at the structure of the process but in our present the challenge is to define the delivery modes and underlying ethics for the entire work environment. This new horizon is the means to overcome cultural and social barriers, mitigating the risks of discrimination. The article will discuss concrete examples of applications, best practices and design strategies.
Designing technologies that reflect the values of equity, diversity and inclusion allows us not to be prisoners of events.

Keywords: Ethics, Social Impact, Stress, Accountability, Design Issue

1. The new technologies are the today's technologies

The introduction of new technologies based on artificial intelligence (AI) is radically transforming the world of work. Digital assistants, robotic interfaces and automated tools are redefining the management of technical, operational and support tasks, improving efficiency and productivity. However, the impact of AI is not limited to the operational dimension: it has profound social and cultural implications that directly affect the health, safety and well-being of workers.

The humanisation of digital and robotic interfaces, through the use of natural voices, realistic visual appearance and empathetic behaviour, brings with it new challenges. The personalisation of these tools can unintentionally amplify social and cultural prejudices, affecting workers' sense of inclusion and belonging. Therefore, adopting an ethical and inclusive approach in the design of these technologies is crucial to ensure safe, fair and diversity-friendly workplaces.

AI is increasingly present in the workplace, with applications ranging from human resource management to advanced robotics. Voice assistants such as Siri, Alexa and Google Assistant have already penetrated the homes of millions of users, revolutionising the way people interact with technology. Home automation is already an integral part of everyday life for many. The revolution of these technologies is entering the world of work with the promise of facilitating operational efficiency. Increasingly, robots with artificial intelligence are being used in sectors such as healthcare, logistics and industrial production, reducing risks for workers and improving the quality of services offered. This new working paradigm will have to be accompanied towards success and not immediately into its possible negative consequences as other technologies have sadly taught us.

The introduction of new technologies raises crucial questions: how does automation affect workers' well-being? What are the psychological implications of interacting with robotic and digital interfaces? And above all, how can we ensure that AI is used ethically and inclusively?

1.1. Bias and Perception Manipulation

Cognitive biases are systematic distortions in the way we process information and make decisions. These thought patterns influence our perception of the world and our behavior, often without our awareness. Biases arise from evolutionary mechanisms that allow the human brain to process large amounts of data quickly, but they can lead to errors in the evaluation and interpretation of reality.

In the context of work and technology, biases influence the way we perceive artificial intelligence and robots. For example, the automation bias leads to excessive trust in automated systems, while the negativity bias makes us fear that the introduction of new technologies could damage our professional role. Furthermore, the so-called anchoring effect can cause first impressions of a technology to influence our overall evaluation in the long term. Awareness of these biases is essential to ensure a balanced adoption of AI in the workplace. An informed and critical approach can mitigate perceptual distortions and promote a more conscious and harmonious integration of new technologies. The role of the employer is therefore to promote a corporate culture based on continuous training and transparency, helping workers to better understand the decision-making processes of AI and their real implications.

One of the most critical aspects of AI concerns the way in which biases are used to shape responses and influence social perception. AI-based technologies are not neutral: they reflect the data with which they are trained, and this data may contain implicit biases derived from the social and economic context.
Digital assistance platforms and search algorithms, for example, are often designed to return answers that are more palatable or acceptable to the user. This means that information can be filtered to conform to certain dominant narratives, thus reinforcing existing social divisions. This phenomenon is known as the 'echo chamber effect', where people tend to only receive content that reinforces their pre-existing beliefs, reducing the possibility of critical and independent thinking.
Furthermore, the way responses are formulated can help shape users' perceptions of the world. If AI emphasises certain viewpoints at the expense of others, the risk is that a distorted version of reality is created, increasing inequalities and perpetuating harmful stereotypes. For example, if the language patterns used by virtual assistants are trained predominantly on Western sources or written by certain categories of people, the responses they provide will reflect such cultural biases.
This dynamic has significant implications for the world of work and society at large. If certain categories of workers see certain biases against them reinforced, this can lead to reduced professional opportunities and increased discrimination. Furthermore, an unregulated use of AI in personnel selection processes may favour candidates with similar characteristics to the profiles already existing in the company, excluding talent that differs by education, ethnicity or gender.

1.2. Our search for a friendly AI

In our daily experience, we are bombarded by advertisements created specifically for us. Similarly, in the future this could lead to extreme personalisation of our AI interlocutor as well. Within a complex system, this could translate into offering the companies of the future interfaces that are ready to stereotype the way work is done. The report 'Equality at Work Facing the Challenges' compiled by the ILO [7] highlights modes of discrimination such as:

- Gender discrimination: Unfavourable treatment based on sex, often manifested through unequal pay, limited career opportunities and gender stereotyping.
- Racial and ethnic discrimination: Differences in treatment due to racial or ethnic origin, which can lead to exclusion or disadvantages in access to employment and working conditions.
- Age discrimination: Disadvantages based on the age of the worker, often affecting both young people, considered inexperienced, and older workers, considered less adaptable.
- Disability discrimination: Obstacles in access to employment and career progression for people with disabilities, often due to prejudice or lack of reasonable accommodation in the workplace.
- Religious discrimination: Unfair treatment based on religious beliefs, which may include denial of leave for religious holidays or imposition of dress codes not compatible with religious practices.

- Discrimination based on sexual orientation and gender identity: Discrimination or harassment directed at individuals because of their sexual orientation or gender identity, creating a hostile or exclusionary work environment.

These forms of discrimination can manifest themselves directly, through explicit acts, or indirectly, through apparently neutral policies and practices that disadvantage certain groups. In this sense, just thinking about standard voice interfaces one can find stereotypes linked to sexism, female voices for subservient roles [1] that can reinforce dynamics of subordination. Furthermore, the low visual and cultural diversity of robotic interfaces may contribute to the alienation of certain groups of workers, limiting the sense of inclusion and participation.

The explicit risk in the described dynamic is related to the creation of 'self-referential bubbles', i.e. digital environments in which workers interact only with technologies that reflect their preferences and cultural background. This phenomenon may reduce the diversity of perspectives and limit the ability of organisations to foster an inclusive and collaborative work environment.

Conversely, it must be emphasised that one would have great difficulty approaching an AI without the context with which we as individuals have established ourselves; repudiating the way we have learnt to establish relationships and define relationships would certainly lead to an unpleasant use of the tool.

An example on this point might be to think about what our interaction with a voice assistant would be like if it were given a white voice, the classic pre-pubescent voice. In the case described, its use would be unnatural.

The field of application and the different types of output must therefore be contextualised and provide for degrees of freedom depending on the characteristics and the result to be obtained.

2. Artificial Intelligence: Between Efficiency and Social Impact

Market trends give us an insight into how artificial intelligence and robotics will take on an increasing role in the manufacturing and domestic worlds [8]; this drive will offer new challenges and increasingly advanced solutions to improve the quality of life. Referring to heavy carpentry or shipbuilding jobs, both health risks, such as manual handling of loads or exposure to carcinogenic substances, and safety risks, such as access to confined spaces or from collapsing structures, could be reduced. In general, reducing the physical workload would have a definite and effective impact. However, while these tools reduce the risk of accidents and improve efficiency, they can also affect people's social and psychological balance. The relationship between users and robot assistants raises questions about the perception of humanity and the emotional impact of interacting with machines that lack real empathy.

A study conducted by MIT and Stanford showed that the way domestic robots interact with users can influence their psychological well-being. If perceived as mere mechanical tools, they can reinforce a sense of alienation and loneliness. In contrast, empathic and personalised interfaces improve the emotional involvement and comfort of the user, reduc-

ing stress levels. This dynamic suggests that, in the design of domestic robots, it is not only efficiency that counts, but also the ability to create a more 'human' interaction.
These studies focus on the domestic side and this raises the alarm as to what the impact may be when these technologies are ripe for large-scale deployment for manufacturing applications. Already many companies in the 4.0 transition have converted many jobs but the new frontier of AI promises, if not properly managed, a much greater impact.

2.1. The Case of the Blade Runner Replicants

The evolution of AI and robotics in manufacturing work recalls the philosophical and cultural debate on the definition of humanity. An emblematic example is the replicants in Blade Runner, synthetic beings created to perform menial jobs but endowed with emotions and consciousness. The film raises the crucial question: what makes an artificial entity truly 'human'? The answer lies not only in its form, but in its actions and ability to form meaningful relationships with humans.
If we translate this reflection into the real world, we can ask to what extent robots should be designed to elicit a sense of familiarity and empathy. Should a domestic robot merely execute commands or should it be able to understand and adapt to the user's emotions? The boundary between machine and human is increasingly blurring, making ethical reflection essential: do we want our digital assistants to be perfectly functional tools or do we want them to have 'humanised' traits to enhance our psychological well-being?

2.2. The ethics we would like applied to AI

In science fiction, there are many novels and films, like the one in section 2.1, that teach us that humanity is not just a biological fact, but a matter of relationships, empathy and perception.
In this sense, news stories already tell us how models of self-driving cars have found themselves preventing potentially moral accidents with pedestrians while causing collisions with other vehicles passing in the other lane.
This brings us back to the trolley dilemma (or trolley problem) is a thought experiment in ethics developed by philosopher Philippa Foot in 1967. It presents the following scenario:
'An out-of-control railway trolley is about to run over five people tied to the tracks. You have the option of operating a railroad switch, diverting the trolley onto a sidetrack where only one person is present. Which is the right choice?'
This dilemma compares two ethical approaches:
1. Utilitarianism – Choosing to divert the trolley to minimise the loss of life (sacrificing one person to save five).
2. Deontology – Avoiding an action that directly causes harm to a person, even if the overall outcome would be more favourable.

The abstract application of this problem becomes more complicated for us human beings when additional variables are introduced. For example, if we were ourselves on the track, which choice would we make and which would we want the self-driving car to take instead of us?

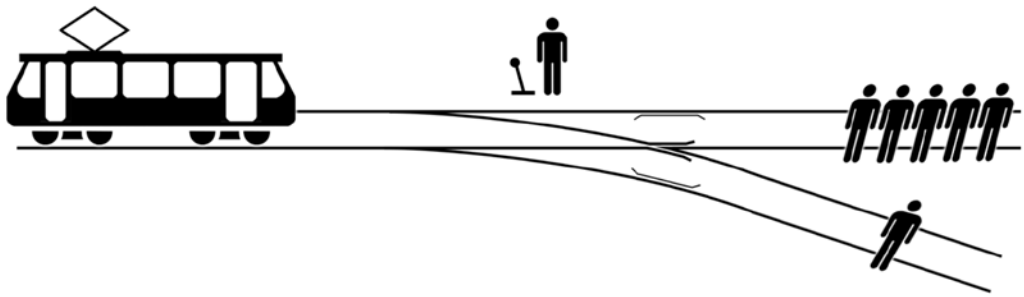


Figure 1. The trolley problem by philosopher Philippa Foot in 1967 [10].

2.3. Implications for the Manufacturing Sector

In the field of industrial robotics and artificial intelligence, the question opened in Section 2.2 translates into practical challenges for the context of automated decision-making:

1. Safety at work – If a robot in a manufacturing plant has to choose between two actions involving harm, how should it be programmed to make the best decision? For example, a robotic arm might have to decide whether to stop to avoid hitting a worker, while risking dropping a load on another worker.
2. Prioritisation in emergencies – If an automation system fails, should AI prioritise the protection of human life or the continuity of production? For example, an emergency system in an automated factory might have to choose between stopping a production line immediately (risking economic damage) or gradually slowing down the process (with greater risk for workers close to the machinery).
3. Legal and ethical responsibility – If an AI system makes a decision that causes damage or casualties, who is responsible? The programmer, the production company, the end user or the AI itself? This raises questions of accountability in industrial automation.
4. Ethical bias in decision-making systems – The programming of industrial AI to handle emergencies must be based on predefined values, but who decides which values to implement? A model based on utilitarianism might always choose the solution that maximises the collective benefit, but it might conflict with work safety regulations, which are based on deontological principles such as the protection of each individual worker.

Teaching ethics to AI interfaces in manufacturing is not only a theoretical issue, but a practical necessity to ensure safety, efficiency and accountability in automated decisions. The challenge is to balance utilitarianism and deontology, ensuring that automation systems protect workers without compromising the effectiveness of industrial operations.

3. Opportunities and Responsibilities

The integration of artificial intelligence into the workplace represents one of the most significant transformations of our time. While automation provides greater safety, efficiency and productivity, it is essential to address the resulting ethical and social implications. For this transition to be sustainable, a responsible approach must be adopted that takes human and

social needs into account. The key to ensuring a balanced integration of AI lies in the design choices, which can be distinguished between those made prior to the introduction of the technology and those concerning the management of its application in the work context.
Right from the development phase, it is essential to clearly define the goals of the technology, and to avoid AI being designed solely to optimise productivity at the expense of human well-being. The way in which decision-making algorithms are structured can decisively influence work dynamics, affecting not only efficiency, but also the workers' perception of their interaction with the machine. Interfaces, if too cold and impersonal, can generate a sense of alienation and detachment, while a more empathetic and intuitive design can facilitate greater acceptance and collaboration between man and machine.
Another fundamental aspect concerns inclusiveness: an artificial intelligence system should not favour some categories of workers to the detriment of others, but be designed to adapt to a diverse user base, guaranteeing accessibility also to people with special needs. Only through careful testing and simulation is it possible to anticipate possible problems and correct critical aspects before actual implementation.
When an AI-based system is actually introduced into a work environment, it opens up a new level of responsibility that requires constant monitoring of its performance and impact on the workforce. The acceptance of the technology by workers depends largely on the training and transparency with which it is implemented. A forced introduction without a proper familiarisation process can generate resistance. The path to be favoured in this regard is that of a gradual integration process, supported by adequate training, which can foster a more positive relationship between man and machine. It is important to emphasise that, even in a highly automated context, the human role remains central. Workers must always be able to intervene to correct any AI errors and be able to interact with it consciously and proactively.
The management of AI in the workplace cannot disregard continuous adaptation to social needs. Technologies, however advanced they may be, must be designed to evolve over time, responding to emerging needs and changing their parameters based on the feedback received. If an automated system starts to generate imbalances or create ethical problems, it is crucial to intervene promptly with updates and improvements. Trust in artificial intelligence is a key element for the success of its implementation: if workers perceive the machine as a hostile or threatening entity, the risk is to create a stressful and uncooperative working environment.

3.1. Assessment of Work-Related Stress and Risk of Discrimination

The introduction of robots and AI into a work environment not only involves operational transformations, but can also have a significant impact on workers' mental health. Constant interaction with automated systems can generate anxiety, stress and a feeling of alienation, especially if workers perceive technology as a threat to their safety and job stability. It is therefore essential that the employer assesses the psychosocial risks arising from these innovations and adopts adequate mitigation measures.
According to Italian Legislation the articole 28 of D.Lgs. 81 del 2008 sad that the employ-

er is required to assess work-related stress (SLC) as an integral part of the risk assessment. INAIL has developed an assessment methodology based on objective and subjective indicators, which include a preliminary analysis through checklists and questionnaires, followed by an in-depth phase in the event that high risk factors emerge. This assessment proposed by INAIL, especially in its preliminary part, which is the most widespread within Italian companies, is not currently able to adequately discretize the emergence of this type of criticality.

In the case of the introduction of AI and robotics, the employer should consider several specific indicators, such as the level of involvement and acceptance of workers with respect to technology, the degree of anxiety related to the possibility of replacing their role and the quality of interactions between humans and automated systems. Another relevant aspect is the monitoring of the frequency of stress-related disorders, such as burnout or decreased motivation, collected through questionnaires and periodic meetings with staff. The reading of the so-called "sentinel indicators" therefore becomes of fundamental importance for the prevention of these risks in all production environments as well as the establishment of a proactive and listening climate by top management.

One of the most significant psychosocial risks linked to AI in the workplace is algorithmic discrimination. AI-driven systems in recruitment, performance evaluation, and workplace monitoring can inadvertently reinforce biases present in their training data. These biases can lead to discriminatory practices, affecting hiring decisions, promotions, and work conditions, and ultimately influencing workers' stress levels.

Case Study: Amazon

Amazon employs over 1.5 million people globally (as of 2023), making it one of the largest employers in the world. When an AI-driven system is implemented at this scale, even small biases in algorithms can have widespread consequences. The company has already been the subject of several situations of interest in order to better understand what the risks of using AI-driven tools can be.

AI and Gender Bias in Recruitment

A well-documented case of algorithmic discrimination occurred with Amazon's AI-driven hiring tool, which was designed to screen job applicants. The system was trained on resumes submitted to the company over a ten-year period, most of which came from male candidates due to historical gender imbalances in the tech industry. Consequently, the AI developed a bias against female applicants, systematically downgrading resumes that included words associated with women, such as references to women's colleges. Amazon ultimately scrapped the tool after recognizing the issue, but the case highlights the risks of implicit bias in AI-based decision-making.

Such biases can exacerbate workplace inequalities and contribute to psychological distress among underrepresented workers, who may feel unfairly disadvantaged or excluded from career opportunities. The stress induced by these biases can manifest as anxiety, decreased motivation, and even burnout, impacting overall workplace well-being.

Workplace Surveillance and Productivity Monitoring

Another significant example of AI-driven discrimination concerns workplace surveillance.

Many companies now rely on AI-powered monitoring systems to track employee productivity, keystrokes, and even facial expressions to gauge engagement. However, these systems often disproportionately penalize certain groups, leading to unintended biases in performance evaluations.
For instance, Amazon's warehouse employees have reported experiencing extreme pressure due to AI-driven surveillance systems that automatically track their work pace and assign "time off task" (TOT) penalties for any period of inactivity. Reports indicate that these systems do not account for necessary short breaks, disproportionately affecting workers with medical conditions or disabilities who may require more frequent pauses. The fear of automated performance reviews and potential termination has led to increased stress, anxiety, and burnout among workers, highlighting the ethical concerns surrounding AI in workplace management.

4. Conclusions

The adoption of artificial intelligence in the workplace should therefore not only be seen as a technological advancement, but as an opportunity to build a more equitable and sustainable future. The issue is not just about efficiency, but how automation can contribute to improving the quality of life and working environment. Inevitably, this issue is linked to a broader reflection, which invokes the broader philosophical and cultural debate. In science fiction works, such as the ones mentioned above, the judgement on humanity is not based on their artificial origin, but on their actions and the way they interact with the world around them. This is the principle that is already partly applied to artificial intelligence systems today: their acceptance will depend not only on their functionality, but on their ability to fit harmoniously into the social and working environment.
The introduction of AI in workplaces must go hand in hand with robust safeguards against discrimination. A failure to do so can lead to legal repercussions, reputational damage, and increased psychological stress among employees. A well-balanced approach – combining technological innovation with ethical responsibility – is necessary to create workplaces where AI supports, rather than undermines, worker well-being.By considering both the psychosocial risks and the ethical challenges posed by AI, organizations can ensure that technology is a tool for inclusion and fairness, rather than a source of exclusion and inequality.
Moreover if the humanity of an AI is judged by its actions, then its success in the world of work will depend not only on what they do, but on how they are designed and managed for the good of the community. Artificial intelligence is not just a set of algorithms and processors: it is a tool that, if used with awareness and responsibility, can become a valuable ally for human progress. However, for this to happen, design and management choices must be made with a clear vision oriented towards the collective welfare, without neglecting the ethical and social implications of its application.

References

[1] UNESCO. (2019). "I'd blush if I could: Closing gender divides in digital skills through education".

[2] Brynjolfsson, E., & McAfee, A. (2014). "The Second Machine Age: Work, Progress, and Prosperity in a Time of Brilliant Technologies". W. W. Norton & Company.

[3] Daugherty, P. R., & Wilson, H. J. (2018). "Human + Machine: Reimagining Work in the Age of AI". Harvard Business Review Press.

[4] Susskind, D. (2020). "A World Without Work: Technology, Automation, and How We Should Respond". Metropolitan Books.

[5] Autor, D. (2015). "Why are there still so many jobs? The history and future of workplace automation". Journal of Economic Perspectives, 29(3), 3-30.

[6] Levy, F., & Murnane, R. J. (2004). "The New Division of Labor: How Computers Are Creating the Next Job Market". Princeton University Press.

[7] Uguaglianza nel lavoro. Affrontare le sfide (2007) Torino, Centro Internazionale di Formazione dell'ILO

[8] "Applications and Societal Implications of Artificial Intelligence in Manufacturing: A Systematic Review" di John P. Nelson, Justin B. Biddle e Philip Shapira (2023)

[9] Blade Runner (1982) film diretto da Ridley Scott

[10] The trolley problem by philosopher Philippa Foot in 1967 – Wikipedia

[11] Cicinelli, R. (2022). "La mente bugiarda: come i bias cognitivi ci mentono sulla realtà". State of Mind

[12] Moore, P. V. (2019). "Invisible workers: AI and the future of work surveillance." Internet Policy Review, 8(2).

[13] Ajunwa, I., & Greene, D. (2019). "Platforms at work: Automated hiring platforms and algorithmic discrimination." Big Data & Society, 6(2).

[14] Lecher, C. (2019). "How Amazon Automatically Tracks and Fires Warehouse Workers for 'Productivity'." The Verge.

Smart Solutions for Fire Emergencies: how Digital Tech is Revolutionizing Evacuations

Giulia De Cet[1*], Andrea Liviero[1], Marco Muraro[1], Chiara Vianello[2,1], Rossana Paparella[1], Daniela Boso[1] and Fabio Dattilo[2]

[1] Department of Civil, Environmental and Architectural Engineering – University of Padua, Padua, Italy

[2] Department of Industrial Engineering – University of Padua, Padua, Italy

* E-mail: giulia.decet@unipd.it

Abstract. With advancements in technology, various innovative products have entered the market, aimed at making the training process more interactive and engaging. The adoption of these new technologies has the potential to overcome many challenges, making the training not only more effective but also more inclusive. This study aims to assess the awareness and effectiveness of digital technologies in emergency evacuations. We explored the potential of advanced tools such as Building Information Modeling (BIM), Virtual Reality (VR), drone photogrammetry, and laser scanner surveying to improve both evacuation procedures and the training related to emergencies. The analysis examined how these tools can be integrated into different phases of an emergency (before, during, and after) to ensure greater efficiency and safety during evacuation operations. Starting from the creation and modeling of environments and evacuation routes through BIM, photogrammetry, or point clouds generated by laser scanning, it is possible to simulate emergency scenarios and prepare personnel for potential evacuations. This type of training would not only benefit staff in workplaces but also rescue operators, who could simulate and prepare for recovery operations in specific and challenging environments, which are often difficult to replicate in real life. Furthermore, virtual reality headsets could be used in the post-emergency phase to analyze actual risk scenes, allowing for a detailed review of the incident and identifying critical points for improvement.

This work is based on an analysis of digital technologies, providing recommendations on how to enhance evacuation procedures and personnel training. The goal is to promote a more inclusive and technologically advanced approach to emergency management, one that can be applied across different settings and contexts.

In conclusion, we believe that just as we learn to read, do math, and ride a bicycle from a young age, and retain those skills throughout life, we believe that education on evacuation should be given the same level of importance. Through training that incorporates digital technologies, it will be possible to transmit these skills from children to teenagers and adults, offering a simulated demonstration of how to apply theoretical concepts in practice. This will expand their understanding of emergency management.

Keywords: Emergency, Digital, Safety, Evacuation, VR, BIM

1. Introduction

The occurrence of fire emergencies in buildings and public spaces poses a significant threat to human safety and property. Effective evacuation procedures are crucial in mitigating the impact of such events and ensuring the safe egress of occupants, including individuals with disabilities. According to statistics from the National Fire Protection Association (NFPA), in the United States alone, fire departments responded to an estimated 1.4 million fires in 2023, resulting in 3670 civilian deaths and 13350 civilian injuries [1]. These figures highlight the critical importance of implementing robust evacuation strategies and training programs to minimize the loss of life and property damage.

Traditional evacuation training methods often face limitations in terms of accessibility, inclusivity, and realistic simulations. Conventional approaches, such as classroom-based lectures, may fail to effectively convey the complexities and dynamics of real-life emergency scenarios [2]. Furthermore, these methods may not adequately address the unique challenges faced by individuals with disabilities, who may require specialized assistance or specific solutions during an evacuation [3].

The advent of digital technologies has open up new avenues for enhancing evacuation preparedness and response. Advancements in areas such as Building Information Modeling (BIM), Virtual Reality (VR), drone photogrammetry, and laser scanning have the potential to revolutionize the way we approach emergency management and evacuation procedures [4].

Building Information Modeling (BIM) is a powerful tool that enables the creation of detailed 3D models of buildings, incorporating various architectural, structural, and mechanical components [5]. These models can be used to simulate evacuation scenarios, analyze potential bottlenecks or obstacles, and optimize evacuation routes. By integrating BIM with other digital technologies, such as VR, emergency responders and building occupants can engage in immersive training experiences, better preparing them for real-life emergencies [6].

Virtual Reality (VR) technology offers a safe and controlled environment for conducting evacuation drills and simulations, minimizing disruptions to daily operations [7]. Immersive VR experiences can improve the effectiveness of training by engaging participants' senses and promoting experiential learning, which has been shown to enhance knowledge retention and skill acquisition [8]. Additionally, VR can be used to simulate various emergency scenarios, including the presence of individuals with disabilities, fostering inclusivity and awareness among emergency responders and building occupants. For example, virtual reality headsets can be employed during the training and preparation phase for workers and emergency responders [9], [10].

Drone photogrammetry, a technique that combines aerial imagery with advanced computational methods, can rapidly capture high-resolution 3D models of buildings and their surroundings [11]. These models can be integrated with BIM and VR systems for pre-evacuation planning and training purposes. During an emergency, drones equipped with thermal cameras can assist in locating and rescuing individuals, even in low-visibility conditions, improving the efficiency and effectiveness of search and rescue operations [12].

Laser scanning technology, which utilizes precise laser measurements to capture the geometry and spatial characteristics of buildings and evacuation routes, can provide highly accurate data for creating detailed 3D models [13]. These models can be used for pre-evacuation planning, as well as post-incident analysis and reconstruction efforts, enabling a comprehensive understanding of the emergency scenario and facilitating the identification of areas for improvement.

The integration of these digital technologies has the potential to enhance evacuation preparedness, response, and post-incident analysis in several ways. By providing realistic simulations and immersive training environments, emergency responders and building occupants can develop a better understanding of evacuation procedures and gain practical experience in navigating various scenarios [14]. Real-time data from drones and BIM models can improve situational awareness and decision-making during an emergency, enabling more informed and effective responses [15]. Furthermore, post-incident analysis using laser scanning and 3D models can aid in identifying areas for improvement and developing strategies to mitigate future risks [16].

However, the adoption of these digital technologies in emergency management and evacuation procedures is not without challenges. Issues such as cost, accessibility, and the need for specialized training and expertise must be addressed to ensure widespread implementation and effective utilization [5]. Additionally, concerns related to data privacy, cybersecurity, and the potential for system failures or errors must be carefully considered and mitigated.

Italian legislation mandates that every worker must receive both general and specific training before beginning their job activities. Additionally, this training must be periodically updated to comply with current legislative provisions [17][18]. The fire safety training program includes both theoretical and practical components.

This study aims to explore the potential of digital technologies, such as BIM, VR, drone photogrammetry, and laser scanning, in revolutionizing evacuation procedures and training. By leveraging these advanced tools, we aim to promote a more inclusive and technologically advanced approach to emergency management, one that can be applied across various settings and contexts.

2. Methodology

This work integrates expertise in engineering, architecture, computer science, and safety to develop innovative technological solutions. A detailed analysis of digital modeling and simulation tools will be carried out to design safe and accessible evacuation routes. The use of digital and smart technologies will improve emergency management. This work represents an opportunity to demonstrate how digital technologies can contribute in the pre and post-emergency phases as well as during emergencies.

This in-depth study has also proven essential for acquiring greater sensitivity and competence in an area crucial for safety and social inclusion.

The work is divided into two main phases: (1) In the first phase, a brief online questionnaire was prepared and administered to a heterogeneous sample of people. The objective was to evaluate their knowledge on how to approach an evacuation test in the presence of people with disabilities; (2) in the second phase, it was examined how digital technologies can be useful for both evacuation and evacuation training. Tools such as the BIM project, photogrammetry with drones, and laser scanning surveys were considered, etc.

It was initially decided to develop a brief questionnaire to be administered to a heterogeneous group of people. Operationally speaking, to achieve the set objective, the following steps were followed: (a) Formulation of the questionnaire; (b) Administration of the questionnaire; (c) Analysis of the results.

As mentioned previously, the objective was to evaluate the participants' knowledge of how to approach an evacuation test in the presence of people with disabilities. In practice, a questionnaire was developed by dividing it into three main sections:

1. Consent to data processing.
2. Section dedicated to general information, where a series of general data was requested from the subject to frame the experimental sample;
3. Section dedicated to the two questions on the work topic.

The tool used for the implementation of the questionnaire is the online program "Google Forms". Based on tests carried out before sharing the link, a completion time of less than 10 minutes was estimated.

The questionnaire was administered by sending the form link, in the period between May and July 2024, collecting 49 responses. The responses provided by the various participants are analyzed below, providing some preliminary considerations. The 49 Italian participants (29 males) were between 21 and 66 years old and used the Italian language to express themselves; 5 were involved in safety at the workplace (approximately 10%); 5 held roles related to safety at the workplace (approximately 10%).

If we analyze questions 9 and 10, which concern the focus of the questionnaire:

1. Question 9 stated: "If you were to find yourself in a situation where evacuation is required, what behaviour would you adopt towards people with disabilities?" It is evident from most of the responses that the word "disability" was understood as "physical disability". The participants therefore considered disabilities that we can easily identify. And what about disabilities that we cannot see?;
2. Question 10 stated: "In your opinion, are there effective tools to assist in the evacuation of people with disabilities?" None of the 49 subjects considered digital technologies as effective tools.

Current directions in scientific research address various aspects of evacuation, for example, Smedberg et al. [19] wondered whether the presence of people with mobility limitations (e.g., people in wheelchairs) can influence the evacuation of other people, thus influencing the decision-making process of nearby evacuees. The researchers used virtual reality to design a choice experiment. The results obtained from 40 Swedish participants indicate that the choice of exit was positively influenced by other people choosing the exit, and a greater effect was observed when the other person was a person in a wheelchair.

3. Analysis

The study yielded significant insights into the potential of digital technologies in revolutionizing evacuation procedures and training.

3.1. BIM

BIM represents an advanced and intelligent process that leverages 3D digital models to plan, design, construct, and manage buildings and infrastructure. Unlike traditional two-dimensional methods, BIM is based on a set of data that virtually describes objects, simulating their actual physical management. This technology allows for the analysis of potential execution complexities and the impact of various decisions in the preliminary stages, enabling more efficient and complete design, and ensuring monitoring of the entire life cycle, from construction to maintenance, and up to disposal. The introduction of an integrated design method, which requires new skills and a structured process, is not easy to implement in work contexts. BIM allows for the creation of a three-dimensional model of a building, an evacuation route, or a generic location of interest for the study of emergency management.

3.2. Virtual Reality

Three types of reality can be distinguished: virtual, augmented, and mixed. Virtual reality is further subdivided into three types: immersive (headset), semi-immersive (Cave), and non-immersive (2D display). The use of this technology ensures the active use of sensory and motor skills to improve the learning process. This phenomenon is well described by Edgar Dale in his "Cone of Experience"[20], in which he suggests that direct experience provides a better basis for the learning process.
This technology has numerous advantages: it is possible to create a repeatable scene in a safe and controlled area. With specific software, risk scenes are constructed in which to immerse people without compromising their safety. This allows, with an initial expenditure (equipment and scenario development), to make a scene repeatable without having to reconstruct it. Virtual reality allows for greater involvement of participants, thus improving the effectiveness of training. Furthermore, it offers a solution to the main drawbacks of traditional evacuation exercises, reducing costs and minimizing disruption of work activities.

3.3. Laser Scanner

The laser scanner is a system based on the measurement of flight time with high-speed waveform digitization technology: a laser pulse is emitted at a fixed frequency, and the time elapsed between emission and reception of the ray reflected by the object is measured. Given the speed of propagation of the pulse in the air and the flight time, the laser-object distance is calculated. To have complete knowledge of the object, the laser pulse is deflected over the entire area of interest. The geometry of the acquisitions will be designed according to the formal and dimensional characteristics of the spaces investigated. The laser scanner provides accuracy values on the restitution of the single point and is currently one of the most suitable tools for acquiring a point cloud aimed at constructing a three-dimensional model on an architectural scale. The use of three-dimensional digital models is a solution rich in potential. Modeling is a strategy in which the idea of similarity to reality plays a decisive role, which is exploited in different ways depending on the type of model being created.

3.4. Photogrammetry with Drone

Photogrammetry is a surveying technique that allows obtaining metric information (shape and position) of three-dimensional objects through the interpretation and measurement of photographic images (photograms).

Photogrammetry is also called a remote sensing technique as it allows determining the characteristics of objects without having physical contact with them.

Technology	Before Emergency	During Emergency	After Emergency
BIM	Produces a base model for implementing virtual environments useful for pre-emergency training [21].	Provides firefighters with clear identification of the building and all its characteristics. Allows creation of an informative database on evacuation routes, location of extinguishing systems, etc. [22]	Produces a base model for implementing virtual environments useful for post-emergency training to learn from incidents [21]. Can be used for quantifying damages to the structure [23].
Virtual Reality	The headset can be used for training and preparing workers and/or emergency personnel [24].		The headset can be used in the post-emergency phase to analyze real-life risk scenarios and study the incident in detail [25].
Laser Scanner	Laser scanning is useful for creating environments where emergency personnel can be immersed using a headset for training purposes.		Laser scanning can be used in the post-emergency phase, along with BIM, to quantify damages caused by an adverse event to the structure [26].
Photogrammetry with Drone	Photogrammetry is useful for training and preparing workers or emergency personnel. Environments can be recreated using photogrammetry with drones [27].	During the emergency phase, the drone will be equipped with a thermal camera to detect heat signatures and locate missing persons, even in low visibility conditions [12].	In the post-emergency phase, the drone equipped with a thermal camera can be used to locate any remaining missing persons or identify other post-fire combustions [11].

Table 1. Applications of digital technologies before, during and after emergencies with supporting scientific references.

4. Results

BIM enables the creation of detailed 3D models of buildings, evacuation routes, and emergency scenarios, facilitating pre-evacuation planning and analysis.
These models can be integrated with other digital technologies, such as VR, to create immersive training environments for emergency responders and building occupants.
BIM models can provide real-time information to emergency responders during an incident, enhancing situational awareness and decision-making.
VR technology offers a safe and controlled environment for conducting evacuation drills and simulations, minimizing disruptions to daily operations.
Immersive VR experiences can improve the effectiveness of training by engaging participants' senses and promoting experiential learning.
VR can be used to simulate various emergency scenarios, including the presence of individuals with disabilities, fostering inclusivity and awareness.
Drone-based photogrammetry can rapidly capture high-resolution aerial imagery and generate 3D models of buildings and surroundings.
These models can be integrated with BIM and VR systems for pre-evacuation planning and training purposes.
During an emergency, drones equipped with thermal cameras can assist in locating and rescuing individuals, even in low-visibility conditions.
Laser scanning technology can accurately capture the geometry and spatial characteristics of buildings and evacuation routes.
The resulting point cloud data can be used to create detailed 3D models for integration with BIM and VR systems.
Post-incident laser scanning can aid in damage assessment and reconstruction efforts.
Indeed, the integration of these digital technologies has the potential to enhance evacuation preparedness, response, and post-incident analysis. By providing realistic simulations, immersive training environments, and real-time data, these tools can improve situational awareness, decision-making, and the overall effectiveness of evacuation procedures.
The key findings are presented in Table 1.

5. Conclusions and Future Developments

The work was divided into two main phases, aimed at evaluating the knowledge and effectiveness of digital technologies in the field of emergency evacuations, with a particular focus on the presence of people with disabilities.
In the first phase, an online questionnaire was prepared and administered to a heterogeneous sample of people. This tool allowed for the collection of valuable data on public awareness and knowledge regarding evacuation in the presence of people with disabilities. The objective was to better understand the gaps and areas for improvement in preparing and raising public awareness on how to properly manage emergency situations involving people with disabilities.
The questionnaire was designed as a knowledge base for future research, to obtain an overview of people's perception of the concept of disability. The obtained data evinces that the term disability is understood as a physical disability, i.e., visible, completely disregarding

disabilities that "cannot be seen." This can be interpreted as a need and opportunity for awareness and training on the facets of disability and the emergency situations that can arise. In the second phase, the focus shifted to analyzing the digital technologies. The potential of advanced tools such as BIM, virtual reality, photogrammetry with drones, and laser scanning was examined to improve both evacuation procedures and related training. The analysis included studying how these tools can be integrated into emergency situations (pre, during, and post) to ensure greater effectiveness and safety in evacuation operations.
This study has highlighted the significant potential of digital technologies in revolutionizing evacuation procedures and training. By leveraging the capabilities of BIM, VR, drone photogrammetry, and laser scanning, emergency management can become more inclusive, efficient, and responsive.
The findings highlight the importance of adopting a holistic approach that integrates these technologies throughout the various phases of an emergency, from pre-evacuation planning to real-time response and post-incident analysis. By doing so, emergency responders and building occupants can benefit from realistic simulations, enhanced situational awareness, and improved decision-making capabilities.
Furthermore, the study underscores the need for collaboration among stakeholders, including emergency management agencies, building designers, technology providers, and research institutions. Such collaboration can foster the development of innovative solutions, standardized protocols, and best practices for the effective implementation of digital technologies in evacuation scenarios.
Future research should focus on addressing the remaining challenges and limitations identified in this study. This includes exploring ways to enhance the accessibility and affordability of these technologies, ensuring their widespread adoption and implementation. Additionally, further investigation into the integration of artificial intelligence and machine learning techniques could potentially enhance real-time decision-making and optimize evacuation strategies based on dynamic conditions.
In conclusion, the adoption of digital technologies in emergency evacuations represents a significant step towards creating safer and more inclusive environments. By embracing these innovative solutions, we can better prepare for and respond to fire emergencies, ultimately saving lives and minimizing the impact of such events.

References

[1] "Fire loss in the United States | NFPA Research." Accessed: Mar. 20, 2025. [Online]. Available: https://www.nfpa.org/education-and-research/research/nfpa-research/fire-statistical-reports/fire-loss-in-the-united-states

[2] S. Gwynne, E. R. Galea, M. Owen, P. J. Lawrence, and L. Filippidis, "A review of the methodologies used in the computer simulation of evacuation from the built environment," Build Environ, vol. 34, no. 6, pp. 741–749, Nov. 1999, doi: 10.1016/S0360-1323(98)00057-2.

[3] K. M. Christensen, S. D. Collins, J. M. Holt, and C. N. Phillips, "The Relationship Between the Design of the Built Environment and the Ability to Egress of Individuals with Disabilities," Review of Disability Studies: An International Journal, vol. 2, no. 3, 2006, Accessed: Mar. 20, 2025. [Online]. Available: https://rdsjournal.org/index.php/journal/article/view/334

[4] E. Ronchi and D. Nilsson, "Fire evacuation in high-rise buildings: a review of human behaviour and modelling research," Fire Science Reviews 2013 2:1, vol. 2, no. 1, pp. 1–21, Nov. 2013, doi: 10.1186/2193-0414-2-7.

[5] C. M. Eastman, P. M. Teicholz, Rafael. Sacks, and Ghang. Lee, "BIM handbook : a guide to building information modeling for owners, managers, designers, engineers and contractors," 2018.

[6] U. Rüppel and K. Schatz, "Designing a BIM-based serious game for fire safety evacuation simulations," Advanced Engineering Informatics, vol. 25, no. 4, pp. 600–611, Oct. 2011, doi: 10.1016/J.AEI.2011.08.001.

[7] M. Kinateder et al., "Virtual reality for fire evacuation research," 2014 Federated Conference on Computer Science and Information Systems, FedCSIS 2014, vol. 2014-January, pp. 313–321, Oct. 2014, doi: 10.15439/2014F94.

[8] S. Bhide, "Fire safety and emergency evacuation training for occupants of building using 3D virtual simulation," 2017.

[9] G. De Cet, C. Vianello, and L. W. Menzemer, "La realtà virtuale è uno strumento efficace per l'addestramento all'evacuazione in caso di incendio?," Quaderno della sicurezza n.1, 2023.

[10] L. W. Menzemer, E. Ronchi, M. M. V. Karsten, S. Gwynne, and J. Frederiksen, "A scoping review and bibliometric analysis of methods for fire evacuation training in buildings," Fire Saf J, vol. 136, p. 103742, Apr. 2023, doi: 10.1016/J.FIRESAF.2023.103742.

[11] F. Remondino, L. Barazzetti, F. Nex, M. Scaioni, and D. Sarazzi, "UAV PHOTOGRAMMETRY FOR MAPPING AND 3D MODELING – CURRENT STATUS AND FUTURE PERSPECTIVES," The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. XXXVIII-1-C22, pp. 25–31, Sep. 2012, doi: 10.5194/ISPRSARCHIVES-XXXVIII-1-C22-25-2011.

[12] C. A. F. Ezequiel et al., "UAV aerial imaging applications for post-disaster assessment, environmental management and infrastructure development," 2014 International Conference on Unmanned Aircraft Systems, ICUAS 2014 – Conference Proceedings, pp. 274–283, 2014, doi: 10.1109/ICUAS.2014.6842266.

[13] J. L. Van Genderen, "Airborne and terrestrial laser scanning," Int J Digit Earth, vol. 4, no. 2, pp. 183–184, 2011, Accessed: Mar. 20, 2025. [Online]. Available: https://www.academia.edu/69872774/Airborne_and_terrestrial_laser_scanning

[14] K. Andrée, D. Nilsson, and J. Eriksson, "Evacuation experiments in a virtual reality high-rise building: exit choice and waiting time for evacuation elevators," Fire Mater, vol. 40, no. 4, pp. 554–567, Jun. 2016, doi: 10.1002/FAM.2310.

[15] Z. Ding et al., "A building information modeling-based fire emergency evacuation simulation system for large infrastructures," Reliab Eng Syst Saf, vol. 244, p. 109917, Apr. 2024, doi: 10.1016/J.RESS.2023.109917.

[16] X. Xiong, A. Adan, B. Akinci, and D. Huber, "Automatic creation of semantically rich 3D building models from laser scanner data," Autom Constr, vol. 31, pp. 325–337, May 2013, doi: 10.1016/J.AUTCON.2012.10.006.

[17] "Gazzetta Ufficiale." Accessed: Feb. 01, 2024. [Online]. Available: https://www.gazzettaufficiale.it/eli/id/2008/04/30/008G0104/sg

[18] “Gazzetta Ufficiale.” Accessed: Feb. 01, 2024. [Online]. Available: https://www.gazzettaufficiale.it/eli/id/2016/08/19/16A06077/sg

[19] E. Smedberg et al., “The impact of people with mobility limitations on exit choice,” Fire Saf J, vol. 140, p. 103900, Oct. 2023, doi: 10.1016/J.FIRESAF.2023.103900.

[20] E. Dale, Audio-Visual Methods in Teaching. 1969.

[21] R. Sacks, A. Perlman, and R. Barak, “Construction safety training using immersive virtual reality,” Construction Management and Economics, vol. 31, no. 9, pp. 1005–1017, Sep. 2013, doi: 10.1080/01446193.2013.828844.

[22] P. Katranuschkov, J. C. P. Cheng, and M. Das, “A BIM-based web service framework for green building energy simulation and code checking,” ITcon Vol. 19, pg. 150-168, http://www.itcon.org/2014/8, vol. 19, no. 8, pp. 150–168, Jul. 2014, Accessed: Mar. 20, 2025. [Online]. Available: http://www.itcon.org/paper/2014/8

[23] R. Volk, J. Stengel, and F. Schultmann, “Building Information Modeling (BIM) for existing buildings – Literature review and future needs,” Autom Constr, vol. 38, pp. 109–127, Mar. 2014, doi: 10.1016/J.AUTCON.2013.10.023.

[24] M. Kinateder et al., “Virtual Reality for Fire Evacuation Research,” vol. 2, pp. 313–321, 2014.

[25] R. Lovreglio, E. Ronchi, and D. Nilsson, “An Evacuation Decision Model based on perceived risk, social influence and behavioural uncertainty,” Simul Model Pract Theory, vol. 66, pp. 226–242, Aug. 2016, doi: 10.1016/J.SIMPAT.2016.03.006.

[26] X. Xiong, A. Adan, B. Akinci, and D. Huber, “Automatic creation of semantically rich 3D building models from laser scanner data,” Autom Constr, vol. 31, pp. 325–337, May 2013, doi: 10.1016/J.AUTCON.2012.10.006.

[27] S. Siebert and J. Teizer, “Mobile 3D mapping for surveying earthwork projects using an Unmanned Aerial Vehicle (UAV) system,” Autom Constr, vol. 41, pp. 1–14, May 2014, doi: 10.1016/J.AUTCON.2014.01.004.

The Adoption of a P-Connect Gateway Together with a System of Electromechanical and Electronic Safety Devices: Advanced Safety Accompanied by Network Protection from External threats

Francesco Lo Giudice[1], Stefano Matterazzo[1] and Lorenzo Baraldo[2,3]
[1] Technical Department, Pizzato Elettrica Srl, Marostica, Italy
[2] Sustain Tech Hub S.p.a. SB (ITALY)
[3] University of Padua, Department of Industrial Engineering (Italy)

* E-mail: flogiudice@pizzato.com, smatterazzo@pizzato.com

Abstract. The technical evolution of interlocking devices in the last decade and the interconnection of production processes and systems introduced by Industry 4.0 have led to the need to digitize the information arriving from the field to be managed uniformly by the supervision device (PLC). It therefore becomes essential to use an interface device that converts the signals coming from the field into a set of bits transmitted within a communication protocol. The P-Connect gateway transmits all safety information of two interlocked guards via a fieldbus safety protocol. The inclusion of the gateway in the safety system brings a series of advantages within the application, including providing additional information on the status of the devices for better maintenance management, reduction of wiring with a consequent reduction of possible errors, in general ensuring greater reliability of the application.

Keywords: Industrial Safety, Safety Fieldbus

1. Evolution of interlocking devices

The risk analysis of industrial machinery is a fundamental process at the basis of the safety and health of workers. The machine designer must consider the safe use of the application as well as the operational efficiency and performance expected by the initial specifications. The ISO 12100 standard represents an indispensable reference for carrying out risk analysis, which involves the assessment and management of potential hazards generated using machinery. Among the most common measures for mitigating risks generated by moving mechanical parts is the application of interlocking movable guards; that is, guards that are opened by the operator to perform specific tasks, the position of which is monitored by specific devices (interlocking devices) that inhibit dangerous operations of the machinery under certain conditions (typically when the guard is open). In other words, interlocking devices are mechanical, electrical or other types of apparatus that, together with the machine control system, have the function of:

- prevent the operation of the hazardous functions of the machine associated with the guard until the guard is closed;
- if the guard is opened while the hazardous functions of the machine are operating, a command is given to bring the machine into a safe state (a stop command).

Interlocking devices are therefore widely used in machinery and in the last decade have undergone significant technological evolution, moving from purely electromechanical technologies to particularly sophisticated devices with active on-board electronics capable of ensuring the highest levels of reliability. The main driver of this technical evolution was the ISO 14119 standard "Interlocking devices associated with guards – Principles for design and selection", published in 2013 by the International Organization for Standardization (ISO). The ISO 14119 standard was recently updated in September 2024, but already in its previous edition (2013) had introduced specific requirements to increase the safety of applications with interlocking guards. Considering that among the most frequent causes of injury on industrial machinery is the tampering of safety functions, especially the tampering of interlocking devices, ISO 14119 has introduced specific requirements to limit the possibility of circumventing the devices themselves.

Thanks to the international spread of the ISO 14119 standard, there has been a growing demand for safer interlocking devices that are protected against possible tampering, especially against the simplest forms of tampering such as actuator substitution (the use of a second actuator makes it possible to circumvent the interlocking function and actuate the machine movements with the guard open).

The last decade has therefore seen the development and spread of RFID (Radio Frequency Identification) technology applied to interlocking devices, precisely following the publication of the second edition of the ISO 14119 standard in 2013. This technology allows the device to identify the code present in the actuator, and therefore compare it with the code associated with the device; in this way it is possible to recognize tampering attempts and ensure safe behavior of the interlocking device. By way of example, a device that uses a 24-bit RFID recognition system for actuator recognition can manage more than 16 million code combinations; it follows that the machine operator who wants to try to tamper with the interlocking function by trying to use a second actuator on the device to work with the guard open, would have less than one in 16 million chances of finding the actuator with the correct code. The ISO 14119 standard defines a "high-level coded actuator" as a coded actuator for which more than 1000 code variants are available, and the different codes are evaluated by the interlocking device.

RFID technology applied to interlocking devices has in fact significantly increased the level of protection against tampering of interlocking devices with separate actuators, making it much more complex to circumvent the interlocking function of the guard.

Figure 1 shows a graph representing a market analysis of sales of electromechanical and RFID interlocking devices in the decade from 2014 to 2023, expressed as a percentage ratio. It is evident that progressively the percentage of sales of RFID interlocking devices has grown to reach almost 30% of total sales of interlocking devices in the year 2023.

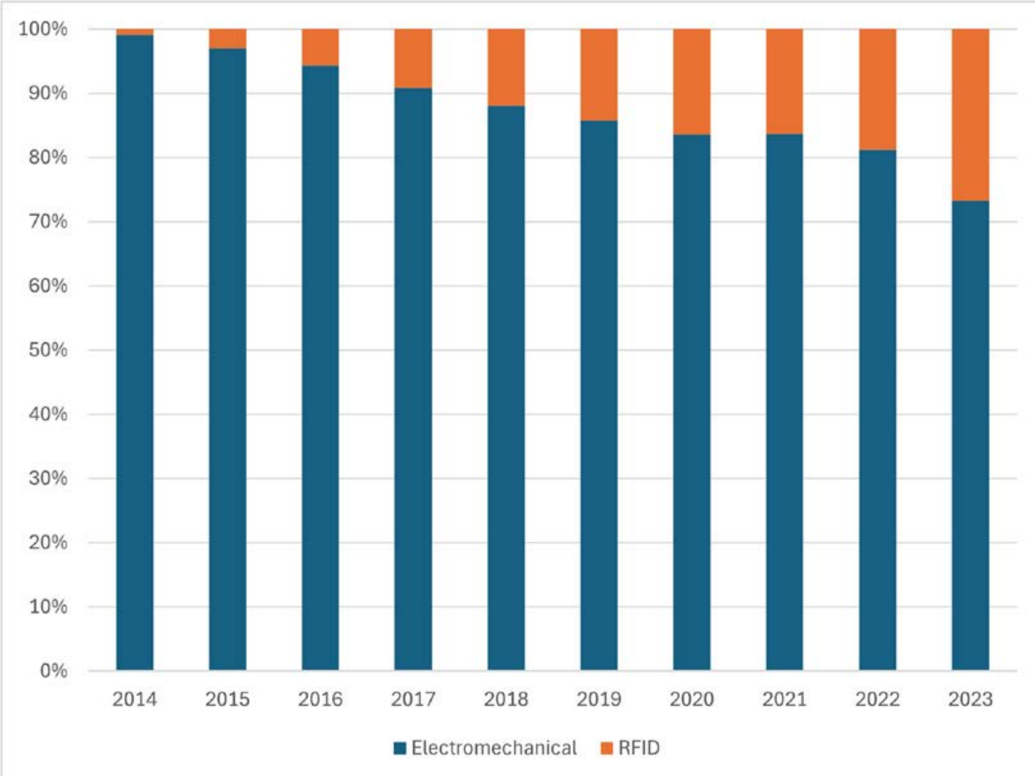


Figure 1. Market analysis of sales of electromechanical interlocking devices and RFID interlocking devices from 2014 to 2023, expressed in percentage.

The introduction of RFID technology on interlocking devices has made it necessary to transition from purely electromechanical technology (basically composed of mechanisms and electrical contacts) to the significant presence of electronics within the devices themselves. Electronics therefore play a fundamental role in new generation devices, allowing greater flexibility, reliability and functionality. The information on the state of the movable guard is processed by an electronic control system that activates or deactivates the safety outputs of the interlocking device based on the conditions detected. Electronics also allow the implementation of advanced functions such as automatic fault diagnostics, event logging and communication with other safety systems. Thanks to electronics, modern interlocking devices are able to guarantee not only a high level of actuator coding, but also a high level of reliability such as SIL3 in accordance with IEC 62061 or PL e in accordance with ISO 13849-1.

A latest generation interlocking device is in fact an active component within the safety system, which is able to provide information on its status, the status of the guard and additional information such as indications of the presence of faults or anomalies.

The connection interface between the interlocking device and the control system is generally of the wired type, where essentially each individual signal entering or exiting the device is assigned to a specific wire within a multi-pole connection cable.
The Table 1 shows the internal connections of an older generation electromechanical Pizzato interlocking device from the FG series and a latest generation Pizzato RFID technology device from the NG series.

FG 60BD1D	Terminals	Signals
	11-12	Closed contact with closed and locked guard
	21-22	Closed contact with closed and locked guard
	31-32	Closed contact with closed guard
	43-44	Open contact with guard closed
	A1	Solenoid +24V AC/DC (power-on to release)
	A2	Solenoid 0V

NG 2D1D411A (RFID)	Terminals	Signals
	A1	+24 Vdc (device power supply)
	A2	0 V (device power supply)
	IS1	Safety input
	IS2	Safety input
	I3	Actuator programming input / reset
	IE1	Solenoid activation input for double channel mode
	IE2	Solenoid activation input for double channel mode
	OS1	Safety output (OSSD)
	OS2	Safety output (OSSD)
	O3	Signalling output, actuator inserted and locked (PNP)
	O4	Signalling output, actuator inserted and locked (PNP)

Table 1. Connection terminals of two types of interlocking devices: electromechanical interlocking device of the Pizzato FG series, and electronic RFID device of the Pizzato NG series.

The device installed in the field is connected to the supervision system by laying a multicore electric cable (with a variable number of poles depending on the complexity of the device, we can consider in a range from 5 to 19 poles for interlocking devices), which must

start from the field and reach the inside of the electrical command and control panel where the PLC (or in general the supervision system) is positioned.
The market for industrial machinery and production plants has evolved in recent years, requiring production systems to be increasingly connected to the grid and be able to collect, or at least provide, a large amount of data regarding, for example, production efficiency, predictive maintenance and energy consumption.
Safety devices have also been progressively involved in this change and the demand for interlocking devices connected to the network is increasingly frequent. The advent of Industry 4.0 has therefore pushed device manufacturers to develop new solutions that allow them to integrate digital technologies within production processes to create interconnected and intelligent systems.
The traditional connection of an interlocking device to the supervision system via multicore cable and physical I/O, gives way to a digital connection where the signals to and from the interlocking device are concretely a series of bits that transit within a specific protocol.

2. Industry 4.0 and Industry 5.0: The Evolution of Industrial Safety

In recent decades, the industrial world has undergone a remarkable transformation thanks to the revolutions of Industry 4.0 and Industry 5.0.
These changes have brought significant innovations in production processes, improving efficiency, customization, and sustainability. One of the most relevant aspects of these revolutions is the impact on industrial safety, which has evolved thanks to the integration of advanced technologies.

2.1. Industry 4.0: Digitalization and Automation

Industry 4.0 has introduced intelligence within automation, digitalization and the interconnection between machines and systems. This paradigm is based on technologies such as the Industrial Internet of Things (IIoT), artificial intelligence (AI), big data, advanced robotics, and additive manufacturing. These tools have transformed production processes by making them more efficient, faster and less exposed to human error.
Advanced automation and the integration of intelligent systems have also led to a change in industrial safety management. Safety systems must ensure the proper functioning of control functions, such as blocking machines in the event of a fault or detecting hazardous conditions.
The use of IIoT sensors and real-time monitoring systems has improved the ability to detect anomalies and prevent failures thanks to predictive maintenance, increasing the reliability and operational availability of machinery. However, the increased complexity of automation systems requires a more rigorous assessment of the "PL" and "SIL" performance levels required for safety functions, according to ISO 13849-1 and IEC 62061.
In addition, the interconnection between machinery and industrial networks raises new challenges related to functional safety, requiring advanced strategies for managing systematic failures and possible interference between software and hardware components. The adoption of redundant control architectures and compliance with the requirements of IEC

61508 and IEC 62061 standards are essential to ensure high reliability of safety systems in the era of Industry 4.0.

2.2. Industry 5.0: Humanism and Sustainability

If Industry 4.0 has focused on efficiency and automation, Industry 5.0 focuses on collaboration between man and machine, with a focus on sustainability, personalization and improving the well-being of workers. This new revolution is based on the use of cobots (collaborative robots), ethical artificial intelligence and advanced human-machine interface technologies.

Industry 5.0 has brought an improvement in not only the physical but also the psychological safety of workers. The adoption of cobots reduces the risks associated with hazardous operations, while augmented reality (AR) and digital twin technologies facilitate training and control of plants in a safe and intuitive way.

Another important aspect is the attention to sustainability. The use of innovative materials and production processes with low environmental impact reduces exposure to harmful substances and improves the quality of the working environment. In addition, advanced ergonomics and flexible automation solutions allow workers to perform safer and less repetitive tasks, reducing fatigue and the risk of injury.

2.3. Comparison of Industry 4.0 and 5.0 in tems of safety

The advent of the two recent industrial revolutions has changed the way industrial plant automation is implemented. This has also influenced the way systems safety is achieved by changing the general approach.

The Table 2 schematizes the main differences between Industry 4.0 and Industry 5.0 regarding especially system safety. If on the one hand for Industry 4.0 the main purpose was to make automation more efficient and performing, on the other hand for Industry 5.0 the intention is to make the coexistence of machines and humans safer and more sustainable.

2.4. Pizzato Elettrica's solutions to digitalization

Companies must face the challenge of integrating the required new technologies quickly, ensuring adequate training for workers and implementing increasingly advanced safety strategies.

Pizzato Elettrica has already created several solutions that meet the needs of Industry 4.0 and 5.0:

- BN Control Panel with IO-Link Technology: This hand control is equipped with IO-Link technology, which enables efficient and integrated communication with industrial automation systems, facilitating real-time monitoring and diagnostics.
- Profinet, EtherNet/IP communication protocol for P-Connect: The adoption of these protocols in P-Connect devices enables secure and reliable communication, which is essential for critical industrial applications.

In conclusion, industrial safety is experiencing an epochal transformation thanks to emerging technologies. The key to a safe and efficient future lies in the combination of intelligent automation, human-machine collaboration and a sustainable approach to production. The industry of the future will not only be more efficient and productive, but also safer and more respectful of human well-being.

Aspect	Industry 4.0	Industry 5.0
Automation	High, often independent of humans	Collaborative, with a focus on human-machine interaction
Physical safety	Sensors and remote monitoring	Cobots and ergonomic technologies
Cybersecurity	Advanced cybersecurity	Greater attention to the protection of personal data
Worker well-being	Process optimization, but less focus on the human aspect	Centrality of man, ergonomics and advanced training
Sustainability	Focus on reducing waste	Eco-friendly production and sustainable materials

Table 2. Schematic representation of the different approaches of Industry 4.0 and 5.0 in the field of industrial safety

3. Application of a P-Connect device on industrial machinery

Pizzato Elettrica with the "P-Connect" gateway allows you to centralize and digitize the signals coming from safety devices, transforming them into data easily accessible via the network. Using industry-standard protocols such as PROFInet and EtherNet/IP™ with the corresponding safe protocols PROFIsafe and CIP Safety™, the signals are safely converted and transmitted to the central control system. This solution is particularly useful in complex production environments, where accurate supervision of multiple safety points is crucial.
Through "P-Connect", signals from devices such as emergency stop devices, interlocking devices and safety sensors are converted into digital format and sent to a central control system. This digitization allows for real-time monitoring and advanced diagnostics, which allows any malfunctions to be detected before they can compromise safety.

3.1. Centralized monitoring

The passage of the information of the interlocking devices through the P-Connect gateway means that all the information relating to the safety of the plant is collected in a single digital interface, simplifying the management of the information itself, which is thus treated uniformly by the same supervisory device (PLC) and also reducing the risk of human error in the installation and testing of the machinery. The interlocking devices are connected in the field through cables equipped with M12 or M23 connectors, thus making it impossible for the installer to make an incorrect connection. The connection of the gateway to the machinery supervision system (generally the PLC, positioned inside a closed electrical panel) is also made by means of cables equipped with a connector. They are therefore standardized connections that are easy to implement, and where the risk of human error is very low.

3.2. Predictive maintenance

The ability to detect malfunction signals in real time allows preventive maintenance interventions to be planned, reducing downtime and operating costs. The P-Connect gateway also provides the control and supervision system with information regarding the supply voltage, current consumption and internal temperature of the gateway. Taking the real-time value of the absorbed current as an example, this parameter, if periodically analyzed by the supervision system, can be used to identify anomaly situations before the fault actually occurs (generally a higher or lower absorption than the norm is a symptom of a malfunction of the P-Connect gateway or one of the connected interlocking devices) thus allowing maintenance to be planned without major impacts on production efficiency. The data provided by the P-Connect gateway to the system is easily identifiable and mapped within the bytes exchanged with the safety PLC.

3.3. Reducing wiring

The digitization of signals allows for a significant reduction in wiring complexity, leading to a simpler and more organized installation. The use of connector connections simplifies the connection activity in the field because it first involves the use of standard cables readily available on the market, and also there is no need for the installer to follow a specific connection diagram as the connector is already installed on the interlocking device and the P-Connect gateway by the manufacturer. A further simplification is given by the fact that P-Connect is designed to be installed in the field, so it is typically fixed in the vicinity of the interlocking devices; this leads to the advantage of being able to use, in most cases, connection cables of limited length.

3.4. Compliance with safety standards

P-Connect complies with current industrial safety regulations, ensuring a safe working environment that complies with international regulations. The gateway is essentially a device that collects safety information in the field and translates it into a series of bits transmitted through a communication protocol. Since this is safety information, the protocol used is certified to ensure the highest level of reliability in accordance with the functional safety standards IEC 62061 (SIL) and ISO 13849-1 (PL). In terms of protection against tampering, the use of the P-Connect gateway makes it even more difficult for those who want to circumvent safety functions. Physical connection terminals for interlocking devices are not accessible, either on the gateway or inside the control cabinet. In this way, the only possibility of tampering is to "simulate" the presence of a device connected to the gateway (create a bypass connector), or it is necessary to act at the level of the supervision system (for example by modifying the program within the PLC).

3.5. Remote location mounting

Interlocking devices are typically installed in positions exposed to possible mechanical damage: they are generally visible and positioned in the frame of the movable guard. The need to insert the devices within a digital ecosystem could have as its first solution the integration of all the electronics necessary for the digital connection directly within the interlocking device itself, thus creating a complex and expensive interlocking device. Considering, however, that as already mentioned, interlocking devices are generally exposed to mechanical shocks and breakages, this choice would mean that in the event of mechanical failure of the device there would be a situation of having to incur high repair or replacement costs, moreover the failure of the device would directly involve a node of the network introducing long maintenance times (think, for example, of the need to reconfigure all the network parameters of the device). The choice to create a separate gateway to be mounted in the field includes at the same time the advantage of using interlocking devices with standard connection (low cost) and still having the P-Connect gateway positioned nearby, but possibly in a position protected against mechanical damage. In the event of a fault in an interlocking device connected to P-Connect, both the continuous operation of the network node (P-Connect) is guaranteed and the repair activity is also faster and cheaper.

3.6. EMC Immunity

In an industrial environment, it is very likely to have sources of electromagnetic interference (EMC) that can compromise the proper functioning of electronic devices. Among the main sources of disturbance we can mention:

1. Electric motors and variable frequency drives (VFDs)
2. Industrial welding machines
3. Pulse drives and power converters
4. Electrical panels and electromechanical relays
5. Electrostatic discharge (ESD)

Another benefit of using P-Connect is the improvement of EMC immunity as you can choose an installation location away from sources of electromagnetic interference.
The adoption of solutions such as “P-Connect” reflects a significant shift in the industrial safety landscape. The integration of connected devices allows not only to improve safety, but also to optimize production processes, increasing the efficiency and competitiveness of companies.

3.7. Application example

Figure 2 illustrates a possible connection of P-Connect for the management of two interlocking guards. Each guard is equipped with an NG series interlocking device with guard locking, featuring integrated control devices, and a P-Kube Krome safety handle with RGB LED strip and integrated illuminated button. Through the four connectors located on the upper side of P-Connect (two 8-pole M12 connectors and two 19-pole M23 connectors), all the signals necessary for the correct management of the connected devices are exchanged. The connections on the lower side of the gateway are instead dedicated to the Ethernet connection and the module power supply. The network connections, highlighted in green, connect the gateway to the programmable logic controller (PLC) or to another P-Connect module, enabling the transmission of safety information in real time. The communication protocols with which data can be exchanged are PROFIsafe, CIP Safety ensuring that safety signals are managed reliably and certified.

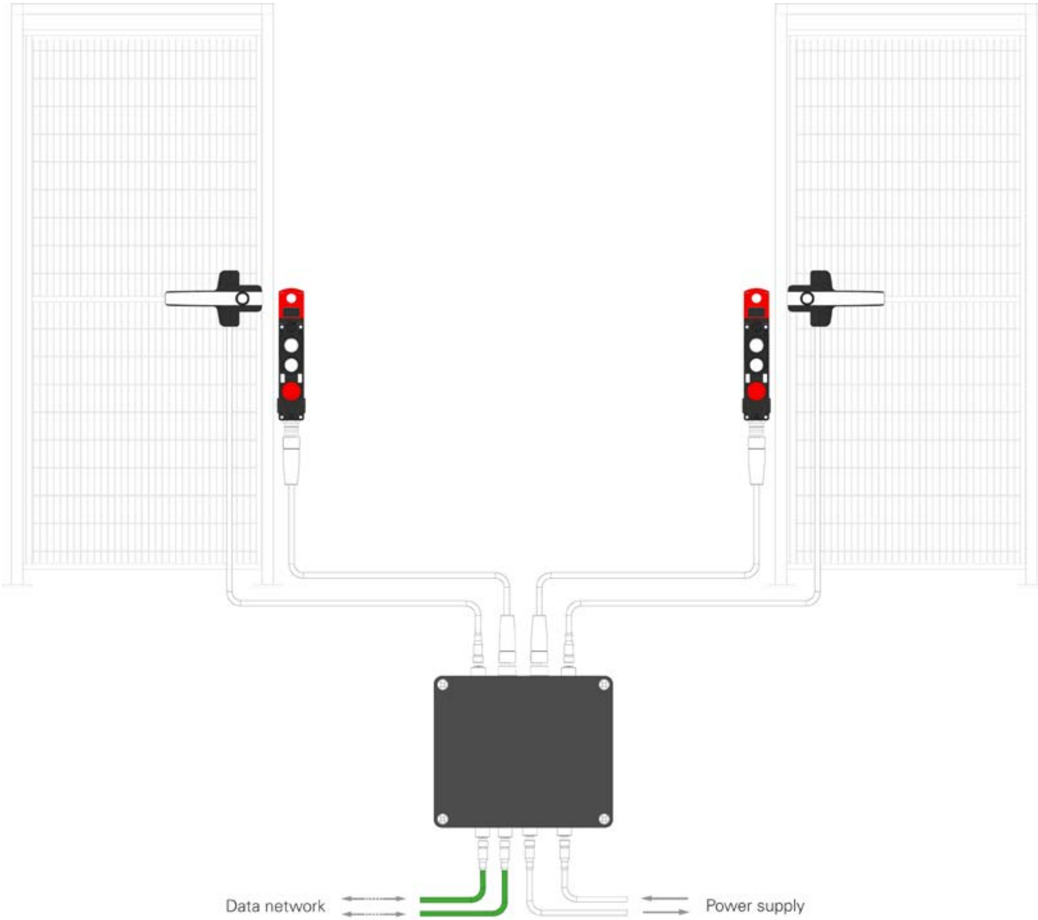


Figure 2. Application example of P-Connect gateway in the management of two complete guards, each one equipped with an interlocking device with locking function, on-board push-buttons and illuminated handle.

3.8. Application example on industrial machinery

In the Figure 3 there is an application example of the P-Connect Gateway in an industrial machine equipped with four guards. In this example, the robotic arm and conveyor belt are protected by a set of perimeter barriers, some of which are movable and equipped with safety interlocks. A configuration like the one in the example in figure 1 involves the installation of two P-Connect gateways for the management of the 4 interlocking devices.
Guards identified as numbers 1, 3 and 4 are monitored by interlocking devices with integrated guard locking with RFID technology, while guard number 2 is monitored by a RFID sensor.

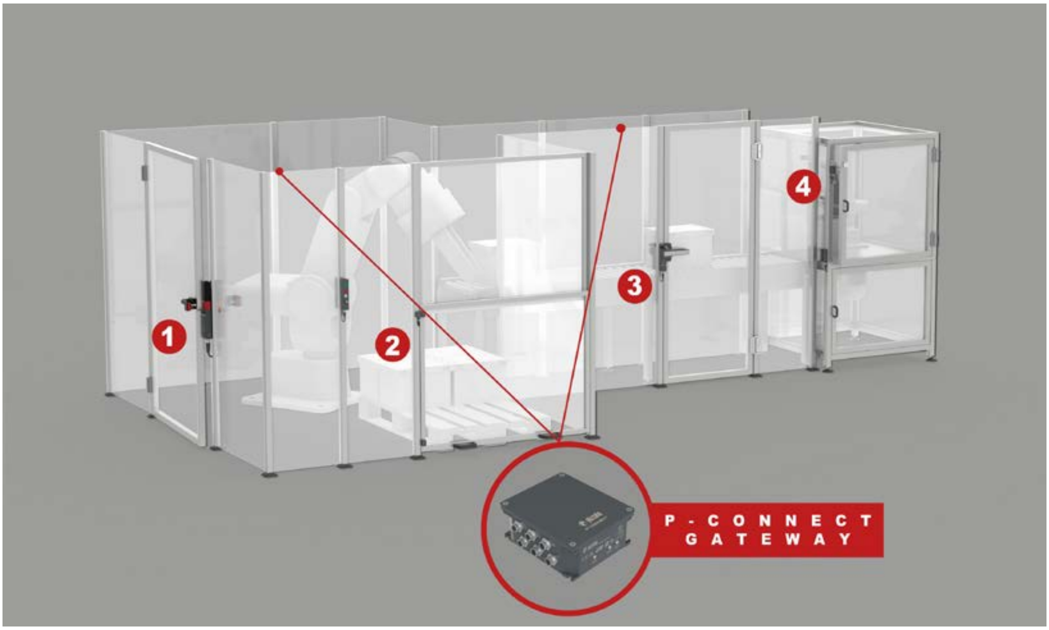


Figure 3. Application example of two P-Connect gateways for connecting four interlock devices: one module for gates 1 and 2, and one module for gates 3 and 4.

The figure shows four interlocking devices by Pizzato Elettrica, usually equipped with 8 or 12-pole M12 connectors for connecting signals to the safety PLC. In a traditional installation, this would require the laying and wiring of between 32 and 48 conductors, since each signal would have to be transmitted directly to the component in charge of supervision within the electrical control cabinet (typically a PLC that receives information from the devices and sends commands through physical inputs and outputs). So a traditional connection would involve laying 4 multicore cables from the devices to the control panel, and the PLC would also have to be equipped with a sufficient number of physical IOs for information management (which in practice means requiring more space inside the electrical panel for the necessary I/O expansions).
The adoption of the P-Connect gateway greatly simplifies this process. The interlocking devices are in fact connected in "plug & play" mode via expansion cables with M12 Male-Female connector, which allow a direct connection to the gateway. The connection process is therefore immediate and with a low possibility of making mistakes in the connection in the field. The gateway is also installed in the field in the immediate vicinity of the devices, consequently the length of the cables can be very limited: in the example of figure 2 we can assume connection cables between the devices and the gateway no longer than 5 meters; This makes the cables themselves more standard and easy to find in the market, benefiting the machine manufacturer.
Finally, from the P-Connect gateway, the connection to the PLC takes place through the Ethernet network cable (standard 8-wire cable), which creates the medium on which all

the information travels within the communication protocol. In the case of the P-Connect gateway, 40 digital I/Os are exchanged with the PLC. Each P-Connect module is equipped with two Ethernet ports, offering the possibility of daisy-chaining with other P-Connect modules and further simplifying the connection.

4. Conclusion

In conclusion, the integration of the P-Connect gateway represents a qualitative leap in the evolution of industrial safety, offering a solution that combines digitization, reliability and compliance with international standards. The ability to centralize in real time the signals coming from interlocking devices and safety sensors, through standard protocols such as PROFInet and EtherNet/IP, makes it possible to eliminate the traditional wiring complexities, drastically reducing the risks of errors during installation. Furthermore, the use of M12 plug & play connectors and the ability to install the gateway in strategic positions to minimize electromagnetic interference, ensure high EMC immunity and greater resistance to tampering attempts. Thanks to these innovations, P-Connect not only facilitates advanced diagnostics and predictive maintenance, allowing timely and targeted interventions, but also promotes the creation of a resilient and flexible network infrastructure, capable of adapting quickly to the dynamic needs of Industry 4.0 and 5.0. Ultimately, adopting P-Connect means embracing an integrated and intelligent approach to safety, which not only enhances the operational efficiency of machinery, but also contributes to raising the competitiveness and sustainability of the entire industrial production process.

References

[1] General Catalogue Safety 2023-2024 – ZE GCS05A22-ENG – Pizzato Elettrica

[2] P-Connect connection gateway BP series Operating instructions – ZE FOG148B24-ENG

[3] ISO 12100:2010 – Safety of machinery – General principles for design – Risk assessment and risk reduction

[4] ISO 14119:2013 – Safety of machinery – Interlocking devices associated with guards – Principles for design and selection

[5] ISO 14119:2024 – Safety of machinery – Interlocking devices associated with guards – Principles for design and selection

[6] ISO 13849-1:2023 – Safety of machinery – Safety-related parts of control systems

[7] IEC 61508:2010 – Functional safety of electrical/electronic/programmable electronic safety-related systems

[8] IEC 62061:2021+AMD1:2024 – Safety of machinery – Functional safety of safety-related control systems

Optimization of Construction Site Safety: An Ontological Approach through the Integration of Time and Costs

Jacopo Cassandro[1*], Claudio Mirarchi[1] and Alberto Pavan[1]
[1] Department of Architecture, Built Environment and Construction Engineering – Polytechnic of Milan, Milan Italy

* E-mail: jacopo.cassandro@polimi.it

Abstract. Ensuring worker safety while maintaining time and cost control is one of the greatest challenges in construction project management. The pressure of meeting deadlines and budgets can result in compromised safety standards, overcrowded sites, and insufficient supervision, increasing the risk of accidents. This research proposes an ontology-based approach to integrate time and cost data and support proactive decision making. Through SPARQL queries, it can be identified overlapping high-risk activities, overcrowded work areas, and inadequate resource allocation. Practical examples demonstrate how this approach reduces risks and enhances project performance, contributing to safer and more sustainable construction management practices.

Keywords: Construction Site Safety, Ontology, Project Scheduling and Cost Control, Decision-Making Support System

1. Introduction

The construction sector faces persistent and multifaceted challenges, particularly in reconciling time and cost efficiency with worker safety. Despite advantages in technology and innovative management methodologies, achieving these objectives simultaneously remains complex. Delays, budget constraints, and overlapping of high-risk activities often lead to unsafe practices, increasing accident risks on construction sites. Overcrowding and resource shortages increase these issues, particularly when incompatible activities occur in shared spaces or workers operate without adequate training or equipment. In many cases, tight schedules and limited resources force project managers to prioritize cost savings over safety, with potentially severe consequences.
Traditional project scheduling and cost management tools are not designed to address the dynamic and interconnected nature of construction activities. These tools operate in a concentrated way on isolated aspects of the project, making it difficult to assess risks and anticipate potential conflicts. Furthermore, the construction industry collects safety information in various formats, leading to interoperability issues. This makes it difficult to share and reuse safety data effectively. This fragmented approach results in a reactive management style,

where problems are addressed only after they arise. To overcome these limitations, there is a growing need for integrated systems capable of analyzing and correlating construction project data in a structured and queryable environment.

This paper proposes an ontology-based approach to construction project management that integrates time, cost and resources data to enhance safety monitoring and support decision-making processes. By using ontologies, that provide a formal representation of concepts and relationships within a domain, is possible to do advanced data querying and reasoning [1]. By using SPARQL queries, the proposed methodology proactively identifies potential risks, such as overlapping incompatible activities, overcrowded work areas, and inadequate resource allocation. It also monitors delays that could lead to hazardous conditions.

This research aims to demonstrate how an ontology-based approach integrating geometry, cost, time and resources data, can help construction site and safety management into a more proactive and integrated process. Practical examples illustrate how this method supports decision-making, improving overall project performance considering safety crucial. Assessing the gap between cost-time control and safety management, this approach represents a significant advance in construction project management practices.

It is structured into Section 2 for displaying background, Section 3 for describing the methodological approach, Section 4 for the research results, with the implementation and definition of the SPARQL queries based on data from a real case study, and into the Section 5 for discussion and conclusion.

2. Background

Safety management in the construction industry has received increasing attention due to its critical role in reducing accidents and improving overall project performance [2], [3]. Traditional safety management approaches are not efficient due to scattered and fragmented information, which is often reactive, addressing accidents after they occur rather than proactively identifying risks during project planning and execution [4], [5], [6].

Annually, more than 60,000 construction workers globally lose their lives due to occupational accidents, making safety management a critical focus in the sector [7]. In Europe, approximately 21% of all fatal workplace incidents occur in the construction industry, highlighting its hazardous nature [8].

Recent advancements in digital technologies, virtual reality, linked data, and ontology-based methods underscore the growing role of digital tools in improving construction safety [3]. These technologies are widely used in tools designed for site hazard prevention and safe project delivery [9].

Farghaly et al. (2022) and Akinlolu et al. (2022) have highlighted the increasing adoption of technology to create safer work environments, showcasing how digital methodologies can enhance safety throughout various stages of a construction project [10].

Technology such as 4D BIM is at the forefront of this transformation. 4D BIM enables time-based simulations of construction activities, allowing safety managers to predict and mitigate potential risks proactively [11]. Abed et al. (2019) demonstrated the potential of a 4D BIM model specifically designed to prevent severe accidents, illustrating the practical

application of these innovations, while Hoeft and Trask (2022) and Martínez-Airesa et al. (2018) showcased how digital methodologies can enhance safety throughout various stages of a construction project [12], [13], [14]. Moreover, different research studies have combined schedule, BIM, and simulation as a tool able to predict risks to minimize conflicts at the workplace, as well as something to be used as an active schedule management tool [15], [16], [17].
Ontology-based methods have also gained significant attention for improving safety management. Farghaly et al. (2022) developed the Safety and Health Exchange (SHE) ontology, a semantic framework based on accident data from the Reporting of Injuries, Diseases, and Dangerous Occurrences Regulations (RIDDOR) and the Health and Safety Executive (HSE) in the UK [18]. The SHE ontology comprises eight key concepts and their relationships, supporting risk identification and management during the design and planning stages. Similarly, Chen et al. (2023) conducted a comprehensive review of ontology-based safety management research from 2012 to 2022, noting the growing interest in using ontologies to enhance safety practices and ensure a common understanding of safety concepts and terminology [3]. However, they also identified key challenges, such as the lack of comprehensive data, limited expertise in ontology development, and insufficient real-world applications.
Despite these technological advancements, current safety management practices remain fragmented, lacking a cohesive framework for continuous and integrated risk assessment [19].
This research aims to bridge this gap by proposing an integrated BIM-based strategy for continuous risk assessment and accident prevention, combining the strengths of digital engineering, ontology-based methods, and real-time data exchange.

3. Methodology

The proposed methodology is structured in three steps to address the challenges of integrating geometry, time, cost and resource management for better safety management in construction projects. This approach uses ontology-based methods and SPARQL queries to proactively monitor risks, ensuring more informed and secure decision-making throughout the project lifecycle (see Figure 1).

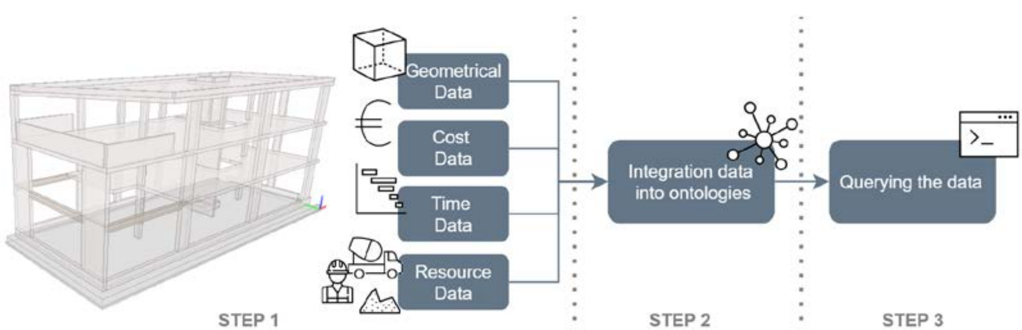


Figure 1. Proposed methodology steps.

3.1. Step 1: Collection of Project Data

In the first phase, the focus is on gathering essential project data, which includes cost, time schedules, resource data, and BIM models. These data sources are collected from multiple formats to form the basic dataset for further analysis.

The cost data is based on the information extracted from the Lombardy Region price list, characterized by a transparent price analysis in which the resources used are clear. The time schedule, provided in XML format, outlines the sequence of tasks and resource planning, specifying the timing and duration of construction activities. The management of construction resources (materials, equipment, and labour) is crucial for defining the unit price used in cost calculations and the activities needed for time planning. The structural BIM model of the building is depicted by using IFC4, which captures the geometric and spatial characteristics of the project. At this stage, these documents remain in their original formats. However, their relationships are carefully reviewed and mapped to ensure proper link between time, cost, and building elements.

3.2. Step 2: Ontology-Based Integration and Data Structuring

In the second step, all collected data are integrated and converted into RDF graphs according to specific ontologies [20]. The primary goal of this phase is to establish clear relationships between geometric elements, scheduling, cost and resources data (material, equipment and labour). By structuring these relations, the methodology enables an integrated representation of project planning, allowing for detailed resource tracking, cost validation, and time scheduling consistency checks.

These ontologies capture the complex relationships between different project documents and data. This structured approach allows for consistent data interpretation across various stakeholders and tools, enabling the detection of high-risk scenarios, such as overlapping incompatible activities or overcrowded work areas or monitoring of resources allocation, which would be difficult to achieve using traditional methods.

3.3. Step 3: SPARQL Query Development and Safety Analysis

The last phase involves creating advanced SPARQL queries to check data consistency across different domains and improve safety management, supporting resource monitoring, and overall project safety analysis. Running these queries within GraphDB, ensure a structured and comprehensive analysis of the interrelated data by utilizing the semantic relationships established in the previous phase. With this approach, valuable insights can be extracted from the combined dataset, supporting decision-making processes throughout the project. This makes it easier to identify potential inconsistencies, optimize resource allocation, and address safety hazards before they become real issues on-site. Ultimately, this method strengthens safety management by offering a data-driven system that enhances accuracy, improves coordination, and supports more informed choices at every project stage.

4. Results

4.1. Case Study

The proposed methodology is validated through a case study of a building located in the

Lombardy Region, Italy. The input data include the structural design in IFC4 format, cost data from the official price list of Lombardy Region, and a time schedule in XML format created with Microsoft Project. For the management and analysis of the data, it is crucial to have the elementary resources used in both cost data and the time scheduling. These datasets were converted into RDF format to enable seamless integration and analysis. The aggregation of these data into RDF graph using a combination of existing and newly developed ontologies was employed [20] allows for advanced consistency checks and cross-domain analysis ensuring detailed risk assessment and safety monitoring.
This integration demonstrates the methodology's ability to identify risks, optimize resource management, and support informed decision-making.
Table 1 provides an overview of the ontologies used, along with their namespaces and prefixes, to ensure that the study is clear and consistent.

Prefix	URI	Description
ci:	<http://w3id.org/ci#>	Cost Item (CI)
cr:	<http://w3id.org/cr#>	Construction Resources (CR)
dtc:	<https://dtc-ontology.cms.ed.tum.de/ontology#>	Digital Twin Construction (DTC)
ifc:	<http://ifcowl.openbimstandards.org/IFC4_ADD2#>	ifcOWL IFC4 ADD2

Table 1. Ontologies and namespaces used in this research.

4.2. Query

The proposed approach was validated through the execution of specific SPARQL queries on the case study. Three key queries were developed to support decision-making in construction safety management. The first question focuses on identifying parallel activities to assess whether they can be considered high risk, helping to prevent hazardous conditions caused by incompatible tasks taking place simultaneously. The second query is for the identification of overcrowded work areas, which can compromise both safety and productivity. Finally, the third query monitors resource allocation to ensure that material, or equipment, or construction worker will be available as required, avoiding delays and ensuring the right balance of on-site resources.
These advanced queries provide a comprehensive view of project risks and resource planning, helping to improve safety protocols and project performance. The proposed approach allows for a more informed and pro-active site safety management process, integrating interconnected data and reducing risks. This will ensure more reliable project results through better management of resources and increased on site safety.

Q1 – Identification of Overlapping Risk Activities

This query identifies scheduled activities that occur simultaneously and may pose safety risks due to their incompatible nature. By identifying these overlaps early on, project managers can reschedule tasks or implement additional safety measures to mitigate potential hazards.

This query retrieves two tasks (`?task1` and `?task2`) along with their respective start and end times (`?start1`, `?end1` for the first task and `?start2`, `?end2` for the second). The query's main functionality is based on comparing the start and end times of the two tasks The `FILTER` conditions ensure that the tasks do not compare with themselves (`?task1 != ?task2`), while the logic `?start1 <= ?end2 && ?start2 <= ?end1` checks for overlaps in the time schedules. This condition effectively identifies any time overlap where the start of one task occurs before the end of the other and vice versa.
Furthermore, the query restricts the analysis to activities scheduled between October 4, 2024 and October 5, 2024, giving a precise time window to identify potential scheduling conflicts (`FILTER (?start1 >= “2024-10-04T00:00:00”^^xsd:dateTime && ?start1 <= “2024-10-05T23:59:59”^^xsd:dateTime)`).
By returning cases of overlapping activities, the query provides project managers with essential data for reprogramming and risk mitigation. Better coordination of work, equipment, and materials is achieved, resulting in fewer workplace congestion and improved overall site safety. Furthermore, identifying these overlaps supports compliance with health and safety regulations, ensuring adherence to many industry standards that require proactive risk assessment for simultaneous operations.
Beyond immediate hazard prevention, the information obtained from this query contributes to the long-term optimization of the construction process, enabling data-driven decision making that improves safety efficiency and performance. By automating conflict detection, the query enables safety monitoring, supporting a more structured and proactive approach to construction site management reassigning tasks, adjusting schedules or prioritizing to prevent safety hazards.

```
PREFIX dtc: <https://dtc-ontology.cms.ed.tum.de/ontology#>
PREFIX cr: <https://w3id.org/cr#>
PREFIX cterm: <https://w3id.org/cterm#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>

SELECT ?task1 ?task2 ?start1 ?end1 ?start2 ?end2
WHERE {
  ?task1 dtc:startTime ?start1 ;
  ?task1 dtc:endTime ?end1 .
  ?task2 dtc:startTime ?start2 ;
  ?task2 dtc:endTime ?end2 .

  FILTER (?task1 != ?task2)
  FILTER (?start1 <= ?end2 && ?start2 <= ?end1)
  FILTER (?start1 >= "2024-10-04T00:00:00"^^xsd:dateTime &&
          ?start1 <= "2024-10-05T23:59:59"^^xsd:dateTime)
}
ORDER BY ?start1
```

Figure 2. SPARQL Code for Q1.

Q2 – Detection of Overcrowded Work Areas

Overcrowding in specific work areas can significantly increase the likelihood of accidents, inefficiencies and reduce overall productivity, especially in complex construction environments where multiple activities are taking place simultaneously. This query highlights areas where multiple tasks converge, helping to optimize worksite planning and maintain safe working conditions.

The query focuses on two specific geometric elements (`IfcSlab_905` and `IfcSlab_2649`), representing objects located within the same construction area. It analyses all the tasks associated with these elements and identifies the labour resources assigned to them. The key functionality of the query is based on comparing the start times (`?startTime1` and `?startTime2`) of the respective tasks. By binding these start times to a common date (`?date`), the query ensures that only tasks occurring on the same day are considered. Using the `COUNT(DISTINCT)` function it is possible to obtain data related to the number of labour resources assigned to each task (`?resourceObject1, ?resourceObject2`) on the same date (`?date`). This count can be used to detect if there are too many labour resources assigned to a specific task or area, which could lead to overcrowding.

The results of this count are grouped by date, using the `GROUP BY` function, and the query counts how many labour resources are assigned to each object. Additionally, the `HAVING` condition, only days when both tasks have active labour resources are added to the results, preventing irrelevant or empty results. This enables the estimation of labour density for specific tasks, such as casting foundations, which often require a high concentration of workers. If both objects have tasks that require labour resources at the same time, the query reports the work area as a potential overcrowding risk, indicating that an excessive workforce concentration can compromise safety and productivity.

By identifying these overlaps, the query helps project managers detect areas where the workforce might be over-allocated, ensuring that the right changes can be made to the planning in order to avoid congestion and optimize resource allocation. Overcrowded work areas present a significant safety risk, as excessive density of worker can increase the likelihood of accidents, communication errors, and workflow inefficiencies. Detecting such conditions early allows for a more balanced allocation of labour resources, preventing critical bottlenecks that could disrupt operations. Additionally, by analyzing workforce distribution across different areas of the site, the query supports time scheduling adjustments, ensuring that labour-intensive activities are distributed efficiently over time. This helps mitigate operational conflicts where multiple teams require the same space or equipment, improving overall site coordination.

This proactive approach to site management is essential for minimizing risks and maintaining a safe and productive construction site. By leveraging structured data and automated consistency checks, the methodology improves on-site safety conditions and ensures smooth project execution through optimized workforce planning.

Q3 – Resource Allocation Monitoring

Ensuring the availability and proper allocation of materials, equipment, and labour is essential for maintaining workflow continuity in construction projects. This SPARQL query is used to monitor resource allocation on construction site, preventing delays and inefficien-

```
PREFIX cr: <https://w3id.org/cr#>
PREFIX dtc: <https://dtc-ontology.cms.ed.tum.de/ontology#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX geom:
        <https://icdd.vm.rub.de/convert/ifc/22acca53-1a47-48f0-bb11-a41965eaed7e#>

SELECT ?date
       (COUNT(DISTINCT ?resourceObject1) AS ?humanResourcesObject1)
       (COUNT(DISTINCT ?resourceObject2) AS ?humanResourcesObject2)
WHERE {
  VALUES (?object1 ?object2) {
    (geom:IfcSlab_905 geom:IfcSlab_2649)
  }

  ?task1ToGeometry cr:refTask ?task1 ;
  ?task1ToGeometry cr:refGeometry ?object1 .
  ?task1 dtc:startTime ?startTime1 .
  ?task1Assignment cr:refTask ?task1 ;
  ?task1Assignment cr:refResource ?resourceObject1 .
  ?resourceObject1 a cr:LabourResource .

  ?task2ToGeometry cr:refTask ?task2 ;
  ?task2ToGeometry cr:refGeometry ?object2 .
  ?task2 dtc:startTime ?startTime2 .
  ?task2Assignment cr:refTask ?task2 ;
  ?task2Assignment cr:refResource ?resourceObject2 .
  ?resourceObject2 a cr:LabourResource .

  BIND(xsd:date(?startTime1) AS ?date)
  FILTER(xsd:date(?startTime2) = ?date)
}
GROUP BY ?date
HAVING (?humanResourcesObject1 > 0 && ?humanResourcesObject2 > 0)
```

Figure 3. SPARQL Code for Q2.

cies by ensuring that materials are distributed according to project requirements. The use of a semantic representation of project data enables an automated and structured assessment of material requirements.

The FILTER condition (`FILTER (?start >= "2024-10-07T00:00:00"^^xsd:dateTime && ?start <= "2024-10-14T23:59:59"^^xsd:dateTime)`) is used in this query to calculate the total materials required for the planned tasks within a defined time period (7-14 October 2024). It achieves this objective by analyzing the semantic relationships between key project components, including tasks, cost items, geometric elements, and assigned resources. The results provide project managers with detailed information on material requirements, retrieving for each resource the material object (`?materialObject`) and the unit of measure (`?um`), calculating the total required quantity (`SUM(?materialQuantity`). The query performs this analysis through a structured aggregation process, binding the physical quantity of each material (`?calculatedQuantity`) to its utilization factor (`?utilizationFactor`). This allows an accurate estimation of the actual material consumption required for each planned task (`BIND (xsd:float(?calculatedQuantity) * xsd:float(?`

utilizationFactor) AS ?materialQuantity)). By linking multiple semantic relationships, the query consolidates data across task-cost (cr:refTask and cr:refCostItem), task-geometry (cr:refTask and cr:refGeometry), cost-resource (cr:refCostItem and cr:refResource), and cost-geometry (cr:refCostItem and cr:refGeometry). This structured approach ensures that all relevant data is considered to provide a comprehensive overview of material requirements.

Query output allows project managers to dynamically monitor material allocation, ensuring that the right amount of materials are available at the right time to avoid supply chain disruptions, overcrowding or shortages. The output aggregates the material quantities based on resource type and unit of measurement (GROUP BY ?materialObject ?um) and orders the output chronologically (ORDER BY ?start). In addition, the information obtained from this query supports logistics optimization, allowing better procurement and storage planning. By integrating this monitoring system into a BIM-based environment, it becomes possible to conduct advanced consistency checks, enhance cross-domain analyses, and align scheduling, cost estimation, and resource planning more effectively.

Ultimately, this ontology-based approach to resource management improves project efficiency by reducing waste, minimizing delays, and enhancing the reliability of supply chains. Provides project stakeholders with a structured and data-driven framework for real-time resource monitoring, ensuring efficient decision making and timely project execution. Fur-

```
PREFIX cr: <https://w3id.org/cr#>
PREFIX xsd: <http://www.w3.org/2001/XMLSchema#>
PREFIX dtc: <https://dtc-ontology.cms.ed.tum.de/ontology#>
PREFIX cterm: <https://w3id.org/cterm#>
SELECT ?materialObject (SUM(?materialQuantity) as ?totalqty) ?um
WHERE {
  ?task dtc:startTime ?start.
  ?task dtc:endTime ?end.
  ?taskToCostItemAssignment cr:refTask ?task .
  ?taskToCostItemAssignment cr:refCostItem ?cost .
  ?taskToGeometryAssignment cr:refTask ?task .
  ?taskToGeometryAssignment cr:refGeometry ?geometry .
  ?resource a cr:Resource.
  ?resource cterm:hasObject ?materialObject.
  ?resource cterm:hasMaterial ?materialType.
  ?resource cr:hasUnit ?um.
  ?costToGeometryAssignment cr:refCostItem ?cost .
  ?costToGeometryAssignment cr:refGeometry ?geometry .
  ?costToGeometryAssignment cr:refParamQuantity ?calculatedQuantity .
  ?costToResourceAssignment cr:refCostItem ?cost .
  ?costToResourceAssignment cr:refResource ?resource .
  ?costToResourceAssignment cr:refParamUtilizationFactor ?utilizationFactor.
  BIND(xsd:float(?calculatedQuantity)*xsd:float(?utilizationFactor) as
      ?materialQuantity)
  FILTER (?start >= "2024-10-07T00:00:00"^^xsd:dateTime &&
          ?start <= "2024-10-14T23:59:59"^^xsd:dateTime)
}
GROUP BY ?materialObject ?um
ORDER BY ?start
```

Figure 4. SPARQL Code for Q3.

thermore, this query can be further improved by incorporating cost evaluation, allowing project managers to assess the economic expenditure associated with resource consumption. By integrating costs, it would be possible to calculate the cost of materials, equipment, and labour, providing an additional layer of decision support for budget monitoring and financial planning. This would enable to evaluate how much needs to be paid at different stages of the project, ensuring a better alignment between resource allocation and financial constraints. However, due to the limited scope of this study, the current implementation focuses primarily on quantitative resource monitoring for improving safety management.

5. Discussion and Conclusion

The proposed ontology-based approach represents a substantial advancement in construction and safety project management, combining geometry, time and cost through integrated semantic data. The use of SPARQL queries enables proactive management by providing detailed information on task scheduling, resource allocation, and potential risks, offering a more comprehensive and dynamic approach compare to the traditional methods.

One of the most important insights from this approach is the ability to identify overlapping high-risk activities. The "Q1 – Identification of Overlapping Risk Activities" query allows for the identification of tasks that are carried out simultaneously and which could pose safety risks due to incompatible resource usage or environments in which the activities take place. By identifying these overlaps early, the system enables project managers to make timely adjustments to the schedule, preventing potentially hazardous situations that could result from simultaneous heavy machinery operation or other high-risk tasks. This proactive risk management, which highlights issues before they occur, is a key advantage of the proposed system over reactive risk mitigation practices typically employed in conventional project management tools.

In addition to managing risk activities, the methodology also emphasizes the importance of monitoring workforce allocation. The "Q2 – Detection of Overcrowded Work Areas" query provides valuable data on potential overcrowding in work areas, a condition that is often linked to both safety risks and decreased productivity. Overcrowding can lead to confusion, accidents, and inefficient use of resources. The query highlights where tasks requiring labour resources overlap in specific areas and for specific creation of elements. These query outputs help the project managers to optimize task sequencing and workspace allocation to prevent overcrowding and ensure that work areas remain clear and manageable. This can significantly improve both worker safety and project efficiency by reducing the likelihood of accidents and improving overall workflow.

Furthermore, the "Q3 – Resource Allocation Monitoring" query plays a pivotal role in ensuring that materials, or equipment, or construction worker are available precisely when needed. Resource management is essential to maintaining the continuity of construction workflows. The real-time monitoring provided by this query ensures that no resources are either underutilized or over utilized, which could lead to delays or inefficiencies. By focusing on material quantities, within a specific data time, this query also assists in maintaining a balance between the availability of resources and project needs. Effective resource allocation contributes to keeping the project on schedule while also supporting worker safety, as it ensures that workers are not overburdened by excessive material handling. This approach can be further refined by integrating cost parameters into the query framework, allowing project managers to not only monitor resource availability but also estimate the cost. This integration would provide a comprehensive overview of both resource utilization and associated costs, supporting more informed decisions.

The integrated nature of the system could allow for a comprehensive monitoring of safety compliance. By monitoring how resources are distributed across different activities and areas, the approach would ensure that safety protocols are respected. It would reduce the likelihood of breaches by providing visibility into the allocation of high-risk assets, such as heavy machinery, and ensures that security measures are taken into account in planning activities.

Furthermore, by consolidating geometry, time and cost data into a unified semantic framework, this system overcomes many of the interoperability issues typical of traditional construction and safety management systems.

Unlike traditional project management tools, which are often reactive, this approach offers an integrated real-time view of the project. Instead of addressing issues only after they have emerged, it provides project managers the ability to anticipate and address risks proactively, enhancing the safety and efficiency of the construction process. This approach allows for better support for decision-making, particularly in dynamic environments where rapid changes in time scheduling or resource availability can have significant impacts.

In conclusion, this research demonstrates that an ontology-based approach can bridge the gap between safety management in construction projects. Using SPARQL queries to analyse interconnected data from multiple domains-geometry, time schedule, cost data-the methodology provides a robust tool for improving project supervision. It supports the identification of overlapping high-risk activities, optimizes labour allocation, tracks resource usage, and ensures compliance with safety measures.

Moreover, the structured nature of this methodology ensures that all project actors, such as project managers or safety managers, can access and interpret data in a unified manner, promoting cross-disciplinary collaboration and improving overall decision-making.

While the current framework significantly improves project monitoring and decision-making, future research should aim to further refine the system's ability to maintain semantic consistency across different data sets and incorporate AI-based methods for better decision support. The integration of Large Language Models could potentially automate the detection of inconsistencies and improve the alignment of project specifications with schedules and cost structures. This would make the system even more adaptive, intelligent, and able to identify and address challenges before they affect project outcomes.

Overall, the proposed approach provides a solid foundation for more integrated, proactive, and sustainable construction management practices that prioritize both project performance and worker safety, enabling a safer, more efficient, and streamlined construction process. Improving the functionality of BIM-based safety monitoring through ontology-based data integration, this research paves the way for smarter, more resilient construction management solutions that can dynamically adapt to the complexities of modern projects.

References

[1] R. Studer, V. R. Benjamins, and D. Fensel, "Knowledge engineering: Principles and methods," *Data Knowl Eng*, vol. 25, no. 1–2, pp. 161–197, Mar. 1998, doi: 10.1016/S0169-023X(97)00056-6.

[2] B. Zhong, H. Li, H. Luo, J. Zhou, W. Fang, and X. Xing, "Ontology-Based Semantic Modeling of Knowledge in Construction: Classification and Identification of Hazards Implied in Images," *J Constr Eng Manag*, vol. 146, no. 4, p. 04020013, Apr. 2020, doi: 10.1061/(ASCE)CO.1943-7862.0001767/ASSET/384C734C-592F-4720-AA60-7D541FB5436D/ASSETS/IMAGES/LARGE/FIGURE9.JPG.

[3] W. T. Chen and T. A. Bria, "A Review of Ontology-Based Safety Management in Construction," *Sustainability 2023, Vol. 15, Page 413*, vol. 15, no. 1, p. 413, Dec. 2022, doi: 10.3390/SU15010413.

[4] S. Zhang, F. Boukamp, and J. Teizer, "Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA)," *Autom Constr*, vol. 52, pp. 29–41, Apr. 2015, doi: 10.1016/J.AUTCON.2015.02.005.

[5] S. Gao, G. Ren, and H. Li, "Knowledge Management in Construction Health and Safety Based on Ontology Modeling," *Applied Sciences 2022, Vol. 12, Page 8574*, vol. 12, no. 17, p. 8574, Aug. 2022, doi: 10.3390/APP12178574.

[6] C. Dong, F. Wang, H. Li, L. Ding, and H. Luo, "Knowledge dynamics-integrated map as a blueprint for system development: Applications to safety risk management in Wuhan metro project," *Autom Constr*, vol. 93, pp. 112–122, Sep. 2018, doi: 10.1016/J.AUTCON.2018.05.014.

[7] H. Lingard, "Occupational health and safety in the construction industry," *Construction Management and Economics*, vol. 31, no. 6, pp. 505–514, Jun. 2013, doi: 10.1080/01446193.2013.816435/ASSET//CMS/ASSET/BD6BEEE9-3412-4C38-8311-38FFDA6FC89F/01446193.2013.816435.FP.PNG.

[8] L. P. Andersen, L. Nørdam, T. Joensson, P. Kines, and K. J. Nielsen, "Social identity, safety climate and self-reported accidents among construction workers," *Construction Management and Economics*, vol. 36, no. 1, pp. 22–31, Jan. 2018, doi: 10.1080/01446193.2017.1339360.

[9] W. Zhou, J. Whyte, and R. Sacks, "Construction safety and digital design: A review," *Autom Constr*, vol. 22, pp. 102–111, Mar. 2012, doi: 10.1016/j.autcon.2011.07.005.

[10] K. Farghaly, W. Collinge, M. H. Mosleh, P. Manu, and C. M. Cheung, "Digital information technologies for prevention through design (PtD): a literature review and directions for future research," *Construction Innovation*, vol. 22, no. 4, pp. 1036–1058, Nov. 2022, doi: 10.1108/CI-02-2021-0027/FULL/PDF.

[11] J. P. Zhang and Z. Z. Hu, "BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 2. Development and site trials," *Autom Constr*, vol. 20, no. 2, pp. 167–180, Mar. 2011, doi: 10.1016/J.AUTCON.2010.09.014.

[12] A. Aziz, S. Ahmed, and F. I. Khan, "An ontology-based methodology for hazard identification and causation analysis," *Process Safety and Environmental Protection*, vol. 123, pp. 87–98, Mar. 2019, doi: 10.1016/J.PSEP.2018.12.008.

[13] M. Hoeft and C. Trask, “Safety Built Right in: Exploring the Occupational Health and Safety Potential of BIM-Based Platforms throughout the Building Lifecycle,” *Sustainability (Switzerland)*, vol. 14, no. 10, p. 6104, May 2022, doi: 10.3390/SU14106104/S1.

[14] M. D. Martínez-Aires, M. López-Alonso, and M. Martínez-Rojas, “Building information modeling and safety management: A systematic review,” *Saf Sci*, vol. 101, pp. 11–18, Jan. 2018, doi: 10.1016/J.SSCI.2017.08.015.

[15] K. Kim and J. Teizer, “Automatic design and planning of scaffolding systems using building information modeling,” *Advanced Engineering Informatics*, vol. 28, no. 1, pp. 66–80, Jan. 2014, doi: 10.1016/j.aei.2013.12.002.

[16] H. Moon, H. Kim, C. Kim, and L. Kang, “Development of a schedule-workspace interference management system simultaneously considering the overlap level of parallel schedules and workspaces,” *Autom Constr*, vol. 39, pp. 93–105, Apr. 2014, doi: 10.1016/j.autcon.2013.06.001.

[17] H. Moon, N. Dawood, and L. Kang, “Development of workspace conflict visualization system using 4D object of work schedule,” *Advanced Engineering Informatics*, vol. 28, no. 1, pp. 50–65, Jan. 2014, doi: 10.1016/j.aei.2013.12.001.

[18] K. Farghaly, R. K. Soman, W. Collinge, M. H. Mosleh, P. Manu, and C. M. Cheung, “Construction safety ontology development and alignment with Industry Foundation Classes (IFC),” *Journal of Information Technology in Construction*, vol. 27, pp. 94–108, 2022.

[19] B. Zhong, H. Wu, H. Li, S. Sepasgozar, H. Luo, and L. He, “A scientometric analysis and critical review of construction related ontology research,” *Autom Constr*, vol. 101, pp. 17–31, May 2019, doi: 10.1016/J.AUTCON.2018.12.013.

[20] Hagedorn, P., Cassandro, J., Sigalov, K., Mirarchi, C., Alberto, P., and König, M. (2025). “A shared resource concept for semantically aligning cost and time domains in construction projects” [forthcoming]. *Proceedings of LDAC2025: 13th Workshop on Linked Data in Architecture and Construction*, July 9-11, 2025.

Revolutionizing Workplace Safety with Computer Vision AI: The Intenseye Solution

Deniz Karakaş[1], Funda Sayın[2] and Riccardo Borghetto[3]
[1] Business Development, Intenseye, London, UK
[2] Occupational Health and Safety director, Intenseye, Istanbul, Türkiye
[3] Behavioral Business Director, Lisa Servizi srl, Venezia, Italy

E-mail: [1]denizkarakas@intenseye.com, [2]funda@intenseye.com, [3]rborghetto@lisaservizi.it

Abstract. Workplace safety remains a critical priority across industries, yet traditional Occupational Health, and Safety (OHS) practices often rely on reactive measures, limiting their effectiveness. Recent advancements in computer vision and artificial intelligence (AI) offer unprecedented opportunities to shift towards proactive safety management. Intenseye, a category leader in AI-driven workplace safety, leverages cutting-edge computer vision technology to transform OHS systems by enhancing hazard detection, risk assessment, continuous improvement and compliance monitoring.
Intenseye's innovative AI solution, which integrates seamlessly with existing CCTV infrastructure to provide 24/7 real-time monitoring. Intenseye's capabilities extend across the manufacturing spectrum, from heavy industries such as oil and gas, steel, automotive, and cement production to diverse manufacturing sectors including food and beverage and textile production. With the ability to detect more than 45+ pre-defined unsafe acts and conditions – such as area controls, (Personal Protective Equipment) PPE compliance, vehicle-related risks, unsafe behaviours, and ergonomics scenarios– Intenseye delivers comprehensive workplace health & safety coverage. Each detection is enriched with actionable insights to empower OHS professionals to take corrective & preventive actions (CAPA) for incident prevention.
Examples from the manufacturing sector illustrate measurable impacts, including significant reductions in workplace incidents, cost savings and safety culture improvement. By bridging the gap between technology and OHS practices, Intenseye demonstrates the transformative potential of computer vision AI to create safer workplaces.

Keywords: Computer Vision, Safety Data Analyitics, Real Time Monitoring, Intenseye, Lagging Indicators

1. Background on Computer Vision AI

Computer vision, a rapidly advancing branch of artificial intelligence (AI), enables machines to interpret and understand visual data. While the technology has existed for decades, recent breakthroughs in machine learning, deep learning, and big data have significantly enhanced its capabilities. Today, computer vision powers innovations in robotics, autonomous vehicles, healthcare, and security.

The field dates to the 1960s when researchers first explored algorithms for visual data interpretation. Its growth accelerated in the 1980s with more powerful computing and digital imaging, followed by major strides in the 1990s as machine learning improved object recognition and image classification.

Computer vision involves key processes:
- Image acquisition – Capturing visual data from cameras or sensors, where data quality directly impacts algorithm accuracy.
- Image processing – Enhancing and analysing images using techniques like filtering, segmentation, and edge detection.
- Feature extraction – Identifying and isolating patterns, objects, and shapes for machine interpretation.

Machine learning algorithms train on vast datasets of labelled images to analyse and classify visual information. As AI continues to evolve, computer vision is set to drive even more groundbreaking applications in the future.

2. Enhancing workplace safety with computer vision AI

The use of computer vision AI to improve workplace safety is a relatively recent development, yet it has quickly gained traction as a powerful tool for preventing incidents and injuries.

AI algorithms are being used to analyse workplaces to improve safety and ensure compliance. These algorithms work by analysing video feeds and other visual data from cameras located throughout the workplace. They are designed to detect and analyse various activities, including the movement of people and objects, as well as environmental factors. The AI algorithms then use this information to identify potential health & safety hazards and to alert workers and occupational health and safety (OHS) teams to investigate the risk and take corrective/preventive action for risk mitigation according to the Control of Hierarchy.

There are several benefits of using computer vision AI for workplace safety. Here are some of the most significant advantages:

- **Shifting from lagging/reactive/retrospective to leading/proactive/predictive (from Safety I to Safety II) safety approach via proactive/predictive risk analysis:** Computer vision AI can analyse workplaces in real-time and alert workers or supervisors to potential OHS risks before they cause injury.
- **Enhanced safety compliance & safety culture:** By monitoring compliance with safety

procedures and informing workers in real time, computer vision AI can help ensure that workers are following safety procedures and taking the necessary precautions.

- **Reduced incidents and injuries:** By identifying potential safety hazards and unsafe acts, computer vision AI can help reduce the risk and severity of incidents and injuries in the workplace.
- **Increased productivity:** When workers feel safe in their workplace, they are more productive and engaged. When incident and injury count decrease, there are fewer production stops due to safety which increase productivity. An organization-wide focus on safety leads to higher worker productivity, which drives short-term revenue growth and supports long-term sustainability.
- **Increased operational efficiency:** Computer Vision AI reduces time allocation for manual site monitoring by safety professionals and allows them to focus more on risk mitigation and continuous improvement via addressing root causes and data analysis for informed decision-making.
- **Cost prevention:** Computer Vision AI reduces the count and severity of incidents and injuries which prevent expenses due to workers' compensation, hospital expenses, penalties, rework, machine damage, product loss etc.

3. How to improve behaviour-based safety BBS through computer vision AI

Behaviour-based safety (BBS) systems offer valuable insights into operational safety and have proven to be effective. However, these systems often encounter challenges in gathering comprehensive data, which can limit their ability to provide a complete picture of workplace safety. These systems are primarily dependent on manual observations, which are subject to observer biases and individual interpretations of safe work practices.

An article by EHS Today [1] shows this by detailing how traditional workplace safety programs, even with extensive knowledge and resources, often fail to achieve continuous improvement and can be ineffective in preventing safety incidents.

While implementing a BBS program has been foundational in workplace safety management systems, it has inherent limitations that reduce its overall effectiveness:

- **Personal bias:** The subjective nature of human observations means that data collected often reflects personal experiences and understanding rather than providing objective insights.
- **Limited peer-to-peer contribution:** Associates may hesitate to bring attention to a colleague or workstation. Even when submissions are left anonymous, the peer-to-peer contributions result in mostly "safe" behaviours observed, providing limited data for meaningful safety improvements.
- **Timing of activities:** There is often a rush to complete BBS activities at the end of reporting periods to meet targets. This can lead to large windows of time where we are collecting little to no data on the safety performance of the workplace.

- **Time-consuming:** The manual process of analysing data for trend identification is labour-intensive and slow, severely limiting the ability to identify and mitigate safety risks proactively. Additionally, the limited amount of data collected can make it hard to identify top areas needing improvement.

These challenges highlight the need for a shift towards more efficient, unbiased approaches in behaviour-based safety programs to achieve safer working environments.

4. How to comply with Ethical AI and Data Privacy rules through computer vision AI

Beyond its safety benefits, computer vision AI prioritizes privacy and ethics in the workplace. Intenseye integrates advanced anonymization techniques to protect frontline workers' privacy, ensuring no biometric data is collected, used, or stored. Fully compliant with local regulations and General Data Protection Regulation (GDPR), its **3D anonymization** method replaces individuals with realistic rendered animations, preserving contextual integrity while guaranteeing irreversible anonymization.

Maintaining top-tier data privacy and security is critical. Intenseye's Service Organization Control **(SOC 2) Type II certification**, building on its Type I compliance, underscores its commitment to the five trust principles: **Security, Availability, Processing Integrity, Confidentiality, and Privacy.**

According to the **International Labour Organization (ILO)** [2]**,** over 300 million workers across 142 countries fear reporting safety concerns due to potential retaliation. This hesitation can lead to preventable injuries. AI's **24/7 monitoring** offers an objective "source of truth" to identify risks proactively–but its deployment must be **human-centric**.

Organizations should apply **Human and Organizational Performance (HOP) principles** [3], which highlight that unsafe behaviours often stem from systemic factors, not individual negligence. Rather than assigning blame, the focus should be on improving workplace conditions. Engaging **employee unions** and securing early workforce **buy-in** fosters a psychologically safe environment where workers feel empowered to raise concerns. A transparent, inclusive approach strengthens workplace safety culture and boosts engagement.

5. The AI-powered OHS platform: Intenseye

Intenseye is an advanced AI-driven Occupational Health and Safety (OHS) platform that leverages existing facility cameras to detect unseen hazards, prevent incidents, and save lives through 24/7 real-time monitoring. Its AI analyses 45+ OHS use cases with high accuracy, safeguarding 100,000+ workers across 25+ countries, processing 22 billion images daily for leading industrial groups and Fortune 500 companies.

Designed for seamless integration, Intenseye requires no additional hardware or sensors, connecting instantly to existing CCTV infrastructure. Its plug-and-play AI models identify at-risk behaviours and conditions, including PPE detection, area controls, unsafe acts, vehicle monitoring, and ergonomics.

The platform combines automation, scalability, and real-time risk detection, ensuring

a secure link between IP cameras and its cloud-based AI system. Camera-agnostic and bandwidth-efficient, it processes any IP camera input with 95%+ accuracy, converting vast CCTV data into actionable insights.
Powered by deep learning, Intenseye continuously improves through data labelled by a dedicated operations team, refining AI models within days to enhance detection precision. Integrated with IoT devices, it delivers real-time alerts and automated responses, enabling proactive safety management.

Here are the major product features:

- **Alerts and Reports:** Immediate notifications to the at-risk individual and notifications to the supervisor. In addition to real-time notifications via email and SMS in the event of an alert, users can also schedule regular automated OHS reports to be sent to their emails, including daily, weekly, and monthly summaries of OHS metrics. These reports are useful for field safety meetings (e.g. TBTs toolbox talks) and regular OHS meetings, allowing organizations to stay informed about their OHS performance and to increase safety awareness.
- **Compliance:** Insights into both positive safety behaviours as well as at-risk behaviours so that OHS teams can prioritize corrective actions according to the compliance rates of the safety scenarios implemented at their facilities.
- **Task management:** Management of corrective actions from creation to completion and demonstrates the real-time impact of the precautions taken.
- **KPI (Key Performance Indicator) Tracking:** With data-backed analytics and insights, the platform shifts the focus from lagging to leading indicators. Companies use these indicators to set up individual, team or corporate-level data-driven KPIs to monitor and improve their OHS performance.
- **Visual analytics:** Data on the high-risk exposure spots, allowing not only for safety and health evaluations but also providing insight into operational efficiency.
- **AI accuracy checks:** Transparent reporting of the AI accuracy rates. This enables users to have confidence in the accuracy of the data analysed by the AI algorithms.
- **Intenseye Chief:** The platform's SafetyGPT feature, Chief is designed to simplify how safety teams interact with their data by providing real-time, actionable insights through a conversational interface. Safety leaders can ask specific questions, generate reports, and receive trends directly from the data collected at their facilities instantly or from the uploaded documents such as procedures or safety audits. With the ability to ask customized questions, safety leaders can quickly understand where improvements are happening and where more focus is needed with also specific recommendations for improvement according to the general safety practice and regulations.
- **EHS Suite:** Audit and site inspection with preloaded checklists and root cause analysis of the findings.
- **Near Miss-Incident-SIF Investigation:** Safety incidents can be analysed using preloaded questionnaires and Root Cause Analysis (RCA) to identify underlying causes. This

data helps detect risk patterns and trends, enabling informed decision-making for Corrective and Preventive Actions (CAPAs).
- **Ergonomics:** Ergonomic risk assessments are conducted using RULA (Rapid Upper Limb Assessment) and REBA (Rapid Entire Body Assessment) scores to identify tasks with a high risk of musculoskeletal disorders (MSDs).
- **Smart devices:** Integrated smart lights, locks, and speakers provide real-time alerts to notify workers of unsafe conditions or actions. These systems also help restrict access to specific areas, machinery, or equipment unless proper authorization or personal protective equipment (PPE) is in place.
- **Mobile App:** A dedicated mobile app enables instant access to safety alerts and related data, both on-site and remotely. Push notifications ensure immediate action can be taken, helping to prevent missed warnings and enhance workplace safety – even when away from the office.

6. Intenseye's real-world impact in BBS Management with Computer Vision AI

The transformation of Behaviour-Based Safety (BBS) management through Intenseye's AI-powered system is evident across industries. To quantify its impact, one customer leveraged Intenseye's technology and identified 597 unsafe behaviours within the same period in which only 3 were reported manually, details given below in Section 6.1. This striking contrast highlights Intenseye's ability to significantly enhance hazard detection through 24/7 monitoring, covering the entire facility simultaneously.

This substantial difference not only showcases enhanced detection capabilities but also reinforces the system's critical role in providing comprehensive safety data and prioritizing the most pressing issues effectively.

On average, Intenseye analyses 8,500 hours of safety data annually in a single facility using 20 cameras. This monitoring time is equivalent to 4.4 years of worker time allocation (calculated based on an 8-hour workday, 20 days per month, totalling 1,920 hours annually).

During this period, Intenseye detects approximately 15,000 unsafe acts and conditions with high severity alerts, all of which have the potential to cause injuries.

According to workplace safety studies, the ConocoPhillips Accident Pyramid (2003) [4] is a widely accepted model for understanding accident causation. Based on this approach, before a fatal workplace accident occurs, the following safety indicators are typically observed:

- 300,000 unsafe acts/conditions (UA/UC) – leading indicator
- 3,000 near misses (NM) – leading indicator
- 300 minor injury accidents (RWC restricted work cases, MTC medical treatment cases, FAC first aid cases) – lagging indicator

- 30 lost-time injury accidents (LTA) – lagging indicator

To prevent serious and fatal workplace accidents, it is crucial to monitor leading indicators such as near misses and unsafe acts/conditions. Intenseye enables this proactive approach by identifying UA/UC incidents in real-time through its AI-powered alerts. These identified hazards are then mitigated using the Hierarchy of Controls, aiming to eliminate or minimize risks before they escalate into injuries or fatalities.

Through risk elimination and proactive intervention, Intenseye helps prevent incidents before they occur. Additionally, it reduces the severity of potential accidents, lowering the risk of Serious Injury or Fatality (SIF), including fatal cases and lost-time accidents (LTA), to minor injuries.

When the 15,000 annual alerts detected by Intenseye as UA/UCs are mapped onto the ConocoPhillips Safety Pyramid [4], they correlate to the prevention of approximately:

- 15 minor injuries
- 2 lost workday cases

This tangible impact demonstrates how Intenseye's Computer Vision AI technology actively contributes to creating safer workplaces by reducing workplace risks.

Additionally, another customer, a major food processing company shared their experience:

"Intenseye's approach really resonates with us, especially how it shifts our focus from merely hitting targets at the end of the month to proactively detecting unsafe behaviours. This allows us to truly prioritize safety over statistics."

This feedback underscores a fundamental shift from traditional, compliance-driven safety metrics to a proactive, prevention-focused safety culture – leading to better safety outcomes and a more engaged workforce with Computer Vision AI.

6.1. Increase Hazard Detection and Reduce Safety Risks – How Intenseye helped a leading food manufacturer in the USA to catch 200x more hazards and achieve a 61% reduction in hazard detections

One of Intenseye's valued customers, a globally recognized meat producer, operates within an industry characterized by potential safety hazards including heavy machinery, sharp instruments, and intense production demands.

Following the integration of Intenseye's AI-powered technology with their existing infrastructure, the company significantly expanded its ability to identify and respond to various safety risks. Specifically, Intenseye's AI was instrumental in improvements in their safety

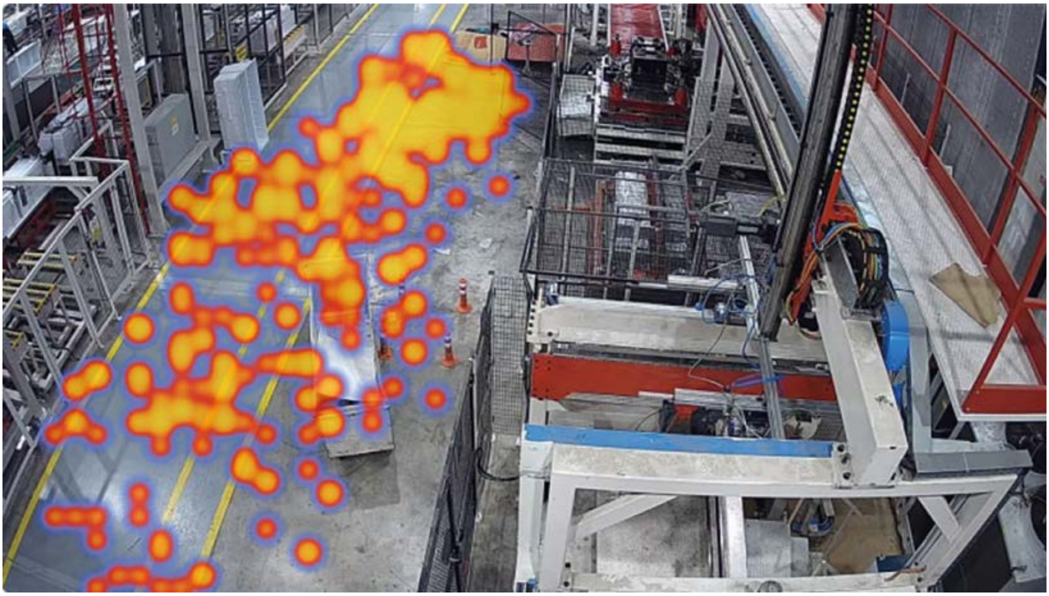


Figure 1. Visual analysis showing the heatmap distribution of detected alerts on the platform dashboard.

management: 61% decrease in unsafe act and condition detections: They conducted targeted training sessions, re-evaluated and improved facility layouts, and engaged in continuous assessment and prompt intervention, all based on the data-driven insights provided by Intenseye's safety management software on their specific hazards.

Compared to the 3 potential hazards documented through manual observations in a month, Intenseye's AI workplace safety software emerged as a crucial assistant, notifying the safety leaders of 597 potential hazards indicating a 200x more hazards detection within the same time. This vast difference underlines Intenseye AI's role in enhancing the scope and precision of hazard detection.

6.2. Increase Speed Limit Compliance Rate and Reduce Speeding Incidents – How Coats, a world leader in thread manufacturing, reduced speeding incidents by 50%

The data-driven insights provided by Intenseye enabled the Coats team to take swift actions, creating an immediate impact. Initial measures, including driver training and targeted behavioural training, resulted in a 20% reduction in speeding detections within the first week. Persistent communication and enforcement of safety requirements and controls led to a reduction of over 50% in speeding incidents. This proactive approach not only improved road safety at the facility but also demonstrated the effectiveness of using OHS management software to prevent safety incidents.

The Madurai New Mill Facility showcases the vital role of technology in enhancing road safety, particularly in high-risk environments. With visible leadership commitment and real-time observation, the facility can efficiently address and mitigate road safety issues, ultimately contributing to the goal of eliminating vehicle-related injuries and fatalities.

6.3. Reduction of TRIR and Enhancing Safety Trust – How a 24% drop in recordable injuries achieved for a global textile industry company

The customer implemented Intenseye including customized OHS scenarios, targeting specific areas such as "Speed limit" and "Working around moving equipment" which led to significant, quantifiable improvements in their safety metrics. The decision to roll out the Intenseye platform globally was made within just two months, demonstrating their agility and commitment to enhancing workplace safety at a large scale. Within just six months, 28 facilities were successfully onboarded, indicating the Intenseye platform's scalability and ease of integration into diverse operational environments.

Dramatic reduction in unsafe acts and conditions: A notable 24% reduction in recordable injuries was achieved across the onboarded facilities in the first year.
Enhanced employee safety: A remarkable 93% of employees reported feeling safer following the implementation of Intenseye. This significant increase in the employees' sense of safety clearly showcases the positive impact Intenseye has created on their workplace safety culture.

Figure 2. Dynamic delimitation area' rule in action, showing hazard detection with a person in very close proximity to an operational forklift.

6.4. Increase Stair Bannister Use Compliance Rate – How a top global beverage company that boosted safety measures and achieved a 92% drop in unsafe behaviours on stairs

Through the insights provided by Intenseye's AI-powered OHS management software, the company identified a high incidence of unsafe behaviours regarding stair banister usage. In response, corrective preventive actions were implemented according to the Hierarchy of Controls, including tailored training programs and the installation of additional signage to reinforce safe stairway practices. These steps were aimed at reminding employees of the correct practices and ensuring they always understood the importance of safety. By utilizing Intenseye's AI to ensure compliance with the critical three points of contact rule, the company achieved a staggering 92% decrease in unsafe behaviours related to stairway usage.

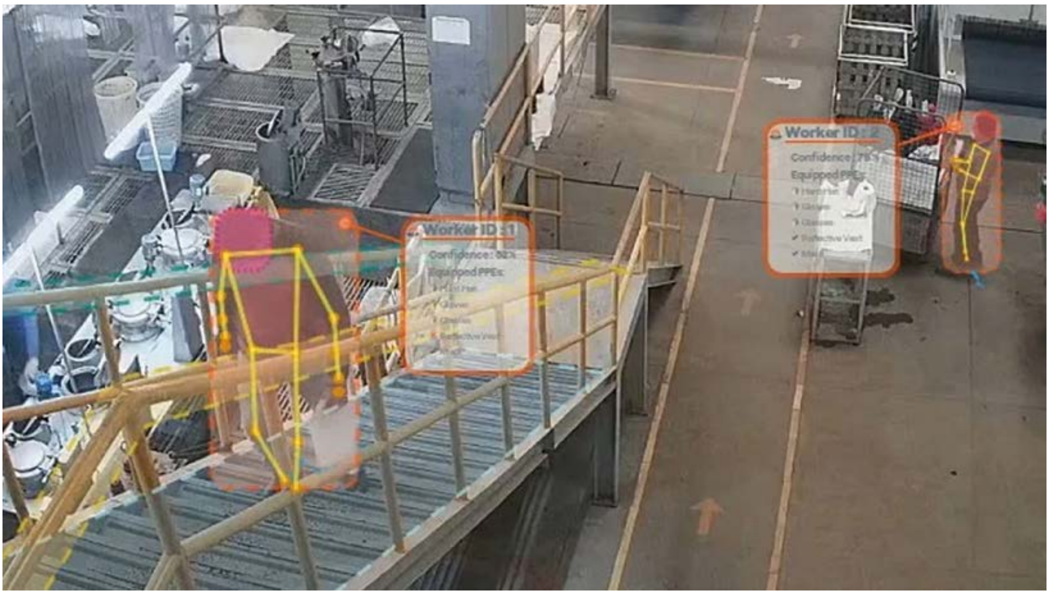


Figure 3. 'Stair banister usage' detection rule in action.

6.5. Reduction of TRIR and Safety Cost – How a top global packaging industry leader reduces total recordable incident rates (TRIR) by 71% and reach a significant cost reduction advantage

A joint analysis conducted with a global packaging industry customer (with $1B in revenue) and Intenseye revealed significant cost differences within the same facilities – comparing areas equipped with Intenseye to those without. The findings highlight the direct financial impact and return on investment (ROI) of Intenseye's AI-powered safety solution, demonstrating up to a 71% reduction in Total Recordable Incident Rate (TRIR), an 83% decrease in recordable incident costs, and a 98% reduction in workers' compensation expenses.

Figure 4. 'Comparison of safety indicators at the sections whitout Intenseye and with Intenseye.

6.6. How AKA Automotive reduced ergonomic risks by 71%

A recent EU-OSHA survey [5] highlights the evolving risks in workplace safety – prolonged sitting 64%, repetitive hand & arm movements 63%, and lifting loads 52% are now among the top concerns. Two top risk factors in 2024 are related to musculoskeletal disorders MSD.

With insights from Intenseye's AI-powered analyses, the company more accurately identified elevated RULA (Rapid Upper Limb Assessment) and REBA (Rapid Entire Body Assessment) scores and took corrective actions to enhance their ergonomic performance and prevent MSD related occupational disease:

- Implemented a hoist system to reduce ergonomic risks associated with repetitive lifting tasks.
- Redesigned the chair and table setups in the assembly department.
- Adjusted workbench heights in welding stations.
- Provided back support belts to personnel for mechanical handling of axles and lifting large-surface materials.
- Delivered 708 man-hours of additional training on ergonomic working techniques to employees.

As a result of these corrective measures, the number of cases reporting musculoskeletal disorders to the occupational physician decreased significantly, from 362 cases in 2023 to 102 cases in 2024 (January–September), marking a 71.82% reduction.

The occupational physician of AKA Automotive, Hakan Aydınlık shares these thoughts on Intenseye and points out the need for transforming how the industry approaches ergonomics: "Protecting the health of workers in physically demanding jobs and enhancing workforce productivity is of great importance. Repeated movements or poor posture can cause cumulative stress on the musculoskeletal system, leading to serious health issues. Therefore, implementing ergonomics training and observing working conditions on-site offer a proactive approach to health by reducing potential risks.

7. Intenseye's real-world impact in Costs of Workplace Safety with Computer Vision AI

Implementing safety AI software across the entire organization not only enhances workplace safety but also significantly reduces occupational health and safety (OHS) costs. It's not about adding another tool to your tech stack but about integrating AI that can help you mitigate risks before they become safety incidents which cost millions.
Safety cost is estimated under 2 main categories as **Direct Costs;** easily measurable & directly Attributable which are immediate financial impacts that arise directly from an incident, accident, or operational failure and **Indirect Costs;** hidden or long-term impacts which are harder to quantify but often have a greater financial and operational impact in the long run.

While direct costs are often covered by insurance, indirect costs can be higher and are usually absorbed by the employer. Preventing workplace incidents through Intenseye AI can significantly reduce both direct and indirect financial impacts. According to the U.S. Department of Labor, Occupational Safety and Health Administration OSHA'S Safety Pays Program [6], over 10K USD expenses, indirect cost/direct cost ratio is 1.1 [7]. And according to NSC [8], in 2022 work injury cost per worker is 1K USD ending up with 167Billion USD total injury cost.

According to estimates based on Eurostat and World Bank data presented by EU-OSHA, work-related accidents and illness cost the EU economy over 3,3% of GDP annually (ca. EUR 460 billion in 2019). [9]

Safe and healthy working conditions are not only a legal and moral obligation – they also pay off economically. Investments in safety and health at workplaces avoid human suffering and protect our most asset – our health and our physical and psychological integrity. Importantly they also have a positive impact on the motivation of employees, on the quality of work and products, on the company's reputation, and on the satisfaction levels of employees, managers and customers and thus on economic success. International research on the return on investments in prevention prove that every dollar invested in safety and health generates a potential benefit of more than two dollars in positive economic effects. Healthy working conditions contribute to healthy business. [10]

But the question remains: how does Intenseye's AI translate into safer facilities and reduced costs for OHS teams? While measuring cost-saving in safety has long been seen as an uphill battle, there are clear statistics that highlight the value of AI.

7.1. Poor OHS practices cost you 30% more

The 2024 Global EHS Readiness Report [11] paints a clear picture: companies with less integrated OHS systems spend up to 30% more on incident-related costs than those with more developed ones. These costs go beyond just medical bills or fines. They include things like damage to your company's reputation, lost productivity, and higher employee turnover–impacts that can be harder to quantify but just as costly. Fragmented information across multiple systems and manual processes complicates OHS management, leading to inefficiencies and potential errors.

Many organizations either use separate, disjointed systems for hazard detection and safety management or rely on outdated, manual processes that are prone to errors and inefficiencies. This fragmented approach often leads to delayed responses to hazards and a reactive rather than proactive safety culture.

This is where AI-powered OHS management software can make a big difference. Intenseye's EHS Suite centralizes incident reporting, task management, inspections, audits, and template creation within a single platform, streamlining communication, ensuring data integrity, and providing a holistic view of all OHS operations. Plus, Intenseye's LLM (Large Language Model) based safety GPT feature, Chief, simplifies and accelerates the process of compiling and analysing data from diverse sources via its advanced AI capabilities, enabling instant data analysis and integration from multiple formats and sources, effectively reducing response times and increasing accuracy.

7.2. 75 million workdays lost due to work-related injuries

In 2022 alone, 75 million workdays were lost due to injuries [8]. That number should be enough to make you rethink your current approach to safety management. The impact of lost workdays extends far beyond one employee's absence. When a key team member is out, it creates a domino effect, slowing down the entire operation. These indirect costs – often difficult to quantify – can quickly surpass the direct expenses of the injury itself, leading to significant financial strain.

By adopting Intenseye's AI, Swire Coca-Cola significantly enhanced their real-time risk identification and mitigation capabilities, leading to a 60% reduction in safety hazards in 2022 alone. Alongside this improvement, they saw a 27% decrease in Lost Day Rates (LDR), modernizing their safety management and making their operations far more efficient.

7.3. Increased penalties per violation

Enforcement for health safety regulation violations have never been more pressing all around the globe.

The Top 10 most frequently cited workplace safety standards by OSHA (Occupational Safety and Health Administration) for FY 2024 are:[12]

Safety Standard: Violation Count

1. Fall Protection – General Requirements: 6,307
2. Hazard Communication: 2,888
3. Ladders: 2,573
4. Respiratory Protection: 2,470
5. Lockout/Tagout (LOTO): 2,443

6. Powered Industrial Trucks: 2,248
7. Fall Protection – Training Requirements: 2,050
8. Scaffolding: 1,873
9. Personal Protective and Lifesaving Equipment – Eye and Face Protection: 1,814
10. Machine Guarding: 1,541

Recently on Jan. 15, 2025, OSHA increased its maximum penalties for serious violations from $16,131 to $16,550 per violation and boosted fines for wilful or repeated violations from $161,323 to $165,514 per violation. [13]

These regulatory changes make it clear that businesses must rethink how they manage safety. Intenseye's AI offers an effective solution by providing real-time leading indicators data that allows you to act swiftly and accurately. By identifying unsafe acts and conditions as they occur, our AI-powered OHS management software equips decision-makers with the insights needed to prioritize actions and allocate resources efficiently. This proactive approach helps teams not only to address risks before they escalate but also to reduce human error, streamline reporting, and ensure compliance with OSHA standards which match with Intenseye' 45+ safety use cases.

Beyond compliance, the true value of AI lies in giving safety and operations teams the tools they need to make OHS an integral part of day-to-day operations, driving long-term improvements that go beyond avoiding fines and focus on truly protecting your workforce.

Figure 5. Intenseye' safety use cases.

7.4. Advanced OHS systems cut workplace injury costs by 50%

A study referenced in the 2024 Global EHS Maturity Study [14] shows that organizations with advanced OHS systems like this witnessed a 50% reduction in the costs associated with workplace injuries and illnesses.

One of Intenseye's customers in the railroad equipment manufacturing industry decided to invest in the platform after calculating the cost of adopting AI and the estimated total cost of injuries. The numbers painted a clear picture: the average cost of just one crushing injury in the workplace is a jaw-dropping $1,700,000. Now imagine investing in AI to make your workplaces safer and healthier. Preventing just one such incident with Intenseye's real-time leading safety indicators and AI-generated data could save over 97% in potential costs. Companies that embrace this Safety AI adoption can not only meet safety program requirements but also unlock a substantial drop in OHS costs through reduced injuries, lower compensation costs, and improved worker well-being.

References

[1] Why Traditional Safety Programs Cannot Achieve Continual Improvement, EHS Today. Available at: https://www.ehstoday.com/safety/article/21908057/why-traditional-safety-programs-cannot-achieve-continual-improvement

[2] ILO Report

https://www.ilo.org/sites/default/files/wcmsp5/groups/public/@ed_protect/@protrav/@safework/documents/publication/wcms_842505.pdf

[3] HOP Principles – The 5 Principles of Human Performance: A contemporary update of the building blocks of Human Performance for the new view of safety, 2019 by Todd E. Conklin PhD

1 Human error is normal.

2 Blame fixes nothing.

3 Learning is vital.

4 Context drives behaviour.

5 How management responds to failure matters.

[4] ConocoPhillips Marine: Safety Pyramid based on a study, April 2003

[5] EU-OSHA Survey https://osha.europa.eu/sites/default/files/documents/ESENER-first-findings-2024_EN.pdf

[6] OSHA Safety Pays Program

https://www.osha.gov/safetypays/estimator-text

[7] OSHA Cost Ratio

https://www.osha.gov/safetypays/tool/inputs

[8] NSC Cost Data

https://injuryfacts.nsc.org/work/costs/work-injury-costs/

[9] EU OSHA Cost https://osha.europa.eu/en/publications/international-comparison-cost-work-related-accidents-and-illnesses/view

[10] EU Vision Zero Safety Pays

https://visionzero.global/7-golden-rules

[11] The 2024 Global EHS Readiness Report – HSI. Available at: https://goto.hsi.com/2024-ehs-global-readiness-report

[12] The Top 10 most frequently cited workplace safety standards by OSHA

https://www.nsc.org/newsroom/osha-reveals-top-10-safety-violations-at-nsc-safet?srsltid=AfmBOop-8jicbra1p0xMRAoSvwVH3yBw8dTLiI5LJI7E0y06l4SowUDG

[13] U.S. Department of Labor, Occupational Safety and Health Administration (OSHA). Available at: https://www.osha.gov/news/newsreleases/osha-trade-release/20250114#:~:text=On%20Jan.,%24161%2C323%20to%20%24165%2C514%20per%20violation

[14] 2024 Global EHS Maturity Study – EY. Available at: https://www.ey.com/content/dam/ey-unified-site/ey-com/en-gl/insights/climate-change-sustainability-services/documents/ey-gl-global-ehs-maturity-study-02-2024.pdf

Digitizing Construction Site Safety Documentation: Benefits, Limitations, and Challenges

Giulia De Cet[1*], Alberto Vicentin[2,1], Carlo Zanchetta[1] and Rossana Paparella[1]
[1] Department of Civil, Environmental and Architectural Engineering – University of Padua, Padua, Italy
[2] Studio Vicentin srl, Brendola, Vicenza, Italy

* E-mail: giulia.decet@unipd.it

Abstract. In the construction industry, the digitalization of safety information has emerged as a pivotal topic, promising to revolutionize the way safety protocols are managed and implemented on construction sites. This research endeavours to critically analyze the benefits, limitations, and challenges associated with the transition from traditional paper-based documentation to digital platforms.

The construction sector has long been characterized by its reliance on physical documentation, ranging from safety manuals to incident reports and risk assessments. However, the advent of digital technologies has paved the way for a paradigm shift, offering the potential to streamline processes, enhance accessibility, and improve overall safety management. By embracing digital documentation, employers and general contractors can leverage real-time data sharing, centralized storage, and seamless collaboration among stakeholders.

This study aims to shed light on the tangible advantages of digitizing safety documentation. These benefits may encompass improved data accuracy, reduced administrative burdens, and enhanced compliance with regulatory requirements. Furthermore, the research will delve into the potential for digital platforms to facilitate proactive risk identification and mitigation, ultimately contributing to a safer work environment for construction workers.

Concurrently, the study will critically examine the limitations and challenges that accompany the digital transformation of safety documentation. Potential barriers may include resistance to change, technological barriers, and concerns surrounding data security and privacy. Additionally, the research will explore the financial implications associated with implementing digital solutions, as well as the need for comprehensive training and user adoption strategies.

By adopting a balanced approach, this study seeks to provide a holistic understanding of the digitalization process, acknowledging both its merits and the obstacles that must be overcome. Through a rigorous analysis of case studies, industry best practices, and stakeholder perspectives, the research will offer actionable insights and recommendations for construction companies. Ultimately, the overarching goal of this research is to contribute to the ongoing discourse on construction site safety and facilitate informed decision-making processes for industry professionals. By critically evaluating the digitalization of safety documentation, this study aims to pave the way for a safer, more efficient, and technologically advanced construction sector.

Keywords: Digitizing, Construction, Safety

1. Introduction

The construction industry has long been characterized by its reliance on traditional paper-based documentation, encompassing safety manuals, incident reports, risk assessments, and a myriad of other critical documents [1]. However, in an era marked by rapid technological advancements, the digitalization of safety documentation has emerged as a compelling opportunity to revolutionize the way safety protocols are managed and implemented on construction sites [2], [3].

The digitalization of safety documentation also presents an opportunity to leverage big data analytics to identify patterns and trends in safety data, enabling proactive and targeted interventions. Furthermore, the adoption of digital solutions can facilitate the sharing of best practices and lessons learned across construction projects and sites, promoting continuous improvement in safety practices.

This research endeavours to critically analyze the benefits, limitations, and challenges associated with the transition from traditional paper-based documentation to digital platforms within the construction sector. By embracing digital transformation, construction companies can leverage the potential to streamline processes, enhance accessibility, and improve overall safety management, ultimately contributing to a safer work environment for construction workers [4], [5].

The construction industry plays a pivotal role in shaping the built environment and driving economic growth. However, it is also a high-risk sector, with numerous hazards and potential safety concerns that can have severe consequences for workers, project timelines, and overall productivity. Ensuring a safe and secure work environment has long been a priority for construction companies, but traditional paper-based documentation methods have often proven cumbersome, inefficient, and prone to errors.

The digitalization of safety documentation presents a compelling opportunity to address these challenges and revolutionize the way safety protocols are managed and implemented on construction sites. By transitioning from physical documents to digital platforms, construction companies can leverage the power of technology to streamline processes, enhance data accuracy, and promote real-time collaboration among stakeholders.

The construction industry has historically been characterized by its resistance to technological change, with many firms clinging to traditional methods and processes [6]. However, the advent of digital technologies has paved the way for a paradigm shift, offering the potential to revolutionize various aspects of construction operations, including safety documentation [6], [7].

The benefits of digitizing safety documentation extend beyond mere process optimization. By leveraging digital platforms, construction companies can gain valuable insights through data analytics, enabling proactive risk identification and mitigation strategies. Furthermore, the integration of digital safety documentation with emerging technologies such as Building Information Modeling (BIM), Internet of Things (IoT) devices, and augmented reality (AR) can further enhance safety management processes, providing real-time monitoring, visualization, and analysis capabilities.
Several studies have highlighted the tangible benefits of digitizing safety documentation. It emphasized the potential for improved data accuracy, reduced administrative burdens, and enhanced compliance with regulatory requirements [8]. Digital platforms facilitate real-time data sharing, centralized storage, and seamless collaboration among stakeholders, enabling proactive risk identification and mitigation [7], [9].
However, the transition to digital safety documentation is not without its challenges. Resistance to change, technological barriers, data security concerns, and financial implications are among the key obstacles that construction companies must navigate. Comprehensive training programs and effective change management strategies are crucial to ensure user adoption and successful integration of digital solutions into existing workflows.
Furthermore, research has indicated that digital documentation can contribute to increased transparency and accountability, as well as streamlined reporting processes. By leveraging digital platforms, construction companies can efficiently track and analyze safety-related data, enabling data-driven decision-making and continuous improvement.
Despite the potential benefits, the digitalization of safety documentation is not without its challenges. Resistance to change and technological barriers, such as limited digital literacy among construction workers and the need for robust infrastructure, have been identified as significant obstacles [10].
To fully harness the benefits of digital safety documentation, a holistic approach is essential. This involves collaboration among stakeholders, investment in robust infrastructure, and the development of comprehensive training programs. Construction companies must also prioritize data security and privacy measures to mitigate potential risks and build trust among workers and stakeholders.
Concerns surrounding data security and privacy have also been raised, as digital platforms may be vulnerable to cyber threats or unauthorized access. Additionally, the financial implications associated with implementing digital solutions, as well as the need for comprehensive training and user adoption strategies, cannot be overlooked [11].
While numerous studies have explored the potential benefits and challenges of digitizing safety documentation, there remains a need for a comprehensive analysis that considers the perspectives of various stakeholders and provides actionable insights for construction companies navigating this transformative journey.

2. Methodology

To gain a comprehensive understanding of the benefits, limitations, and challenges associated with digitizing safety documentation, a mixed-methods approach was employed. This involved conducting a literature review to identify existing research and industry reports, as well as conducting semi-structured interviews with safety experts. Additionally, case studies of construction companies that have implemented digital safety documentation solutions were analyzed to gather real-world insights and best practices.

The literature review encompassed academic publications, industry reports, and government documents related to construction site safety, digital transformation, and the adoption of emerging technologies in the construction sector. This provided a solid theoretical foundation and identified key themes and areas of focus for further exploration.

Semi-structured interviews were conducted. These interviews aimed to capture first-hand experiences, perspectives, and insights regarding the benefits, challenges, and practical considerations of implementing digital safety documentation solutions.

Furthermore, case studies of construction companies that have successfully implemented digital safety documentation platforms were analyzed. These case studies provided valuable insights into the implementation processes, user adoption strategies, and the tangible impacts on safety performance, productivity, and overall project management.

By triangulating data from multiple sources, including literature, interviews, and case studies, a comprehensive understanding of the digitalization of safety documentation in the construction industry was obtained. This approach ensured the validity and reliability of the research findings, while also capturing the nuances and complexities inherent in this transformative process.

3. Benefit, Limitations and Challenges of Digitizing Safety Documentation

The research findings revealed a multifaceted landscape surrounding the digitalization of safety documentation in the construction industry, highlighting both the potential benefits and the challenges that must be addressed (see Table 1).

4. Conclusions

The research findings underscore the transformative potential of digitizing safety documentation in the construction industry. By embracing digital transformation, construction companies can leverage improved data accuracy, streamlined reporting processes, enhanced collaboration, and data-driven decision-making capabilities. However, the successful implementation of digital safety documentation solutions requires addressing challenges such as resistance to change, technological barriers, data security concerns, financial implications, and the need for comprehensive training and user adoption strategies.

To navigate this transformative journey successfully, construction companies must adopt a strategic and holistic approach. This involves fostering a culture of innovation and continuous improvement, investing in robust digital infrastructure, and prioritizing workforce training and development. Collaboration with technology providers, industry associations, and academic institutions can facilitate knowledge sharing, best practice adoption, and the development of industry-wide standards and guidelines.

The construction industry must adopt a holistic approach to the implementation of digital solutions, involving all stakeholders and ensuring a gradual but consistent transition.

Benefits	Improved Data Accuracy and Accessibility	Digital platforms enable real-time data entry and centralized storage, reducing the risk of errors associated with manual data entry and ensuring easy access to safety-related information for authorized personnel.
	Streamlined Reporting and Compliance	Digital documentation facilitates efficient reporting processes, enabling construction companies to comply with regulatory requirements and industry standards more effectively.
	Enhanced Collaboration and Communication	Digital platforms promote seamless collaboration and communication among stakeholders, enabling real-time sharing of safety-related information and facilitating coordinated efforts in risk mitigation and incident response.
	Data-Driven Decision Making	By leveraging digital platforms, construction companies can collect and analyze safety-related data, enabling data-driven decision-making and continuous improvement in safety practices.
	Increased Transparency and Accountability	Digital documentation provides a comprehensive audit trail, enhancing transparency and accountability in safety management processes.
Limitations and Challenges	Resistance to Change	The construction industry has historically been resistant to technological change, and the adoption of digital safety documentation may face resistance from workers accustomed to traditional paper-based methods.
	Technological Barriers	Limited digital literacy among construction workers, inadequate infrastructure, and compatibility issues between different digital platforms can pose significant challenges to the successful implementation of digital safety documentation solutions.
	Data Security and Privacy Concerns	Digital platforms may be vulnerable to cyber threats, data breaches, or unauthorized access, raising concerns about data security and privacy.
	Financial Implications	Implementing digital safety documentation solutions can be costly, requiring investments in hardware, software, and training, which may be a barrier for smaller construction companies with limited resources.
	Training and User Adoption	Comprehensive training programs and effective change management strategies are crucial to ensure user adoption and successful integration of digital safety documentation solutions into existing workflows.

Table 1. Benefits, Limitations and Challenges of Digitizing Safety Documentation.

Collaboration among academics, practitioners, and standardization bodies is essential to develop standards and guidelines for the effective use of digital safety documentation. Furthermore, challenges related to data management and privacy need to be addressed by implementing robust cybersecurity measures and data governance policies.

Additionally, construction companies should consider leveraging emerging technologies such as artificial intelligence, machine learning, and blockchain to further enhance the capabilities and security of digital safety documentation solutions. These technologies can automate processes, provide predictive analytics, and ensure data integrity and transparency, ultimately contributing to a safer and more efficient construction environment.

To fully harness the benefits of digital safety documentation, a holistic approach is essential, involving collaboration among stakeholders, investment in robust infrastructure, and the development of comprehensive training programs. Construction companies must also prioritize data security and privacy measures to mitigate potential risks and build trust among workers and stakeholders.

Furthermore, the research highlights the importance of continuous improvement and adaptation in the digital transformation journey. As technology evolves, construction companies must remain agile and responsive, embracing new innovations and best practices to optimize their digital safety documentation processes.

5. Future Developments

As the construction industry continues to evolve, several future developments can be anticipated in the realm of digital safety documentation:

1. Integration with Advanced Technologies: The integration of digital safety documentation with emerging technologies such as Building Information Modeling (BIM), Internet of Things (IoT) devices, and augmented reality (AR) can further enhance safety management processes. These technologies can provide real-time monitoring, visualization, and analysis capabilities, enabling proactive risk identification and mitigation. For example, IoT sensors embedded in personal protective equipment (PPE) or construction machinery can continuously monitor safety conditions and alert workers or supervisors to potential hazards. Augmented reality applications can overlay safety information and instructions onto the physical environment, enhancing situational awareness and facilitating safer work practices.
2. Artificial Intelligence and Machine Learning: The application of artificial intelligence (AI) and machine learning algorithms can revolutionize safety documentation processes. AI-powered systems can automate data entry, identify patterns and anomalies, and provide predictive analytics, enabling construction companies to anticipate and mitigate potential safety risks more effectively. Machine learning models can be trained on historical safety data to recognize potential hazards, recommend preventive measures, and optimize safety protocols based on real-world scenarios.
3. Blockchain Technology: The adoption of blockchain technology can enhance data security, transparency, and immutability in digital safety documentation. Blockchain-based platforms can provide tamper-proof records, enabling secure and auditable documen-

tation of safety-related information. This can be particularly valuable in cases of accidents or legal disputes, where the integrity and authenticity of safety documentation are crucial.

4. Augmented Reality (AR) and Virtual Reality (VR): The integration of digital safety documentation with technologies such as Augmented Reality (AR) and Virtual Reality (VR) can revolutionize worker training and awareness in the construction industry. AR/VR simulations can recreate hazardous situations in a safe environment, allowing workers to learn and practice safety procedures in an immersive and effective manner. This can improve hazard recognition, risk assessment, and decision-making skills, ultimately enhancing overall safety on construction sites.
5. Digital Twins: The creation of digital twins of construction sites, integrating real-time data from IoT sensors and BIM, can enable continuous monitoring of safety conditions and prediction of potential hazards. These digital models can support proactive safety measure planning and optimization of construction processes. By simulating various scenarios and analyzing data from multiple sources, digital twins can help identify potential safety risks before they occur, allowing for timely interventions and mitigation strategies.
6 Standardization and Interoperability: As the adoption of digital safety documentation solutions increases, there will be a growing need for standardization and interoperability among different platforms and systems. Industry-wide collaboration and the development of common standards can facilitate seamless data exchange and integration, enhancing efficiency and collaboration across the construction sector. Standardized data formats, protocols, and interfaces will enable different digital solutions to communicate and share information seamlessly, promoting a more cohesive and integrated approach to safety management.
7. Continuous Training and Upskilling: As digital technologies continue to evolve, construction companies must prioritize continuous training and upskilling programs to ensure that their workforce remains proficient in the latest digital safety documentation tools and processes. The rapid pace of technological change necessitates ongoing education and skill development for workers at all levels, from frontline construction personnel to management and safety professionals. Embracing a culture of lifelong learning and providing accessible training resources will be crucial for maximizing the benefits of digital safety documentation and fostering a safety-conscious workforce.

By embracing these future developments and staying at the forefront of technological advancements, the construction industry can further optimize safety management processes, enhance worker safety, and contribute to a more sustainable and efficient construction sector.

However, it is crucial to acknowledge that the adoption of digital safety documentation solutions is not a panacea for all safety challenges in the construction industry. While technology can provide powerful tools and insights, it must be complemented by a strong safety culture, effective leadership, and a commitment to continuous improvement from all stakeholders involved.

Furthermore, the integration of digital solutions into existing workflows and processes must be carefully managed to ensure a smooth transition and minimize disruptions. Change management strategies, clear communication, and ongoing support for workers are essential to foster user adoption and maximize the benefits of digital safety documentation. As the construction industry continues to evolve and embrace digital transformation, it is imperative to strike a balance between technological innovation and human-centric approaches. While leveraging the power of digital tools, construction companies must also prioritize worker well-being, foster a culture of safety, and promote open communication and collaboration among all stakeholders.

By adopting a holistic and balanced approach, the construction industry can harness the full potential of digital safety documentation, creating a safer, more efficient, and more sustainable future for the built environment.

References

[1] Y. Zou, A. Kiviniemi, and S. W. Jones, "A review of risk management through BIM and BIM-related technologies," *Saf Sci*, vol. 97, pp. 88–98, Aug. 2017, doi: 10.1016/J.SSCI.2015.12.027.

[2] R. Woodhead, P. Stephenson, and D. Morrey, "Digital construction: From point solutions to IoT ecosystem," *Autom Constr*, vol. 93, pp. 35–46, Sep. 2018, doi: 10.1016/J.AUTCON.2018.05.004.

[3] S. Zhang, F. Boukamp, and J. Teizer, "Ontology-based semantic modeling of construction safety knowledge: Towards automated safety planning for job hazard analysis (JHA)," *Autom Constr*, vol. 52, pp. 29–41, Apr. 2015, doi: 10.1016/J.AUTCON.2015.02.005.

[4] R. Sacks, A. Perlman, and R. Barak, "Construction safety training using immersive virtual reality," *Construction Management and Economics*, vol. 31, no. 9, pp. 1005–1017, Sep. 2013, doi: 10.1080/01446193.2013.828844.

[5] H. Guo, H. Li, G. Chan, and M. Skitmore, "Using game technologies to improve the safety of construction plant operations," *Accid Anal Prev*, vol. 48, pp. 204–213, Sep. 2012, doi: 10.1016/J.AAP.2011.06.002.

[6] T. D. Oesterreich and F. Teuteberg, "Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry," *Comput Ind*, vol. 83, pp. 121–139, Dec. 2016, doi: 10.1016/J.COMPIND.2016.09.006.

[7] S. Tabatabaee *et al.*, "Investigating the Barriers to Applying the Internet-of-Things-Based Technologies to Construction Site Safety Management," *Int J Environ Res Public Health*, vol. 19, no. 2, Jan. 2022, doi: 10.3390/IJERPH19020868.

[8] Y. Zou, A. Kiviniemi, and S. W. Jones, "Developing a tailored RBS linking to BIM for risk management of bridge projects," *Engineering, Construction and Architectural Management*, vol. 23, no. 6, pp. 727–750, 2016, doi: 10.1108/ECAM-01-2016-0009.

[9] Y. Shvets and T. Hanák, "Use of the Internet of Things in the Construction Industry and Facility Management: Usage Examples Overview," *Procedia Comput Sci*, vol. 219, pp. 1670–1677, Jan. 2023, doi: 10.1016/J.PROCS.2023.01.460.

[10] M. R. Hosseini *et al.*, “BIM adoption within Australian Small and Medium-sized Enterprises (SMEs): an innovation diffusion model,” *Construction Economics and Building*, vol. 16, no. 3, pp. 71–86, Sep. 2016, doi: 10.5130/AJCEB.v16i3.5159.

[11] G. Amuda-Yusuf, “Critical success factors for building information modelling implementation,” *Construction Economics and Building*, vol. 18, no. 3, pp. 55–73, Sep. 2018, doi: 10.5130/AJCEB.V18I3.6000.

The IMPACT Methodology for the Protection of Industrial Facilities and Tertiary Sector

Roberto Barro[1*], Fabio Zorzini[1], Andrea Dusso[1] and Matteo Sanavia[1]
[1] SAFEXPERTISE, integrated safety solutions. Udine, Rovereto, Padova

* E-mail: info@safexpertise.com

Abstract. Adverse events and natural catastrophes happen unexpectedly causing impacts to people, resources, facility, environment, and business continuity. The disruption of a single company's operations can also affect an entire supply chain, a chain that can be broken by the failure of a single link. These business safety risks, however, are not always addressed in the appropriate time and method, and the consequences for occupants, buildings, plant, properties, and machinery are considered only after the effects resulting from the occurrence of an adverse event have been established. The identification and assessment of "impact scenarios" that may affect an industrial plant is a process aimed at understanding the effects on a given object, structure, or business situation in the face of events such as a fire or earthquake, in order to identify risk situations and thus be able not only to identify areas on which to intervene but also on which to focus more quickly or with appropriate protection measures. The methodology behind such analyses and risk assessments for business areas is called "IMPACT" (Identification and Mapping of Impacts for the Planning of Interventions the Analysis of Risks and Operational Continuity in the Technical Area); developed to improve, including possibly through progressive interventions, the safety of industrial plants in the event of adverse man-made and natural events such as fires and earthquakes, providing the situational picture of what could happen to company assets (building, facilities, people). The result is an operational tool for business decision support useful for evaluating and defining safety improvement interventions that can guarantee better results in terms of cost-effectiveness, as they are aimed at solving potential strategic problems for the company's business continuity in addition to compliance with legal obligations. Impact maps can complement the risk assessment document and provide useful guidance for Business Impact Analysis and Business Continuity assessments.

Keywords: Impact Scenario, Impact Analysis, Business Impact Analysis, Business Continuity

1. Introduction

Adverse events such as fires and earthquakes occur unexpectedly, posing risks to people,

resources, facilities, the environment, and business continuity. The disruption of a single company's operations can have cascading effects on the entire supply chain, where the failure of a single link can compromise the stability of the whole system.
Despite the relevance of these risks, often they are not addressed proactively and in a comprehensive way, but in a reactive and fragmented way. Indeed, in many cases, organizations lack a structured and coordinated approach to identifying and mitigating these risks. This approach is frequently the result of fragmented responsibilities across specialized technical roles – fire prevention, seismic protection, flood mitigation – without a comprehensive, managerial-level view of the overall risk, that considers also the interrelations between risks. Furthermore, the consequences of the adverse events for buildings, industrial plants, assets, and machinery are typically assessed only after a disruptive event has occurred, or because there is some normative requirement to fulfill. Moreover, risks are often poorly synthesized and don't help the company management to take strategic decision-making.
As a result, preventive actions are perceived merely as regulatory obligations, rather than as investments in operational resilience. On the other hand, when risk scenarios are clearly defined, properly weighted, and effectively communicated, managers can fully understand the potential impact on business operations – even of seemingly minor failures. For example, the collapse of a poorly restrained canopy can prevent access to a logistics center for hours, leading to significant delays and financial losses.
To support management in identifying potential risks in advance and defining the most effective organizational and technical countermeasures, this work presents the IMPACT methodology.
The identification and assessment of impact scenarios affecting an industrial plant is a structured process designed to analyze the potential consequences of events such as fires or earthquakes. By evaluating these scenarios, companies can gain a deeper understanding of their vulnerabilities, enabling them to identify high-risk areas requiring immediate attention, prioritize mitigation efforts and protection measures effectively, implement targeted strategies to enhance safety and operational resilience.

2. Methodology

The IMPACT methodology is based on existing methods and on the internal experience gained over the years, with the aim of integrating them into a single tool for the Identification and Mapping of impacts, the Planning of interventions, and the Analysis of risks and operational Continuity in the Technical area (IMPACT).
IMPACT uses the survey and assessment modes of VISUS (Visual Inspections for defining Safety Upgrading Strategies) [2] and exploits its concept of impact scenarios, including for graphical rendering through icons. The multi-hazard VISUS methodology adopted by UNESCO within the Comprehensive School Safety framework, in line with the Sendai framework for disaster risk reduction 2015–2030. VISUS was conceived and developed to provide decision-makers with a quick assessment of safety situations, upgrading needs, and status conditions of a large set of existing learning facilities. The methodology is the result of progressive improvements derived from multiple applications in pilot projects worldwide

and in international peer reviews.
IMPACT uses the RADAR (‘Recon Analysis for Detecting the Actual situation and the improvement Requests) [3] method for partitioning and assessing the physical environment and the implications for business continuity and intervention assumptions and priorities. RADAR provides the decision-makers with an overview of the main aspects for modernization (safety, functionality, sustainability, adaptability, comfort) and substantial information for planning interventions. Decision-makers could use RADAR to define integrated modernization strategies with resilience improvement, monitor the situation of the facilities, and understand the effectiveness of interventions.
IMPACT uses the concepts of Technical Triage [1] for rapid assessments and color-coding sense. Technical Triage was proposed and developed by the SPRINT-Lab research group at the University of Udine as a tool to support the National Fire Department's activities of rapid assessment of damage to buildings damaged by the 2012 Emilia earthquake for rapid planning of safety interventions and was subsequently refined and tested in exercise scenarios and widely used in both national and international real-world emergency contexts. For seismic structural assessments, it uses the rapid methods FIRSTEP-M (Masonry) [6],[7] and FIRSTEP-RC (Reinforced Concrete) [4],[5] while for fire and explosion-related assessments it uses the general methods INSPECT (INspection and Study of Potential Emergency-scenarios for Countermeasure Tailoring) [9] and GRISU (Usage Scenario Grid method in Italian “metodo delle GRIglie di Scenari di Utilizzazione) [8] in addition to more specific methods for fire development [12], [13], explosions [11] and egress [10].

The IMPACT methodology identifies the potential consequences of impact scenarios, i.e., adverse events that may reasonably be expected following a fire or earthquake.
Due to the heterogeneous and extensive nature of industrial plants, they cannot always be easily divided into homogeneous areas based on characteristics and functions.
For example:

- The plant may consist of multiple buildings built at different stages of its expansion. The buildings have different structural peculiarities, furthermore they can house different activities and operations and if they are not structurally independent, they can interact with each other when an adverse event occurs.
- Functional areas, i.e. the areas that house the plant's activities, may span different structural units but remain homogeneous in terms of the processes that are carried out there.

In the methodology the units of analysis are the so-called Functional areas, i.e. subsections of the facility characterized by as uniform as possible functional and operational characteristics. To effectively represent the impact scenarios, a graphical mapping approach has been adopted. This allows the identification of potential impact zones, i.e. the areas that can be affected by the effects of an adverse event. This approach allows to consider at the same time both the buildings and the functional areas.
Indeed, these maps are overlaid on the functional areas of the plant to allow a rapid understanding of the situation. This representation has a dual purpose:

1) It correlates critical areas with personnel presence and evacuation routes,
2) it allows the Company to evaluate which parts of the production process may be disrupted in the event of a critical incident.
For key functional areas, detailed sheets can be developed incorporating descriptive data, potential impact scenarios, identified vulnerabilities (i.e. evidence of critical issues that can generate the impact scenarios) and the specific countermeasures. This data can provide useful indications for Business Impact Analysis or Business Continuity assessments, providing a vision of the behaviour of the physical environment in which the Company's activities are inserted in the event of adverse events.

A comprehensive list of countermeasures has been developed to address the most common deficiencies identified during the analysis. Where multiple solutions are available to resolve a given issue, the different possible approaches are specified.
The list serves as a strategic guideline for overcoming the critical issues but does not constitute a design specification; the latter can only be defined based on the detailed construction characteristics of the building and to the construction constraints related to the production process. These aspects may be the subject of subsequent in-depth analysis.

The methodology follows a multi-level approach, progressively increasing the level of detail of the analysis.
The levels are the following:
- Level 1 – Rapid site inspection and document analysis for the identification of potential impact scenarios and initial mappings.
- Level 2 - Completion of scenario mapping for all identified impacts.
- Level 3 - Specific in-depth analyses for the design of specific interventions.

A scenario method, such as the one adopted, allows for an immediate visualization of the potential consequences of an adverse event on the industrial plant, facilitating risk assessment and decision-making.

2.1. Impact scenario and assignment of criticality levels

At this stage, Impact scenarios are categorized based on the two types of adverse events considered: fire and earthquake. The methodology is designed to be integrated with further types of adverse events, also incorporating existing assessments already performed for other purposes.
In the event of an earthquake, impact scenarios could be the following:
- Global structural collapse, due to lack of resistance in the pillars/columns, lack of mechanical connections or insufficient mechanical connections, compressive and shear failure of walls/partitions.
- Local structural collapse, due to lack of mechanical connections or insufficient mechanical connections, lack of resistance in the beams or absence of structural joints or small-sized technical joints.

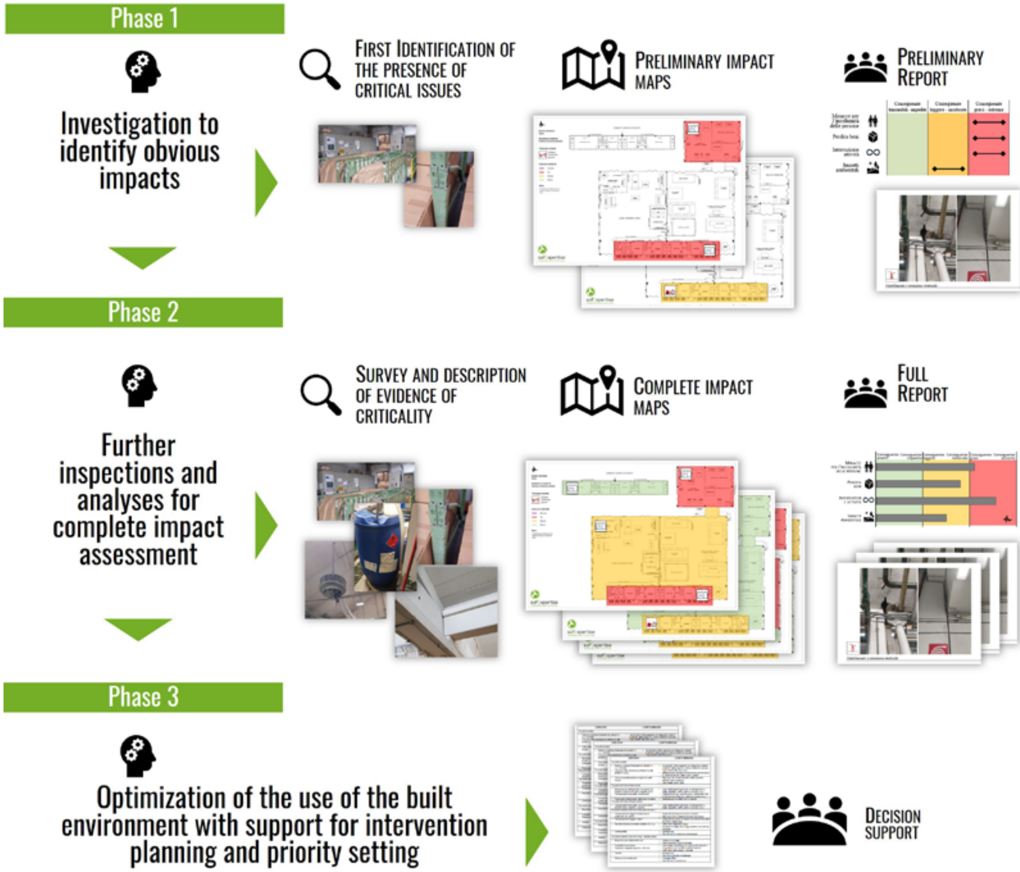


Figure 1. IMPACT a multi-level approach.

- Failure of non-structural elements of a building/architectural type, due to very slender and/or poorly connected internal infills, external infill panels not effectively restrained, detachment of cladding, critical vertical glazing, false ceilings not effectively restrained, light horizontal closures (e.g. sheds) supported and/or poorly connected and critical horizontal glazing.
- Failure of non-structural mechanical/system elements due to heavy machines or equipment with only static/vertical connections, large diameter suspended ducts or pipes, interaction between systems, slender and/or poorly connected shelving, structurally slender mezzanines and/or without anti-seismic countermeasures, heavy materials placed at high levels of shelving/mezzanines, heavy machines or equipment with only static/vertical connections, lack of mechanical connections or insufficient mechanical connections, resistance deficiencies
- Secondary effects caused by unstable equipment, suspended ducts or pipes with insufficient restraints and interactions between systems.

In the event of a fire, the possible impact scenarios could be the following:

- Ignition of a small, isolated fire. The fire remains confined to a single combustible item or near the area of origin because the heat released is not sufficient to spread the fire to other combustibles. Combustibles are separated both horizontally and vertically. The ignition is mainly due to failures of machinery or electrical systems, electrical panels and wiring exposed to damage, electrical system failures.
- Fire development and propagation within a compartment. The fire can be further characterized in more detailed scenarios based on reference [12]: Isolated fire with prevalent vertical propagation or torching effect (Combustibles are separated in the horizontal plane, while in the vertical plane there is a continuous distribution of fuels, so that the flames could propagate in vertical direction); Fire with prevalent horizontal propagation (Continuous fuels arrangement in linear or planar configuration in the horizontal plane, while in the vertical plane, all materials rest on the surface or immediately above the floor or ground); Fire with vertical and horizontal propagation (Continuous fuel arrangement in both the horizontal and vertical plane, constituting a single large fuel package. The fire can propagate both horizontally and vertically and it can reach the full involvement of all the combustibles inside the enclosure); Wall/ceiling fire (Continuous fuel arrangement on walls and/or ceiling and/or floor, e.g. lining materials, insulation). Examples of indicators to consider are inadequate deposits of flammable liquids (e.g. paints, solvents), combustible materials stacked at height, active protection systems not present or not adequate, improper storage in the processing areas.
- Fire spread beyond the compartment due to inadequate compartmentation, excessive or incompatible fire loads, unsealed system penetrations, or insufficient separation distances, active protection systems not present or not adequate.
- Effects of explosions where flammable or unstable solid, liquid and gaseous substances are stored or handled. The effect can be further characterized in more detailed scenarios based on reference [11]
- Failure of structural or non-structural elements due to construction deficiencies, geometric or material vulnerability to fire (e.g. steel structure with tensile elements like chains or tie rods, extremely slender block walls, metal fixings exposed to fire)
- Emergency management challenges due to overcrowding, unaddressed presence of disabled individuals, blocked escape routes, excessively long or complex escape routes, lack of alternative evacuation paths, inadequate or absent smoke and heat ventilation systems, poor fire alarm system and egress signals.

Each impact scenario is assigned a criticality level, categorized into four classes: VERY HIGH – HIGH – MEDIUM – LOW. The assigned level is strictly linked to the response of the built environment to a given scenario.

In the graphical representations and summary documents, a color-coded system is used to visually indicate criticality levels, facilitating quick interpretation of results.

3. Example of identification and mapping of impact scenarios

The IMPACT methodology follows an iterative process, comprising the following steps:

- Site inspections and analysis of site-related documents.
- Identification of building units and functional areas.
- Identification of potential critical issues.
- Evaluation of possible impact scenarios.
- Mapping of the impact scenarios highlighting the associated critical issues.
- Preliminary definition of possible countermeasures.

Following an on-site inspection, the plant is divided into functional areas, i.e. subsections of the facility characterized by uniform functional and operational characteristics; each functional area may be separated from those adjacent by separation elements such as walls and floors or – in the open – barriers or separation distances. Such elements may be permeable to the adverse effects and often difficult to define.

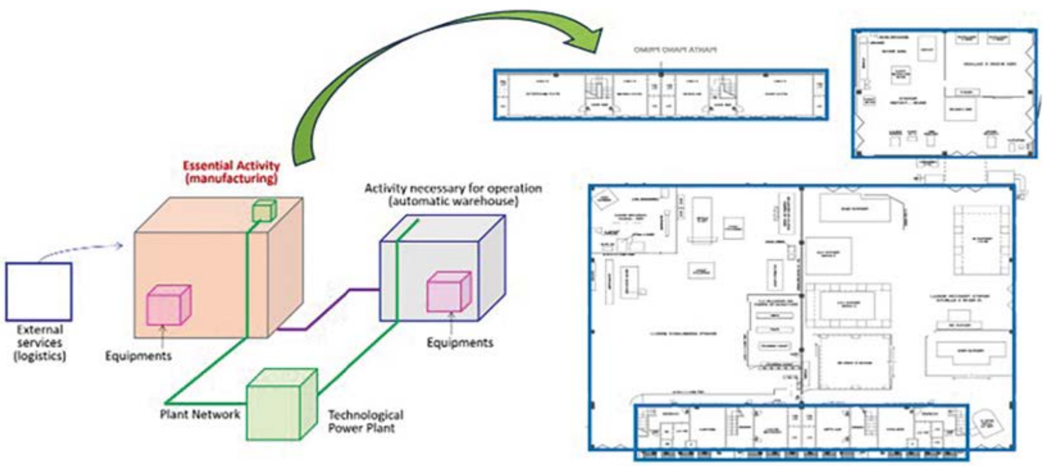


Figure 2. Identification of functional areas of the facility to apply the IMPACT methodology.

The excerpt of the methodology outlined here focuses only on seismic risks. To gain a comprehensive understanding of the risks affecting the plant, the methodology must then be implemented for the other adverse events.

3.1. Adverse event: earthquake

The "level 1" analysis investigate what could happen in the company following a seismic event. What could happen is described through impact scenarios and the analysis process examines: where in the company the scenario could occur; why the scenario could take place; how the identified criticality can be mitigated and what level of investment is required to reduce vulnerabilities (Fig. 2).

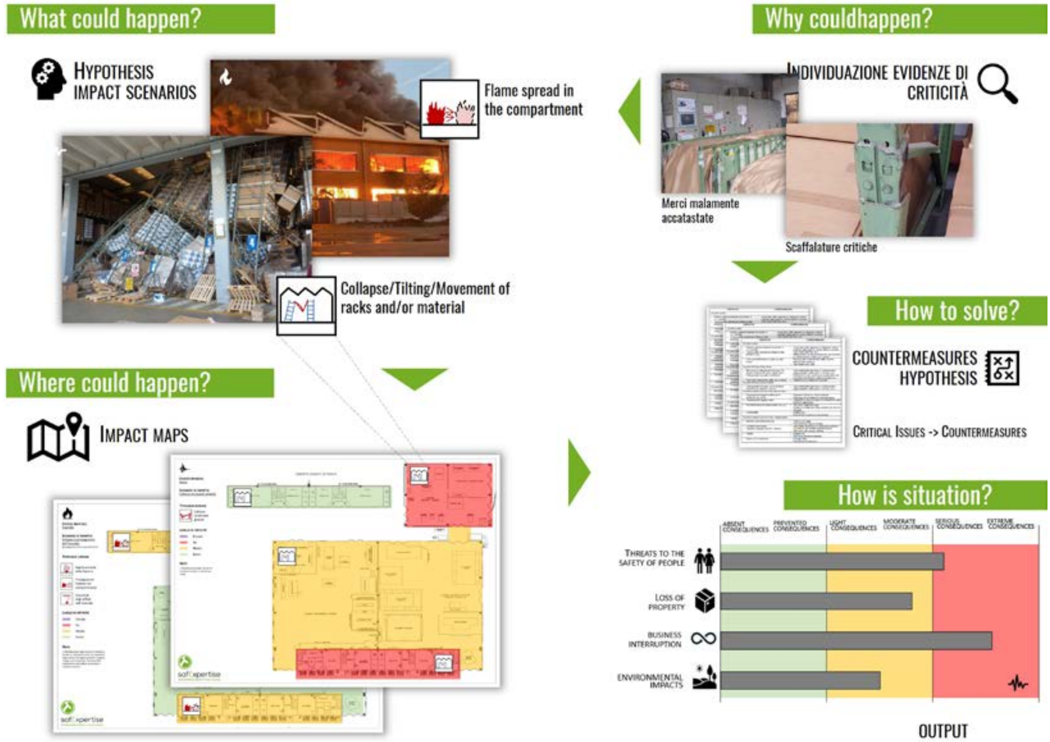


Figure 3. The logical process of IMPACT methodology for the protection of industrial facility and tertiary sector.

We consider as an example the impact scenario identified as "collapse of non-structural elements and mechanical systems". That impact scenario can be categorized into three primary cases:

1. Fall of equipment or system components, primarily involving machinery with only static/vertical connections, large-diameter suspended ducts or pipes with poor seismic restraints, and system interactions.
2. Collapse/overturning of racks or stored materials, due to slender or poorly connected racks, structurally weak mezzanines without seismic protection, and heavy materials positioned at high levels.
3. Collapse/overturning of roof installations or elevated equipment, caused by heavy equipment with only static/vertical connections, insufficient mechanical restraints, or resistance deficiencies.

This impact scenario is assessed across all the functional units of the plant and a mapping is carried out identifying the relative level of criticality for each sector based on the assessed situation.

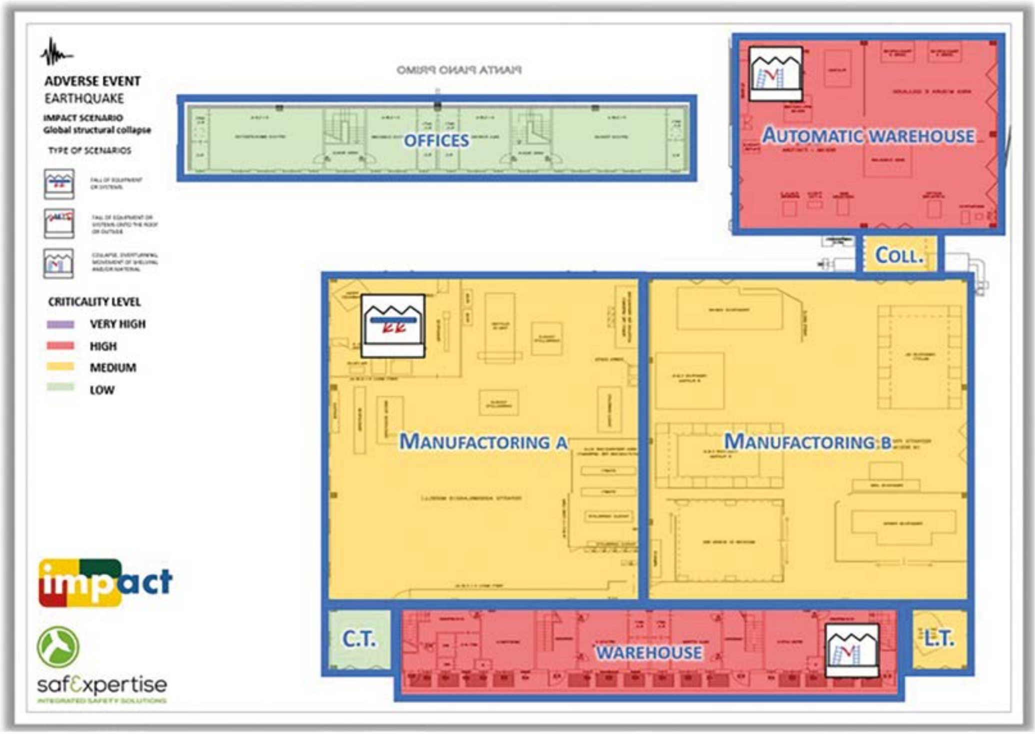


Figure 4. Example of IMPACT map referring to the collapse scenario of non-structural elements of a mechanical or plant type.

4. Conclusions

Impact scenario events occur unexpectedly, posing risks to people, assets, business operations, the environment, and business continuity. However, many companies address these risks primarily as a response to regulatory requirements, often implementing only minimal compliance measures without fully considering the potential consequences of an adverse event on their activities. IMPACT provides a structured approach to risk identification and mitigation. Its key output consists of impact scenario maps (Fig. 3), which visually represent potential adverse events and their effects on different company areas. By overlaying impact scenarios on plant functional areas, these maps enable a rapid and intuitive understanding of the situation, facilitating prioritization of interventions and further analyses, identification of critical areas requiring immediate attention, and development of integrated risk reduction strategies that consider multiple adverse event scenarios. The results of the assessment are presented using an easy-to-understand graphic language, making it an effective communication tool, useful for communicating both within the company (workers, management and technical staff), and with external parties, such as insurance companies. IMPACT mapping makes it possible to quickly identify the critical issues, nonconformities and vulnerabilities present within the plant in order to define a list of priority activities to be carried out with the aim of reducing the risk associated with the issues identified.

Beyond regulatory compliance, IMPACT can serve as a useful tool for a business continuity planning. Indeed, it can help an organization's management to:

- Identify and minimize impact scenarios.
- Maintain essential functions during and after a disruptive event.
- Ensure operational resilience even during a crisis.
- Define minimum acceptable levels of operation for critical business areas.

By integrating IMPACT maps into the risk assessment framework, companies can obtain valuable insights for Business Impact Analysis (BIA) and Business Continuity assessments, strengthening their preparedness and resilience in the face of potential threats.

References

[1] Grimaz, S., & Malisan, P. (2020). Multi-hazard visual inspection for defining safety upgrading strategies of learning facilities at territorial level: VISUS methodology. International Journal of Disaster Risk Reduction, 44. https://doi.org/10.1016/j.ijdrr.2019.101435

[2] Grimaz S. (coord.), Malisan P., Pividori A., Ponticelli L., Ruzzene E., Zorzini F. et al. (2021). "Manuale Triage tecnico. Valutazione e trattamento delle criticità strutturali". Università di Udine e Corpo Nazionale dei Vigili del Fuoco - Ministero dell'Interno.

[3] Grimaz S., Ruzzene E., Zorzini F., Situational assessment of hospital facilities for modernization purposes and resilience improvement. International Journal of Disaster Risk Reduction, 66. https://doi.org/10.1016/j.ijdrr.2021.102594

[4] Franceschinis R., Gattesco N., Zorzini F., "Assessment of the seismic capacity of existing masonry buildings", Building Materials and Building Technology to Preserve the Built Heritage, Vol. 2 Part 1, pages 224-233, WTA Pubblications – Proceedings of the 2ndWTA-International Ph.D. Symposium, Brno 2011.

[5] Gattesco N., Franceschinis R., Zorzini F., "Metodologia per la stima della resistenza sismica degli edifici in muratura", XIV Convegno ANIDIS, Bari 2011.

[6] Gattesco N., Franceschinis R., Zorzini F.,"Stima della vulnerabilità sismica delle strutture in c.a. mediante procedura semplificata", XV Convegno Anidis, Padova 2013.

[7] Gattesco N., Franceschinis R., Zorzini F., "Analytical simplified procedure for the evaluation of the RC buildings", 15th World Conference on Earthquake Engineering, Lisbon 2012.

[8] Grimaz S., Dattilo F., Maiolo A., 2014, Inspect: a new method for fire safety in existing premises, Chemical Engineering Transactions, 36, 61-66.

[9] Grimaz S., Pini A., 1999. Valutazione del rischio incendio e della sicurezza equivalente. EPC Libri, Roma.

[10] Grimaz S., Dusso A., Zorzini F., Tosolini E., 2014. "People's Movement in Narrow Paths with Different Width". Chemical Engineering Transactions. 36:79-84

[11] Dusso A., Grimaz S., Salzano E., 2015. Quick Assessment of Explosion Hazard in Small Premises, Chemical Engineering Transactions, 43.

[12] Dusso A., Grimaz S., Salzano E., 2016. Quick Assessment of Fire Hazard in Chemical and Pharmaceutical Warehouses, Chemical Engineering Transactions, 48.

[13] Dusso A., Grimaz S., Salzano E., 2016. Rapid Estimation of the Heat Release Rate of Combustible Items, Chemical Engineering Transactions, 48.

Industrial Pavements Skid Resistance Evaluations for Workers Safety Check and Improvement

Marco Pasetto[1] and Giovanni Giacomello[1*]
[1] Department of Civil, Environmental and Architectural Engineering, University of Padova, Padova, Italy

* E-mail: giovanni.giacomello@unipd.it

Abstract. Into industrial plants with assembly lines and warehouses, smooth and polished concrete floors are often used to have surfaces suitable for the presence of forklifts and the passage of workers. These floors are often slippery and dangerous for workers, especially in the presence of water. Indeed, in the construction of industrial floors, synthetic products (resins) are often used. However, that are not suitable for the frequent passage of forklifts, especially in the case of wet floors. The authors performed several tests to evaluate the surface roughness of floors in some industrial plants in northern Italy to provide indications for using the most appropriate material for this type of floor. In all cases, the floors were very slippery and not suitable for the transit of forklifts and workers, especially in the case of wet floors. The companies therefore used new synthetic products to improve working conditions in the factories. Through new on-site tests, it was demonstrated that the use of new products ensures excellent resistance to slip/skid, even in the case of wet surfaces. It is necessary to provide suitable specifications for the construction of such pavements, which is currently not mandatory and not even used consistently and by everyone. Moreover, companies need to analyse the risks and dangers for workers carrying out tests on the pavements before their actual use by workers to. New materials can obtain good floor finishes with absence of fast surface wearing and high chemical and mechanical resistance. Furthermore, innovative technologies for surveying/testing of skid resistance could be implemented out improving the safety of industrial floors and reducing the risk of slips and falls for workers.

Keywords: Skid Resistance, Workers Safety, Rigid Pavements, Industrial Floors, Synthetic Resins

1. Introduction

Slips, together with trips and falls, are a common cause of occupational accidents for workers. Slipping and falls accidents are often caused by the decrease of slip resistance of flooring and/or footwear. Those accidents are indicated as “falls on the same level” (they occur on level surfaces with no or little changes in inclination), with respect to “falls from height” (that describes falls from a roof or scaffold).

As in Europe, in Italy over a third of workplace accidents are caused by slips, trips and falls. These are the third leading cause of accidents in all production sectors, with approximately 15% of all accidents for which the causes are known. According to the European Agency for Safety and Health at Work (Eu-Osha) and INAIL, falls on flat surfaces cause the greatest number of accidents in all work sectors, and are the main reason for absences from work, especially in small and medium-sized enterprises. This type of accident can sometimes have serious consequences, with absences from work lasting 38 days, an average duration second only to falls from heights and entanglement accidents [1, 2].
Over 90 per cent of major injuries from slipping accidents involve broken bones, and much pain, suffering and financial loss for society [3].
The risk of "fall on the same level" due to slipping and the prevention of this type of accident is regulated by Italian Legislative Decree 81/2008 [4] and by the Decree of the Minister of Public Works 236/1989 [5]. These regulations establish the minimum safety requirements for floors (as well as for stairs and ramps) and the criteria for risk assessment, which the employer is obliged to observe to identify appropriate improvement measures.
Among the indications provided, these standards specify that floors must be fixed, stable and not-slipping. Some of the main precautions are the constant cleaning, good maintenance state and inspection/checking activities on floors/pavements.
Many types of floors/pavements are available in the literature to pave the working areas, such as thin hot-mix asphalt overlay, open graded friction course, and ultra-thin bonded wearing course. Also, many processes/treatments are used to improve walkability/ride quality and/or the slip/skid resistance, i.e. diamond grinding, grooving, micro-milling, shotblasting/abrading, chip seal, slurry seal, microsurfacing, cape seal, scrub seal, and high friction surfacing. Generally, many industrial and public structures are paved with concrete or high friction surfacing. In the first case, after the curing of the concrete (with a specific mix-design), the surface is treated with some specific products, and it is polished. In the second case, high friction surfacing is constituted by a resin binder (epoxy, methacrylate, polyester, etc.) spreading over the pavement surface (typically concrete) followed by broadcasting or dropping a 1- to 3-mm abrasion and polish-resistant aggregate onto the resin (bauxite, quartz or silica sand). In many cases the synthetic resin and the aggregates were mixed together and laid on the concrete support, creating a more tenacious layer [6, 7, 8, 9].
Skid resistance is one of the most important characteristics of the floors/pavements. Skid resistance, together with bearing capacity, surface regularity, surface drainage, structural integrity, is one of the main important functional/structural characteristics of the pavements.
The aim of this paper is to provide an example of constant and continuous inspection activity over time to evaluate the condition of pavements of some industrial plants in Northern Italy. The authors have evaluated the condition of pavements made of different materials and in different conditions of use over several years. The work has highlighted the need to define a specification and to standardize the main requirements of certain types of materials used for the construction and renovation of industrial pavements.
The constant inspection and check of working pavements is the best action to safeguard the life and safety of workers during their activities.

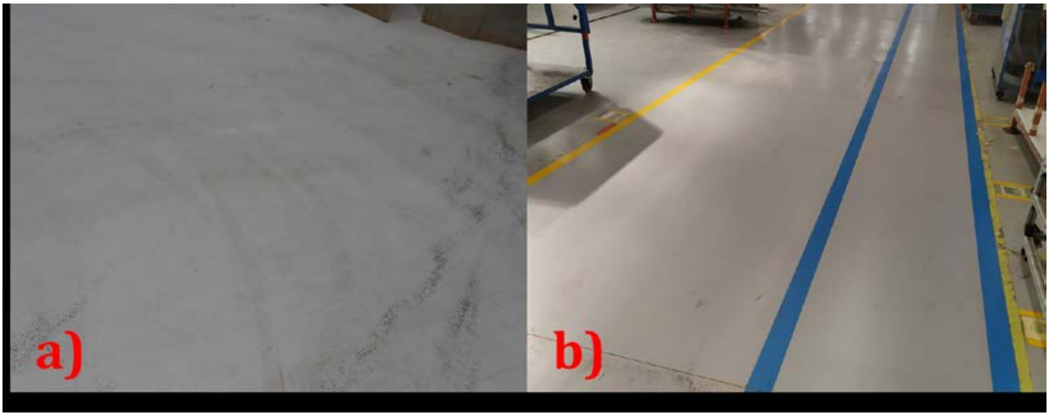


Figure 1. Industrial pavements: a) concrete smooth and polished and b) epoxy resin (mixed with aggregates) surfaces.

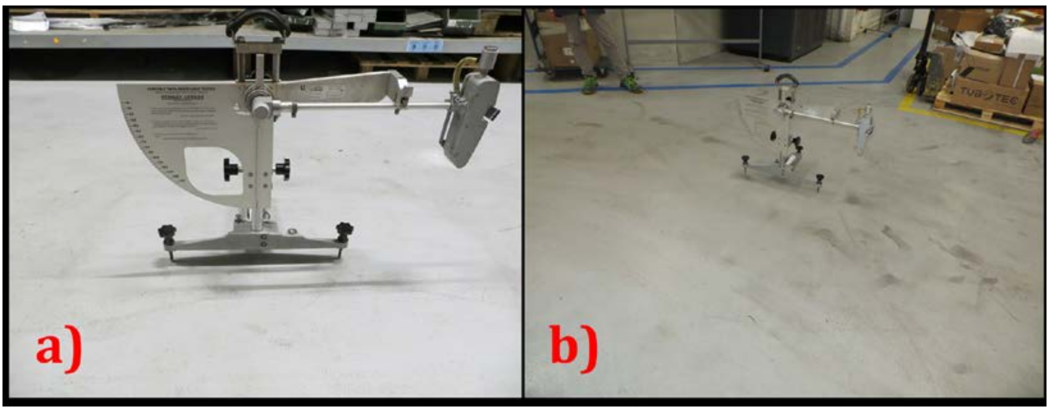


Figure 2. Skid tester: a) during the rest position and b) during a test on an industrial pavement.

2. Materials and methods

2.1. Materials

In this work the authors faced with traditional industrial pavement surfaces, built in polished concrete or in a layer of mix of synthetic resin and quartz aggregates. These ones have long-lasting properties, and toughness (for a better mechanical resistance). This layer has a final thickness between 3 to 5 mm.
In particular, the industrial plants in Northern Italy are built with most parts of the floors covered with mixes of aggregates and epoxy resins and with several areas paved with concrete (Figure 1a and Figure 1b). The authors tested both types of pavements.
Industrial plants are constituted by several assembly lines and some supply warehouses. Most workers are in the assembly lines, and some are in the supply warehouses, transporting the components for assembly lines from delivery trucks/vans to the supply warehouses.

When needed, the workers carry out these components from supply warehouse to assembly lines. So, the forklifts stress more the pavements on supply warehouses, than the ones used on the assembly lines. Moreover, the forklifts stress more the surfaces of the pavement on the point where curves and rotation need to be performed (Figure 2b – tire marks are clearly illustrated).
Normally concrete is laid where the solicitations can be high (intensive passages of forklifts and other heavy machines). Synthetic resin is laid where be the passage of workers only or also where are some passages of forklifts combined to the walkable areas of workers.

2.2. Methods

There are several methods to measure the slip/skid resistance of the industrial floors/pavements. The tests are subdivided mainly into fixed and portable testers. In the first case are enclosed the side force test, the locked wheel test, the fixed slip test and the variable slip test. Contactless (image based and laser-based testes) and with contact tests (British Pendulum Test, Dynamic Friction Test, Sand Patch Test and Outflow Test) are the second ones [10]. The authors used a skid tester, analysing the skid resistance to evaluate the safety of the workers in their activities and to inspect the state of the pavements, as many researchers already done [11, 12]. This was done because the skid tester can more easily to conduct, and the results can be more clearly connected with the passages of the forklift.
The instrument (Figure 2a), also known as “Skid Tester” or “British Pendulum”, measure the slip/skid resistance of a floor/pavement using the “Pendulum Test Value” (PTV) or the “British Pendulum Number” (BPN) index. Test, instrument, operating methods and calculation of the indexes are defined by the European standard EN 13036-4 [13]. The method is primary used to test the surface characterization (i.e. the resistance to sip/skid) of road and airport pavements. However, in this case it is used to test an industrial pavement. The method can be applied in the field or in the laboratory, and the procedure for carrying out a test is simple, cheap, easy and fast.
The Pendulum Tester incorporates a spring-loaded slider made of a standard rubber mounted to the end of a pendulum arm. Upon releasing the pendulum arm from a horizontal position, the loss of energy as the slider assembly (a rubber pad and an aluminum backing) passes over the test surface is measured by the reduction in length of the upswing using a calibrated scale [14].
Once positioned on the surface (Figure 2b), the instrument needs to be calibrated, the height is adjusted until the pendulum slider touches the pavement within a certain length using the gauge. The surface is wet by creating a film of water on the pavement because it is in poor grip conditions (wet pavement) that the worst skid resistance can be offered by the pavement. The pendulum is released, and a rod indicates the value on a graduated scale. This value is the “Pendulum Test Value” (PTV).
The pad is 76.2 mm length, 25.4 mm width and 6.35 mm height. Since the pad is made of rubber, the temperature of the pavement/air influences the value of the “PTV” index. So, the temperature of the pavement, rubber pad, air and water need to be measured. To have a value of skid resistance on a specific point on the surface, at least 5 measurements must

be performed. The value of the "PTV" index is the average of these five values. The value of the "PTV" index must be reduced to the nearest integer. Furthermore, the calculated value must be "corrected" as indicated in the standard (EN 13036-4 [13]), to consider that the rubber pad can vary its consistency as the temperature varies and can influence the measurement of the "PTV" index.
The swipes of the "Skid Tester" were carried out parallel to the direction of travel of the forklifts passing through the industrial plant (as indicated in the standard). The temperature of the pavement surface and the temperature of the rubber pad need to be found within the range of 5°C – 40°C, as indicated in the reference standard. Furthermore, the temperature of the water used to wet the tested surface did not differ by less than 15°C from that of the air during the tests.

3. Results

The authors performed the tests on three industrial plants in the North of Italy and in three different year (2015, 2020 and 2022). For each year the authors tested 16 points on the pavements of each industrial plants: 8 points for the passages of the forklifts (4 points for the pavements formed by epoxy resin and quartz aggregates, and 4 points for the polished concrete pavements) and 8 points for the areas dedicated to the passages of the workers only (4 points for the pavements formed by epoxy resin and quartz aggregates, and 4 points for the polished concrete pavements).
All the tests are performed also in dry cases to evaluate the state of the pavement surfaces simulating the "good conditions" (without water) of the pavement itself.

	Pavement types							
	1) Synthetic resin[a]		2) Concrete smooth surface[a]		1) Synthetic resin[b]		2) Concrete smooth surface[b]	
Years	dry	wet	dry	wet	dry	wet	dry	wet
2015	78	25	90	40	91	34	83	60
2020	69	22	85	38	82	19	82	57
2022[c]	104	41	84	37	100	36	82	58

[a] Forklifts and workers presence.
[b] Only workers presence.
[c] After new laying of the synthetic resin on pavement n. 1.

Table 1. Results of the tests performed on the several pavements and during the three years of pavement inspections (mean values of PTV value corrected).

Testing each point in dry and wet cases, the total number of the tests will be 32 per one industrial plant and per one year.
Before the tests performed in 2020 the employer decided to renew the pavement on synthetic resin, to improve the values of the skid resistance of the pavements.
The results of the tests were grouped for the several pavement types and for the different years as shown in Table 1 (mean values of PTV value corrected).
The authors took note about the temperature of the pavement, rubber pad, air and water. Moreover, at least 5 measurements were performed on all the specific point on the surfaces. The authors calculated the value of the "PTV" index, averaging the five values for each point. The calculated values were "corrected", as indicated in the standard, to consider the variation of the rubber pad consistency as with the variation of temperatures. The values illustrated in Table 1 are already corrected.
The authors carried out the swipes of the "Skid Tester" parallel to the direction of travel of the forklifts only if these passed through the tested point. The temperature of the pavement surface and the temperature of the rubber pad were within the range of 5°C – 40°C, and the temperature of the water used to wet the surfaces did not differ by less than 15°C from that of the air during the tests.

4. Discussion

After the first five years (from 2015 to 2020), all the pavements were subject to wear of the surface, decreasing the values of the skid resistance. Only the surfaces less solicited (with the passages of workers only) had a less decrease in the skid resistance. The forklift weights accelerated the wear of the surfaces, with respect the ones subjected only to workers passages. After the new laying of the synthetic resin at the end of 2021, the tests conducted in 2022 indicated that a renewal of the surface treatment can restore satisfactorily the skid resistance of the pavements.
Typically, skid resistance depends on micro-texture and macro-texture of the pavement surface. Micro-texture refers to the small-scale texture of the pavement aggregate component (which controls contact between the tire/shoes footwear rubber and the pavement surface) while macro-texture refers to the large-scale texture of the pavement due to the aggregate particle arrangement (which controls the escape of water from under the tire and hence the loss of skid resistance with increased speed). Skid resistance changes over time. Typically, it increases in the first two years following construction as the pavement is worn away by passages of tires and rough aggregate surfaces become exposed, then decreases over the remaining pavement life as aggregates become more polished [15].
These statements are valid also for industrial pavement surfaces: the renewal of the pavements surface restore the micro- and macro-textures, giving an extension of the life of the pavements.
Furthermore, some problems, like the forklifts exit/enter from/to the plants during the rainy days, can be easily solved. In many cases, with a wear surfaces the movements of the forklift, especially in presence of water, become more unexpected and a serious problem for the workers.

On the other hand, the pavement in smooth and polished concrete better last in terms of skid resistance, both for forklifts and workers. Comparing the evolution of the skid resistance of the concrete with the one of the synthetic resins, the concrete preserves their characteristics of skid resistance, suggesting that the materials keep for more time the micro- and macro- textures. However, the surfaces with new synthetic resin have the highest values and higher than the concrete, probably for the presence of new aggregates into the mixtures.
The tests performed on wet conditions demonstrated that many surfaces with the time change gradually to situation not consistent with the safety of the workers. Wet conditions are the worst one: the pavement surface in these cases reach values very low, and, in some cases, these are not acceptable for workers. For example, the synthetic resin in 2020 shows values around 22 – 19. These values indicate a slipping surface. Concrete surfaces keep a minimum value of skid resistance during the time. The surfaces treated with the synthetic resin once renewed can come back to the top skid characteristics.
During the last set of tests on an industrial plant a wrong type of synthetic mix (epoxy resin and aggregates) was not validated because the skid characteristics resulted to be fall down with respect the ones verified in the others two industrial plants. After this, this industrial plant removed the synthetic resin and use another product better than the first one.
These means that it is important to define a technical specification for these works, indicating the minimum requirements and the check/inspections activities and the products quantities. More important is the definition of the minimum requirements for the safe and less risky work environment.

5. Conclusions

Starting from three cases studies in Veneto Region, the authors inspected, checked and evaluated the slip/skid resistance about industrial pavements for safety workers purposes. All the pavements (in concrete and in synthetic resin) were analysed for seven years (from 2015 to 2022). The results highlighted that the concrete has a better predisposition to withstand under severe conditions (forklifts passages), with respect to the synthetic pavement. This type of surface treatment is more prone to the wear and tear of the vehicle's passages, reducing during the time its skid resistance.
Tests in wet conditions demonstrated that all the surfaces experienced less skid resistance, reaching the worst condition after five years from the first laying. Tests in dry conditions demonstrated that all pavement surfaces exhibit satisfactory skid resistance, favoring the safety of the workers.
The authors highlight that it is necessary to define a technical specification about the pavements for industrial plants, indicating the key requirements for the materials to be used. It could be better to distinguish from critical and not critical zones, to define more quickly the type of pavement during the design and/or the renewal of the pavement. Moreover, it is suitable to fix some limitation about the performance of the materials, such as a value equal to 20 for the skid resistance for the industrial pavement: a value less than 20 is not acceptable for safety and health of workers (not only for person, but also for the person working with or near the vehicles, like the forklift).

Beyond the functional/structural characteristics of the pavements, also costs need to be considered. The cost of synthetic resins can be higher than that the concrete. However, the thickness of the synthetic resins is very small, than the costs could be limited. In this study the authors demonstrated that after seven year was necessary a renewal of the synthetic pavements, indicating that this material can withstand for many years prior to fall down into the main characteristics. It is important also to remind that the costs to keep safe the workers are necessary, and it cannot be reduced.

The authors highlight the need to define technical specifications and standards for the main requirements of the use of certain types of materials into the construction and renovation of industrial pavements. In this regard, new materials could help to reduce the risk and preserve the health of the workers. These new materials are new synthetic (polyurethanic and epoxy) resins, with better characteristics of adherence and resistance to wear-and-tear. In more cases, these resins are more sustainable because reduce environmental impact (last epoxy resin type is plant-base) for their low emission of volatile organic compounds. These new materials, more than the already existing ones, need to be focused and contextualized to define technical specifications and minimum requirements.

Concluding, the employer needs to keep the maximum standard for the safety of the workers, especially for the accidents indicated as "falls on the same level", that cause in Italy over a third of workplace accidents. So, more frequent operations on the renewal of the pavement treatments means a more attention to the safety of the workers, and it is an investment on the healthy status of the plant. Moreover, future developments and innovation could play an important role in improving the safety of industrial floors and reducing the risk of slips and falls for workers.

Indeed, technological innovation is changing the industrial flooring industry, especially inspection and maintenance processes. Future developments, such as, use of drones and 3D scanners to measure and monitor surfaces, or cameras and recognition systems using artificial intelligence to detect low skid resistance values, will help to analyse floor conditions in real-time and alert about risky areas. Additionally, radiant heating systems integrated into floors are becoming increasingly common, improving comfort for workers and reducing energy costs (saving moneys). Adopting these emerging and innovative solution, i.e incorporating monitoring sensors, will conduct to define the "smart floors". These technologies coud offer significant advantages in terms of predictive maintenance (more accurate and efficient management of industrial plants) and a positive impact on workers' safety and health. This will involve developing guidelines and technical specifications for the implementation of such systems in companies, in design, construction and maintenance, activities.

References

[1] EU-OSHA – European Agency for Safety and Health at Work. (2022). "Slips, trips and falls". Available: https://oshwiki.osha.europa.eu/en/themes/slips-trips-and-falls#_edn1.

[2] E. Attaianese, G. Duca, G. De Margheriti, P. De Joanna, *Valutare il rischio di caduta in piano*, Edizioni Edicampus, Roma, 2015 (in Italian).

[3] J. Carpenter, D. Lazarus, C. Perkins, "Safer surfaces to walk on – reducing the risk of slipping". CIRIA, 2005.

[4] Decreto legislativo 9 aprile 2008, n. 81, "Attuazione dell'articolo 1 della legge 3 agosto 2007, n. 123, in materia di tutela della salute e della sicurezza nei luoghi di lavoro". Available: https://www.normattiva.it/uri-res/N2Ls?urn:nir:stato:decreto.legislativo:2008;81~art306. (in Italian).

[5] Decreto Ministeriale 14 giugno 1989, n. 236, "Prescrizioni tecniche necessarie a garantire l'accessibilità, l'adattabilità e la visitabilità degli edifici privati e di edilizia residenziale pubblica sovvenzionata e agevolata, ai fini del superamento e dell'eliminazione delle barriere architettoniche." Available: https://www.normattiva.it/uri-res/N2Ls?urn:nir:ministero.lavori.pubblici:decreto.ministeriale:1989-06-14;236~art8!vig=. (in Italian).

[6] M. Pasetto, G. Giacomello (2014), "Experimental analysis of waterproofing polymeric pavements for concrete bridge decks", *The International Journal of Pavement Engineering and Asphalt Technology*, Vol. 15, Issue 1, pp. 51-67.

[7] D. K. Merritt, C. A. Lyon, B. N. Persaud, Evaluation of Pavement Safety Performance, Report FHWA-HRT-14-065, U.S. Department of Transportation, Federal Highway Administration, Washington, USA, 2015.

[8] M. Pasetto, A. Baliello, G. Giacomello, E. Pasquini, "Ultra-thin whitetopping for asphalt pavement rehabilitation: the influence of the interlayer in the properties of the double-layered system", in *Proc. of the 11th International Conference on the Bearing Capacity of Roads, Railways and Airfields*. Trondheim, Norway, 2022.

[9] G. Giacomello, A. Baliello, E. Pasquini, M. Pasetto, "Thermal and bonding behavior of synthetic thin pavements for concrete bridge decks", in *Proc. of the 1st Conference of the European Association on Quality Control of Bridges and Structures*, Padova, Italy, 2021, pp. 1359-1367.

[10] B. Mataei, H. Zakeri, M. Zahedi, and F. Nejad, "Pavement Friction and Skid Resistance Measurement Methods: A Literature Review". *Open Journal of Civil Engineering*, vol. 6, 537-565, 2016.

[11] K. J. Waluś, Ł. Warguła, B. Wieczorek, P. Krawiec, "Slip risk analysis on the surface of floors in public utility buildings", *Journal of Building Engineering*, vol. 54, 2022.

[12] A. Kumar, T. Tang, A. Gupta, K. Anupam, "A state-of-the-art review of measurement and modelling of skid resistance: The perspective of developing nation", *Case Studies in Construction Materials*, vol. 18, 2023.

[13] Road and airfield surface characteristics – Test methods – Part 4: Method for measurement of slip/skid resistance of a surface: The pendulum test, EN 13036-4, 2011.

[14] Highway Research Board, National Academy of Sciences, National Cooperative Highway Research Program Synthesis of Highway Practice 14: Skid Resistance, Washington, D.C., 1972.

[15] T.F. Fwa, Determination and prediction of pavement skid resistance–connecting research and practice, *Journal of Road Engineering*, vol. 1, pp. 43-62, 2021.

Artificial Intelligence in Machine Safety Functions

Batoul Kalout[1*] and Dainese Diego[1*]
[1] Department of Management and Engineering, University of Padua, Italy
* These authors have contributed equally to the study and are co-authors

E-mail: batoul.kalout@studenti.unipd.it, dainese.diego@unipd.it

Abstract. According to recent statistics held by the ILO (International Labor Organization), nearly 3 million workers die every year due to work-related accidents and diseases [1]. This number calls for taking immediate action to enhance workplace safety and conditions. In recent years, artificial intelligence has expanded its scope to encompass numerous sectors, ranging from web search engines to automated vehicles. However, like all technologies developed by humans, it is prone to errors, necessitating the adoption of a standard to guide the development of AI software within safety functions to govern such integration. This paper will analyze the points discussed in the ISO/IEC 5469:2024 standard: Functional Safety and AI Systems, addressing the risks associated with AI systems and how to mitigate them to ensure an adequate level of safety that enables their implementation in machine safety functions. Furthermore, it will examine the verification and validation phase of these systems, guiding developers on how to achieve safe and reliable systems.

Keywords: AI, Industrial Safety, Safety Functions, ISO/IEC 5649:2024

1. Introduction

According to the definition provided by the European Parliament [2], artificial intelligence (AI) is the form of intelligence that a machine or system can possess, allowing it to make decisions to achieve specific objectives. Unlike traditional software-based systems, which operate exclusively under predefined conditions, systems based on AI can deal with situations outside the set of conditions for which they were designed or programmed.

This particular nature of AI has contributed to growing interest in it in recent years, as it has become nearly impossible to discuss contemporary technological advancements without referencing this innovative domain. For instance, it is uncommon to visit a website without encountering a chatbot designed to assist with tasks and inquiries. Furthermore, the applications of AI have expanded across various fields, achieving advancements such that autonomous vehicles, once relegated to the realm of science fiction, are now accessible to society at large.

In the context of industrial safety, AI has been instrumental in significantly enhancing this area. A pertinent example of this integration is predictive analysis, which relies on the capacity to forecast future trends by examining data derived from past observations and incidents. This methodology facilitates the implementation of preventive measures, thereby aiding in the reduction of potential adverse outcomes. Specifically, when a predictive system gathers information regarding prior workplace accidents, it can analyze these events to determine "how" and "why" they transpired. This enables more sophisticated and effective risk management strategies.

For example, "General Motors" has adopted an advanced AI program that facilitates the real-time analysis of data from vehicles, to anticipate potential dangers before they occur; statistics indicate that, in the space of a year, accidents in the workplace have decreased by about 25% [3]. Further applications of AI in safety functions include predictive maintenance and automated inspection, which allow the detection of signs of damage, oil leaks, electrical hazards, or other types of malfunctions. This approach offers maintenance professionals the opportunity to promptly address issues before they become apparent.

However, it is important to note that AI systems are not yet completely reliable; in fact, there have been incidents where this highly sophisticated technology has failed, sometimes with fatal outcomes. In 2018, a self-driving vehicle developed by Uber hit and killed a pedestrian in Arizona [4]. This event raised questions about the transparency of Uber's self-driving technology and the ability of the car to adequately perceive its surroundings.

In light of the above, AI appears to be a promising resource in the field of safety. In fact, in the new EU Machinery Regulation 2023/1230, which will come into action in 2027, it has been added in Annex I, among the components for which one of the conformity assessment procedures must be applied, the safety components that adopt a partially or completely self-evolving nature and that guaranteed safety functions. Regarding this point, it is necessary to have a standardized guideline to verify and validate the system's compliance with safety requirements.

All this underlines the urgency of establishing a regulation that allows evaluation of the integration of this technology into machines' safety functions. In this regard, the ISO/IEC 5469 [5] standard has been adopted, which will constitute our point of discussion in this paper.

The following paper will discuss the applicability of AI in safety functions, risk factors associated with AI and relative solutions, the verification and validation phase, and final suggestions.

2. Classifications of AI Systems

According to the IEC 61508-4-2010: Functional safety of electrical/electronic/programmable electronic safety-related systems [6] a safety function is a function to be implemented by an E/E/PE safety-related system or other risk reduction measures, that is intended to achieve or maintain a safe state for the EUC, in respect of a specific hazardous event. Based on this definition, it is essential to ensure that these functions are reliable and safe. Here comes the role of functional safety which is a discipline that focuses on verifying the proper design of systems that perform safety functions; thus, stating the safety requirements for such systems. Achieving an acceptable level of functional safety depends on different factors such as the functionality of the system, how it contributes to the overall safety of the system, and what risks can be introduced.

This goes the same for AI-based safety functions, but noting their particular nature, the ISO/IEC 5469 standard stabilized classification criteria to ensure the safe integration of such systems in safety functions. For this purpose, the standard has proposed 6 usage levels of the application based on which the applicability of AI in the safety function is accepted or not. Figure 1 shows a mapping of this classification.

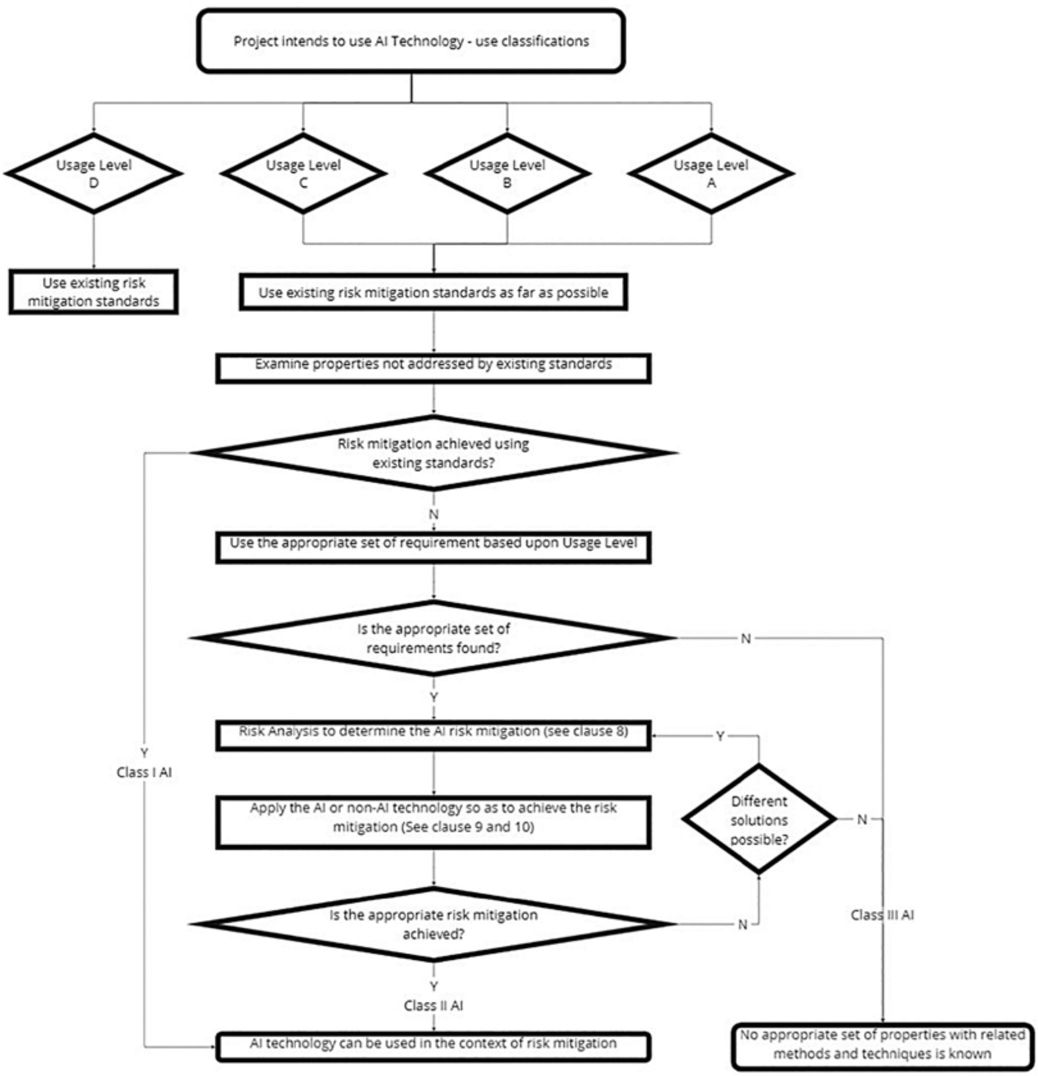


Figure 1. Classification of AI systems.

As seen in the figure we can differentiate between 4 usage levels A, B, C, and D where both levels A and B are split into two sublevels A1, A2, and B1, B2.

A1 / A2: AI is integrated into the safety function, where a usage level of A1 refers to the capability of the system to make decisions autonomously whereas this capability is not present in systems with an A2 usage level. A simple example of this is the "Hazard detector" which is a monitoring system based on machine learning algorithms that analyze the changes in ambient circumstances such as temperature fluctuations or the presence of toxic gases… etc. [7]

B1 / B2: Refers to the case where AI is used at the level of production of the system and thus not a part of the safety function, whereas a B1 usage level refers to the case where the AI system can autonomously take decisions but this is not the case for B2 levels. One example of such a system is a validating system in which AI is integrated. [7]

C: When AI is not integrated into the safety function it can implicitly affect the output of the system. A pertinent example is the integration of AI-based systems to optimize energy consumption; in instances where such systems are utilized in machinery dedicated to chemical processes characterized by high energy consumption during peak hours, an aggressive reduction in energy demand could significantly impact the cooling system, thus affecting the safety function. [7]

D: this level refers to the case where AI doesn't affect or implicitly the decision made by the safety function, such as 3D printers. [7]

In light of this classification of usage levels, the standard delineates three categories of AI systems:

- Class I: This category encompasses systems that can attain a safe state solely by adhering to the measures prescribed by existing safety standards. Systems classified within this category may be integrated into safety functions without any restrictions.
- Class II: This designation applies to systems for which an acceptable safety level cannot be achieved using only the methods currently available. However, upon reaching a desirable safe state through these available methods and solutions, such systems may subsequently be incorporated into safety functions.
- Class III: This classification pertains to systems for which it is impossible to achieve a safe state utilizing any existing solutions. Consequently, these systems are prohibited from being integrated into safety functions.

This classification urges us to discuss thoroughly in the next paragraph the risks associated with these technologies and the different solutions that have been invented to handle them and take advantage of the power of AI.

3. Risks of AI technologies and Mitigation measures

Initially, it is imperative to emphasize that the most pivotal component, which plays an indispensable role in the establishment of a reliable and secure system, is the underlying model and algorithms. Indeed, the efficacy and safety of a well-functioning system predominantly hinges on its ability to accurately produce the intended outputs irrespective of the input provided. This aspect is elaborated upon within the context of this AI technology element, which is designated as the most critical factor regarding safety and functionality according to ISO/IEC 5469 standards [5]These models are essentially mathematical equations that depend on parameters on which the system bases its function. Those parameters have to satisfy a set of requirements that are defined by the IEC 61508; these are:

- Completeness and Correctness with respect to safety requists
- Absence of ambiguity and intrinsic errors
- Safe interaction between normal functions and those related to safety.

3.1. Completeness And Correctness

Regarding the first point, failing to achieve the completeness and correctness of the model risks the system facing many problems among which:

- Bias
- Overfitting
- Failure to achieve robustness
- Vulnerability to adversarial attacks

To discuss thoroughly these points, as a case study a "safe-position monitor" will be considered as an example of reference.

3.1.1. Bias

A model or system is "biased" when there are groups within the input dataset that are overrepresented relative to others [8,9]. This bias results in a model that may perform effectively under common and frequently encountered conditions but exhibits erroneous and unstable behavior in novel situations or those previously marginalized during the training phase. It is important to consider that the system under study (safe position monitor) has been trained in work environments with low worker density or where there is minimal interaction with mobile objects. If such a system were employed in a collaborative industrial robot within a storage facility, it could lead to numerous issues and pose risks to both personnel and other machinery present at the workplace, as it would not adequately analyze surrounding conditions, thereby leading to incorrect decisions. Consequently, the data must possess sufficient diversity to represent real-world states as accurately as possible. An effective strategy also involves implementing metrics for quantifying data bias within the dataset.

3.1.2. Overfitting

Overfitting represents a significant issue that must be avoided. It refers to the ability of a model to provide accurate and correct predictions only for a dataset similar to that used during the training phase; conversely, when the model is confronted with a new dataset, it fails to operate adequately, resulting in erroneous and inaccurate decisions [10]. The primary cause of this phenomenon is the use of an excessively limited dataset during training, which does not encompass all possible variables that the system might encounter [10]. For instance, a positioning monitoring system designed to operate within a specific speed range may fail if this range is exceeded, thereby creating an unsafe condition in the work environment. The system could then access hazardous areas based on surrounding environmental conditions. In addition to the importance of using representative data that broadly covers all anticipated scenarios, there exists a methodology known as "cross-validation"[11]. This technique involves dividing the available dataset into subsets or folds, where one of the folds is used as a validation set while the others are employed in the training phase. This procedure is repeated to allow for validation of the system across all available folds; subsequently, the results from each validation phase are analyzed to ultimately achieve a system capable of generating outputs as accurately as possible across a wide array of data.

3.1.3. Lack of robustness

A concept of significant importance is robustness. A system is defined as robust when it possesses the capacity to operate safely under any conditions, specifically in the presence of variations in environmental circumstances, even if such conditions were not anticipated during the training phase [12]. Furthermore, the system demonstrates a degree of tolerance toward failures in the sensory system or contradictory inputs and external disturbances. It is evident, therefore, that this concept or property is essential in AI systems when implemented in safety functions. The robustness of the system significantly depends on model design. A crucial aspect pertains to the data used for training: these must be of high quality and sufficient to avoid overfitting; they should be collected in a manner that allows the system some form of generalization concerning situations that will arise in the real world. Regularization represents another pertinent technique related to this concept, as it involves generalizing the model through a reduction in its complexity; the primary objective of this strategy is to enable the model to learn rather than merely memorize it [13]. This can be achieved through techniques that reduce the weight of certain parameters or neurons (in the case of neural network algorithms) within the model, with the intent of making the algorithms less dependent on such components for output generation. While we will not delve into detail regarding this technique, several methods are listed below:

- L2 and L1 regularization
- Dropout
- Early stopping
- Dataset augmentation

Another methodology, however, is not related to the model itself and involves implementing a degree of redundancy in detection systems and hardware, which is fundamental for proper system functioning. This is particularly essential in critical safety systems.

3.1.4. Vulnerability to adversarial attacks

Furthermore, understanding the security requirements of software systems constitutes an essential aspect that must be addressed by an AI model integrated into a security function. A critical requirement pertains to the system's immunity to adversarial attacks, which are executed by cyber criminals with the intent to manipulate and alter the functioning of the AI model. One method for safeguarding the system against such attacks involves training the model using contradictory inputs, allowing it to become familiar with this type of data and thus accurately classify information during operational phases; this technique is known as "adversarial training"[14]. Another approach outlined in the regulation under review pertains to extracting disturbances that have been artificially introduced into the system, such as through High-Level Representation Denoisers; this essentially relies on implementing a system that eliminates and enhances performance concerning inputs containing disturbances that could lead to confusion at the interpretative level for the model [5, 15]. This method has been classified as superior among other techniques due to its applicability to both white-box and black-box systems, with examples including MagNet and Defense-GAN [14, 15]. Randomization of data represents an additional approach that can be implemented to mitigate the impact of such disturbances and enhance the system's resilience against malicious attacks. This method involves introducing random perturbations to the input, thereby reducing the likelihood that an attack will easily manipulate the model. A crucial point to emphasize is that the non-linearity of the model serves to bolster the system's immunity against these attacks. A prudent course of action to ascertain whether our system is sufficiently robust against such threats is to address two fundamental questions [16]:

- How can we define an adversarial example that effectively manipulates the model while causing minimal disturbance?
- How can we train the model in a manner that minimizes the probability of it being compromised by an attack?

By addressing these two questions, engineers are encouraged, at a design level, to consider methods for maximizing the system's immunity against such attacks.

3.2. Absence of ambiguity

Moving on, one of the most crucial requirements is the absence of ambiguity and intrinsic errors. Ambiguity, in this context, refers to the condition in which the system begins to make unstable and uncertain predictions and decisions. This can arise from ambiguities in the data collected during the training phase; when the data contains unclear or contradictory information, such as when a security position monitoring system is fed data that does not account for obstacle dimensions in its determinations, it can generate confusion for the system during its analysis of the current situation. Therefore, the first aspect to ensure is the constant availability of a dataset characterized by high quality and clarity. Another source of ambiguity within a system may stem from model ambiguity itself, namely when the model is too complex to be easily interpreted or, conversely when it is too simplistic to adequately address relatively challenging situations. Indeed, a highly complex model may become susceptible to even minor errors, while an excessively simple system might fail to perform appropriately at the level of its predictions [17]. Therefore, it is essential to appropriately adjust the model in relation to its complexity. Regarding overfitting, we have already discussed relevant techniques. Furthermore, ambiguity also manifests through a certain degree of uncertainty in the predictions and decisions made by the model. For instance, a model applied to a system may generate forecasts about the location of a vehicle with some uncertainty regarding its safety. This form of ambiguity can be mitigated through methods of ambiguity quantification, such as the Bayesian method, which fundamentally represents a statistical approach grounded in probability related to available information; thus, it updates its parameters based on incoming data; which is illustrated in Figure 2. Consequently, the prior distribution combined with updated data allows for the determination of the posterior distribution. Ambiguity may also arise from a lack of clarity in defining the objectives of the model [18]. For example, consider a fire alarm system in an industrial facility: this system must alert workers while simultaneously triggering an emergency shutdown of machinery. In this case, the model must establish clear priorities; it should first halt operations and subsequently send out the alert. It is essential that the system does not prioritize the transmission of alert messages over the shutdown of machinery, as this could pose significant risks to workplace safety. One strategy to mitigate the effects of unavoidable ambiguities involves ensuring the presence of dedicated human resources for managing the situation and oversight once any operational errors within the system are identified [19]. Such systems, in the context of automation, are referred to as “human-in-loop systems.” In these systems, workers collaborate with the system to make informed decisions based on information analyzed by the model.

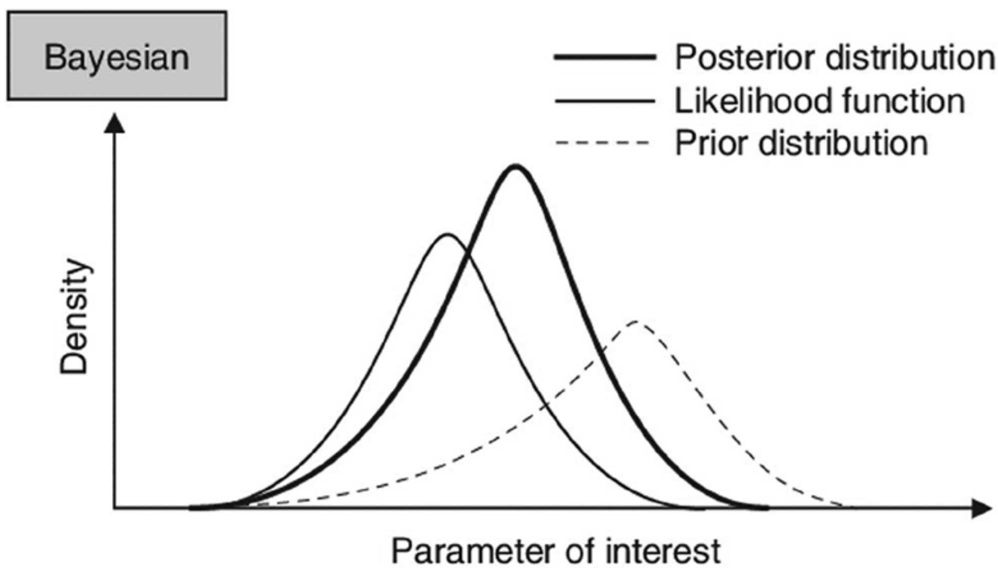


Figure 2. The statistical distribution of the Bayesian method.

3.3. Interference

Another fundamental requirement is to ensure the absence of unintentional and potentially hazardous interferences between the safety functions and non-safety functions of the system. This principle, as outlined by the ISO 26262 standard [20], translates into the prevention of cascading failures that could lead to dangerous situations among various systems, particularly between those critical for safety (which manage safety functions) and those dedicated to normal functions. Three types of interference are identified that may occur and must be minimized: temporal and execution interferences, memory interferences, and information exchanges. The first category refers to a situation where the operation of software responsible for a safety function is influenced by another software system associated with a normal function. A strategy to address issues related to blocking or delays arising from this situation is the implementation of a watchdog within the operating system; this approach allows for monitoring and recovery of blocked functions [21].

The second type of interference pertains to memory and refers to a situation in which one software component modifies the code stored by another element. This issue can be addressed through the hardware implementation of a memory protection unit, which is tasked with identifying errors that arise as a result of these modifications. This unit issues an interrupt request that compels the error management system to restart all software elements involved in the interruption [21].

4. Supervision

Before delving deeper into the topic of supervision, I would like to outline several instances where autonomous AI has demonstrated failures resulting in significant issues:

- On July 19, 2022, a robot designed for playing chess caused a seven-year-old boy's finger to break [22]. During the game, the robot exhibited confusion and failed to keep pace with the child's actions; while the child was positioning his finger to make his next move, the robot mistakenly interpreted the finger as a chess piece and grasped it for several seconds before external intervention could remove the boy's finger. Therefore, failing to correctly analyze and comprehend the situation led to this incident, which could have been avoided through the integration of a supervisory element capable of accurately assessing whether the received input was appropriate.

- On November 8, 2023, in South Korea, a robot operating on a distribution line caused the death of a maintenance worker during an inspection of its sensor. The robot mistakenly identified the individual as an obstacle to be removed, violently crushing him against the line and inflicting severe neck injuries that resulted in his death. This incident serves as yet another illustration of the potential disasters arising from complete reliance on and trust in automated systems [23].

These are just two of the many incidents where the complete dependence and fidelity on AI systems make it evident that the autonomy of a system is not always advantageous; thus, in many situations, supervision becomes necessary as ideal conditions are seldom achieved in electronic and computing contexts. When considering functions related to safety, this necessity becomes particularly urgent due to the involvement of personnel health. In general, supervision is manifested through two primary modalities: the first involves the implementation of a control and monitoring system known as SCADA systems, aimed at validating the proper functioning of the main AI system, which in our case study is integrated into a safety function, and taking appropriate actions once an error is verified; the second modality is characterized by oversight from an operator and management of the situation when an error or malfunction is identified [24].

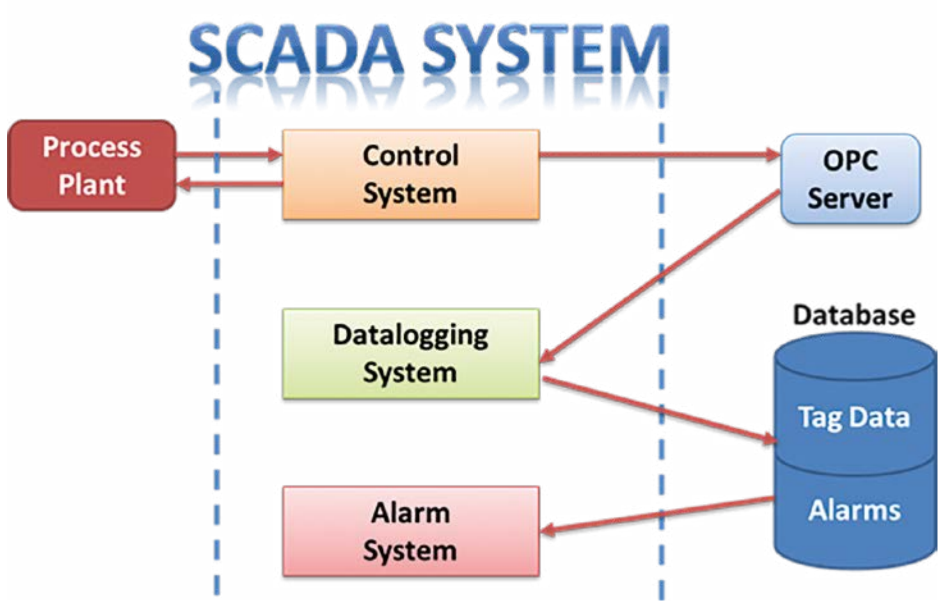


Figure 3. SCADA system structure.

In the context of a safety function, it is imperative to discuss the input and its analysis. Indeed, to activate an emergency function, the input must be analyzed and acquired with precision; for instance, in the case of a fire alert system integrated into a robot or machine, thermal sensors must operate correctly in order to generate a stop and send an alert following an anomalous increase in temperature. Therefore, within such systems, it is essential to implement a supervisory element for the sensors that ensures an accurate assessment of the input; these must be integrated to operate effectively.
Another aspect of a supervisory system pertains to verifying proper functioning and analyzing the system itself. Consider a safety position monitoring system, which is significantly influenced by the ability of the system to estimate and analyze the situation and surrounding environment. As highlighted in previously mentioned examples, in the specific case of a

robot operating on a distribution line, the difficulty in discerning whether the object before it was a person led to a serious incident. Consequently, integrating a supervisory system capable of ensuring correct interpretation could have prevented such an event.
Another approach to implementing supervision is known as "Supervision Human Control" (SHC), which fundamentally relies on the intervention of a designated operator to regain control in the event that an error in the system's operation is identified. However, it is essential to highlight that this method has limitations that compromise its reliability. According to documented literature, this approach is plagued by problematic aspects: the first concerns the loss of situational awareness on the part of the operator, while the second pertains to circumstances where conditions are altered, resulting in confusion for the operator, who may be unable to autonomously manage such situations. An additional disadvantage relates to the excessive trust placed by the operator in decisions made by the machine, and this reliance increases proportionally with how well the system has been functioning. Nonetheless, human intervention proves effective in managing scenarios where adversarial attacks may occur, as it ensures that a dedicated individual is available to detect any attempts by hackers.

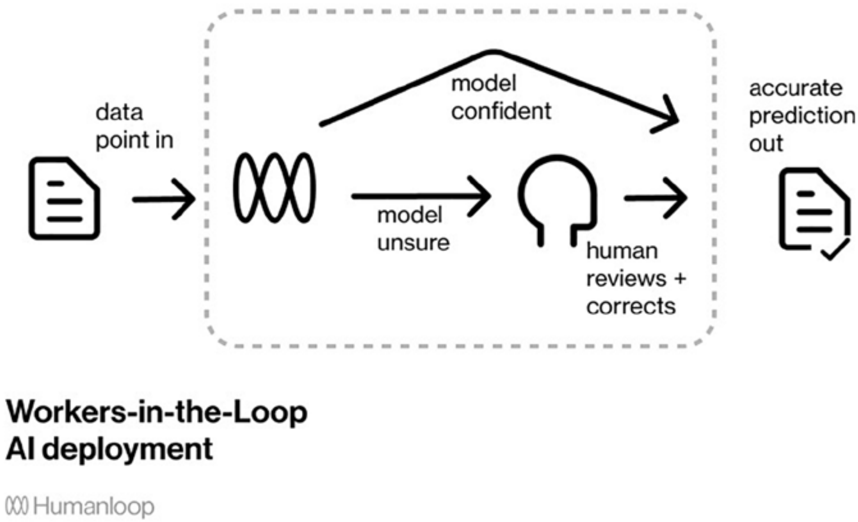


Figure 4. Human in the loop system.

Therefore, from what has been presented, it becomes evident that this supervisory function is implicated concerning both the application of the system and its operational functions, clearly reflecting an analysis of the system's risks.

5. Verification and validation

A fundamental phase at the conclusion of the production cycle of any system, including those lacking safety functions, is represented by verification and validation (V&V). Verification entails ensuring that the product has been constructed in accordance with established requirements, while validation refers to the process through which it is confirmed that the final product effectively meets the anticipated needs; in summary, verification addresses the question "Has the product been designed correctly?" whereas validation pertains to "Is this the right product?".

AI systems, as can be inferred from the points discussed in previous sections, possess characteristics that necessitate a deeper exploration of verification and validation processes when integrated into safety functions. This section of the standard examines the V&V phase for machine learning-based AI systems; thus, they are defined as data-driven systems, meaning their learning is based on acquired data.

One of the challenges associated with the verification and validation phase is the probabilistic nature of machine learning models. Indeed, because these models are based on statistical principles, they do not exhibit high determinism, which introduces additional complications. More specifically, within the context of verification and validation, designers must ensure that the decisions and outputs generated by the system comply with established requirements and operate without errors; however, due to their inherent uncertainty, it is challenging to assert with certainty that the system will always make the correct decision. Naturally, this aspect in AI systems can be mitigated through the adoption of various methods and techniques. Among the applicable tests for AI systems are those outlined in ISO/IEC TR 29119-11:2020: Software and System Engineering – Software Testing [25]. Techniques such as DeepCover and DeepTest are specifically referenced for "white box" systems but can also be adapted for application to AI systems.

5.1. System level testing

A fundamental component in the validation and verification process is system-level testing, which primarily focuses on assessing the interactions among various software and hardware components within a complex system, with the aim of identifying its overall functionality. This type of testing predominantly relies on simulations that can be conducted in a virtual environment rather than in the physical world. It is noteworthy that tests performed in real-world settings are generally economically disadvantageous due to their high costs; furthermore, they can sometimes pose safety risks, thereby limiting their application. Finally, a system evaluated solely within a real-world context does not ensure that all conditions are consistently met, and therefore may not be fully compliant [26]. However, this does not negate the necessity of utilizing specific tools under certain circumstances, particularly when the system must be configured within a complex environment. In fact, in such situations, simulators may fail to accurately represent all relevant variables and elements. Consequently, it is advantageous to employ both techniques to leverage their mutual benefits. This phase can be done through virtual simulation or physical testing.

5.2. Explainable AI

Explainability, as defined by the EN ISO/IEC 22989:2023 standard, refers to a characteristic that an AI system may possess and is manifested in the clear expression of the factors

that significantly influence the decisions made by the system for human understanding. Consequently, it is prudent to leverage this aspect for validation purposes, as it provides designers with insight into the reasoning employed by the system, allowing them to assess its correctness. However, this consideration is only applicable if the system is sufficiently explainable, which largely depends on the type of intelligence that the system embodies; indeed, the same standard indicates that AI systems based on Deep Neural Networks (DNN) pose considerable challenges in terms of explainability due to their inherent complexity.
Another aspect addressed by the standard concerning the utility of explainable AI is that, even if the level of interpretability of the system is deemed insufficient, and reliable techniques for achieving this are yet to be discovered, certain methods can still be referenced in this context to gain insight into the logic underlying the system's evolution. One such technique is the "heatmap"[27]. A heatmap serves as a graphical representation that highlights significant elements upon which the system's decisions are based. This technique has demonstrated considerable efficacy in elucidating complex systems such as neural networks (NN). Other methods that have been developed include LIME (Local Interpretable Model-agnostic Explanations), Saliency Maps, and SHAP (Shapley Additive explanations), among others. Analyzing the information derived from various interpretations provided by these techniques enables designers to assess whether they comply with the requirements for the system's functional safety.

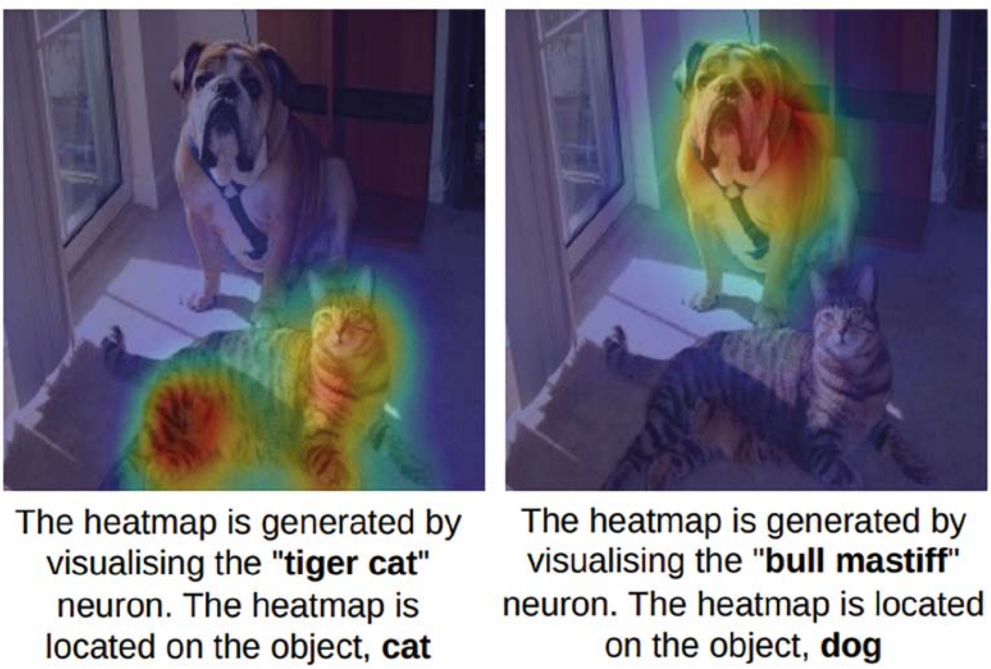


Figure 5. Heat Map.

6. Conclusion

However, findings from research and regulations indicate that the adoption of AI technologies in safety functions remains limited. This limitation can be attributed to the fact that AI is still evolving. Given the sensitive nature of safety functions, various risks and challenges during its developmental stages—such as the validation and verification of AI systems—can hinder its application in machine safety.

References

[1] *Nearly 3 million people die of work-related accidents and diseases*. International Labour Organization. (2023, November 23). https://www.ilo.org/resource/news/nearly-3-million-people-die-work-related-accidents-and- diseases#:~:text=safety%20and%20health- ,Nearly%20 3%20million%20people%20die%20of%20work%2Drelated%20accidents%20and,sustained%20non%2Dfata l%20work%20injuries.

[2] "Che Cos'è L'intelligenza Artificiale? | Tematiche | Parlamento Europeo," Tematiche | Parlamento Europeo, Mar. 9, 2020. [Online]. Available: https://www.europarl.europa.eu/topics/it/article/20200827STO85804/che-cos-e-l-intelligenza-artificiale-e-come-viene-usata.

[3] psico-smart.com, "Future Trends in Workplace Safety: Predictive Analytics and AI Applications." [Online]. Available: https://psico-smart.com/en/blogs/blog-future-trends-in-workplace-safety-predictive-analytics-and-ai-applications-162719.

[4] BBC News, "Uber's Self-driving Operator Charged Over Fatal Crash," Sep. 16, 2020. [Online]. Available: https://www.bbc.com/news/technology-54175359.

[5] ISO/IEC 5469:2024, Functional Safety and AI Systems, International Organization for Standardization, 2024.

[6] IEC 61508-4:2010, Functional Safety of Electrical, Electronic, and Programmable Electronic (E/E/PE) Safety-Related Systems – Definitions and Abbreviations, International Electrotechnical Commission, 2010.

[7] J. Perez-Cerrolaza et al., "Artificial Intelligence for Safety-Critical Systems in Industrial and Transportation Domains: A Survey," ACM Computing Surveys, vol. 56, no. 7, pp. 1–40, Apr. 2024, doi: 10.1145/3626314.

[8] R. Aghemo, "Robustezza e Spiegabilità Dell'Intelligenza Artificiale," Medium, Jan. 7, 2022. [Online]. Available: https://raffa-aghemo.medium.com/robustezza-e-spiegabilit%C3%A0-dellintelligenza-artificiale-7dfd625646c1. [Accessed: Feb. 23, 2025].

[9] X. Zhang et al., "Towards Risk-Aware Artificial Intelligence and Machine Learning Systems: An Overview," Decision Support Systems, vol. 159, p. 113800, 2022.

[10] Amazon Web Services, Inc., "What Is Overfitting? – Overfitting in Machine Learning Explained," [Online]. Available: https://aws.amazon.com/what-is/overfitting.

[11] GeeksforGeeks, "Cross validation in machine learning," GeeksforGeeks, 7 Aug. 2024. [Online]. Available: https://www.geeksforgeeks.org/cross-validation-machine-learning.

[12] CyberLaws Europe, "What does 'robustness (robust AI)' mean? – Legal definition," CyberLaws, 28 Aug. 2023. [Online]. Available: https://www.cyberlaws.it/en/2023/what-does-robustness-mean-legal-definition.

[13] “Regularization in Machine Learning.” GeeksforGeeks, 5 Aug. 2024, www.geeksforgeeks.org/regularization-in-machine-learning.

[14] Qiu, Shilin, et al. “Review of Artificial Intelligence Adversarial Attack and Defense Technologies.” Applied Sciences, vol. 9, no. 5, Mar. 2019, p. 909, doi:10.3390/app9050909.

[15] F. Liao, et al., “Defense against adversarial attacks using high-level representation guided denoiser,” arXiv, 8 Dec. 2017. [Online]. Available: https://arxiv.org/abs/1712.02976.

[16] A. Madry, et al., “Towards deep learning models resistant to adversarial attacks,” arXiv, 19 Jun. 2017. [Online]. Available: https://arxiv.org/abs/1706.06083.

[17] J. Brownlee, A gentle introduction to uncertainty in machine learning, 25 Sept. 2019. [Online]. Available: https://machinelearningmastery.com/a-gentle-introduction-to-uncertainty-in-machine-learning.

[18] Massed Compute, “FAQ answers – Massed Compute,” Massed Compute, 27 Sept. 2024. [Online]. Available: https://massedcompute.com/faq-answers/?question=How+does+machine+learning+handle+uncertainty+and+ambiguity%3F.

[19] A. Yadav, “Human-in-the-loop systems in machine learning – biased algorithms,” Medium, 12 Oct. 2024. [Online]. Available: https://medium.com/biased-algorithms/human-in-the-loop-systems-in-machine-learning-ca8b96a511ef.

[20] ISO 26262-2:2018, Road vehicles – Functional safety, International Organization for Standardization, 2018.

[21] Tasking, “Freedom from interference (FFI),” Tasking, Feb. 2021. [Online]. Available: https://resources.tasking.com/sites/default/files/2021-02/TASKING-Whitepaper-Freedom-from-Interference-Pt-1_WEB.pdf.

[22] J. Chadwick and F. Jackson, “Worst robotic accidents in history – after chess robot breaks seven-year-old boy’s finger in Russia,” Mail Online, 26 Jul. 2022. [Online]. Available: https://www.dailymail.co.uk/sciencetech/article-11046663/Worst-robotic-accidents-history-chess-robot-breaks-seven-year-old-boys-finger-Russia.html.

[23] The Peninsula Newspaper, “South Korean man killed by industrial robot,” The Peninsula Qatar, 8 Nov. 2023. [Online]. Available: https://thepeninsulaqatar.com/article/08/11/2023/south-korean-man-killed-by-industrial-robot.

[24] F. J. Folgado, et al., “Review of Industry 4.0 from the perspective of automation and supervision systems: Definitions, architectures and recent trends,” Electronics, vol. 13, no. 4, p. 782, Feb. 2024, doi: 10.3390/electronics13040782.

[25] ISO/IEC TR 29119-11:2020: Software and System Engineering – Software Testing.

[26] I. Majzik, et al., “Towards system-level testing with coverage guarantees for autonomous vehicles,” in 2019 ACM/IEEE 22nd International Conference on Model Driven Engineering Languages and Systems (MODELS), IEEE, 2019.

[27] O. Tursun, et al., “Towards self-explainability of deep neural networks with heatmap captioning and large-language models,” arXiv preprint arXiv:2304.02202, 2023.

Enhancing Safety in Construction Sites Through Digitalisation and Technological Innovation

Giulia De Cet[1*], Leonardo Rabbi[1], Carlo Pellegrino[1] and Daniela Boso[1]

[1] Department of Civil, Environmental and Architectural Engineering – University of Padua, Padua, Italy

* E-mail: giulia.decet@unipd.it

Abstract. The construction industry is a fundamental pillar of the economy in many developed nations, experiencing steady growth but also carrying significant safety risks. Each year, thousands of construction workers face hazards that threaten their health and well-being. According to the National Institute for Insurance against Accidents at Work (INAIL), the primary causes of injuries include falls from heights, physical strain, and climate-related effects. Historically, construction has been one of the most hazardous sectors due to the physical demands on workers and exposure to environmental conditions. Ensuring worker safety remains a top priority in all construction projects to protect personnel, contractors, and subcontractors while maintaining overall well-being.

New technologies play a crucial role in improving construction site safety. Digital solutions such as Building Information Modeling (BIM), cloud-based safety management platforms, and environmental monitoring systems enable more effective hazard identification and risk mitigation. This research explores the impact of technological innovation on construction site safety, focusing on modern solutions and their practical applications. These advancements not only prevent incidents but also enhance overall operational efficiency, contributing to safer and more productive work environments.

A case study on the Padova Engineering Hub construction site provides practical insights into the integration of advanced safety technologies. Various aspects of technological implementation are analyzed, including benefits and challenges encountered. Findings indicate that digital tools significantly improve hazard identification, risk management, and emergency response. However, challenges such as system integration and data management require careful planning. Overall, this study highlights the transformative potential of technological solutions in construction safety, emphasizing the need for a holistic approach that considers both technical and human factors.

This research contributes to the growing body of knowledge on construction site safety and technological innovation. By examining real-world applications, it provides valuable insights for industry stakeholders, policymakers, and researchers, informing best practices for leveraging technology to create safer and more sustainable construction environments.

Keywords: Safety, Digitalisation, Construction Site

1. Introduction

The construction sector is a key driver of economic growth in many advanced nations. However, it remains one of the most hazardous industries, with thousands of workers facing life-threatening risks each year. According to INAIL[1], the leading causes of accidents include falls from heights, physical exertion, and climate-related factors. The combination of strenuous labor, high-risk environments, and inadequate safety communication often leads to occupational injuries and illnesses[2].
Despite strict regulations, safety measures are not always effectively communicated, shared, or enforced. Factors such as insufficient training, lack of risk awareness, and tight project deadlines contribute to workplace accidents[3]. Prioritizing worker safety is essential to protecting all personnel involved in construction projects.
Technological innovation plays a pivotal role in enhancing safety on construction sites. Digital tools such as BIM [4], VR [5], cloud-based safety platforms, and wearable monitoring devices [6] are revolutionizing safety management by enabling real-time hazard identification, risk assessment, and emergency response.
This study explores how these advancements contribute to improving construction site safety. The research is structured into two main parts. The first section analyzes emerging technologies transforming the construction sector. The second part presents a case study on the Padova Engineering Hub, providing practical insights into the integration of safety technologies in a real-world context.

2. Emerging technologies for the construction sector

The construction industry is undergoing a technological revolution, with innovative solutions enhancing safety and efficiency[7]. This section explores key advancements that are reshaping safety management on job sites. From powerful digital modeling tools to advanced monitoring systems and immersive training environments, these technologies offer unprecedented opportunities to mitigate risks, improve worker well-being, and streamline operations.

2.1. Building Information Modeling (BIM)

BIM is a digital methodology that facilitates the creation and management of all information related to a building or infrastructure throughout its lifecycle. Unlike traditional 2D models, BIM integrates architectural, structural, and operational data into a single platform, improving coordination and decision-making. A key advantage of BIM is interoperability, allowing multiple disciplines to collaborate seamlessly.

2.2. Cloud portal

Cloud platforms provide secure, real-time access to safety documentation, reducing reliance on physical records. These systems improve document organization, facilitate compliance checks, and enable seamless collaboration among stakeholders.
This technology is rapidly expanding in construction site safety, offering a centralized platform for organizing personnel and equipment documentation. It simplifies access for companies and safety professionals, ensuring quick retrieval of records when needed, including

during inspections, thereby reducing the risk of misplaced documents.
Online document management enhances collaboration by allowing office staff and remote workers to securely access shared files in real time. Compared to paper archives, cloud portals offer more efficient document control, enabling real-time tracking of personnel on-site, immediate identification of expired documents, and automated monitoring of expiration dates based on issue dates.
Additionally, automated alerts notify users of expiring certifications, ensuring continuous compliance with safety regulations and reducing administrative burden.

2.3. Artificial Intelligence (AI)

The integration of artificial intelligence (AI) in construction site safety presents a significant opportunity to enhance workplace security, prevent accidents, and reduce risks.
Access control is crucial on all construction sites, as unauthorized personnel pose a serious safety hazard. Construction sites are inherently risky environments, and untrained individuals may unknowingly put themselves in danger. Therefore, tracking site access and ensuring that only authorized personnel enter is essential. AI-powered intelligent cameras can monitor site entrances, recognize personnel and vehicles, and immediately alert security teams in case of unauthorized access. Strategically placing these cameras ensures comprehensive coverage of entry points.
AI can also help prevent fires, particularly in high-risk areas containing flammable materials, potential gas leaks, or equipment that generates open flames. Thermal cameras detect infrared radiation emitted by heated objects, converting it into grayscale images based on temperature differences. This enables continuous 24/7 monitoring, even in low-visibility conditions such as fog or darkness.
Equipped with AI, these cameras can analyze detected heat sources, distinguishing routine activities (e.g., welding) from actual fire hazards. This allows for real-time alerts in the event of dangerous heat anomalies, improving site safety and fire prevention.

2.4. Training with Virtual Reality (VR)

Advanced technologies like virtual reality (VR) are increasingly being used to enhance the effectiveness and interactivity of training. With standardized, cost-effective solutions now available, the future may see a shift toward personalized training programs tailored to specific industry needs.
Emerging digital tools, such as BIM, can further support safety training on construction sites, making sessions more engaging, efficient, and inclusive. These technologies enable training in participants' native languages, improving accessibility and comprehension. Moreover, practical, hands-on experience remains the most effective method for reinforcing learning.

2.5. Internet of Things (IoT) devices and wearable devices for worker health during site operations

IoT systems consist of interconnected devices that communicate with the cloud through various connection methods. Once the data reaches the cloud, the software processes it and determines whether to trigger an action or issue an alert.

In construction site safety, wearable devices – resembling everyday accessories like watches, rings, and necklaces – can be integrated. These include smart helmets, jackets, shoes, gloves, and belts, which monitor movements, hazardous area entry, falls, heat exposure, and harmful emissions. The collected data is then transmitted to a platform via a smartphone or other mobile device.
Additionally, smart personal protective equipment (PPE) can track workers' health by measuring physiological parameters such as heart rate, body temperature, and blood oxygen saturation.

2.6. Wearable robotic exoskeleton for manual handling of loads

To reduce the risk of injuries or pathologies related to manual load handling, workers can use wearable robotic exoskeletons designed to support lifting tasks. In construction, this technology significantly reduces muscle fatigue and prevents biomechanical overload.
An exoskeleton is an external structure worn by an operator to enhance strength and physical capabilities. It can be active (motorized) or passive (without motors), with the primary goal of minimizing physical strain and injury risks. These devices are increasingly adopted in industries such as construction, manufacturing, and logistics.
Exoskeletons come in two main types: rigid-frame models and soft exosuits, which transfer forces from the actuators worn on the body through the musculoskeletal system. They are typically powered by motors or hydraulic systems, offering sufficient mechanical support to handle loads. Depending on the application, exoskeletons can be designed for specific body areas – legs, back, and shoulders – or as full-body robotic suits.
These advanced tools are transforming manual labor by providing essential physical support, reducing fatigue, and significantly improving workplace safety, ultimately helping to prevent long-term occupational injuries.

2.7. Airbags against falls

In the construction industry, the risk of falling from heights is a major concern, particularly for workers operating on scaffolding, ladders, or elevated structures.
In recent years, several global companies and start-ups have focused on enhancing safety for those working at heights. Inspired by motorcycle racing, an Italian company has patented one of the first wearable airbags for fall protection, officially recognized as PPE.
This airbag system, designed to mitigate fall-related injuries, inflates within milliseconds upon detecting a fall, shielding the worker's back, chest, and head from impact. Equipped with sensors and a control unit, it continuously monitors movement and posture, ensuring rapid activation when needed.
This innovative technology marks a significant advancement in construction site safety, offering enhanced protection for workers in high-risk environments.

3. Case Study

The project involves the construction of the new Engineering Hub, commissioned by the University of Padua (Italy). The site is located on Via Niccolò Tommaseo, within the exhi-

bition district. This area holds significant public interest due to its strategic location. The Hub will be just a ten-minute walk from the Padua railway station, with a bus stop directly in front of the site, ensuring excellent accessibility via public transportation. Positioned between Pavilion 1 and Pavilion 7 of the Padua exhibition center, the new Engineering Hub will also attract visitors attending trade fair events.
The building is primarily constructed using wood, employing glued laminated timber (glulam) beams and columns, X-LAM walls and floors, and box floors. This prefabricated design significantly reduces construction time. Each day, approximately two truckloads of prefabricated wood components (floors and walls) arrive on-site.
Given the limited storage space for materials, precise coordination between transport logistics and assembly is essential. The objective is to install the delivered components within the working day, ensuring the unloading area remains clear for the following day's deliveries.
The foundation consists of a slab-on-grade made of concrete, poured in two phases in February 2024. Concrete curbs were then integrated into the slab, where galvanized steel beams were positioned to anchor the X-LAM structure.
The building is designed with compartmentalization in mind, featuring a connective space divided into two sections: one spanning the ground and first floors, and the other covering the second and third floors.
The new Engineering Hub is designed to be an environmentally friendly structure, aligning with the University of Padua's 2018-2022 sustainability commitments, which focus on reducing the institution's carbon footprint and energy consumption.
To ensure high sustainability standards and optimal energy performance, the building is being designed and constructed to meet LEED Platinum certification requirements. LEED (Leadership in Energy and Environmental Design) is an internationally recognized certification system for sustainable building design and construction. Achieving this level of certification requires the integration of advanced strategies and technologies, with the support of sustainability experts.
Beyond its advanced construction system, the Engineering Hub site also stands out for its innovative approach to safety management. The project prioritizes safety both within and outside the construction site.
Efficient document management, rigorous oversight, and meticulous site organization form the foundation for achieving a safe and well-coordinated work environment. These elements contribute to an exemplary construction process, ensuring both operational efficiency and worker safety.

3.1. BIM

The entire Engineering Hub building was designed using BIM technology for the architectural, mechanical, and electrical components (see Figure 1). Thanks to this technology, which provides a 3D visualization of the project and allows for phase-by-phase planning aligned with the construction schedule, the identification of risks and potentially hazardous situations is significantly more precise.
BIM also proved highly effective for performing various measurements and material quan-

tity calculations, such as square meters or cubic meters. For instance, calculating the total square meters of roof insulation was almost instantaneous using BIM. In contrast, a traditional CAD-based approach would have been more time-consuming and prone to errors.

Figure 1. A rendering of the Engineering Hub.

3.2. Cloud portal

To efficiently manage the documentation of personnel on-site, cloud-based document archiving was implemented. This system allows for streamlined document management, enabling safety officers to verify that all individuals present on-site are authorized to access the area. For the Engineering Hub project, an external provider was tasked with managing the portal. Companies and their subcontractors were given credentials to access the platform and upload the necessary documentation.

The portal is user-friendly, featuring a homepage with a drop-down menu offering various options. Among these, the "Construction Sites" section lists different projects along with key details such as the client's name and site location.

By selecting the magnifying glass icon next to the identification code of a specific site, a menu opens where users can view essential documents, including the Safety and Coordination Plan, the work schedule, and the site layout. Below this section, a list of companies currently or soon to be active on-site is displayed, distinguishing between main contractors and subcontractors.

The system provides a quick overview of document compliance through color-coded indicators: green indicates that all required documents have been successfully uploaded ; orange signals that additional documentation is needed.

By selecting a specific company, users can access detailed information about the firm and its responsibilities. Scrolling further, a list of employees is displayed, along with a preview of their document validity, their assignment status, and expected employment end date.
By opening an individual employee's profile, all relevant details—such as contract type, assigned site, and employment duration—are accessible. The same page contains all necessary documents required for the worker's regular presence on-site. Additionally, personalized searches can be generated based on an individual's role and qualifications.
The system automatically generates a list of mandatory documents for site access, such as medical examinations, general and specific safety training, and the delivery of personal protective equipment. For workers assigned to specialized tasks, the portal operator can request additional documentation tailored to the required qualifications.
A key advantage of the portal is its ability to prevent document expiration oversights by sending alerts before any document becomes invalid.
The main challenge encountered in using the platform was the difficulty faced by some self-employed workers or small, less tech-savvy companies in navigating the system. In these cases, the issue was resolved by manually uploading their documents, which they submitted via email.

4. Conclusions

The adoption of advanced technologies in construction marks a significant shift aimed at enhancing safety on construction sites and reducing risks for workers[2]. This paper has explored various technological innovations, with particular focus on BIM, cloud portals, AI, virtual reality, Internet of Things (IoT) devices, wearable technologies, and tools for preventing falls and addressing risks associated with manual load handling.
Some of these technologies, such as BIM and cloud-based document management portals, were employed in the construction site case study presented herein. It is hoped that technological advancements will continue to shape the construction industry, significantly reducing risks for workers. The integration of these innovations not only enhances safety but also improves the efficiency and sustainability of construction projects[8].
However, it is important to acknowledge that the implementation of these technologies requires ongoing commitment in terms of training, skill development, and investment in new solutions. Despite their potential, many of these technologies remain underutilized, and some companies, particularly smaller ones, are hesitant to adopt them due to the additional resource requirements. To address this challenge, government institutions should step in by providing funding and economic incentives, such as National or European contributions, to promote the adoption of these advanced technologies.
Training for workers must remain a top priority, ensuring they possess the necessary technical expertise and a comprehensive understanding of safety practices, as well as proficiency in using new tools and technologies[9]. Given that the risk of accidents in a workplace like a construction site can never be entirely eliminated, it is essential to mitigate these risks through proper training and careful planning to prevent unforeseen conflicts among the various stakeholders involved in the project.

Excessive confidence, complacency, and distractions can lead to underestimating the potential dangers associated with the work being carried out. Therefore, a balanced approach is critical in maintaining a culture of safety.

In conclusion, technological innovation is a key driver in enhancing safety on construction sites, offering substantial opportunities to reduce risks and create safer work environments. However, the success of these initiatives depends on the collaboration of all parties involved, as well as a sustained commitment to continuous improvement and innovation. Only through an integrated and proactive approach can we unlock the full potential of these technologies and secure a safer, more sustainable future for the construction industry.

5. Future Developments

The construction industry is evolving, with technological advancements playing a key role in shaping its future. Several emerging technologies and trends are set to significantly impact construction site safety and worker well-being[10].

One major area gaining momentum is the integration of artificial intelligence and machine learning into construction processes. These technologies can transform site safety by enhancing risk assessment, hazard identification, and real-time monitoring [11]. AI systems can process data from sources like sensors, drones, and BIM models to detect hazards and provide proactive safety recommendations [12]. Machine learning algorithms can identify patterns and anomalies, enabling early detection of unsafe conditions and allowing for timely interventions[13].

Another development is the increasing use of robotics and automation in construction tasks. Robotic systems can handle hazardous or physically demanding jobs, reducing injury risks. For example, robotic demolition machines safely dismantle structures, minimizing exposure to debris. Autonomous vehicles and equipment improve site logistics and material handling, reducing accidents involving human operators.

The integration of advanced sensor technologies and the Internet of Things (IoT) will also play a crucial role in site safety. Wearable devices, environmental sensors, and smart equipment can provide real-time data on worker health, exposure levels, and equipment performance, enabling proactive interventions such as alerts for hazardous conditions or preventive maintenance for equipment.

Furthermore, virtual and augmented reality technologies offer new opportunities for training and safety simulations. VR can create realistic construction scenarios, allowing workers to practice safety protocols without actual risk, while AR overlays safety information in real-time, guiding workers through the physical environment.

As the industry embraces digitalization, cybersecurity will become essential to protect safety-critical systems from data breaches or hacking. Strong cybersecurity measures are needed to safeguard automated processes and data integrity.

Sustainable construction practices are also gaining traction, driven by concerns over climate change and resource depletion. This shift may require new safety protocols for eco-friendly materials and construction methods.

Collaboration among stakeholders will be vital to accelerate the development and adoption

of these technologies. Industry-academia partnerships, research, and knowledge-sharing platforms will foster innovation and best practices.
However, successful integration will require addressing challenges such as workforce training, regulatory updates, and cost considerations. Training programs will ensure workers can effectively use new technologies, while regulatory bodies must adapt safety standards to these innovations. The cost-effectiveness and ROI of these technologies must also be evaluated, particularly for smaller firms.
In conclusion, the future of construction site safety will be shaped by advancements in AI, robotics, VR, IoT, and sustainability. While these technologies offer significant potential to improve safety, their success depends on collaboration among industry stakeholders, regulatory bodies, and academic institutions. By embracing innovation and addressing challenges, the construction industry can create a safer, more efficient, and sustainable future.

References

[1] "Relazione annuale 2023." Accessed: Mar. 31, 2025. [Online]. Available: https://www.inail.it/portale/it/inail-comunica/pubblicazioni/rapporti-e-relazioni-inail/rapporti-e-relazioni-inail-dettaglio.2024.10.relazione-annuale-2023.html

[2] Z. Zhou, Y. M. Goh, and Q. Li, "Overview and analysis of safety management studies in the construction industry," *Saf Sci*, vol. 72, pp. 337–350, Feb. 2015, doi: 10.1016/J.SSCI.2014.10.006.

[3] H. Guo, Y. Yu, and M. Skitmore, "Visualization technology-based construction safety management: A review," *Autom Constr*, vol. 73, pp. 135–144, Jan. 2017, doi: 10.1016/J.AUTCON.2016.10.004.

[4] G. De Cet, N. Miazzi, R. Paparella, and D. P. Boso, "How Building Information Modeling Technology Supports Safety on Construction Sites: The Case Study of a Water Reservoir in Italy," *Buildings 2025, Vol. 15, Page 403*, vol. 15, no. 3, p. 403, Jan. 2025, doi: 10.3390/BUILDINGS15030403.

[5] X. Li, W. Yi, H. L. Chi, X. Wang, and A. P. C. Chan, "A critical review of virtual and augmented reality (VR/AR) applications in construction safety," *Autom Constr*, vol. 86, pp. 150–162, Feb. 2018, doi: 10.1016/J.AUTCON.2017.11.003.

[6] I. Awolusi, E. Marks, and M. Hallowell, "Wearable technology for personalized construction safety monitoring and trending: Review of applicable devices," *Autom Constr*, vol. 85, pp. 96–106, Jan. 2018, doi: 10.1016/J.AUTCON.2017.10.010.

[7] T. D. Oesterreich and F. Teuteberg, "Understanding the implications of digitisation and automation in the context of Industry 4.0: A triangulation approach and elements of a research agenda for the construction industry," *Comput Ind*, vol. 83, pp. 121–139, Dec. 2016, doi: 10.1016/J.COMPIND.2016.09.006.

[8] C. Nnaji and A. A. Karakhan, "Technologies for safety and health management in construction: Current use, implementation benefits and limitations, and adoption barriers," *Journal of Building Engineering*, vol. 29, p. 101212, May 2020, doi: 10.1016/J.JOBE.2020.101212.

[9] H. Guo, Y. Yu, and M. Skitmore, "Visualization technology-based construction safety management: A review," *Autom Constr*, vol. 73, pp. 135–144, Jan. 2017, doi: 10.1016/J.AUTCON.2016.10.004.

[10] I. Awolusi, E. Marks, and M. Hallowell, “Wearable technology for personalized construction safety monitoring and trending: Review of applicable devices,” *Autom Constr*, vol. 85, pp. 96–106, Jan. 2018, doi: 10.1016/J.AUTCON.2017.10.010.

[11] M. Muzafar, “Building information modelling to mitigate the health and safety risks associated with the construction industry: a review,” *International Journal of Occupational Safety and Ergonomics*, vol. 27, no. 4, pp. 1087–1095, 2021, doi: 10.1080/10803548.2019.1689719.

[12] X. Yi, J. Wu, X. Yi, and J. Wu, “Research on Safety Management of Construction Engineering Personnel under ‘Big Data + Artificial Intelligence,’” *Open Journal of Business and Management*, vol. 8, no. 3, pp. 1059–1075, Apr. 2020, doi: 10.4236/OJBM.2020.83067.

[13] C. N. Egwim *et al.*, “Artificial Intelligence in the Construction Industry: A Systematic Review of the Entire Construction Value Chain Lifecycle,” *Energies 2024, Vol. 17, Page 182*, vol. 17, no. 1, p. 182, Dec. 2023, doi: 10.3390/EN17010182.

The Impact of New Technologies in Collision Avoidance: an Applied Experience of Speed Control and Impact Detection in Material Handling with Forklift Trucks

Alberto Vicentin[1,2*], Paola Visciano[3] and Edoardo Tovo[3]
[1] Studio Vicentin srl, Brendola, Vicenza, Italy
[2] Department of Civil, Environmental and Architectural Engineering – University of Padua, Italy
[3] Il Vecchio Forno srl, Brogliano, Vicenza, Italy

* E-mail: alberto.vicentin@unipd.it

Abstract. Material handling within workplace environments simultaneously represents an indispensable operational necessity, a significant cost factor, and a primary risk to workers' safety and health. Materials inevitably arrive, pause, move, remain in storage, and ultimately depart from production facilities and storage locations, creating a network of flows and routes traditionally managed by workers operating handling equipment. In this context, the forklift operator assumes a central role. Considerable efforts have been made, and further opportunities exist, to optimise internal movements and enhance safety for forklift operators and other personnel. Despite the complexity and variety of scenarios, the human contribution to forklift operation remains widespread, nearly ubiquitous, and presumably never entirely replaceable due to its flexibility and adaptability. This human involvement entails associated injury risks stemming from environmental conditions, equipment malfunctions, work regimes, and human error. These risks can be significantly and progressively reduced but cannot be entirely eliminated in work environments where forklifts operate alongside other vehicles, various equipment, and, crucially, ground personnel. The applied experience presented herein concerns the joint implementation of two digital matrix improvement solutions in forklift management within an industrial food sector facility: 1. Zone-based Speed Control Telemetry System; 2. Automatic Impact Detection System. This applied research aims to evaluate the implementation and efficacy of two digital solutions for forklift management within an industrial food processing facility, in order to enhance workplace safety in material handling operations, leveraging digital technologies to mitigate risks associated with forklift operations in dynamic industrial environments. The study seeks to: (a) Assess the reduction in incident occurrences following the implementation of these systems; (b) Evaluate forklift operators' adherence to and participation in the initiative; (c) Analyse operators' feedback regarding risk perception and operational compatibility.

Keywords: Material Handling, Safety, Forklift, Speed Control, Impact Detection

1. Introduction

The production processes of manufacturing companies consist of transformation and processing phases connected to each other through physical transfer operations of raw materials, semi-finished and finished products. In addition, the global size of the market makes the logistics sector increasingly large and strategic, where the arrival, storage and departure of goods are the core business of the entrepreneurial initiative. The optimal management of material handling must constantly combine two fundamental and essential needs, which can sometimes be opposed in the field: productivity and safety.

In this context, the function of the worker in charge of the use of means of transport and lifting, including the forklift driver driving the forklift, is traditionally central. Much has been done and much can be done to optimize internal movements and promote the safety of forklift drivers and other people present [1] [2], including:

- Organisation of spaces and routes in processing departments, warehouses, and loading/unloading areas;
- Provision of equipment compliant with essential safety requirements mandated by current regulations and subject to regular inspections and maintenance;
- Preparation of personnel through mandatory qualifying training and dedicated health surveillance assessments;
- Automation of movements, where feasible, through "unmanned" mechanised transfer systems (conveyor belts and roller conveyors, elevators and lifts, driverless mobile equipment);
- Intensive and structured utilisation of storage volumes through arrangements that increase material stability and limit rotation.

The applied experience presented herein concerns the joint implementation of two digital matrix improvement solutions in forklift management within an industrial food sector facility:

1. ZONE-BASED SPEED CONTROL TELEMETRY SYSTEM [3]: The installation of fixed devices in work environments creates immaterial entry and exit gateways corresponding to high-risk zones for moving forklifts. These fixed devices communicate with passing vehicles, imposing selective and temporary speed limitations. In critical zones, speed reduction is no longer left to the discretion and prudence of the operator but is remotely controlled through a digital regulation and monitoring system. Outside high-risk zones, i.e., before entering and after exiting the gateways, the operator regains full control over the vehicle and its speed.

2. AUTOMATIC IMPACT DETECTION SYSTEM [4]: The installation of an accelerometer on the forklift allows precise and timely detection of undesired mechanical impacts experienced by the vehicle, recording a set of information (date, time, impact level, etc.) and triggering preset reactions differentiated by impact level (recording only; driver alert; deceleration or stopping requiring intervention to unlock). Information is digitally transmitted to a remote control and archiving portal, accessible in real-time. The system can be combined with the provision of a personal key to each operator for vehicle start-up, thus facilitating correlation between events and users.

2. Description of the application experience in a food industry

2.1. The work context

The applied experience takes place in an industrial company in the food sector, Il Vecchio Forno s.r.l., which produces and markets leavened desserts for special occasions (panettone, pandoro, colomba, logs and Easter lambs) and rusks, under its own brand and not see Figure 1). Founded in 1986, the company now employs a total of almost 200 people, is spread over two production sites, one in the Brogliano (VI) area and one in the Cornedo Vic.no (VI) area, and is a reference partner of Italian and international Retail for Private Labels of naturally leavened bakery products [5] [6].

Figure 1. Production of panettone and rusks [5-6].

The activity is characterized, for the dessert part, b y a high seasonality, which includes two different production periods, Easter and Christmas, interspersed with moments of "low season". In particular, at the beginning of the year the production of Easter leavened products is started, in both industrial sites, and this period lasts approximately until the Easter holiday. This is followed by the so-called "long low season", i.e. a period in which production is stopped and maintenance, deep cleaning, technological updating and expansion of the plants are carried out from time to time. Christmas production ends close to the Christmas holidays and is followed by a period of "short low season". At the Brogliano site, the production of rusks is also carried out throughout the year and therefore without a seasonal character.

This study refers to the industrial site of Brogliano, divided into two communicating buildings: one used for production and the other used as a warehouse. The total covered area amounts to 40,000 m^2 and houses 4 production lines: two lines of leavened products for special occasions, an artisanal packaging line for leavened products for special occasions, a line of rusks. The annual volumes amount to 14 million pieces of leavened products for special occasions and 25 million packs of rusks.

The processing cycle of the confectionery production lines, although differentiated by prod-

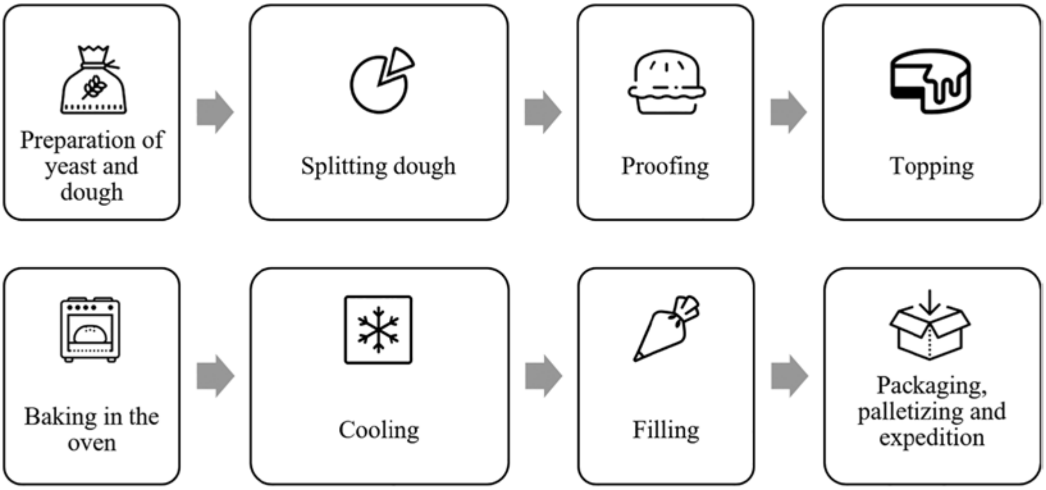


Figure 2. Processing cycle of confectionery production lines – Summary diagram [6].

uct types, recipes and any fillings, is developed indicatively according to this sequence of phases (see flowchart in Figure 2 for a summary diagram): procurement and storage of raw materials on site; preparation of yeast; first dough and first leavening; second dough; splitting according to the predetermined weight; stationing in the proofing chamber; any topping; baking in the oven; cooling; any filling; wrapping in bags and subsequent packaging in cardboard or metal cases; grouping into boxes; Palletizing; storage of pallets in the warehouse; expedition.

The processing cycle of the production line of rusks, also in this case differentiated by recipe, develops approximately according to this sequence of phases (see flowchart in Figure 3 for a summary diagram): procurement and storage of raw materials on site; dosage of ingredients and dough; splitting according to the predetermined weight; formation of dough balls; transformation of the balls into loaves of bread into trays; rise; baking in the oven; cooling; cut into slices; spreading the slices on a conveyor belt; roasting in the oven; packaging in single-dose packages and subsequently in larger packages; grouping into boxes; Palletizing; storage of pallets in the warehouse; expedition. The flowchart in Figure 3 shows a summary diagram of the cycle.

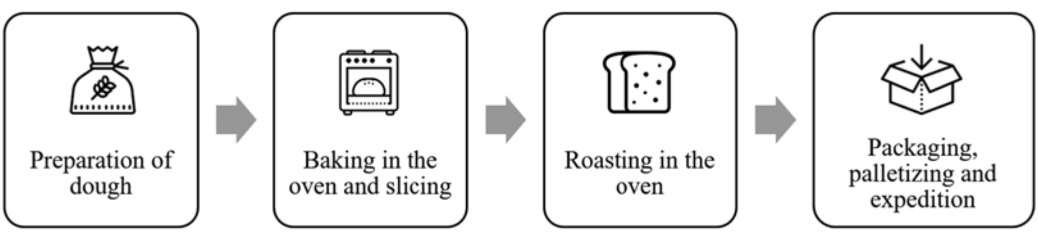


Figure 3. Processing cycle of the rusk production line – Summary diagram [6].

2.2. Background in material handling risk management at the industrial site

From the brief description of the working context, the importance of handling and storage within the plant is evident, both for the size and complexity of the industrial site and for the seasonality and arrivals/shipments regime that inevitably requires solutions of accumulation, stock, buffer and internal movement. In this regard, an indicative list of the equipment in use on the Brogliano company site is reported: 20,000 m^2 of covered storage area developed on two floors (ground floor and first basement); n° 2 freight elevator systems connecting the two floors; fleet of 21 electric forklifts and 4 electric pallet trucks.

The prevention and protection measures put in place for some time to manage risks from the handling of materials in the plant include the following actions:

- a specific assessment of the risks from internal roads and goods handling, developed in a dedicated document by way of in-depth analysis and integration of the general risk assessment document;
- a lay-out of the internal road network, with a distinction between vehicle and pedestrian routes, attached to the specific assessment referred to in the previous point;
- initial training for forklift operators, with periodic updating, in accordance with current national legislation;
- the definition of the list of employees authorized to use forklifts;
- operating safety instructions on how to safely use forklifts and on precautions to avoid dangerous interference between vehicles and pedestrians;
- a procedure for the access of external transporters to the spaces pertaining to the company, with rules and prohibitions regarding the numbers and times of admission, criteria for interaction with internal staff, accessibility to toilets and refreshment facilities, etc

2.3. Application methods of the two innovative solutions

In the industrial reality described so far, the two digital technological solutions presented in the "Introduction" paragraph were introduced in September 2023. The choice derives from a commitment of the company and the professionals with whom it collaborates towards the continuous improvement of the levels of performance and protection, monitoring the evolution of the proposals available on the market and, sometimes, stimulating the market itself to promote and perfect personalized formulas. On the other hand, it should be pointed out that the experimentation of these innovations directly in the field, in a working context already in full operation, inevitably conditioned by pre-existing production, logistical, organizational and even individual and relational factors, puts elements of practical constraint and people's distrust of change and at the same time offers a reliable test bench, although statistically limited, to measure the empirical effectiveness of the initiative.

In the specific case of material handling with forklifts, the search for room for improvement was favored by some episodes of near misses recorded in the plant in the period 2021-2022, including an event assessed and treated as particularly significant by the company's Prevention and Protection Service: the breakage of the front and top windows of a forklift due to a collision, fortunately without injuries for the attendant on board. Added to this were some circumstances of impact damage found on the vehicles only a posteriori, without reporting to the employees directly involved and without the possibility of reconstructing the dynamics and analyzing the causes. The following contextual needs were therefore shared internally:

- further reduce the risk of collisions between forklifts and contact with people on the ground, especially in the most critical areas due to traffic intensity, type of attendance, narrowness of space and visibility limitations;
- have a punctual, timely and detailed detection of accidents/collisions, even minor ones.

A historic supplier of handling equipment was consulted, which had already been dedicating itself for some time, also in partnership with other parties, to the development and application of new technologies to improve safety in the use of forklifts, in the wake of reports, needs and requests from its customer base. After in-depth analysis and comparisons on technical and economic feasibility, the supplier proposed the joint application of the two solutions: 1. Zone-based Speed Control Telemetry System; 2. Automatic Impact Detection System.

It started by implementing the equipment related to the two systems on a selection of four forklifts operating in the areas at greatest risk: the confectionery packaging area and the rusk packaging area. Before commissioning, the workers involved were informed about the operation and purpose of the new equipment and signed a dedicated form for taking charge of a personal and nominal key for switching on the trolley.

In the early days of operation of the Automatic Impact Detection System there were numerous impact events, distributed over a large scale of entities, while the phenomenon has gradually been reduced up to the current data which attest to a significant decrease in quantity and force: internal testimonies show that probably in the initial phase the employees, not yet accustomed to automatic remote monitoring on the trolley, maintained the previous methods both in maneuvering and in communication, and then gradually correcting the approach. The decision to force the truck to run slowly after a level 3 impact (classified as "serious") was also functional, with the need to unlock it using a master key supplied to the person in charge: the latter is therefore immediately involved and, together with the restoration of the truck's normal running speed, can carry out an immediate analysis of the incident in the field.

The Zone-based Speed Control Telemetry System On the other hand, it had a double immediate effect, as the automatic reduction of speed to 5 km/h in critical areas on the one hand immediately reduced the risk of accidents but on the other hand significantly increased the time of service to the production lines. As a result, in the first application phase, there was a tendency to deactivate the system during periods of peak production, thus neutralizing its benefits precisely at the times of greatest usefulness. On the basis of this first experience, it was decided to involve the warehouse managers in a re-examination of the spaces for placing the materials necessary for packaging, obtaining a reduction in internal distances and thus compensating for the slower transits in critical areas with an optimization of flows.

At present, both systems are active and operating on 4 forklifts at the Brogliano production site and the related information is regularly monitored and processed by the company's Prevention and Protection Service. For the sake of completeness, it should be noted that there is a concrete limitation in terms of application deriving from the impossibility of installing the devices on third-party manufacturers' vehicles, compared to the widespread practice among user companies of using mixed fleets.

3. Worker consultation and risk perception

The correlation between technological solutions and people's behaviour is already evident in the application experience illustrated above, as it is in any occupational safety and health experience. The understanding and interpretation of one's role by the individual worker and workers in relation to each other, the degree of adherence and participation in improvement processes and, above all, the perception of risk and awareness of one's own direct contribution are discriminating elements for the functioning of the occupational safety and health management system.

Based on this, the initiative aims to promote an easy and agile consultation process for workers regarding their experience of the two innovative systems illustrated above. Three separate questionnaires were developed and administered, two intended for the operators of the forklifts in which the devices were installed and one for workers "on the ground" (not forklift drivers) operating in the packaging areas of sweets and rusks. The tool used for the questionnaire implementation was "Google Forms". The questionnaire was shared by sending a link via email. It was designed to highlight the most interesting aspects of the personal point of view, behaviour and reaction, combined with the enhance of simple and immediate involvement of operators of different roles and backgrounds.

The following paragraphs present the contents and results of the consultation.

3.1. Questionnaire for forklift operators with Zone-based Speed Control Telemetry System

The questionnaire was administered exclusively to forklift operators on which the Zone-based Speed Control Telemetry System was installed and activated. Here are the questions along with the multiple choice possibilities.

First question: Have you noticed a change in the speed of the forklift after installing the device? Possible Answers: Yes, it's much slower in some areas | Yes, it's slightly slower in some areas | No, I haven't noticed any significant changes | No, I'm not sure.

Second question: How do you rate the effectiveness of the device in slowing down the speed in the intended zones? Possible answers: Very effective | Quite effective | Not very effective | Not effective at all.

Third question: Do you think the slowdown device increases safety when using the forklift? Possible answers: Yes, definitely | Yes, in part | No, I don't think anything changes | No, I think it can be dangerous.

Fourth question: Has the slowing down of the forklift in specific areas impacted your work efficiency? Possible Answers: Yes, it has slowed down my work significantly | It had an impact, but not a significant one | It had no impact | I'm not sure.

Fifth question: Do you think the device helps reduce the risk of accidents or damage to people and equipment? Possible answers: Yes, definitely | Yes, in part | No, I don't think so | I don't know.

Sixth question: Do you feel safer while using the forklift with the device active? Possible Answers: Yes, I Feel Much Safer | Yes, a little safer | I don't see a difference | No, I don't feel safe anymore.

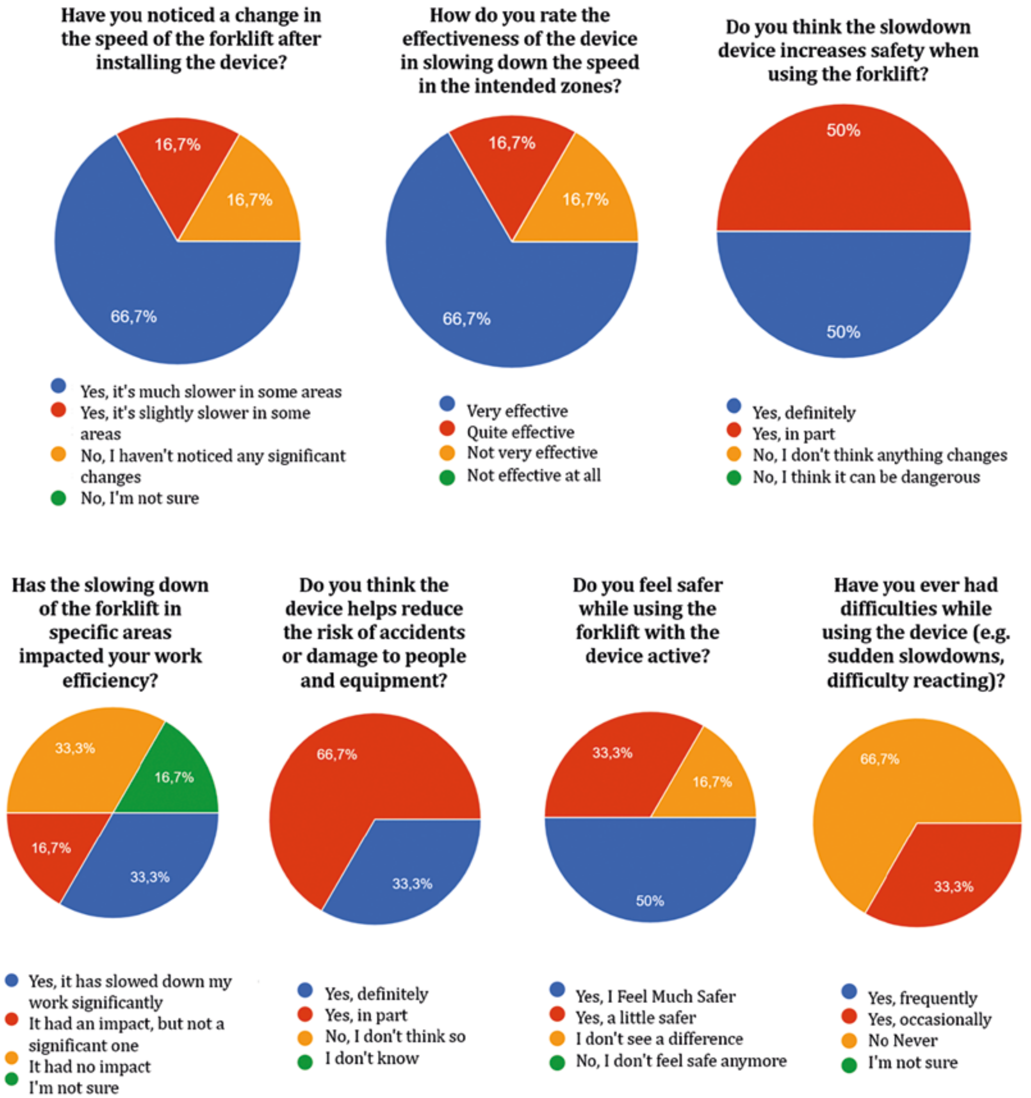


Figure 4. Results of questionnaire for forklift operators with Zone-based Speed Control Telemetry System.

Seventh question: Have you ever had difficulties while using the device (e.g. sudden slowdowns, difficulty reacting)? Possible answers: Yes, frequently | Yes, occasionally | No Never | I'm not sure.
Eighth question: What suggestions or improvements would you propose regarding the speed slowdown device? | Free answer
The results of the six compilations received are graphically represented in Figure 4. For the

last question, in the open field, some interesting answers are reported: "In my opinion, speed in protected areas should be increased a little more, not because I don't want to respect the rule, but the low speed worsens in some moments on the psychological state. This is because it is not possible at times to satisfy all the requests that arrive at the same time." | "We have to reduce speed when we turn corners and in areas where there are a lot of people passing by, and when it rains you have to go very carefully. Thank you"

3.2. Questionnaire for forklift operators with Automatic Impact Detection System

The questionnaire was administered exclusively to forklift operators on which the Zone Automatic Impact Detection System was installed and activated. Here are the questions along with the multiple choice possibilities.
First question: How long have you been using the forklift with the new shock detection system? Possible Answers: Less than a month | 1-3 months | 3-6 months (25%) | More than six months (75%).
Second question: How do you evaluate the effectiveness of the automatic shock detection system? Possible answers: Very effective (75%) | Effective | Quite effective (25%) | Ineffective.
Third question: Have you ever received a warning (following a slight or medium impact) while using the forklift? Possible answers: Yes, frequently | Yes, occasionally (75%) | No, never (25%).
Fourth question: When the trolley goes into "turtle" mode after a serious impact, how do you feel? Possible answers: Safe, it's a good protection system (75%) | A little frustrated but I understand the need for security | Annoying, slows down my work too much (25%) | Never have I ever been in turtle mode.
Fifth question: How do you evaluate the use of the personal key to identify the user of the cart? Possible answers: Very helpful (75%) | Profit (25%) | Useless.
Sixth question: Do you feel that using your personal key improves shock management and liability? Possible answers: Yes, definitely (75%) | Yes, in part (25%) | No, nothing changes | I'm not sure.
Seventh question: Have you ever had difficulty using your personal key (e.g. forgetting it, difficulty in recognising)? Possible Answers: Never (100%) | Rarely | Sometimes | Often-
Eighth question: Have you been adequately informed on how to use the personal key and the shock detection system? Possible answers: Yes, completely (100%) | Yes, in part | No, not enough | No, not at all.
Ninth question: Do you feel more responsible for driving the forklift thanks to the personal key? Possible answers: Yes, very much (75%) | Yes, a little | No, I don't see any difference (25%).
Tenth question: Have you noticed improvements in general safety when using the forklift thanks to these systems? Possible answers: Yes, significant improvements (100%) | Yes, some improvement | No, no change | No, security seems to have worsened.
Eleventh question: Have you found that the shock detection system has had an impact on working times (e.g. due to turtle mode)? Possible Answers: Yes, it slowed down significantly (50%) | Yes, it slowed down a bit (50%) | No, it had no impact on the timing | No, it has even sped up operations.

Twelfth question: Is there anything you think could be improved in the shock detection system or in the management of the personal key? | Free answer
Considering the limited number of compilations received (four), the graphic representation is considered to be of little significance and it is preferred to report directly next to each answer option, above, the relative percentage incidence. For the last question, in the open field, some interesting answers are reported: "It is a very important thing, so we try to avoid doing damage. Thank you for asking me this question." | "Personally no. But I often find forklifts empty, or with the battery charger attached without charging. I think that all those who use the forklift in packaging must be made responsible for how important it is not to underestimate some operations that create discomfort for others."

3.3. Questionnaire for workers "on the ground" (not forklift drivers) in the packaging areas

The questionnaire was administered exclusively to workers "on the ground" (not forklift drivers) operating in the packaging areas of sweets and rusks. Here are the questions along with the multiple choice possibilities.
First question: How do you evaluate the effectiveness of the zone slowdown device in improving safety in the work area? Possible Answers: Very Effective | Effective | Quite effective | Not very effective.
Second question: Do you think that reducing speed in specific areas improves overall safety? Possible Answers: Yes, Definitely | Yes, but only in certain areas | No, I don't think it improves security | I'm not sure.
Third question: Is there any improvement you would suggest for the Zone Retarder System or the Shock Detection System? | Free answer.
The results of the twenty-six compilations received are graphically represented in Figure 5. For the last question, in the open field, an interesting answers is reported: "For me, the slowdown has already led to an increase in attention both on the part of the forklift driver and those who travel on foot, I think they may be enough".

4. Conclusions

The work presented here starts from the evidence, widely spread in industrial companies and in the growing logistics sector, that the handling of materials in the workplace represents both a fundamental operational necessity, an important cost item and a primary risk factor for the safety of workers. Technological and organizational evolution today offers various solutions to improve and optimize handling activities, even in traditional processes based on the use of worker-driven forklifts.
The applied experience concerns the joint implementation of two digital matrix improvement solutions in forklift management within an industrial food sector facility: 1. Zone-based Speed Control Telemetry System; 2. Automatic Impact Detection System. The two systems were put into practice on some forklifts and in some significant areas of the industrial site and the effects on the field were monitored both in terms of compatibility with production needs and in terms of the reduction of the risk of accidents.

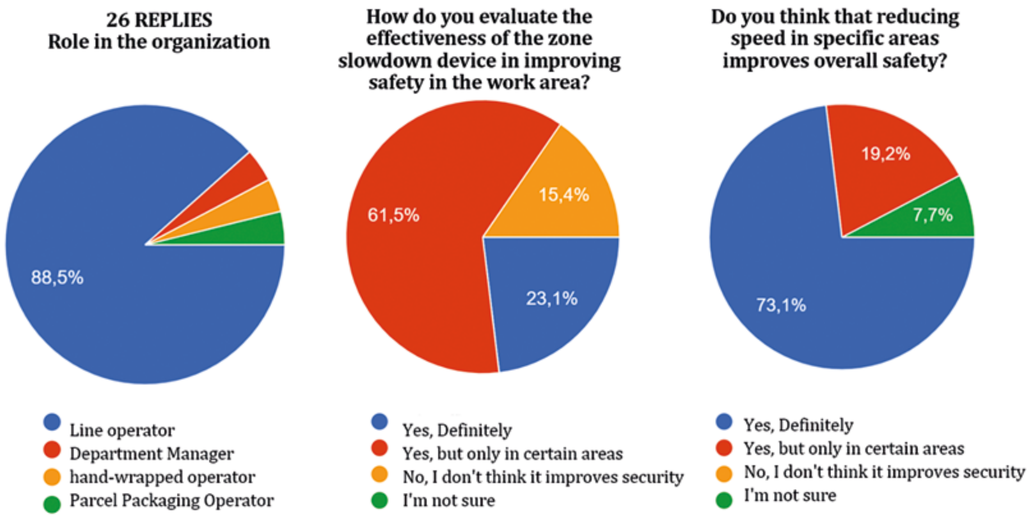


Figure 5. Results of questionnaire results for workers "on the ground" (not forklift drivers).

The reduction in the number and severity of events, together with the results of the questionnaires, make it clear that the systems applied have had a positive effect, both in terms of objective risk in the workplace and in terms of workers' perception of improved safety in the packaging departments. Most of the operators who joined the questionnaire (about 65%) found positive effects following the installation of the two devices in the areas where they were installed.
The company is continuing to search for new technological solutions compatible with all types of forklifts, in order to overcome the "brand" limit set by the installations tested so far. The goal is to refine, develop and extend the use of the Zone-based Speed Control Telemetry System and the Automatic Impact Detection System, respectively, to other critical areas of industrial plants and to the entire fleet of forklifts.

References

[1] Decreto Legislativo 9 aprile 2008, n. 81

[2] "Guida alla sicurezza della viabilità delle imprese" – 2002 – E.B.E.R. Ente Bilaterale Emilia Romagna.

[3] "Manuale di Uso e Installazione EGOpro SAFE ZONING UWB PLUS – Revisione 4" –2022 – Advanced.

[4] "Manuale Jungheinrich FMS- Versione 1" – 2022 – Jungheinrich AG Microwave Engineering s.r.l.

[5] «Il Vecchio Forno s.r.l.» [Online]. Available: https://www.ilvecchioforno.com/

[6] "Tesi di Laurea Magistrale Ingegneria della Sicurezza Civile e Industriale – D.M. 10/03/1998 e D.M. 02/09/2021 a confronto: indagine sulla percezione dei lavoratori in tema di gestione delle emergenze" – Laureanda: Giorgia Urbani – Relatore: prof.ssa Chiara Vianello – A.A. 2022-2023.

Euro 15,60

ISBN 979-12-81229-19-8