Artificial Intelligence Contributions to Extending the Current Limitations of Virtual Reality for Integrating Operator Safety in Early-Stage Industrial Machinery Design

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***Abstract*— Compliance with European standards now constitutes an essential for machine safety. Today, the integration of user safety is no longer regarded as a constraint, but as a function that the system must fulfill and as a responsibility shared by all stakeholders. However, the persistence of numerous accidents reveals the boundaries of a predominantly normative approach. This article presents an analysis of the contribution of Virtual Reality (VR) as a complementary tool for more effectively integrating human factors and operator safety from the design phase onward. First through a review of the literature, we demonstrate how VR made possible to anticipate working situations, reduce residual risks, and improve user-centered design. Subsequently, a prospective investigation is proposed to identify courant limitations of VR. Finally, we analyze the role of Artificial Intelligence (AI), which could potentially address and overcome these limitations.**

Keywords-User Safety; Virtual Reality; Design Process; Artificial Intelligence."

I. INTRODUCTION

User safety represents a big challenge in industrial systems. Despite the application of European directives and harmonized standards, statistics show a continued prevalence of occupational accidents. In 2023, the EU recorded approximately 2.83 million non-fatal workplace accidents, while the number of fatal accidents reached 3,298 [1]. These findings have led research efforts to focus on the early integration of human factors into design processes. In this context, VR has emerged as a key technology for overcoming the limitations of traditional approaches based only on standards [2]. The advent of AI has further strengthened the potential of VR, enabling more advanced prevention strategies and more accurate simulations of both technical and human behavior.

In Section 2 user safety integration in design phase is presented and risk assessment in Section 3. In Section 4 the contributions of VR are presented and its limitations are discussed in Section 5. AI potential contributions are proposed in Section 6 before concluding in Section 7.

II. INTEGRATION OF USER SAFETY FROM DESIGN PHASE

User safety is still not sufficiently integrated into the design process of mechanical systems [3]. It is often addressed late in the development cycle after the completion of CAD models, primarily to comply with the technical requirements of standards such as ISO 12100:2010 and EN 614.

European standards (Machinery Directive, ISO 12100, ISO 13849) provide a structured methodological framework for risk analysis. However, they are based on assumptions about use situations that are often idealized and imagined by designers. As a result, they struggle to represent real operator activity, adaptive strategies, human variability, and contextual constraints. These limitations partly explain the persistence of residual risks after compliance has been achieved.

Moreover, industrial machines are becoming increasingly complex, and it is difficult to account for all operating conditions related to the environment or actual use due to their high variability. This rapidly creates a gap between the way designers envision system use—based on various simulations, including those performed using VR—and the use actually emerges in practice as shown in Figure 1.

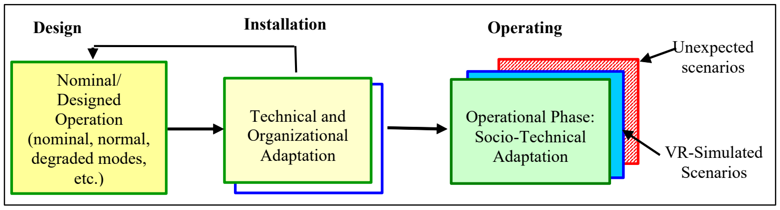

Figure 1. Evolution of the Gaps Between VR-Simulated Scenarios and the Real-Life System

Our involvement in this research problem aims to examine the impact that the integration of VR had on the design process of machines and industrial systems. Although standards are not static and evolve over time to better address designers' needs, and although VR can facilitate their application, we have observed that they are still predominantly applied during the final stages of the design process. This late integration tends to increase the complexity of the designed system

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(through the addition of sensors, barriers, etc.) and requires cumbersome procedures, thereby increasing the operator's workload. Furthermore, existing standards insufficiently address technological hybridity within a single system, particularly as systems are likely to evolve throughout their life cycle as shown in Figure 2.

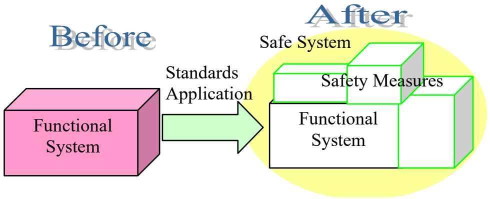

Figure 2. Current Integration of Standards Viewed as Increasing System Complexity

In general, a potentially hazardous phenomenon generated by a technical solution is delimited within a zone according to its nature. Depending on the phenomenon or phenomena present, this zone may be defined in terms of surface area or volume. This concept refers to any area inside and/or around a system in which a person is exposed to a risk of injury or adverse effects on health. Such a zone is generated, within a working situation [4], by a system or a component while performing a task or operating in idle mode.

The hazard zone can be identified at three levels:

- The most elementary level, corresponding to the technical solution that generates the hazardous phenomenon and zones.
- The system level, which represents the "assembly" dimension of technical solutions. At this level, hazardous zones defined at the first level may be modified or may even disappear. Figure 3 shows the effect of assembly options on the size and position of hazardous zones

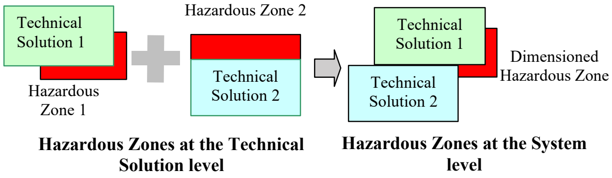

Figure 3. Dimensioned Hazardous Zones at the System Level

1. At the working situation level, the hazard zone does not exist prior to the installation of the system but results from the integration of the system at the site of use.

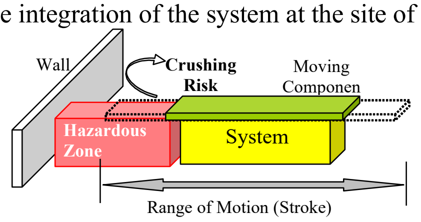

Figure 4. The Hazardous Zone in the Working Situation

Figure 4 shows installing a moving component in nearby a wall may create a hazardous zone due to the risk of crushing or trapping between the two systems, or between the moving component and the wall.

III. RISK ASSESSMENT

According to ISO 12100, risk Assessment is based on a combined analysis of, on one hand, the severity of potential harm and, on the other hand, the Frequency and duration of exposure to the hazard, as well as the technical and human Possibilities of avoiding harm. Figure 5 illustrates the parameters required for risk Assessment. Risk analysis and the selection of preventive measures have been detailed in [5]. The method enables designers and manufacturers to conduct risk analyses based on operators anticipated or foreseeable interventions, thereby identifying and implementing appropriate preventive measures for hazardous situations.

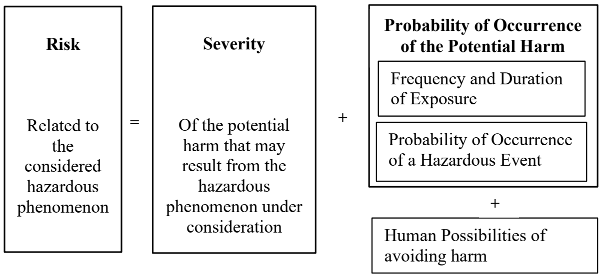

Figure 5. Risk Assessment Elements according to ISO 12100

The method suggests examining each operator task, operation by operation, in as much detail and concreteness as necessary. It involves listing the tasks and then performing a risk analysis by considering the various situations that could lead to harm. The designer is expected to anticipate resulting scenarios, including potential malfunctions, and to select appropriate preventive measures.

IV. CONTRIBUTIONS OF VIRTUAL REALITY

First of all, we should note that VR is not a normative method for risk assessment, but rather a tool that supports risk estimation, integrated into the design process of a machine or system.

VR has been widely used for the analysis and improvement of safety in industrial and intralogistics systems by integrating it into design, risk assessment, and training processes [3]. The authors clearly indicate that VR serves as a complementary or alternative technology to traditional approaches:

1. Enabling Immersive evaluation of hazards and countermeasures that are difficult to capture using standards alone.
2. Enabling the simulation of realistic working situations prior to machine manufacturing.
3. Offering the possibility of immersing operators, ergonomists, and designers in interactive virtual environments.
4. Facilitating the analysis of postures, gestures, movements, visibility, and accessibility.
5. Also allowing the identification of hazardous scenarios that are not anticipated by conventional normative risk analyses.

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As confirmed by [6], for existing working situations or for the design of new situations that are highly similar to existing ones, VR enables the simulation of degraded conditions (fatigue, cognitive load, etc.), realistic contexts (noise, reduced visibility, etc.), rare or hazardous events (failures, human errors, etc.), and non-linear sequences of actions. Real operating conditions, which are often excluded from normative models, thus become observable, repeatable, and measurable.

Reference [7] demonstrates that virtual environments can be used to simulate operator activities while assessing postural constraints and a variety of operational strategies. This indicates that VR facilitates the examination of actual behaviors (gestures, postures, etc.) under constraints, which is critical for analyzing the gap between prescribed and real work and for detecting emerging risks.

A. VR role in design process,

When integrated into the design process, VR becomes an early validation tool. In [8], the authors analyzed the impact of VR on the design process and proposed guidelines for its integration. They emphasize that the potential of VR strongly depends on human-centered approaches and thoughtful methodological integration, rather than on systematic or purely technological adoption. VR enables the testing of different machine configurations, layouts, and procedures, including emergent behaviors and complex contextual situations. User feedback collected in virtual environments contributes to refining the design before costly physical prototyping phases. This approach reduces late design iterations and enhances the robustness of the design from a safety perspective.

VR also plays a significant role in modeling and simulating user behavior around the designed system. In certain cases, when the expected performance is not achieved, VR allows designers to question the initial design assumptions and to identify the need for modifications. While VR can influence and support the evolution of Computer-Aided Design (CAD) models, this influence is not automatic in all cases. Rather, VR primarily serves as an immersive evaluation and feedback tool that guides design changes. By immersing designers and users in full-scale 3D CAD models with natural interactions, VR makes ergonomic, safety, and accessibility issues visible—issues that are not always detectable through conventional screen-based reviews or 2D inspections.

VR enables the simulation of actual system use by incorporating human variability (body size, reach, etc.), co-activity with other operators, and realistic environments (lighting conditions, obstacles). Observations made in VR provide actionable insights that can be used to adjust CAD models prior to physical prototyping. So, issues identified in VR can be annotated and directly communicated to the design team, thereby creating a feedback loop toward the CAD model [9]. In some software environments, it is possible to generate collision markers, ergonomic constraints, or physical limitations. The authors in [10] noted that VR and digital human modeling are commonly employed within the context of Industry 4.0 for ergonomic assessment. However, their application remains limited when it comes to evaluating physical ergonomics across the various phases of product development. In their study, the authors propose a set of design guidelines that integrate VR and digital human modeling in order to anticipate physical ergonomics evaluations of assembly processes while the product is still under development.

B. VR role in risk assessment

VR also plays a significant role in risk assessment, notably through the following contributions:

1. Identification and characterization of hazardous situations: VR enables the simulation of normal, foreseeable, and degraded use scenarios by visualizing human–machine interactions. This makes it possible to reveal hazardous phenomena related to kinematics, accessibility, and actual operator gestures. As a result, VR enriches the identification of hazardous zone and hazardous situations, which constitutes a prerequisite for risk assessment. In [11], the authors found that VR-based risk assessment constitutes a robust and effective alternative to traditional document-based or CAD-based approaches. Although differences in hazard identification were observed between simple and more detailed virtual models, the overall risk evaluation outcomes remained largely comparable across model complexities. Based on their results, the authors recommend a progressive increase in model fidelity throughout the different phases of machine development, enabling risks to be identified in an economically and operationally efficient manner.
2. Contributions to risk assessment process:
   a) Severity of harm. VR helps to understand where and how the human body is exposed by visualizing impact, crushing, or shearing zones. It also allows comparisons of potential severity across different design concepts.
   b) Frequency and duration of exposure. VR makes it possible to simulate task repetitiveness and to observe the actual time operators spend in hazardous zones. Different operational scenarios (production, adjustment, maintenance) can be tested, leading to a more realistic assessment of human exposure to hazards.
   c) Possibility of avoidance of harm. One of the major contributions of VR concerns the evaluation of avoidance possibilities. By visualizing available reaction times, escape paths, and constrained postures or human reflexes, VR enables a concrete assessment of avoidance potential—an aspect that is often poorly evaluated using drawings or static representations.
3. Comparison of design concepts: VR allows multiple solution architectures to be compared in order to estimate which design generates fewer hazardous zones, reduces exposure, and facilitates avoidance.

Although VR does not directly produce a normative risk level, it provides observations and usage scenarios, either anticipated by designers or derived from real work situations involving similar systems or machines. These elements support technical arguments that are subsequently formalized within the ISO 12100 risk assessment framework to guide design choices and risk reduction measures. Consequently, through the use of VR, risk assessment evolves from a purely documentary requirement into a decision-support tool for conceptual design.

V. CURRENT LIMITATIONS OF VR

Despite the strong contributions of VR to improving the performance of socio-technical systems, several recent scientific studies confirm that VR still faces substantial technical and economic barriers. These include limited hardware performance, high equipment and development costs, stringent technical requirements for integration and practical use, as well as constraints related to accessibility and maintenance. In the following, we discuss the current limitations of VR manifest at twelve levels detailed in the next 12 points :

1. Limitations related to VR itself and its use: [12] conducted a systematic review analyzing the use of VR (and Augmented Reality) for hazard detection and prevention. Their review highlights several methodological and technological limitations in current VR-based hazard recognition applications, including the lack of realistic scenarios, insufficient contextual learning, limited validation of results, restricted dynamic behavior of simulations, and persistent technological issues. These findings indicate that, although VR demonstrates strong potential in training, simulation, and design, such limitations continue to hinder its widespread adoption and generalization, particularly in industrial and safety-critical environments.
2. Limitations related to the maturity of design concepts: VR models used in early design phases are often incomplete or approximate. At upstream stages of the design process, kinematics are frequently hypothetical; velocities, masses, and inertias are not yet defined; and the materials and energy flows involved remain unknown or unquantified [13]. Under such conditions, VR may create an illusion of risk control, potentially masking unmodeled hazards such as vibrations, fatigue, or component failure. Consequently, while VR can make certain hazards visible, it cannot reliably quantify their severity, leading to possible underestimation of risk.
3. Limitations arise from the nature of risk assessment methods themselves: This is particularly evident in the qualitative treatment of harm severity, as real physical energies are often unknown during early design stages. The underlying physical dynamics and real-world energy levels are often unknown or insufficiently modeled at these stages [6]. The authors, demonstrate that although RV and virtual environments can be immersive and interactive, the fidelity of perception, movement, and physical relationships is constrained by current technologies. In other words, even when a hazardous situation is represented, the simulation does not necessarily reproduce the physical mechanisms, forces, energies and impacts that determine the actual severity of an accident. Additional challenges include the lack of realistic or contextualized scenarios and insufficient validation of results, which further limitations the reliability of VR-based risk assessment.
4. Limitations concern the integration of VR into the design process. During the early stages of product development, when such physical parameters are not yet fully defined or available. Strand [14] emphasizes that, VR environments often lack sufficient realism and functional depth to support detailed design tasks, particularly when accurate representation of physical interactions and energy levels is required. In [15], authors further argue that technical constraints directly influence how VR can be positioned within the design process, explaining why it remains complementary rather than substitutive. In [13], a systematic review of 49 papers emphasizes that although VR is used for certain design tasks, there is still no consensus or clear guidance on how to effectively apply VR during the conceptual design phase. This reflects the difficulty of handling immature or incomplete conceptual models in early design stages. They conclude that VR has not yet demonstrated a consistent and validated capability to manage such uncertainties. Similar conclusions are reported by [16], who highlight persistent challenges, including difficulties in assessing VR effectiveness during conceptual design, the lack of agreed-upon metrics for its use, and discrepancies between promising results and studies questioning its generalized effectiveness.
5. Limitations exist in capturing real work and actual user activity. Reference [17] describes an activity-centered ergonomic approach that distinguishes prescribed work from real work and emphasizes the analysis of real operational strategies. While this perspective strongly justifies the use of VR for activity analysis, it also highlights the difficulty of fully reproducing real gestures, adaptations, and decision-making processes in virtual environments.
6. Human and cognitive limitations affect VR-based evaluations. The perception of danger is subjective, and users may under- or overestimate risks depending on their expertise (expert versus novice). Extreme postures and compensatory strategies are often poorly anticipated. As a result, VR cannot guarantee homogeneous and objective risk evaluations. Reference [18] shows that VR alters functional body size perception and perceived distances due to sensorimotor distortions inherent to immersive systems (vergence, accommodation conflict). Reference [19] similarly demonstrates that spatial perception in VR is not strictly equivalent to reality, introducing depth and distance biases that can affect design decisions where spatial precision is critical.
7. The representation of the human body in VR is not neutral. Standardized anthropometries, idealized gestures, or the absence of real fatigue influence how users perceive hazards. In [20], the authors show that avatar morphology affects perceived affordances, while [21] demonstrates that manipulating virtual body size or shape (body ownership illusion) alters distance perception and motor judgments. Such biases have direct

implications for the evaluation of hazardous zones and safety distances.

8. Normative and regulatory limitations are substantial. VR cannot be considered proof of conformity, as standards such as ISO 12100 require formal analyses (FMEA, structured risk assessment, etc.). Consequently, VR results must be translated into normative frameworks. In [22], the authors analyze safety and privacy risks associated with XR technologies and argue for proactive regulation, highlighting the absence of harmonized standards addressing the intrinsic or extrinsic safety of VR systems in industrial contexts.
9. VR does not compute a regulatory risk level and cannot replace severity–frequency–avoidance matrices. It neither certifies compliance nor substitutes formal risk calculations. The European Parliament report on virtual worlds [23] underscores unresolved issues related to safety, responsibility, and legal frameworks. Reference [24] further shows that only a small proportion of VR safety studies rely on solid theoretical or normative foundations, and that standardized performance criteria and long-term evaluations are largely lacking.
10. Certification-related limitations remain critical. VR cannot be used to certify performance levels required by ISO 13849, as reliability calculations (MTTFd, DCavg, CCF) and documented validation activities remain indispensable. The standard does not recognize simulation alone as sufficient evidence for achieving required performance levels of safety-related control systems.
11. Economic and technical limitations constrain adoption, particularly for small and medium-sized enterprises. The combined costs of 3D modeling, usage scenario development, safety expertise, and VR implementation often result in limited return on investment. Technical challenges include limited interoperability between VR, CAD, and risk analysis tools, frequent updates, and the lack of automatic CAD model modification in most traditional systems. Although integrated platforms such as digital twins and immersive CAD environments (Siemens NX VR, Dassault 3DEXPERIENCE, Autodesk VRED) offer partial solutions. References [25] and [26] confirm that hardware limitations, high costs, interoperability issues, and user discomfort remain major obstacles.
12. Finally, immersive VR can have adverse effects on users. Reference [27] shows that even short immersive VR sessions can induce postural instability, disorientation, blurred vision, and nausea in vulnerable populations. More recent studies [28] and [29] report cybersickness, increased physiological stress markers, and decreased cognitive performance following prolonged VR exposure, indicating persistent effects that limit its use for precise or extended tasks.

In summary, a VR simulation constitutes a socio-technical system combining digital models, usage scenarios, and immersive human interaction to explore and analyze situations before they physically exist. While VR enables early anticipation of design and safety issues, it does not replace safety engineering practices or normative risk analysis, but rather complements them.

VI. ARTIFICIAL INTELLIGENCE CONTRIBUTIONS

VR has demonstrated significant potential for improving the integration of human factors and safety in the design of industrial machinery. However, as discussed in previous sections, VR presents several current limitations that reduce its effectiveness in early design phase and risk assessment. Artificial Intelligence (AI) offers targeted solutions to address these current limitations, enhancing VR's predictive, generative, and evaluative capabilities. Reference [30] highlights that, in high-risk training contexts, the integration of AI with VR significantly enhances the predictive, generative, and evaluative capabilities of VR-based simulations. So, AI could contribute to mitigate the ten key VR l current limitations cited above. In the following, we present the the nine identified potential contribution of IA.

1. Immature Models in the Conceptual Phase: To address models' limitations, AI could contribute to developpe predictive models based on machine learning and probabilistic reasoning. These models can estimate plausible ranges for velocities, masses, and inertias using historical databases of similar systems (case-based reasoning). Bayesian approaches could allow uncertainty to be explicitly modeled, generating risk envelopes rather than single-point estimates [31]. Additionally, AI could automate labor-intensive tasks such as scenario generation, collision detection, and postural analysis, reducing dependence on human expertise. These approaches enable a transition from deterministic simulations to informed, uncertainty-aware VR simulations, making VR scalable and more applicable in industrial contexts, including SMEs.
2. Difficulty in Quantifying Harm Severity: To address this boundary, AI Contribution manifest by coupling AI with biomechanical models allows the estimation of indirect harm indicators, such as probable impact zones, applied forces, and likely injury scenarios [32]. Learning from accident databases links geometric configurations to expected severity levels. So, AI could transform immersive observation into reasoned severity metrics, providing actionable data for risk evaluation.
3. Lack of Realistic and Contextualized Scenarios: Although VR scenarios may involve automated animations or scripted behaviors, they are most often manually designed at a conceptual level. The selection of situations, events, and interactions is typically driven by expert assumptions rather than generated autonomously by the system., failing to account for rare events, human errors, or co-activity, AI techniques such as reinforcement learning and automated planning can generate realistic, context-aware scenarios, including extreme or non-intuitive sequences that designers may overlook [33]. This could evolve VR from an illustrative tool to a generative and exploratory environment, expanding the scope of risk analysis.
4. Difficulty Integrating VR into the Design Process: Although guidelines exist for integrating VR into the

design process [8], industrial adoption remains heterogeneous. AI could function as a meta-decision layer, linking VR, CAD, and risk assessment workflows. Recommendation systems could suggest optimal VR interventions based on design maturity and development stage. So, AI could enable systematic integration of VR into the design process, enhancing coordination rather than supporting isolated applications.

5. Incomplete Representation of Real Work: While VR struggles to replicate real operator strategies and task variability, AI could learn from field data (videos, sensors, industrial log, etc.) to model real operator behaviors. Behavioral AI could simulate diverse profiles, accounting for expertise level, fatigue, and stress. So, VR simulations could become more accurately reflect real-world operations, bridging the gap between prescribed and actual work.
6. Human Subjectivity and Cognitive Biases: Hazard perception naturally varies across users, which can lead to inconsistent risk assessments in VR alone. By integrating AI, VR can be enhanced with quantitative indicators—such as exposure time, minimum distances, and joint angles—providing additional insights to support evaluation. AI can help identify potential perceptual biases and highlight critical aspects of operator behavior, strengthening the objectivity and reliability of VR-based assessments while complementing expert judgment.
7. Lack of Regulatory Recognition: VR alone cannot serve as proof of compliance with standards. However; AI could translate VR observations into structured, traceable normative arguments aligned with ISO 12100 and other regulations, supporting formal risk analyses. So, AI could act as a bridge between VR insights and regulatory frameworks, complementing but not replacing formal requirements.
8. Inability to Certify Safety Functions (ISO 13849): because VR cannot substitute for reliability calculations required for certification. the use of AI could prioritize critical safety functions for detailed analysis and detect risky system architectures early, guiding subsequent certification efforts to facilitate informed decision-making during certification planning without replacing formal compliance processes.
9. VR significant technical and economic burdens: Implementing VR in industrial design and safety assessment is resource-intensive, requiring substantial hardware, software, modeling, and expert personnel to create realistic scenarios, detect collisions, and evaluate operator postures. AI can mitigate these technical and economic burdens by automating time-consuming tasks, such as scenario generation, collision detection, and postural analysis. Machine learning and procedural generation methods can create a wide variety of realistic operational scenarios with minimal human input, while AI-driven algorithms can identify potential hazards automatically. This reduces reliance on highly specialized personnel and accelerates the evaluation workflow. As a result, VR becomes more scalable and industrially applicable, particularly for small and medium enterprises that have limited resources. By lowering labor costs and increasing the throughput of VR-based analyses, AI enhances the return on investment and facilitates broader adoption of VR for safety and design purposes.

These non-exhaustive identified potential contributions of AI need more explication about how they could be applied, to be verified an validated.

VII. CASE STUDY

This case study considers the early design phase of a semi-automated industrial packaging machine. The objective is to show how VR supports early safety assessment and how Artificial Intelligence (AI) can enhance current limitations.

Step 1: VR-Based Safety Assessment

A VR environment is created from preliminary CAD models, enabling immersive simulation of operator–machine interactions. Designers and safety engineers can explore operating and maintenance scenarios, identifying hazards such as collision risks, poor visibility, or non-ergonomic postures. This approach enables: early detection of safety and ergonomic issues, improved collaboration between stakeholders, and iterative design refinement at reduced cost. However, limitations persist: operator behaviors are often predefined, scenario coverage is limited, and risk assessment relies heavily on expert judgment.

Step 2: AI Contributions: in this case AI can be introduced to enhance VR-based safety assessment in three key areas:

1- Scenario Generation: Machine learning techniques can automatically generate diverse operating conditions, including rare or unexpected situations (e.g., abnormal machine states or emergency interventions). This improves the coverage of risk analysis beyond manually defined scenarios.

2- Behavioral Realism: AI models enable more realistic simulation of operator behavior by incorporating variability, reaction times, and non-ideal actions. This allows better representation of real-world human–machine interaction.

3- Risk Identification Support: AI can analyze interaction data within the VR environment to detect hazardous patterns, such as repeated proximity to dangerous components or unsafe sequences of actions. This supports systematic and data-driven risk identification.

Step 3: Linking VR and AI techniques: AI techniques, particularly in natural language processing, may assist in interpreting safety standards and linking them to design features. In this case, such tools could help identify applicable requirements and guide early design decisions, reducing the risk of non-compliance.

We could note that the combined use of VR and AI enables a more proactive approach to safety integration by shifting risk assessment to earlier design stages. Key benefits include improved hazard detection, increased scenario diversity, and enhanced decision support. However, challenges remain, including the need for high-quality

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training data, integration into existing design workflows, and validation of AI outputs in safety-critical contexts. Therefore, the approach should be seen as complementary to traditional safety methods rather than a replacement. This case study demonstrates the potential of combining VR and AI to enhance early operator safety assessment in industrial machinery design. While conceptual, it provides a realistic illustration of how these technologies can improve current practices and supports future work toward implementation and validation.

VIII. CONCLUSION ET FUTURE WORK

VR represents a significant lever for enhancing the integration of human factors and operator safety in the design of industrial machinery. Complementing European standards, VR enables better anticipation of real work situations and reduces residual risks. While it does not replace regulatory frameworks, VR allows concrete verification of preventive measures defined through normative risk assessment and introduces an experimental, human-centered dimension that strengthens both functional compliance and user acceptability.

The systematic integration of VR into design processes offers a promising avenue for more proactive, user-centered safety. However, the limitations identified—technical, methodological, human, and regulatory—highlight the need for further research to mitigate these constraints. In particular, the integration of AI could enhance VR by generating and analyzing a wider range of usage scenarios, including hazardous situations, thereby supporting more comprehensive risk assessment.

Future developments combining VR, advanced digital models, and AI offer the potential for dynamic and predictive risk evaluation. By incorporating human variability and real operating conditions, these approaches can further improve accident prevention and reduce work-related musculoskeletal disorders at the earliest stages of design. In future work, such advancements will be positioned VR/AI as a critical tool that need evaluation and validation for the next generation of human-centric, safe industrial systems.

REFERENCES

[1] [Europa.eu 2025], "Rapport on virtual worlds – opportunities, risks and policy implications for the single market" https://www.europarl.europa.eu/doceo/document/A-9-2023-0397_EN.html, 2026.04.17.

[2] K. Lewczuk and P. Żuchowicz, “Virtual Reality Application for the Safety Improvement of Intralogistics Systems”, Sustainability, vol. 16 issue. 14, 6024. doi.org/10.3390/su16146024, 2024

[3] L. Valentini, V. Weistroffer, F. Grandi and M. Peruzzini, “Digital toolkit for human-centered machine design: development and testing of an innovative system integrating virtual reality and HMI digital prototypes”, *Int J Adv Manuf Technol*, 2025. doi.org/10.1007/s00170-025-16943-4.

[4] R. Hasan, A. Bernard, J. Ciccotelli and P. Martin, “Integrating safety into the design process: elements and concepts relative to the working situation”, Safety Science. Vol. 41, Issues 2–3, 2003, pp 155-179, doi.org/10.1016/S0925-7535(02)00002-4.

[5] M. Compare, E. Zio, E. Moroni, G. Portinari and T. Zanini, “Development of a methodology for systematic analysis of risk reduction by protective measures in tyre production machinery”, Safety Science, Vol. 110, Part A, 2018, Pages 13-28, doi.org/10.1016/j.ssci.2018.07.027.

[6] G. Personeni and A. Savescu, “Ecological validity of virtual reality simulations in workstation health and safety assessment”, Front. Virtual Real., 16 February 2023 Sec. Virtual Reality in Industry, Vol. 4, 2023, doi.org/10.3389/frvir.2023.1058790.

[7] M. Zare, N. Bert, M. Norval, J. C. Sagot and A. Garrigou, “Diversité des stratégies opératoires en situation réelle et en environnement virtuel”, Archives des Maladies Professionnelles et de l'Environnement, Vol. 86, Issue 3, 2025 doi.org/10.1016/j.admp.2025.102855.

[8] S. Stadler, and J. R. Chardonnet, “Embracing virtual reality: Empowering professionals in the design process”, CRC Press, (2024), doi 10.1201/9781003306078-2

[9] A. Prinz, K. Y. Lee, A. Gupta, S. Park and D. Göhlich, “CAD in Virtual Reality: Integration of Solid Modeling in Standalone VR Application”, Proceedings of the Design Society. 2025;5:831-840. doi:10.1017/pds.2025.10097.

[10] A. G. Silva, et al., “Design Guidelines for Combining Digital Human Modeling and Virtual Reality to Foresee Workplaces Ergonomics Issues During Product Development”, Applied Sciences, 15(13), 2025, doi.org/10.3390/app15137083.

[11] P. Puschmann, T. Horlitz, V. Wittstock and A. Schütz, “Risk Analysis (Assessment) Using Virtual Reality Technology - Effects of Subjective Experience: An Experimental Study”, Procedia CIRP, Vol. 50, 2016, Pages 490-495, doi.org/10.1016/j.procir.2016.04.115.

[12] T. Faiz, M. T. K. Tsun, A. Mahmud, and K. Y. A. Sim, “Scoping Review on Hazard Recognition and Prevention Using Augmented and Virtual Reality”, Computers, 13(12), 307, 2024, doi.org/10.3390/computers13120307.

[13] T. Liao and J. She, “How does virtual reality (VR) facilitate design? A review of VR usage in early-stage engineering design”, Proceedings of the Design Society. 2023, 3:2115-2124. doi:10.1017/pds.2023.212.

[14] I. Strand, “Virtual Reality in Design Processes: - a literature review of benefits, challenges, and potentials. Form Akademisk”, vol. 13, issue 6, 2020, doi.org/10.7577/formakademisk.3874.

[15] F. V. De Freitas, M. V. M. Gomes and I. Winkler, “Benefits and Challenges of Virtual-Reality-Based Industrial Usability Testing and Design Reviews: A Patents Landscape and Literature Review”, Applied Sciences, vol. 12 issue 3, 2022, doi.org/10.3390/app12031755

[16] A. Abughalia, C. Stechert, “A Decade of Virtual Reality in Product Development: A Literature Review of Effectiveness, Challenges, and Future Research”, Procedia CIRP, Vol. 136, 2025, Pages 438-443, doi.org/10.1016/j.procir.2025.08.076.

[17] F. Barcellini, M. Cerf and M. Lacomblez, "Developmental foundations of Activity-Centered Ergonomics: knowledge encounters to construct both a critical analysis of work and developmental set-ups". Ergonomics. 68 (6): pp. 813–831, 2025, doi:10.1080/00140139.2024.2415965.

[18] X. M. Wang, A. Mazalek, C. M. Sabiston, T. N. Welsh, “Virtual Reality Alters Perceived Functional Body Size, Human-Computer Interaction”, arXiv:2510.00824, 2025, doi.org/10.48550/arXiv.2510.00824.

[19] G. Kurpinar et al., “On the strengths and weaknesses of virtual reality in distance estimation in AEC domain: a meta-analysis of literature 2014–2024”. Virtual Reality 30, 27, 2026, doi.org/10.1007/s10055-025-01276-0.

[20] T. Akkoc, E. Ugur, and I. Ayhan, “Trick the Body Trick the Mind: Avatar representation affects the perception of available action possibilities in Virtual Reality”, Human-Computer Interaction, 2020, doi.org/10.48550/arXiv.2007.13048.

[21] H. Ryu and K. Seo, “The illusion of having a large virtual body biases action-specific perception in patients with mild cognitive impairment”. Sci Rep 11, 24058, 2021, doi.org/10.1038/s41598-021-03571-7.

[22] Hine, E. et al., “Safety and Privacy in Immersive Extended Reality: An Analysis and Policy Recommendations”. DISO vol.3, issue 33, 2024), doi.org/10.1007/s44206-024-00114-1

[23] Europarl 2023, Website, https://www.europarl.europa.eu/doceo/document/A-9-2023-0397_FR.html?utm_source=chatgpt.com. 2026.04.17.

[24] D. Scorgie, Z. Feng, D. Paes, F. Parisi and T. W. Yiu, “Lovreglio R., (2024) Virtual reality for safety training: A systematic literature review and meta-analysis”, Safety Science, Vol. 171, 2024, doi.org/10.1016/j.ssci.2023.106372.

[25] Y. Yang, “Technical Challenges Affecting the Popularization of Virtual Reality Technology”, Proceedings of International Conference on Mechanics, Electronics Engineering and Automation (ICMEEA 2024), Advances in Engineering Research 240, doi.org/10.2991/978-94-6463-518-8_26.

[26] A. D. Samala et al., “Virtual reality in education: global trends, challenges, and impacts game changer or passing trend?”. Discov Educ 4, 229 (2025). doi.org/10.1007/s44217-025-00650-z.

[27] M. Pau et al., “Cybersickness in People with Multiple Sclerosis Exposed to Immersive Virtual Reality. Bioengineering (Basel)”. 2024 Jan 24;11(2):115. doi: 10.3390/bioengineering11020115. PMID: 38391601; PMCID: PMC10886275.

[28] S. Vlahovic, L. Skorin-Kapov, M. Suznjevic, and N. Pavlin-Bernardic. “Not just cybersickness: short-term effects of popular VR game mechanics on physical discomfort and reaction time”, Virtual Reality 28, 108 (2024). doi.org/10.1007/s10055-024-01007-x.

[29] D. Zielasko, B. Rehling, B. Von Dawans, and G. Domes, “Do Not Immerse and Drive? Prolonged Effects of Cybersickness on Physiological Stress Markers And Cognitive Performance”, doi.org/10.48550/arXiv.2506.11536.

[30] P. Fernández-Arias, A. Del Bosque, G. Lampropoulos, and V. Vergara, “Applications of AI and VR in High-Risk Training Simulations: A Bibliometric Review”, *Applied Sciences*, *15*(10), 2025, 5424, doi.org/10.3390/app15105424.

[31] Y. Gal, P. Koumoutsakos, F. Lanusse, G. Loupe, C. Papadimitriou “Bayesian uncertainty quantification for machine-learned models in physics”, *Nat Rev Phys* **4**, 573–577, 2022, doi.org/10.1038/s42254-022-00498-4.

[32] Y. Jiang et al., “Analyzing Crash Severity: Human Injury Severity Prediction Method Based on Transformer Model”, *Vehicles*, *7*(1), 5, 2025, doi.org/10.3390/vehicles7010005.

[33] C. Lu, "Test Scenario Generation for Autonomous Driving Systems with Reinforcement Learning", 2023 IEEE/ACM 45th Proceedings (ICSE-Companion), Melbourne, Australia, 2023, pp. 317-319, doi: 10.1109/ICSE-Companion58688.2023.00086.