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Human-centred data-driven redesign of simulation-based training: a qualitative study applied on two use cases of the healthcare and industrial domains

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# Human-centred data-driven redesign of simulation-based training: a qualitative study applied on two use cases of the healthcare and industrial domains

**Abstract.** Among the main features of Industry 4.0, digitization and the evolution of the human-machine interaction occupy a central role. These concepts are transferring even in the health domain, moving toward Healthcare 4.0. The new concept of Industry 5.0 further promotes the human-centric perspective focusing on the consideration of human factors. In this context, training for workers, both in the industry and in the healthcare sectors, needs to be strongly human-centred to be efficient and effective.

This paper refers to simulation-based training and aims to provide a transdisciplinary framework for the simulation assessment from the learners' perspective. The final scope is to outline a set of data-driven guidelines for the simulation optimization and redesign, throughout a human-centred approach, aiming to improve the workers' performance and the overall learning process, considering the physical, cognitive, and emotional conditions. The proposed method is suitable for each kind of training (both traditional and with the use of virtual reality/augmented reality systems) and relevant for every sector. Two different use cases are presented, respectively referring to the healthcare and industry fields, proposing a unique assessment protocol. The healthcare use case considered the low-fidelity simulation of lumbar puncture, while the industrial use case referred to the replacement of the engine oil filter on tractors. Although the great differences between the content of the use cases, Table 4 the results obtained about performance as well as cognitive and emotional states are close enough to define a common set of guidelines to redesign and optimize the simulation-based training.

**Keywords.** Healthcare 4.0, Industry 4.0, Simulation-based training, Design optimization, Human Factors, Ergonomics.

# 1. Introduction

The fourth industrial revolution, i.e., Industry 4.0 (I4.0), closely refers to a disruptive change in the production systems thanks to the integration of novel technologies into manufacturing processes, such as the information and communications technology (ICT), Internet of Things (IoT), Cyber Physical System (CPS), Enterprise Integration (EI), and Enterprise Architecture (EA). In Industry 4.0, advanced physical machineries are integrated with networked software and sensors, with the final aim of adding value and knowledge to the industrial processes and thus obtaining better economical and societal outcomes [1]. In a broader meaning, besides the enabling information and communication technologies involved, the fourth industrial revolution also includes aspects of enterprise management, work organization, and training. Among the main features of I4.0, digitization and the evolution of the human-machine interaction (HMI) occupy a central role: the concept of digital twin can make processes smarter and more efficient [2], automation is no longer merely technology-oriented but also human-oriented [3], interfaces can be adapted to the users' needs and the contextual issues [4], in order to make data exchange and communication more automatic and intelligent. These concepts are transferring even in the health domain, moving the eHealth and its environment towards the concept of Healthcare 4.0 (HC4.0) [5]. New efficient solutions to mitigate and overcome long-lasting healthcare issues can be developed thanks to the use of IoT, Big Data analysis, Cloud and Fog Computing, and related technologies. Within this perspective, the main health-related application scenarios include the monitoring of physiological and pathological signals for the self-management, wellness and disease monitoring, the personalized healthcare, cloud-based health information systems, rehabilitation, telemedicine, and assisted living [5].

Moreover, the new concept of Industry 5.0 (I5.0) recently introduced by the European Commission further promotes the human-centric perspective. I5.0 promotes more skilled jobs compared to I4.0, based on the integration of the human brainpower and cognitive thinking with the intelligent systems already introduced in the factory through I4.0 [6]. I5.0 asks for a human-centric design solution that focuses on the consideration of human factors with the technologies within industrial systems [7]. Among the feasible applications of I5.0 concepts, the authors want to mention the intelligent healthcare and the education domain. For the first one, it is possible to imagine the use of collaborative robots for complicated surgeries, as well as routine check-ups. The use of intelligent wearable devices (e.g., smartwatches, sensors, etc.) can constantly record the patients' health-care data in real-time and machine learning algorithms can then be applied for the diagnosis [8]. Concerning the education domain, I5.0 pushes for better-trained specialists to foster an effective, sustainable, and safe production. In [9] authors question if the traditional education is enough to educate a worker in the I5.0 era or if an improved education system is needed. Indeed, the operator requires making decisions in fields such as robotics and artificial intelligence, and this is only possible with the education 5.0 skills (i.e., the fusion of technology and communication and leadership) [10].

Therefore, it is clear how the human role gains greater importance shifting from I4.0 to I5.0. Tasks become increasingly shared between humans and machines, requiring not only new models to manage and control the processes [11] but also to understand and consider the users' needs [12], according to human-centred approaches [13, 14]. Indeed, while the operators need to control the processes and advanced intelligent machines, they face not only low-level physical tasks but also high-level mental tasks (e.g., problem-solving, abstraction, managing) with a consequent increment of the cognitive load [15]. In this context, the operator can be supported with technical solutions, such as virtual reality (VR) [16] or augmented reality (AR) applications [17, 18], able to supply real-time relevant data that may reduce the dependency on the operator memory and decrease human errors. The same considerations remain valid also in the Healthcare 4.0 context, where the convergence of AR and the IoT in smart glasses (used during surgeries, education, etc.) is another observable trend [19]. In the meantime, the need for adequate training of workers, both in the industrial and the healthcare sectors, arises. To be efficient and effective, training needs to be strongly

human-centred. Consequently, the analysis of Human Factors (HF) assumes critical importance in understanding whether and how the training procedure is supporting the workers to leverage their skills effectively. Moreover, wearable devices can be used to monitor workers' conditions under stressful or difficult situations, and proper warnings should be provided when needed [20].

Training activities and the use of innovative technologies can impact the workers' cognitive conditions and performance. For this reason, the enabling technologies, spread during the fourth and fifth industrial and healthcare revolutions, should be exploited to collect workers' data, useful for the optimization and customization of the working environment, as well as of the training paths. Human-in-the-loop models would guide the working and training conditions redesign, in a human-centred vision. Indeed, as suggested in [21], the education should be redesigned focusing on human-centric, transdisciplinary aspects, and analysing the human-agent/machine/robot/computer interaction. Also, the monitored and collected workers' data could be used to develop data-driven, real-time changing training simulations, to customize the educational experience towards a more effective and engaging activity. In this context, the present work aims at exploring and investigating the technological devices, protocols, and data analysis that would serve as a common basis for the study of the variables that affect human performance, physical, cognitive, and emotional conditions during simulation-based training, in several contexts. It is presented as a qualitative study to better show the applicability of the proposed protocol and set-up in different fields; in particular, the presented use cases refer to the healthcare and industrial domains, but, for example, also simulation-based training for firefighters, soldiers, drivers would benefit from this approach.

## 2. Research Background

Human Factors and Ergonomics (HF&E) have been introduced in engineering to add the physical, psychological, social, and cultural needs of human beings, to the mechanical, electrical, and manufacturing requirements considered during the product/system design [22]. Moreover, HF&E is fundamental also in the evaluation of the human-machine interaction and the evaluation of the user experience (UX), helping in the improvement of human performance, the optimization of physical and mental workload, comfort, and perceived effort, and the reduction of the risks associated with user errors. In particular, ergonomics is indispensable in this context, concerning the design of systems, machines, or interfaces, based on the users' needs and requirements [23]. The human factors integration (HFI) [24] pushed to adopt the most suitable technologies to validate the new processes and create new interaction features to valorise human capabilities [20]. To optimize the workers' wellbeing and improve, at the same time, the working conditions and expected results, HFI applies the data related to users' needs, limitations, and ergonomics within the design engineering process. Nevertheless, today the main challenge is to understand how to effectively implement HFI by selecting the most proper techniques to evaluate the UX and the human-machine interaction according to the specific context of application, to mutually enhance the system performance and the workers' wellbeing [25, 26].

For some decades, simulation has been used for educational purposes in several fields. It is defined as an imitation of a real system, supplied with or without VR/AR systems, able to mimic the real situation both in practical and behavioural contents. Indeed, its main advantage is the opportunity to involve the participants in a very immersive experience, avoiding the risks that would arise in real situations. For this reason, simulation is considered an excellent tool to reduce errors in high-risk industries (e.g., aviation, defence, nuclear energy), and even healthcare.

It has been demonstrated that physical and cognitive ergonomics strongly impact manufacturing performance, and, consequently, factory productivity. Indeed, prolonged sensations of outrageous mental effort and stress may result in the user's burnout, lower performance, and reduced productivity [27]. For these reasons, training sessions should be designed based on the operators' cognitive and physical needs, to

improve the quality of human-machine interaction and, finally, the workers' performance. Indeed, for human performance optimization, it is fundamental to avoid stressful physical and mental conditions, and cognitive under- and over-loads. For this reason, the analysis of physical and cognitive ergonomics is becoming more and more indispensable, even in the industrial sector.

On the other side, the healthcare industry has begun to use simulation because it allows repeatedly practicing simulated complications without putting the patient at risk, thus, consequently, reducing the chance of bad outcomes in the real practice [28]. Moreover, beyond the learning of practical procedures and technical skills, simulations also offer the healthcare staff the opportunity to learn several non-technical skills such as clinical decision-making, situation awareness, team working, and communication skills. For this reason, simulation-based training is considered an optimal solution for preparing and assessing human responses to real-life problems: it provides the opportunity to experience realistic training in terms of both clinical practice and stress management.

The stress role in the simulation context is crucially important together with the cognitive load. Indeed, during simulations, the participant is simultaneously exposed to the realism of the event, and to the demand to execute the correct intervention. Concerning the stress, while its feeling should be similar to that one felt in real practice, in the meantime, it should be maintained within certain limits, avoiding acute stress, which can compromise the performance and post-traumatic stress disorders. Regarding the mental effort, it should be balanced to avoid, on one side, low levels of attention, and, on the other side, cognitive overload which may compromise the learning path and the acquisition of new skills. In this context, the importance of a transdisciplinary approach to analyse the impact of training simulations on learners' stress, cognitive load, perceptions, workload, and performance is undeniable. Indeed, only with a comprehensive methodology, it would be possible to study the effectiveness of the training simulation from the students' perspective.

Psychological fidelity is considered very critical and more important for learning and transfer than the other dimensions of fidelity [29]. Accurately reproducing stressful conditions is one of the most fundamental and challenging aspects of simulation design. During the design of simulations and simulators, great attention must be placed on the realism and feeling of immersion. Also, the inclusion of pedagogical and psychological expertise in the design and development of educational devices is essential [30]. The pedagogical framework, that characterizes the simulation-based training, allows the students to experiment with the same workflow and workload that they would experience in real practice [31]. The design of training simulations passes through a careful analysis of learning objectives, technology to be used, instructor role, performance assessment, and so on.

The cognitive conditions and emotional states (such as stress, anxiety, frustration, effort, etc.) of learners must be considered before, during, and after the simulation, to understand its effect on such conditions. According to ISO 10075-3 [32], the mental workload can be measured through performance assessment methods, self-assessment methods, and physiological measurements methods. Among the three different assessment techniques, the performance measures (in terms of task completion time and error rate) are used in most of the works related to training in the industrial field [33, 34, 35], while the self-assessment method is the most applied in the healthcare simulation field [36]. The self-assessment provides information on how humans subjectively evaluate various aspects of workload for accomplishing a task, using questionnaires or psychometric scales. The NASA Task Load Index (NASA-TLX) is the most used tool for workload subjective assessment. It consists of a multidimensional questionnaire that rates perceived workload under six different dimensions: mental, physical, and temporal demands, performance, effort, and frustration levels [37]. However, subjective user ratings can be misleading metrics of simulation effectiveness [38]. The class of physiological measures considers physiological responses of the body that are believed to be correlated with the cognitive load. Indeed, changes in psychophysiological parameters, such as heart rate (HR), heart rate variability (HRV), electrodermal activity (EDA), breathing rate (BR), brain activity (EEG), muscular activity (EMG), eye activity (EOG, pupil diameter, gaze entropy, and velocity), can be indirect

indicators of mental workload. However, even the physiological measures can be affected by physical activity or external factors, not related to the mental effort needed to perform the task. For this reason, it is important to combine different classes of measurements, to cope with the singular limitations of each one. According to the ISO 10075-1 [39], psychological stress is the effect of all conditions with a mental impact on a subject, either cognitive or emotional. It emerges when the perceived demands of the environment exceed a person's ability to cope with these demands [40]. Commonly recognized stressors include technical complications, time pressure, distractions, interruptions, errors, and increased workload [41]. Also, for the detection of psychological stress four main criteria are used [32]: psychological, physiological, behavioral, and biochemical. The most common analyses typically include the subjective assessment based on self-reports (such as the State-Trait Anxiety Inventory (STAI) [42] or the Numerical Analogue Scale (NAS) [43]) and physiological assessment based on HR and EDA monitoring. Examples of the application of physiological measurements exist in the literature [44,45], but they are not widespread. For these reasons, it is evident the need of including a multi-dimensional assessment.

Moreover, even the ergonomics of the simulation room and instruments' layout must be considered both in relation to the cognitive and physical demands of learners. Physical effort assessment mainly refers to the study of the postures assumed by the workers and the effort in handling loads, tools, and equipment, also considering the operating spaces and the workstation layout. Among the several assessment methods, the most applied ones are the Rapid Upper Limb Analysis (RULA), the Rapid Entire Body Assessment (REBA), the Ovako Working posture Analysis System (OWAS), the Occupational Repetitive Actions (OCRA) analysis, and the NIOSH equation for handling tasks [46]. The acquisition of the data necessary to perform the analysis has been based, for decades, on the direct observation of the worker during the execution of a specific task, by an experienced ergonomist. In recent years, the spread of motion capture devices has been exploited to automate this phase, with considerable benefits in terms of time, costs, and accuracy of results [47].

Even if education in healthcare focuses on high-stakes environments and the acquisition of complex manual and cognitive skills, human factors are not well integrated and adopted into medical training [48]. Indeed, the number of successful implementation and development of medical simulations is relatively small compared with the manufacturing industry. However, even a proper assessment of the operator's cognitive response in terms of stress and mental load during simulation training is still lacking [27]. Therefore, it emerges the need for data acquisition for the simulation training effectiveness assessment, and consequent optimization and redesign, from a user-centred design perspective.

This paper refers to the use of training simulations and aims to provide a transdisciplinary framework for the simulation assessment from the learners' perspective. In the study, the simulation is low-fidelity and consists of the imitation of a real system on physical mock-ups, without the use of VR/AR technologies. Indeed, the adoption of virtual tools could introduce further effects and increase the complexity of the UX assessment. Thus, in this study, we prefer to focus on physical simulations. The final scope is to outline a set of data-driven guidelines for the simulation optimization and redesign, throughout a human-centred approach, aiming to improve the workers' performance and the overall learning process, considering the physical, cognitive, and emotional conditions. The proposed method is suitable for each kind of training (both traditional and with the use of systems for VR/AR) and relevant for every sector (not only the industry and healthcare). The proposed framework aims at measuring the quality of training in terms of performance as well as the UX considering the cognitive and emotional states of the trainees and defining specific guidelines to optimize the simulation-based training. Further development of the proposed simulation-based setup could include also VR/AR technologies.

### 3. Method

#### 3.1 Assessment Framework

To assess the simulation training effectiveness, several transdisciplinary aspects have to be analysed before, during, and after the simulation (Figure 1). Based on this accurate and extensive assessment, it is then possible to outline the recommendations to redesign and optimize the simulation. However, first, the simulation's features must be defined. Once the learning objectives and pedagogical content have been specified, several items need to be determined:

- Simulation's setting and layout: detailed definition of the simulation setting in terms of room characteristics, equipment, and tools to be used. It has to be specified how and where instruments must be placed following safety and ergonomics guidelines. Also, eventual digital/virtual content must be considered and properly designed;
- Simulator and technology: identification of the simulator and its specific characteristics (e.g., level of fidelity, haptic features, type of interaction with the learner), and eventual devices for VR and AR applications;
- Instructor's and learners' roles: detailed definition of assignments and tasks to be accomplished by the learners and by the instructor during the simulation, and the interaction among them.

All these items should be redesigned and optimized through the analysis of learners' data collected before, during, and after the simulation, as shown in Figure 1.

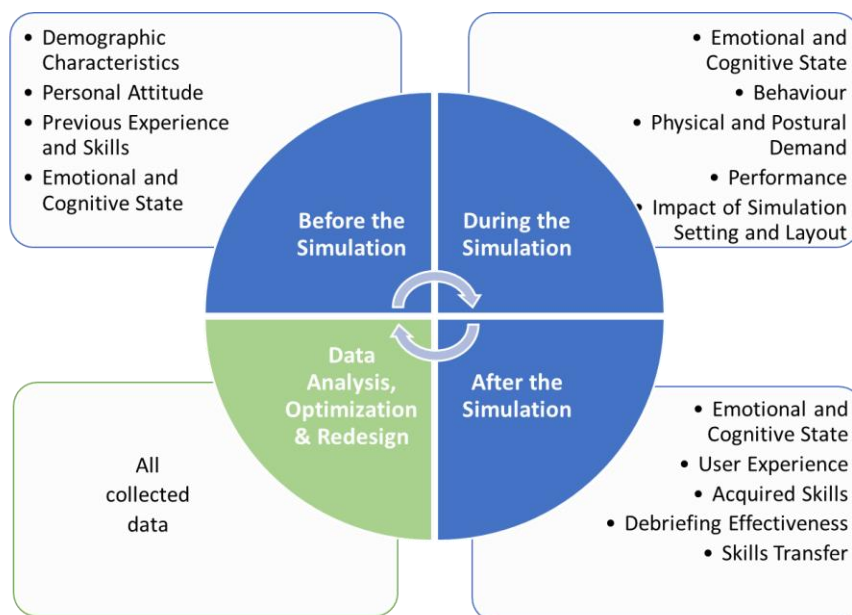


Figure 1: Human-centred redesign and optimization framework for simulation-based training

This framework has been proposed to support the redesign of simulation-based training in different contexts: it allows the simultaneous analysis of both the physical and cognitive workload of learners, their emotional conditions and experience, their performance, and the acquired skills, before, during, and after the simulation. Since the mental and emotional conditions of the learner may depend on factors external to the simulation, the assessment goes through the different training phases and allows the data comparison and the discrimination of the simulation's features that affect the learner's state and performance.

The collected data mainly refer to subjective assessment of cognitive and emotional states (e.g., through the administration of surveys such as NASA-TLX, STAI, NAS for stress assessment, UX structured questionnaire), the collection of physiological parameters (e.g., heart rate, heart rate variability, electrodermal activity, pupil diameter), the analysis of users' movements and postural conditions for the objective analysis of stress,

cognitive, and physical workload, and specific performance indicators (e.g., number of committed errors, task execution time, number and correctness of the acquired skills, request of assistance).

### 3.2 Technological set-up

The method, and, as a consequence, the technological set-up, has been designed to be less intrusive as possible for the learner. Indeed, if the technological set-up is not properly defined, it may influence the physical and cognitive perception, altering the overall performance and skills acquisition. For this reason, the set-up should involve the minimum set of non-invasive wearable devices for the monitoring of motions and physiological parameters. **Table 1** shows some examples of suitable smart devices:

*Table 1: Smart devices for data acquisition*

	Collected variables	Examples of commercially available devices	Notes
Cognitive domain			
Smart chest band or bracelet	HR, HRV, EDA monitoring	Zephyr BioHarness: chest band that allows the recording of HR, HRV, BR, temperature, acceleration, and posture.	It is suggested to select only one of these devices to avoid learners complaints due to the wearing of such technologies, and consequently, the worsening of the performance.
		Empatica E4: light wristband, similar to a smartwatch, able to measure EDA, skin temperature, Blood Volume Pulse (BVP) from which the HR and IBI can be derived	
Smart glasses	Eye-tracking	Tobii Pro Glasses 2: equipped with four infrared cameras that records eye movements. The system consists of the head unit (glasses) and the recording unit, in which are stored batteries, and an SD memory card. A full HD camera in the head unit provides the user point of view. They are also equipped with a microphone, accelerometers, and gyroscopes to track head movements.	Even if several devices are available, a wearable eye-tracking system similar to a pair of glasses can be the best, lightest and ergonomic solution for this kind of application. If VR or AR training is performed, eye-tracking could be directly acquired through the VR/AR head-mounted display.
		J!ns Meme smart glasses: electrooculogram embedded with a gyroscope, used for the analysis of eye movements (saccades, fixations, and blinks).	
Physical domain			
Motion capture system	Users' movements, human activity, hand gestures	HTC Vive Trackers 3.0 can be attached to any part of the body, by proper straps, in order to achieve the motion capture of a joint or a body segment. Each tracker calculates its position based on the infrared signals emitted from a set of base stations that have to be properly positioned in the space.	-
		Xsens' motion trackers that are able to capture dynamic movements on-body ensuring full 3D motion analysis, with a low intrusiveness for users.	



Even if the EEG analysis is very useful for the study of the cognitive conditions, it is here excluded for two reasons: 1) the learners movements during the simulation-based training highly affect the EEG signal, and 2) the EEG headsets are quite intrusive to be worn during the training.

The use of an external camera is suggested to video record the learners, from a fixed position, during the simulation-based training and to subsequently correlate specific events to the learner's cognitive and physical states. Room temperature, lighting, and sound conditions should be kept constant during the simulation training, to avoid the learners conditioning.

### 3.3 Data Analysis

Proper integration and processing of the collected data can provide the assessment of the learner's UX and conditions and, consequently, of the simulation training effectiveness. Based on the data analysis, it is possible to redesign and optimize the simulation, in a human-centred vision.

Several measures, from different areas, can be exploited to analyse the features included in the UX assessment framework:

- Technical area (which includes the technical aspects of the used simulator and technology): in a user-centred perspective, system usability and UX related to the use of the simulator and/or advanced technologies (e.g., VR/AR devices) are assessed through ad-hoc questionnaires and usability tests.
- Physical ergonomics area (which comprehends simulation setting and layout, physical demand, and demographic characteristics): the physical ergonomics should be analysed by using wearable sensors or virtually through different digital human models. Also, the learners' demographic characteristics (i.e., age, weight, height) should be collected and studied through statistical regression models to understand their effect on the simulation execution;
- Pedagogical area (that includes instructor's and learners' roles, previous experience and skills, performance, acquired skills, and skill transfer): the performance should be evaluated during the simulation by using specific checklists and recording times, errors, and attempts. The acquisition of skills should be assessed both with a comparison between the pre-and post-simulation and then on-field to evaluate the skills transfer;
- Psychological area (which comprehends emotional and cognitive states and personal attitude): feelings such as frustration, anxiety, or effort, could be assessed through self-assessment, comparing the learners' perception before and after the simulation, and then through statistical analysis. The cognitive load and the stress could be monitored in real-time using smart wearable devices for the acquisition of physiological parameters. In this way, it is possible to discern between perceived and physiological cognitive/emotional states and understand the variables that most affect the simulation effectiveness;

Therefore, thanks to the application of this multi-dimensional, transdisciplinary analysis and the use of different assessment methods, it is possible to study:

- Perceived stress, anxiety, frustration, mental effort through the self-assessment questionnaires: variation between pre- and post- simulation.
- Objective stress and cognitive load based on the continuous physiological monitoring (e.g., heart rate, heart rate variability, breathing rate, electrodermal activity, ...) before, during, and after the simulation (i.e., comparison between stressful and restful tasks or simulation phases), thanks to proper algorithms for signal analysis.
- Differences in learners' opinions about the usefulness of simulation-based training.
- Usability of the simulator and/or other technologies and user experience of the learners (in relation to the simulation layout too).
- Performance and skills evaluation for the single tasks or the overall simulation.

- Standard central trend measures for the description of the demographic characteristics, the performance, the biometric indices, as well as for the analysis of the responses to the self-assessment questionnaires.
- Statistical single and multiple linear regression analysis to discover the variables that affect students' performance, stress, and cognitive load, during the simulation-based training.

Based on these relationships among variables, it is possible to define specific guidelines for the optimization and redesign of the simulations, to improve the simulation effectiveness and balance the levels of stress and cognitive load experienced by the learners.

## 4. Use Cases

In this section, two different use cases are presented to show how the proposed assessment framework can be applied to simulation-based training in various contexts, such as industry and healthcare.

### 4.1 Assessment Protocol

To show the adaptability of the assessment framework, a unique assessment protocol is proposed for both use cases as shown in Figure 2. Briefing, theory explanation and a practical demonstration session are made by the instructor before the beginning of the simulation. In this session, the simulation procedure is carefully explained and showed step-by-step, giving importance to eventual wrong approaches and keeping the learners aware about possible errors which may occur in each step. The instructor illustrates how to solve these eventual issues, giving the opportunity to the learners to manage the mistakes, during the simulation training, by themselves, fostering the transversal soft skills such as critical thinking, decision-making, and problem solving. At the end of the simulation training, a debriefing session may be conducted by the instructor to analyse the committed errors and understand the learners feeling and emotions perceived during the training (in this way, especially in the medical field with the emergency room simulations, cases of stress, excessive anxiety, and mental overload in managing the procedure can be discussed and solved).

Four different questionnaires (i.e., NAS, STAI, NASA-TLX, and a survey to analyse aptitude and previous experience of learners) are administered before and after the simulation to assess the subjective stress, cognitive load, anxiety, frustration, effort, and workload perceived by the learners, and to distinguish their variations due to the training. NAS is administered at the arrival in the room (NAS 1), after putting on the wearable devices and trackers (NAS 2), and twice after the simulation (immediately after the simulation end (NAS 3) and after a five-minute rest period (NAS 4)), to study the trend of the perceived stress. The State-Trait Anxiety Inventory (STAI) is a double form concerning the anxious *trait* of the subject (in his/her daily life) and the anxious *state* of the subject at the moment of answering the survey. In the proposed protocol, a double stage STAI is administered: the *trait* form is answered only before the simulation, while the *state* form is answered twice (before and after the training) to evaluate the perceived level of anxiety in those precise moments, and analyse how it varies in relation to the training simulation. The NASA-TLX questionnaire is administered after the simulation to record the learners' opinions about the perceived workload, and in particular about the mental, physical, temporal demands, effort, performance, and frustration. The aptitude survey is administered before the training to understand the learners' aptitude and familiarity with simulations and advanced technologies, and their previous experience in similar tasks.

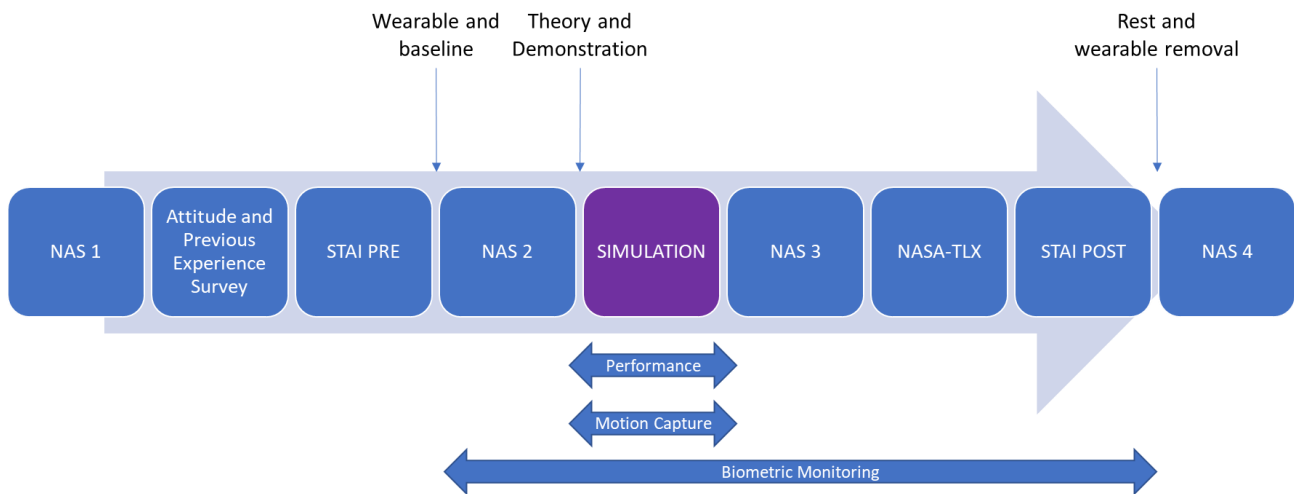


Figure 2: Assessment Protocol

The selected physiological parameters (i.e., HR, HRV, EDA, PD) are collected through the non-invasive wearable devices, before, during, and after the training, to assess the objective levels of stress and cognitive load experienced by the learners, and to detect eventual mental overload and stressful conditions. A baseline is recorded for the physiological signal monitoring at rest, before and after performing the training. The learners are also asked to wear a set of trackers to enable motion capture for postural and physical workload analysis during the simulation.

Moreover, the learners' performance is analysed for each task of the entire procedure, in terms of committed errors, the number of attempts, consultations with the instructor, execution times, and task correctly/incorrectly performed, or not performed. Also, a skill questionnaire should be administered before and after the simulation, to verify the learning.

## 4.2 Simulation Training in Healthcare

The healthcare use case considered the low-fidelity simulation for the training of rachicentesis, which is a specific lumbar puncture for the collection of the liquor, for diagnostic purposes. Low-fidelity simulations in the medical field are usually used for the training and enhancement of practical, technical skills. The rachicentesis is a surgical technique that involves inserting a thin needle (usually 22 gauge, 75mm long) into the space between the arachnoid meninx and the pia mater (i.e., in the subarachnoid space that contains the cerebrospinal fluid). For the execution of this procedure, the patient can be positioned in the lateral foetal position or sitting on the bed with the back arched forward. Rachicentesis requires maximum asepsis because, with this manoeuvre, the internal space of the central nervous system is put in communication with the environment. Thus, the operator can proceed with the needle insertion only after having identified the anatomical landmarks and ensured disinfection. The goal of the simulation-based training is to learn how to perform the puncture and become able to let the liquor spill out. Indeed, if the needle is non-inserted in the right place and with the right depth, the liquor would not come out. The simulated procedure and the needed tools are summarised in Table 2.

Table 2: Tasks sequence and required tools for the simulation-based training for the rachicentesis

Task	Required Tools
1. Reception and positioning of the patient	None
2. Palpation of anatomical landmarks	None
3. Disinfection	Sterile gauze
4. Correct grabbing of the needle	Needle
5. Threading the needle in the correct point	Needle

6. Extracting the needle stylet	Needle and stylet
7. Waiting for the liquor spilling out	None
8. Taking the test tube	Test tube
9. Collecting the cerebrospinal fluid	Test tube
10. Re-inserting the stylet into the needle	Needle and stylet
11. Removing the needle	Needle
12. Tamponing the skin	Sterile gauze

The simulation-based training has been performed in the Faculty of Medicine of Università Politecnica delle Marche by 148 students (mean age = 26 years old, SD = 1.02) from the 6<sup>th</sup> year of Medicine and Surgery Course. Participation in the test was voluntary and all participants signed informed consent before the test. All of them presented a normal vision and did not need corrective lenses; none of them had heart issues. The simulation was performed singularly by each student, one student at a time. The simulation duration varied from a few minutes to half an hour, according to the learner's skills and ability (mean duration of  $6.3 \pm 4.8$  minutes). Simulations sessions were scheduled both in the morning and in the afternoon. **Table 3** describes the features of the simulation-based training to be analysed for its redesign and optimization.

*Table 3: Training features – Healthcare use case*

	Description
<b>Technical area</b>	
Used Simulator	Lumbar puncture trainer by Gaumard®
<b>Physical Ergonomics area</b>	
Simulation setting and layout	Desk with: skill trainer in the centre, tools on the right. Instructor and other learners are in the same room of the trainee.
Posture, Physical demand	The trainee sit on a chair in front of the skill trainer, moving only the arms and the hands.
Demographic characteristics	Gender, age, weight, height, percentiles are collected.
<b>Pedagogical area</b>	
Instructor's role	The instructor has to explain and demonstrate the procedure first. Then, he/she may help the trainee during the simulation.
Learner's role	The learner has to perform the simulation on his/her own.
Previous experience and skills	Questionnaires are administered to collect data about the experience in practicing invasive procedures and the relevance of the thesis to the lumbar pucture.
Performance	Specific checklists are defined to collect execution times, numbers of errors and attempts, correctly/incorrectly/not performed tasks.
Acquired skills	Theoretical surveys are administered before and after the training.
<b>Psychological area</b>	
Cognitive state	Perceived mental demand is analysed after the training with NASA-TLX and cognitive load is monitored during the training through the recording of the physiological parameters.
Emotional state	Frustration, anxiety, effort, and perceived stress are assessed through self-assessment questionnaires administered before and after the training. Stress is also monitored during the training through the recording of the physiological parameters.
Personal attitude	Learners feedback about their aptitude toward the simulation-based training and the use of technology are collected through closed-ended questions before the training.

The simulator used for the training was the lumbar puncture trainer by Gaumard®. The room layout included a desk with the skill trainer and, on the right, all the instrumentation useful and needed for the practice. The room layout was not optimal, since the student performing the simulation, the students watching the simulation, and the teacher should not be in the same room. Indeed, their presence may influence the performance of the student who is practicing the rachicentesis, and also his/her feeling of stress and pressure.

The percentage of students developing a thesis pertinent to the rachicentesis was equal to 54.05%, while 27.70% of them have already had experience in practicing invasive procedures. All the variables related to the simulation setting, used technology, simulation tasks, and learners' characteristics have been recorded.



Figure 3: One student performing the simulation-based training for the rachicentesis

#### 4.3 Simulation Training in Industry

The industrial use case referred to the mechanical field, in particular to training for maintenance operations on tractors. The use case focused specifically on a set of manual tasks for the replacement of the engine oil filter. This maintenance activity is considered one of the most frequent and time-consuming on tractors, and can be both physically and mentally demanding, depending on the tractor layout and task complexity. The main difficulty refers to the oil filter accessibility since it is positioned beyond the power steering tubes and other components, that are hard to remove.

The workflow consisted of disassembling a set of machine parts to access the filter, the replacement of the exhausted oil filter with a new one, and the reassembly of the product parts. Contextually with the engine oil filter replacement, the temperature sensor of the pre-fuel filter is usually controlled and eventually replaced. The simulated procedure was taken considering commercial tractors produced by CNH Industrial. The entire task sequence of the simulation-based training and the needed tools are reported in Table 4. If no tools are required, the task is executed with bare hands.

Table 4: Tasks sequence and required tools for the simulation-based training for the replacement of tractor engine oil filter

Task	Required Tools
1. Remove electrical wires bracket	Wrench
2. Remove cover bracket	Socket wrench
3. Unplug electrical switch	None
4. Unscrew engine oil filter with tools	Strap wrench

5. Unscrew engine oil filter manually	None
6. Disconnect power steering pipes (n.2)	Wrench
7. Unplug gasoline pipe	None
8. Unplug temperature sensor electrical switch	None
9. Unscrew pre-fuel filter with tools	Strap wrench
10. Finalize to unscrew pre-fuel filter manually	None
11. Unscrew temperature sensor from pre-fuel filter	None
12. Screw the new temperature sensor on the pre-fuel filter	None
13. Screw the pre-fuel filter manually	None
14. Finalize to screw the pre-fuel filter with tools	Strap wrench
15. Plug temperature sensor electrical switch	None
16. Plug gasoline pipe	None
17. Pump the gasoline into the filters	None
18. Connect power steering pipes (n.2) manually	None
19. Connect power steering pipes (n.2) with tools	Wrench
20. Fill new filter with oil	None
21. Screw engine oil filter manually	None
22. Screw engine oil filter with tools	Strap wrench
23. Plug electrical switch	None
24. Mount cover bracket	Socket wrench
25. Mount electrical wires bracket	Wrench

The simulation-based training has been executed in the XiLab laboratory of the University of Modena and Reggio Emilia, to easily apply the proposed protocol analysis as defined for the research. It involved eight participants (mean age = 25.6 years old, SD = 2.236), among students and researchers from the same faculty in Mechanical Engineering or Industrial Engineering. Participation in the test was voluntary and all participants signed informed consent before the test. All of them presented a normal vision and did not need corrective lenses; none of them had heart issues. The simulation was performed singularly by each participant, one at a time. The simulation duration varied from about five minutes to a quarter hour, according to the learner's experience and ability. Simulations sessions were scheduled both in the morning and in the afternoon. Table 5 describes the training features to be analysed for its redesign and optimization.

Table 5: Training features – Industrial use case

	Description
<b>Technical area</b>	
Used Simulator	Physical mock-up of the tractor engine with some original parts (e.g., oil filter, fuel filter, the supports, the fuel pipes, and the cover bracket) mounted on a wooden structure supported by a metallic stand.
<b>Physical Ergonomics area</b>	
Simulation setting and layout	A table with the needed tools is placed on the left of the mock-up. Only the instructor is in the same room of the trainee.
Posture, Physical demand	The trainee stands in front of the simulator, turning left to pick and place tools over the table.
Demographic characteristics	Gender, age, weight, height, percentiles are collected.
<b>Pedagogical area</b>	
Instructor's role	The instructor has to explain and demonstrate the procedure first. Then, he/she may help the trainee during the simulation.
Learner's role	The learner has to perform the simulation on his/her own.

Previous experience and skills	Questionnaires are administered to collect data about previous experience in maintenance tasks, in using mechanical tools and monitoring devices.
Performance	Specific checklists are defined to collect execution times, numbers of errors and consultations, correctly/incorrectly/not performed tasks.
Acquired skills	Theoretical surveys are administered before and after the training.
<b>Psychological area</b>	
Cognitive state	Perceived mental demand is analysed after the training with NASA-TLX and cognitive load is monitored during the training through the recording of the physiological parameters.
Emotional state	Frustration, anxiety, effort, and perceived stress are assessed through self-assessment questionnaires administered before and after the training. Stress is also monitored during the training through the recording of the physiological parameters.
Personal attitude	Learners feedback about their aptitude toward the simulation-based training and the use of technology are collected through closed-ended questions before the training.

In order to replicate the desired task, a physical mock-up of the tractor engine involved in the process was recreated in the laboratory, using some original parts of the tractor, such as the filters (e.g., oil filter, fuel filter), the supports, the fuel pipes, and the cover bracket. These parts were mounted on a wooden structure supported by a metallic stand. Electrical wires were replicated using plastic pipes similar to the original ones for size and shape, in order to have the same encumbrance. The electrical wire brackets and the electrical connectors were 3D printed because the original parts were not available. The tools needed for the maintenance tasks were placed over a table, positioned next to the mock-up, also useful to pose the unmounted parts, as it usually happens in the repair shop and workshops. For the research purposes, even a laptop was placed over the table, to administer the questionnaires when needed.

The 62.5% of the participants did not have previous experience with engine maintenance tasks, even if the 50% had previous experience in using mechanical tools. Also, the 62.5% of them are familiar with the use of monitoring devices.

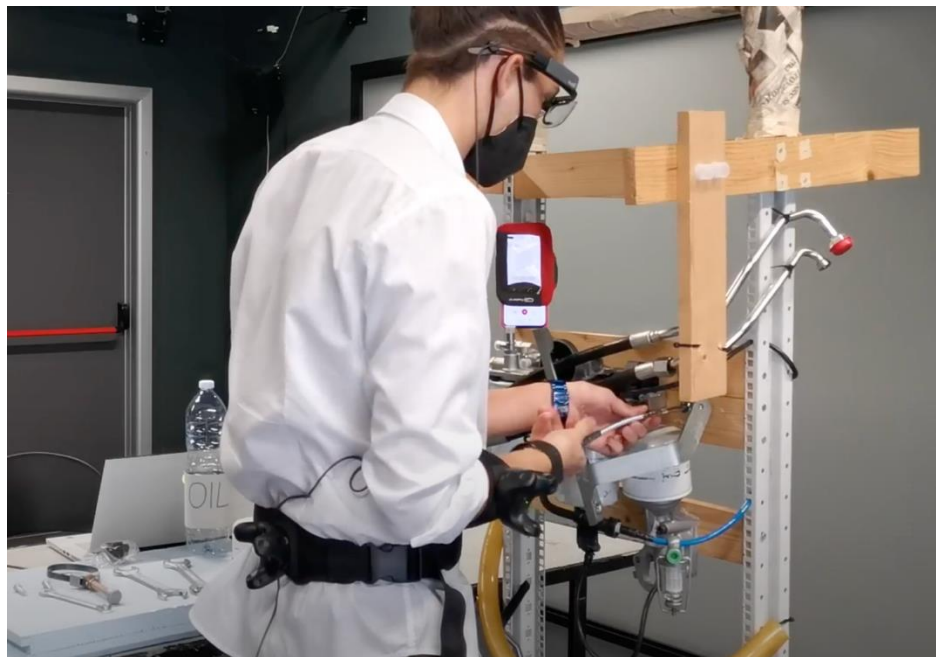


Figure 4: One learner performing the simulation-based training for the replacement of tractor engine oil filter



## 5. Results

Qualitative results and common redesigning guidelines for both use cases are hereunder described to show the suitability of the assessment protocol and technology to considerably different domains.

### 5.1 Qualitative Results for Simulation Training in Healthcare

The self-assessment questionnaires and the physiological signals of the 148 students were singularly analysed, as well as the performance. Then, all these variables were then assessed through several models of multiple linear regression analysis. Particularly critical issues did not emerge. The statistical analysis highlighted that learners' performance is not influenced by perceived and physiological stress. Cognitive load and stress levels were well balanced during the simulation, and they turned back to basal levels after the end of the training. However, an additional evaluation of physical ergonomics, concerning the impact of the workplace layout should be accomplished. Indeed, from this analysis, the height of the desk with respect to the height of the learner seems to have an influence on the perceived effort. Moreover, this analysis revealed that rachicentesis simulation comprehends too many tasks. Indeed, students have to remember the tasks sequence and how to correctly execute them. This may cause a chain of negative events: an excessive number of tasks to be remembered may lead to cognitive overload, working memory overstepping, decrease in learning and performance, increase in committed errors, increased simulation time, an increment of stress, effort, and frustration. A good solution to avoid cognitive overload (and related consequences) could be providing informative feedback during the simulation. Feedback could be supplied by the instructor or through augmented reality applications developed ad hoc for that kind of simulation. Also, since the time needed to succeed obviously depends on the number of attempts, other kinds of feedback could be provided to foster and speed up the lumbar puncture execution. For example, various haptic feedbacks could be added by integrating the skill trainer with force or pressure sensors. The learner's performance could be captured to provide him/her with positive or negative real-time feedback using immersive mixed reality applications. The combination of haptic and visual feedback through AR could guide and assist the learner in the procedure. This would reduce the number of attempts in stinging the lumbar spinal canal, and consequently also the time to success, the stress, the frustration, and the effort.

### 5.2 Qualitative Results for Simulation Training in Industry

The self-assessment questionnaires and the physiological signals were singularly analysed, as well as the achieved performance in terms of time and number of errors. Statistical models were not applied mainly due to the limited number of participants, but standard central trend measures of the variables were taken to analyse mean and median values (i.e., the trend of stress, cognitive load, anxiety, etc. related to the simulation-based training). Also, feedbacks and comments collected during the tests were useful to assess the overall UX. The analysis of the performance highlighted how taller users were requested to stay bent forward to accomplish some sub-tasks, with a decrease in the performance. Moreover, few specific sub-tasks were characterized by low visibility. Consequently, the system layout should be optimized to be more comfortable also for taller users. Regarding the cognitive and emotional states, the analysis of questionnaires and physiological measures highlighted that the perceived stress increases after a certain time. This is probably due to the need to correctly perform several tasks, which leads to an increment in the mental demand, as well as stress and fatigue. Indeed, stress perception decreases at the end of the simulation, probably because performance anxiety is perceived at the beginning of testing while decreasing at the end.

### 5.3 Guidelines for Simulation Training Redesign and Optimization

Table 6 summarizes the results from both use cases and provides some basic guidelines to solve the principal simulation's issues, related to the learners' performance, and cognitive and emotional conditions, as revealed by this study. Even though the use cases are pretty different, it is interesting to notice that the results obtained about performance as well as cognitive and emotional states are close enough to define a common



set of guidelines to redesign the simulation-based training. In both cases, AR applications could be useful to decrease the users' workload and reduce anxiety and stress, especially for long procedures.

Table 6: Guidelines for simulation-based training redesign and optimization

	Guidelines for redesign and optimization
<b>Performance</b>	
High workload causes: <ul style="list-style-type: none"> <li>• Increment of simulation time</li> <li>• Increment of errors</li> </ul>	Feedback about the tasks' sequence and execution could be provided during the simulation, also by the use of AR applications.
Success is not reached if the instructor practically assists the learner	The instructor should only assist the learner with advice, without interrupting his/her simulation execution. Additional instructions could be provided through AR applications.
Performance is worse in the afternoon or after a certain period	Lesson contents could be divided into two sessions: theory in the morning and simulation in the afternoon (real cases could happen every time of the day).
The effort is higher for tall subjects	System layout and/or simulator position must be optimized according to ergonomic principles.
<b>Cognitive and Emotional States</b>	
Anxiety before the simulation can compromise performance and learning	The instructor should calm down the learners during the briefing.
Stress is higher when more errors are committed	If too many errors are committed, the instructor should give theoretical help. In this sense, AR applications could be used to guide the learner, avoiding excessive errors, and consequently decreasing stress.
For a long simulation duration: <ul style="list-style-type: none"> <li>• Stress increases</li> <li>• Frustration increases</li> <li>• Effort increases</li> </ul>	The simulation duration could be reduced (and consequently even stress, effort, and frustration) by providing feedback that could help the learners in the correct execution of the tasks (also, in this case, an AR support is suggested).

## Conclusions

This work underlined the relevance of the application of transdisciplinary approaches for the design and optimization of simulation-based training in different fields. Indeed, in the simulation context, all the pedagogical, technical, ergonomic, and psychological dimensions assume a great weight. As it is important to achieve high performance through a valuable pedagogical path, it is also fundamental to assure a good stress balance: simulation should bring learners to a stress level similar to that one in the real practice, and, at the same time, it should not provoke excessive stress which may damages performance. The same reasoning should be done for the cognitive load. Indeed, to guarantee better performance and the best skills memorization, the mental effort should not be too low, and, at the same time, cognitive overload must be avoided. Also, the physical domain must be considered: the learners should feel physically comfortable during the simulation. Moreover, beyond the aspects treated in this work, even the technical features of the simulators and the level of fidelity should be taken into account, both from the psychological and engineering points of view.

In this paper, low-fidelity simulation-based training has been analysed. Simulation is realized by physical set-ups, properly created for the two use cases, respectively in healthcare (i.e., rachicentesis) and industry (i.e., tractor maintenance). The use of VR/AR applications has been specifically avoided at this stage, in order to

avoid further complexity in the UX assessment. However, the use of these technologies could improve the learning outcomes and immerse the students in a simulation environment more likely to the real field, enhancing the cognitive and emotional conditions. On the other hand, the use of advanced technologies could compromise or slow down the learning curve, having a negative impact also on the perceived stress. For this reason, it is evident the necessity of the proposed transdisciplinary assessment framework.

Future works will also consider the real-time data analysis, in order to guide step-by-step the simulation, and more advanced simulation-based setup, including VR/AR. The same assessment framework should also be considered for on-field applications.

## References

- [1] Y. Lu, Industry 4.0: A survey on technologies, applications and open research issues, *Journal of Industrial Information Integration*, 6, (2017), pp. 1–10. <http://dx.doi.org/10.1016/j.jii.2017.04.005>
- [2] L. Lattanzi, R. Raffaeli, M. Peruzzini, M. Pellicciari, Digital twin for smart manufacturing: a review of concepts towards a practical industrial implementation, *International Journal of Computer Integrated Manufacturing*, (2021), <https://doi.org/10.1080/0951192X.2021.1911003>
- [3] E. Prati, M. Peruzzini, M. Pellicciari, R. Raffaeli, How to include User eXperience in the design of Human-Robot Interaction, *Robotics and Computer Integrated Manufacturing*, 68, (2021), 102072, <https://doi.org/10.1016/j.rcim.2020.102072>
- [4] A. Ardanza, A. Moreno, Á. Segura, M. de la Cruz, D. Aguinaga, Sustainable and flexible industrial human machine interfaces to support adaptable applications in the Industry 4.0 paradigm, *International Journal of Production Research*, 57(12), (2019), pp. 4045-4059, DOI: 10.1080/00207543.2019.1572932
- [5] G. Aceto, V. Persico, A. Pescapé, Industry 4.0 and Health: Internet of Things, Big Data, and Cloud Computing for *Healthcare 4.0*, *Journal of Industrial Information Integration*, 18, (2020), 100129. <https://doi.org/10.1016/j.jii.2020.100129>
- [6] S. Nahavandi, Industry 5.0 – a human-centric solution, *Sustainability*, 11 (16), (2019), 4371.
- [7] B. Friedman, D.G. Hendry, *Value Sensitive Design: Shaping Technology with Moral Imagination*, Mit Press, (2019).
- [8] A. Haleem, M. Javaid, Industry 5.0 and its expected applications in medical field, *Curr. Med. Res. Pract.*, 9 (4), (2019), pp. 167–169.
- [9] M.D. Kent, P. Kopacek, Do we need synchronization of the human and robotics to make industry 5.0 a success story?, in: *The International Symposium for Production Research*, (2020), pp. 302–311.
- [10] P. K. R. Maddikunta, Q-V Pham, B. Prabadevi, N. Deepa, K. Dev, T. R. Gadekallu, R. Ruby, M. Liyanage, Industry 5.0: A survey on enabling technologies and potential applications, *Journal of Industrial Information Integration*, 26, (2022), 100257, <https://doi.org/10.1016/j.jii.2021.100257>
- [11] C. Cimini, F. Pirola, R. Pinto, S. Cavalieri, A human-in-the-loop manufacturing control architecture for the next generation of production systems, *J. Manuf. Syst.*, 54, (2020), pp. 258–271.

- [12] M.P. Pacaux-Lemoine, D. Trentesaux, G.Z. Rey, P. Millot, Designing intelligent manufacturing systems through Human-Machine Cooperation principles: A human-centered approach, *Comput. Ind. Eng.*, 111, (2017), pp. 581–595.
- [13] F. Longo, L. Nicoletti, A. Padovano, Smart operators in industry 4.0: A human-centered approach to enhance operators' capabilities and competencies within the new smart factory context, *Comput. Ind. Eng.*, 113, (2017), pp. 144–159.
- [14] F. Grandi, L. Zanni, M. Peruzzini, M. Pellicciari, C.E. Campanella, A Transdisciplinary digital approach for tractor's human centred design, *Int. J. Comput. Integr. Manuf.*, 33, (2019), pp. 377–397.
- [15] F. Kong, Development of metric method and framework model of integrated complexity evaluations of production process for ergonomics workstations. *Int. J. Prod. Res.* 57, (2018), pp. 2429–2445.
- [16] S. Mattsson, A. Fast-Berglund, D. Li and P. Thorvald, Forming a cognitive automation strategy for Operator 4.0 in complex assembly, *Computers & Industrial Engineering*, 139, (2020).
- [17] O. Danielsson, M. Holm, A. Syberfeldt, Augmented reality smart glasses in industrial assembly: Current status and future challenges, *Journal of Industrial Information Integration*, 20, (2020), 100175, <https://doi.org/10.1016/j.jii.2020.100175>
- [18] N. Karnik, U. Bora, K. Bhadri, P. Kadambi, P. Dhatrak, A comprehensive study on current and future trends towards the characteristics and enablers of industry 4.0, *Journal of Industrial Information Integration*, in press
- [19] G. Schneikart, W. Mayrhofer, Revolutionizing solutions of technological assistance for the integration of lab and office activities in biomedical research, *Journal of Industrial Information Integration*, 26, (2022) 100333, <https://doi.org/10.1016/j.jii.2022.100333>
- [20] I. Zolotová, P. Papcun, E. Kajáti, M. Miškuf and J. Mocnej, Smart and cognitive solutions for Operator 4.0: Laboratory H-CPPS case studies, *Computers & Industrial Engineering*, 139, (2020).
- [21] D.G. Broo, O. Kaynak, S.M. Sait, Rethinking engineering education at the age of industry 5.0, *Journal of Industrial Information Integration*, 25, (2022), 100311, <https://doi.org/10.1016/j.jii.2021.100311>
- [22] ISO 9241-210, Ergonomics of human system interaction - Part 210: Human-centered design for interactive systems, (2010).
- [23] F. Grandi, M. Peruzzini, C. E. Campanella, M. Pellicciari, Application of Innovative Tools to Design Ergonomic Control Dashboards, In: *Transdisciplinary Engineering for Complex Socio-technical Systems – Real-life Applications*, 12, (2020), pp. 193-200.
- [24] P. Waterson, S.L. Kolose, Exploring the social and organisational aspects of human factors integration: A framework and case study., *Saf. Sci.*, 48, (2010), pp. 482–490.
- [25] F. Longo, L. Nicoletti, A. Padovano, Modeling workers' behavior: A human factors taxonomy and a fuzzy analysis in the case of industrial accidents, *Int. J. Ind. Ergon.*, 69, (2018), pp. 29–47.
- [26] A. Papetti, F. Gregori, M. Pandolfi, M. Peruzzini, M. Germani, A method to improve workers' well-being toward human-centered connected factories, *J. Comput. Des. Eng.*, 7, (2020), pp. 630–643.
- [27] R. Etzi, S. Huang, G. Wally Scurati, S. Lyu, F. Ferrise, A. Gallace, A. Gaggioli, A. Chirico, M. Carulli and M. Bordegoni, Using virtual reality to test human-robot interaction during a collaborative task, in *Proceedings of*

the ASME 2019, International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, IDETC/CIE2019, (2019).

[28] S. L. Dawson and J. A. Kaufman, The imperative for medical simulation, In: Proceedings of the IEEE, 86, (1998), pp. 479-483.

[29] G. Norman, K. Dore and L. Grierson, The minimal relationship between simulation fidelity and transfer of learning, Medical Education, 46, (2012), pp. 636–647.

[30] A. Holzinger, M.D. Kickmeier-Rust, S. Wassertheurer, M. Hessinger, Learning performance with interactive simulations in medical education: Lessons learned from results of learning complex physiological models with the HAEMOdynamics SIMulator, Computers & Education, 52, (2009), pp. 292–301.

[31] S.S. Elshama, How to apply Simulation-Based Learning in Medical Education? IberoAmerican Journal of Medicine, 02, (2020), pp. 79-86.

[32] ISO 10075-3, Ergonomic principles related to mental workload // Part 3: Principles and requirements concerning methods for measuring and assessing mental workload, (2004).

[33] M. Otto, E. Lampen, P. Agethen, M. Langohr, G. Zachmann and E. Rukzio, A Virtual Reality Assembly Assessment Benchmark for Measuring VR Performance & Limitations, in Procedia CIRP, (2019).

[34] S. Hoedt, A. Claeys, H. Van Landeghem and J. Cottyn, The evaluation of an elementary virtual training system for manual assembly, International Journal of Production Research, (2017).

[35] S. Khalid, S. Ullah, N. Ali, A. Alam, N. Rasheed, M. Fayaz and M. Ahmad, The effect of combined aids on users performance in collaborative virtual environments, Multimedia Tools and Applications, (2020).

[36] M. Scafà, E. Brandoni Serrani, A. Papetti, A. Brunzini, M. Germani, Assessment of Students' Cognitive Conditions in Medical Simulation Training: A Review Study, In: International Conference on Applied Human Factors and Ergonomics (AHFE 2019), Advances in Intelligent Systems and Computing, 958, (2020), pp. 224–233.

[37] S. Hart and L. Staveland, Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research, Advances in Psychology, 52, (1988), pp. 139-183.

[38] M.T. Curtis, D. Granados, and M. Feldman, Judicious Use of Simulation Technology in Continuing Medical Education, Journal of Continuing Education in the Health Professions, 32, (2012), pp. 255-260.

[39] ISO 10075-1 Ergonomic principles related to mental workload - Part 1: General issues and concepts, terms and definitions, (2017).

[40] R. Lazarus and S. Folkman, Stress, appraisal, and coping, Springer Pub. Co., (1984).

[41] A. Brunzini, A. Papetti, E. Brandoni Serrani, M. Scafà and M. Germani, How to Improve Medical Simulation Training: A New Methodology Based on Ergonomic Evaluation, in AHFE 2019, (2020).

[42] C.D. Spielberger, R.L. Gorsuch, State-Trait Anxiety Inventory for Adults: Sampler Set, Manual, Test, Scoring Key; Mind Garden: Redwood City, CA, USA, (1983).

[43] A. Brunzini, A. Papetti, M. Germani, P. Barbadoro, D. Messi, E. Adrario, Mixed Reality Simulation for Medical Training: How It Affects Learners' Cognitive State. In Advances in Simulation and Digital Human

Modeling; AHFE 2021; Lecture Notes in Networks and Systems; Springer: Berlin/Heidelberg, Germany, 264, (2021).

[44] A. Brunzini, M. Peruzzini, F. Grandi, R.K. Khamaisi, M. Pellicciari, A Preliminary Experimental Study on the Workers' Workload Assessment to Design Industrial Products and Processes, *Appl. Sci.*, 11, (2021), 12066, <https://doi.org/10.3390/app112412066>

[45] A. Brunzini, A. Papetti, D. Messi, M. Germani, A comprehensive method to design and assess mixed reality simulations, *Virtual Reality*, (2022), <https://doi.org/10.1007/s10055-022-00632-8>

[46] M. Joshi and V. Deshpande, A systematic review of comparative studies on ergonomic assessment techniques, *International Journal of Industrial Ergonomics*, 74, (2019), 102865.

[47] M. Peruzzini, F. Grandi, S. Cavallaro, M. Pellicciari, Using virtual manufacturing to design human-centric factories: An industrial case, *Int. J. Adv. Manuf. Technol.*, 115, (2020), pp. 873–887.

[48] F.J. Seagull, Human Factors Tools For Improving Simulation Activities In Continuing Medical Education, *Journal Of Continuing Education In The Health Professions*, 32, (2012), pp. 261–268.