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Human factors and ergonomics considerations in the industrial metaverse

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Abstract The industrial metaverse is a new and emerging topic in smart manufacturing, extending the previous Industry 4.0 concept of cyber-physical systems in manufacturing. The trend is in its early phase, and the definition of the concept is still forming. The goal of this paper is to study the industrial metaverse from the human factors and ergonomics (HF/E) point of view to ensure that the related design and development efforts have a holistic approach. Three industrial metaverse work scenarios were created and assessed from the HF/E point of view. Based on the scenario analysis, new opportunities and challenges were identified related to user experience, usability, usefulness, user acceptance, ergonomics, safety and ethics. This paper is one of the first to start the HF/E discussion related to the metaverse, and its findings can be used both by the research community and the industry when stepping into the era of the industrial metaverse.

Keywords: human factors and ergonomics; industrial metaverse; industry 4.0; virtual reality; augmented reality.

1 Introduction

The metaverse is expected to become the next generation Internet as a shared virtual space that connects multiple virtual worlds via the Internet, allowing users, represented as digital avatars, to communicate and collaborate as if they were in the physical world (Cheng et al., 2022). The metaverse was first coined in the novel Snow Crash by Neal Stephenson (Stephenson, 1992). The novel describes the metaverse as a virtual environment, parallel to the physical world, in which users interact through avatars. The metaverse is seen as a seamless convergence of our physical and digital lives, creating a unified, virtual community where people can work and socialize (Meta, 2022, Morgan, 2022).

The metaverse can be seen as a universal virtual world focusing on social interaction, enabled by multiple 3D virtual environments connected via the Internet (Cheng et al., 2022). Driven by recent advances in emerging technologies such as extended reality (XR), artificial intelligence (AI) and blockchain, the metaverse is stepping from science fiction to an upcoming reality (Wang et al., 2022). Technologies that enable multisensory interactions support merging physical and virtual realities (Mystakidis, 2022, Lee et al., 2021, Park and Kim, 2022). Augmented and virtual reality (AR/VR) technologies (or XR technologies) create experiences from virtual objects superimposed upon the real world

(Azuma, 1997) onto totally immersed virtual environments (Kalawsky, 1993). The interaction can vary in the reality-virtuality continuum, which is a continuous scale ranging between the completely real (reality), and the completely virtual (virtuality) (Milgram et al., 1995).

Several application fields have been proposed for the metaverse, such as healthcare, manufacturing, office, education, smart cities, gaming, e-commerce, marketing, human resources, real estate and finance (Wang et al., 2022, Huynh-The et al., 2023, Park and Kim, 2022). As more generic application areas, there can be simulation, design, social interaction, online collaboration and a creator economy (Wang et al., 2022, Park and Kim, 2022). Work-related application possibilities have also been suggested by other researchers: enterprise digitization (Bian et al., 2021), telework (Choi, 2022) and maintenance (Siyaev and Jo, 2021b). While most visions and scenarios of the metaverse still focus on consumer applications, the metaverse is expected to also have a major impact on business and industrial environments (Mystakidis, 2022, Yao et al., 2022). The metaverse opens the door to future digital collaboration, where users can work together in a virtual world (Bian et al., 2021). Many industrial companies have used digital twins and XR technologies in marketing, design, training and process optimization, but now they are enhancing their visions towards the industrial metaverse, e.g. BMW (2021), Hyundai (2021), Johnson and Hepher (2021).

The emergence of the industrial metaverse is changing industrial work, the jobs available and the required skills. The Industry 4.0 vision already highlighted the change towards 'cyber-physical systems', referring to the trend of seamless integration of the physical and virtual in work environments and work tools (Kagermann et al., 2013, Zhou et al., 2019). Many of the metaverse-enabling technologies have been used already in the fourth industrial revolution (Kagermann et al., 2013) in smart factories (Frank et al., 2019, Osterrieder et al., 2020, Lu, 2017, Wang et al., 2016, Sigov et al., 2022, Xu et al., 2018, Damiani et al., 2018). The impacts of Industry 4.0 on industrial jobs have been described in Operator 4.0 visions (Romero et al., 2016). These visions describe different ways how cyber-physical systems change the work of individual factory operators. Kaasinen et al. (2022) extend the Operator 4.0 vision by describing smooth collaboration in human-machine teams where human and machine capabilities complement each other, and where on-site and remote workers have individually tailored work roles based on their personal capabilities, skills and preferences. Lu et al. (2021) describe how humans and machines form intelligent teams that collectively sense, reason, and act in response to incoming manufacturing tasks and contingencies. The metaverse extends the Industry 4.0 visions towards a perpetual and persistent multiuser environment merging physical reality and digital virtuality (Mystakidis, 2022). In manufacturing, the metaverse is expected to speed up production process design, motivate collaborative product development, improve condition control and fault detection, as well as obtain high transparency for producers and customers (Huynh-The et al., 2023). In addition, the metaverse can provide new possibilities for training (Mystakidis, 2022, Siyaev and Jo, 2021a).

In smart manufacturing, new technologies have physical and cognitive effects on human operators (Kumar and Lee, 2022). Therefore, it is important to consider human factors and ergonomics (HF/E) systematically when new technologies emerge in manufacturing and change the ways of working (Kaasinen et al., 2019, Kadir and Broberg, 2021, Neumann et al., 2021). For example, how to design VR systems (Stanney et al., 2003, Kalawsky, 1999) and how they impact users' well-being (e.g. cybersickness (Chang et al., 2020, Caserman et al., 2021), workload (Xi et al., 2022, Khojasteh and Won, 2021) and social aspects (Freeman et al., 2022, Blackwell et al., 2019, Moustafa and Steed, 2018). Kadir et al.'s (2019) literature review showed that there should be more empirical HF/E research related to Industry 4.0 technologies, and research should take a holistic view by considering all strategic, tactical and operational organisation levels. Reiman et al.'s (2021) review revealed similar results: simultaneous development of technological and HF/E capabilities is needed in the manufacturing industry. Therefore, a holistic approach to technology development is also needed when building the metaverse (Lee et al., 2021).

The metaverse concept is still emerging, and its definition has not been established. The focus of this paper is on the concept of the industrial metaverse, and we consider it as a possibility to extend the current use of digital twins and XR technologies. Compared to traditional XR studies, the metaverse has a strong service approach with content that supports especially sustainability and social meaning (Park and Kim, 2022). We think that in the industrial metaverse, workers can work only in virtual settings, combine both virtual and physical worlds or only work in a physical environment but use data via the industrial metaverse. Users may access the industrial metaverse by using XR technologies or more traditional means of manipulation.

The metaverse will radically change how industrial work is organized and carried out in different industrial domains. That is why, even though the concept is still emerging, we want to initiate the discussion related to HF/E aspects in the industrial metaverse. Human factors and ergonomics is a scientific discipline that studies human-system interaction to optimise human well-being and overall system performance (IEA, 2000). Human factors are especially important when designing technologies for the work context. The goal of this paper is to consider HF/E issues related to the industrial metaverse. The purpose of starting this discussion is to actively be a part of designing and shaping the industrial metaverse to ensure its suitability for workers and their needs. The paper presents three possible work scenarios in the industrial metaverse and assesses HF/E issues related to them. The paper first describes a scenario creation and analysis process. Three industrial human-centric metaverse scenarios are described in Section 3. In Section 4, HF/E issues related to the industrial metaverse are described based on the assessment of the scenarios. Finally, suggestions for HF/E considerations are proposed in the discussion section, and the conclusions are drawn.

2 Scenario creation and analysis process

To start the discussion related to important HF/E issues in industrial metaverse, a scenario-based design (Carrol, 1999) approach was utilised. The approach was selected since it offers an easy way to present new systems and designs in future contexts (Stanton, 2017). A scenario description contains actors and a description of their environment, goals and objectives, and sequences of actions (Go and Carroll, 2003). This section describes the creation process of the scenarios describing future industrial work utilising the industrial metaverse (Figure 1). In addition, it describes how the scenarios were assessed from the HF/E point of view by using 'Design and Evaluation Framework for Operator 4.0 Solutions' (Kaasinen et al., 2019, Aromaa and Heikkila, 2022).

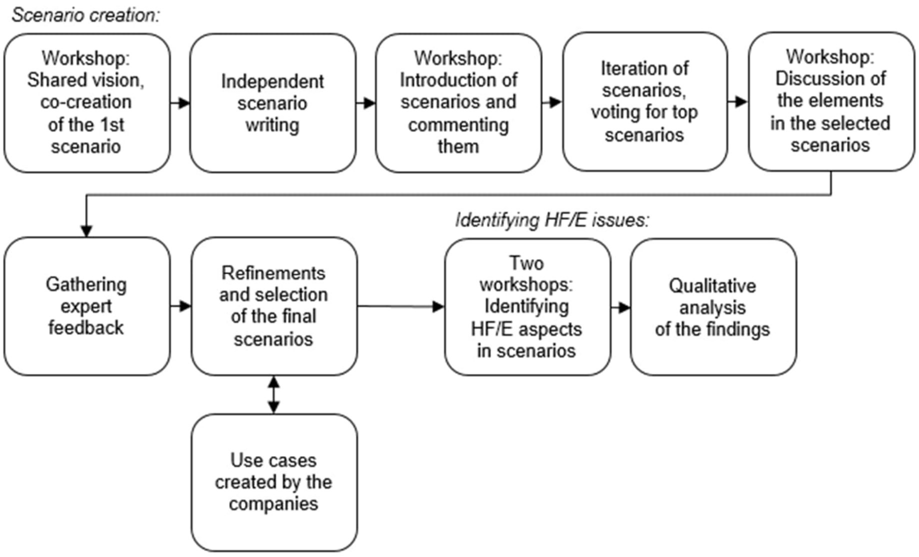

Figure 1: The process to identify human factors and ergonomics related topics in the industrial metaverse consisted of scenarios creation and HF/E identification phases. The whole process was completed in four months.

2.1 Scenario creation

Five researchers each having over 20 years of expertise in the area of HF/E and the transformation of industrial work participated in the process. The background of participating researchers was multidisciplinary: psychology, engineering, ICT, education, and arts. They had been studying the user experience and potential of novel technologies (e.g., robotics, AR/VR systems) in industry and service sectors in several national and international projects. All had participated in a recent one-year research project focusing on Industry 4.0 driven transformation of industrial work from the workers' point of view. The creation of scenarios included several online workshops utilising a co-creation platform (Miro) and studying the relevant metaverse literature to get a thorough understanding of the metaverse technologies and opportunities.

In the first online workshop, the five HF/E researchers first discussed the concept of the metaverse and how the worker roles in manufacturing may change in the future. The first scenario was outlined as group work on a Miro board and co-written to generate a shared understanding of the main elements and format included in the scenarios. After that, the worker roles considered relevant were listed as the basis for further scenarios. Afterwards, the researchers wrote 1–2 scenarios independently before the next workshop. In addition, a table of key characteristics included in the scenarios (worker, goal of a task, task, environment, technologies) was used to outline the scenario writing process. Altogether, eight scenarios were written. In the second workshop, all eight scenarios were introduced and discussed. The participants added questions and comments to each scenario on the Miro board to gain clarification or give further ideas related to the content. After that, as an offline task, the scenario descriptions were iterated based on the comments.

Furthermore, the researchers voted for the three top scenarios that had the most relevant elements. In the next online meeting, the most voted five scenarios were discussed and refined to include the most essential elements from the other scenarios.

To assess the relevance of the proposed scenarios, they were sent to two experts having technical or business-oriented expertise in industrial work to gain feedback regarding the clarity and credibility of the scenarios. The received comments were minor and related to innovating the descriptions further and for example, to including more international elements in the scenarios. No comments indicated that the scenarios would not be plausible or related to the industrial metaverse.

Parallel to the scenario creation process, opportunities of the metaverse were discussed with representatives of nine companies. The company representatives were manager and director level people. There were three types of companies in the discussions: potential industrial metaverse user companies, solution provider companies, and consultancy companies. Three of them represented building sector, one transportation/logistics, one digital infrastructure, one manufacturing, one virtual content creation and the two consulting companies focus on renewal of work, organisations and business. The user companies were all large and the solution provider and consultancy companies included both large and SME companies. The participants from the companies were asked to describe use cases in which novel metaverse capabilities are integrated in industrial operations to provide benefits to workers and companies. The purpose was to see what kind of industrial metaverse use cases companies create. In total, the participants proposed 17 use cases in which metaverse technologies could provide benefits. Two companies did not describe their own use case, but others provided 1-4 use cases per each. Some topics were mentioned by several companies. The topics of the use cases are:

- New solution ideation and development
- Design evaluations and services (2)
- Logistical operation planning
- Product installation process
- Manufacturing process and project execution
- Remote site/process supervising
- Maintenance (2)
- Training (critical tasks) (3)
- Visualising task progress and to compare different scenarios
- Digital twin of the worksite in near real-time
- Digitalised procurement process and supply chain management
- Advanced robotics
- Sales and on-site design

The company use cases were compared with the proposed scenarios. The content of the use cases had similarities with the scenarios even though the original scenarios focused only on manufacturing work. For example, companies mentioned remote monitoring, maintenance, training, real-time digital twins, and advanced robotics. It was notable that the company use cases were tightly related to current work processes and the employer-employee relationship rather than novel partnerships and contracts that could be possible in the future industrial metaverse. Finally, the scenarios were refined, and three scenarios were selected for the HF/E assessment. The final scenarios are presented in Section 3.

2.2 Identifying human factors and ergonomics issues

After the scenarios were created, two similar workshops were organised to focus on identifying HF/E aspects of the scenarios. First workshop was carried out with the original five researchers while the second workshop was carried out with three external researchers who had not participated in the process previously. The three new participants were senior researchers with over 15 years of experience on HF/E research of complex systems (e.g., nuclear and defence sectors). Two of them had degrees in psychology and one in engineering.

To identify possible HF/E topics that might emerge in the industrial metaverse, a 'Design and Evaluation Framework for Operator 4.0 Solutions' (Kaasinen et al., 2019, Aromaa and Heikkila, 2022) was applied as an approach to taking a holistic view of HF/E topics when considering the proposed scenarios. The part of the framework that introduces a list of immediate implications of technology usage for users was adapted. It highlights seven topics to consider in human-technology interaction: user experience, usability, usefulness, user acceptance, ergonomics, safety and ethics (Kaasinen et al., 2019, Aromaa and Heikkila, 2022). Some of the topics overlap, but the framework was chosen to ensure the extensive identification of HF/E issues in the industrial metaverse scenarios from relevant human-centric perspectives. In this study, the seven topics are applied in a following way. A user experience is seen as user's perceptions and responses derived from the use of a system, product or service (ISO 9241-11, 2018). The usability is seen as achieving goals with effectiveness, efficiency and satisfaction in a specified context of use (ISO 9241-11, 2018). Usefulness is considered from the point of view of how a worker thinks that using a system will support their work performance (Davis, 1989). Acceptance of technology can include both perceived ease of use and perceived usefulness (Davis 1989). Here the acceptance is considered from the acceptability point of view – perception of a system before its use and likeliness to use it. Ergonomics is considered from the individual's physical and cognitive ergonomics points of views (IEA, 2000). If workers are protected from a danger, risk or injury the work or the interaction with the system can be defined as safe. Key principles of ethics to consider are privacy, autonomy, dignity, reliability, inclusion and benefit to society (Ikonen et al., 2009).

The participants of the workshops worked on one scenario at a time, walked it independently through, and added comments related to the presented HF/E topics of the framework. The participants were instructed to consider the HF/E topics one by one, starting from what kind of user experience issues can be identified from the scenario, then considering usability and so on. After the workshops, the findings from all three scenarios related to each HF/E topic were qualitatively analysed. For each HF/E topic, findings were collected from both workshops and from all the scenarios. Then the findings related to the HF/E topic were analysed, identifying opportunities and challenges the industrial metaverse may raise. The results are described in Section 4.

3 Work scenarios in the industrial metaverse

In this section, we describe the resulting three co-created scenarios of human work in the industrial metaverse. The scenarios give snapshots of the ideas, but they do not comprehensively address all aspects of the industrial metaverse. The scenarios should be seen as representative examples, and it is more than likely that there will be work roles and tasks that are beyond our current thinking.

3.1 Scenario 1: Remote operation and maintenance in the process industry

Paul works in the process industry. His job is to oversee the production process and optimise its operations together with artificial intelligence (AI). There are many different ways to monitor processes in the industrial metaverse. Today, Paul stays at home: he steps on the virtual reality (VR) treadmill and puts on the VR headset (Figure 2). This allows him to walk around the virtual factory and monitor operations.

Figure 2: Paul monitors the status of the process from his home using VR headset.

While walking in the metaverse, Paul gets an alarm message displayed on his VR headset view. The message indicates that the oil pressure in one machine has dropped. Paul sweeps the machine's interface to his view and stops the machine by pressing a virtual button. He then teleports himself to the side of the machine and sees that the tube on the machine is coloured red.

Based on the sensor data, AI proposes that the most probable failure is a crack in the tube and suggests various action options. To confirm AI's suggestions, Paul opens real cameras' views of the factory floor via the metaverse and checks the real situation. Artificial intelligence is right: there is a small crack in the tube. From the actions that AI suggested, Paul chooses welding. He calls a welding robot to come to the scene and follows its digital twin moving in the metaverse.

Paul controls the operation of the welding robot in the metaverse but realises that the welding task is too challenging for him. He contacts a partner company, ProMetaWelding, which sells top-class welding services in the metaverse. Sara from ProMetaWelding arrives as an avatar at the scene in the metaverse. She remotely operates the welding robot and is able to fix the crack. Sara's avatar turns to Paul and says that the work is done. Paul thanks for the help, opens the machine's interface to his view and restarts the machine. He then teleports himself up under the factory ceiling. From there, he visually checks that the whole process is working smoothly.

3.2 Scenario 2: Collaboration in human-robot teams

Olivia is an assembly worker, and she is starting her morning shift on the factory floor. Today, Olivia's team has a collaboration robot and Jose, a familiar co-worker. The robot's real-time remote control allows you to work from anywhere - this time Jose works from home.

A 3D representation of the factory has been created for metaverse access. Both Olivia and Jose access the metaverse from their own locations. Olivia has augmented reality (AR) glasses through which she can see the physical factory environment and Jose’s virtual avatar (Figure 3). Jose has a light and comfortable virtual headset at home with which he can virtually see the factory environment, the robot and Olivia’s avatar.

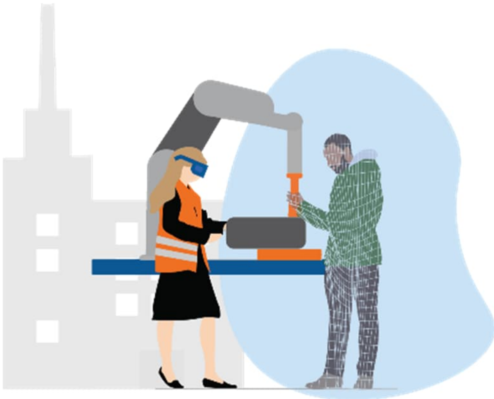

Figure 3: Olivia works together with the robot and Jose, who she can see through AR glasses.

Olivia exchanges news with Jose in the metaverse and begins assembly work with the collaboration robot. The collaboration robot turns the part to the angle Olivia wants to ensure that Olivia can do her job safely and maintain a good working position. The robot adapts to Olivia's way of working and monitors and reacts to Olivia's movements. The ErgoMeta program used by the factory provides feedback on the view of Olivia's AR glasses, as Olivia's avatar has worked in the metaverse for a long time in a poor ergonomics position. Olivia is grateful for the reminder and changes her posture. The robot also adjusts its height based on the feedback and Olivia's position change.

Olivia follows the assembly instructions provided in the AR view during the complex work task. Jose is also participating in this task with the collaboration robot. Jose remotely controls the robot through the metaverse with a haptic device. The work task requires precision and active communication between Olivia and Jose. Although Olivia only sees Jose's avatar through AR glasses, the collaboration is natural and smooth.

3.3 Scenario 3: Recruiting, training and flexible work roles

Laura has just retired after a long career in traffic control. She still would like to work part-time but in a less hectic environment. She has heard from her friends that many factories offer assembly jobs with employee-specific schedules.

In the metaverse, she finds virtual factories hosted by different companies. In the virtual factories, potential employees can have a tour to see what is going on the shop floor and what kinds of jobs are available (Figure 4). It is also possible to discuss with the avatars of actual employees to learn more about the factory work and what it includes. Laura gets interested in an electric bike factory where robots and workers seem to work smoothly side by side. Laura logs into the factory and with the appropriate interaction tools, she can get hands-on experience in the jobs she is interested in.

Figure 4: Laura is looking for interesting job opportunities.

The work feels nice and doable, and Laura registers for training in the metaverse. She gets a personally tailored training programme, and she starts learning at her own pace, a few hours every day. After she has finished the training, she registers for a qualification exam that can be taken in the metaverse. An artificial intelligence-based supervisor analyses Laura's performance and tells her what issues she still needs to practise.

After successfully passing the exam, Laura receives a work permit and an official work offer. Laura confirms that she will be available to work up to 15 hours per week and can work either remotely in the metaverse or at the actual factory, which is close to Laura's home. Laura is surprised to see how well assembly work can be carried out remotely in the metaverse. She is also happy to work on-site, offering help to colleagues who prefer working via the metaverse.

4 Human factors and ergonomics topics in the industrial metaverse

This section describes the results of the scenario analysis work, where the three scenarios were assessed based on the topics of the framework (user experience, usability, usefulness, user acceptance, ergonomics, safety and ethics). The scenarios are referred to as Scenario 1 (S1), Scenario 2 (S2) and Scenario 3 (S3).

4.1 User experience

When considering the user experience, the novelty value of the industrial metaverse is expected to be in the new level of immersion and interactivity. These influence the experience of work, both while working remotely in the metaverse and while working on-site supported by colleagues in the metaverse. The various interaction tools available allow a personalised experience. For example, the treadmill presented in S1 provides an excellent experience of moving in the factory, but it may also divide opinions. Some people may feel hesitant to use it if it does not feel natural or they are worried that they may fall. It is important to allow the employee to choose the personally most convenient interaction tools. Immersion is supported not only by giving a realistic feeling of presence on the factory floor but also by possibilities not available in the physical world, like in S1, where Paul is flying above the factory floor to see the whole process. An important issue regarding user experience is how the metaverse can support the feeling of a smooth workflow. For instance in S1, AI-powered advice supports smooth decision-making and provides a feeling of being in control. The metaverse can provide a realistic experience of factory work for potential employees and trainees as described in S3. The flexibility in choosing where and when to work can contribute to a positive experience.

Scenario 2 describes working on-site with virtual workmates. A key concern is how smooth and natural it would feel to collaborate and interact with avatars. The worker should be able to differentiate avatars that represent remote and on-site workers. Another concern is whether all the virtual elements support work or whether they create an overwhelming experience with too much sensory input. Similarly, for those working remotely, it can be questioned how realistic the virtual environment would be. Does realism support immersion? Does immersion always support a positive experience? And how well does the virtual environment support the feeling of a smooth workflow? To maintain the sense of the actual factory environment and to avoid detachment from the work community, the workers should also regularly work in the physical factory. Socializing with teammates in the actual factory environment supports mutual learning and sharing tacit knowledge, as well as building the community. It can be questioned whether the metaverse will enable similar spontaneous activities.

4.2 Usability

New interaction tools can improve usability while they also may raise new kinds of usability challenges. The possibility to choose personally preferred interaction tools can improve usability. Compared to traditional control rooms, the metaverse can provide a better overview of the factory, thus providing a better connection to the real world. In some tasks, it may be beneficial to use a specific view of the virtual factory, emphasizing visually the most important things. Fluent interaction will require precise tools and reliable and high-speed networks. Usability is improved with robots that adjust their positions according to the human worker.

All users may not feel comfortable with moving and acting in the virtual environment or operating work machines remotely. Remote assembly or maintenance work as described in the scenarios will require interaction tools that provide a convincing look and feel. The metaverse may introduce new virtual interaction tools that may not be intuitive to use, and it may take time to learn to use them fluently. The workers may face a dual learning challenge as they must learn to work in the metaverse and learn the actual work tasks. If employees work from home, they may not have the best possible interaction tools available. The same challenge may raise in situations like the one described in S3, where Laura is trying out factory work in the metaverse. The physical environment at home may limit the possibility to use interaction devices such as a treadmill. The augmented information may cause information overload to the user if there is too much content or it is contradictory, for instance in S2, Olivia sees the avatar of her workmate and work instructions via AR glasses simultaneously. Several sources of data may also cause conflicts and uncertainty for the user. Augmented information must be positioned precisely, for instance, the avatar of the workmate needs to act in the correct position and distance in S2. Remotely operated robots also introduce a usability challenge, as it may be unclear to the worker who is controlling the robot. If an avatar is the controller, it may not be evident to others that the avatar is in charge of the movements of a certain robot.

4.3 Usefulness

Usefulness is important to consider especially when utilising novel technologies in a work context. Metaverse solutions have already been introduced for the design and configuration of production processes, facilitating collaborative design and assessment of production efficiency, ergonomics, and safety (Caulfield, 2021). Our scenarios describe how the metaverse enables remote work and remote collaboration. A convincing visual view of the factory and the processes in it can make work more efficient by giving an overview and supporting identifying and finding locations in the factory. Artificial intelligence solutions can support getting a data-based analytical view of the production process and optimizing the production as well as maintenance actions. Via the metaverse, it can be made easier to reach needed external experts, even globally. The same digital twin of the factory can enable different usage possibilities. For example, the metaverse can support recruitment and training, as described in S3. Via the Metaverse, more potential candidates to recruit can be reached, and potential workers get a more accurate view of their future job during the recruitment and training. This improves the possibilities to get skilled workers for the available jobs the metaverse facilitates using the best experts, for instance in maintenance operations, even if the required expert were in a different country. When working on-site, AR glasses make working more efficient by providing readily available and situationally relevant guidance.

However, it can be questioned whether the metaverse is too heavy a solution for some tasks that could be carried out by more traditional means. The cost of the required infrastructure, for the employer and the employees, should be in line with the benefits gained. From the worker's point of view, it is good that the metaverse could enable part-time work (S3), but from the companies' perspective, finding an adequate workforce may be a challenge.

4.4 User acceptance

The acceptance of working through the metaverse depends on several factors: smoothness of interaction with technology, the equipment and interaction devices used, as well as the appearance, content, and logic of the metaverse. For younger people, the acceptance may be higher because they are familiar with digital and even virtual environments. But for older people, there may be several unfamiliar elements that require learning, which may hinder initial acceptance. However, the possibility of remote working as such is expected to increase user acceptance. A remote work possibility is especially important for people working part-time (e.g. Laura in S3). Regarding AI-based systems, acceptance depends on the role given to AI. Optimally, AI should propose actions, and humans should make the decisions.

One of the benefits of the metaverse is the possibility to introduce job opportunities in realistic demo environments and provide opportunities for job trials and hands-on practising through the metaverse (e.g. S3). For a job candidate, it increases the possibility to find a job that would be suitable for oneself and one's life situation. For example, a simple job that an ambitious full-time worker might find repetitious may be ideal for a student or a retired person looking for a part-time job. In addition, the metaverse enables a personalised pace of studying and learning, which supports the inclusion of people with diverse backgrounds and skills.

The identified challenges related to user acceptance were connected to collaboration between Olivia, Jose and a robot in S2. When the metaverse is used for constant co-working with actual robots and workers on the factory floor, it raises more concerns. What is it like to work in the metaverse? What equipment is needed at home for remote working? Can working with collaborative robots raise fears and anxiety? User acceptance of interacting with avatars may be limited, both because it may mean a new kind of monitoring of the worker and it changes the interaction between workers and other collaborators.

4.5 Ergonomics

Future work scenarios in the industrial metaverse include both benefits and challenges for ergonomics. As a benefit, working in the metaverse could provide more versatile interaction means and therefore improve the well-being of workers. For example, it is possible for Paul to use a treadmill to walk if he chooses to do so, but it is not mandatory. In addition, it may be possible to access the metaverse with different means of manipulation, for example, with a head-mounted display, mobile phone, PC, etc. The versatile use of interaction devices also provides better access for people with different capabilities and skills. People who have physical and/or cognitive disabilities may do part-time work and remotely operate systems. Many different data sources can be connected in the metaverse. For example, it is possible to integrate information from well-being devices with the status of the machine data and gain knowledge about human-machine teamwork (e.g. S2). This may help proactively maintain and even increase the workers' well-being. However, sometimes notifications about poor posture or energy expenditure may feel annoying and unnecessary.

The main concerns related to ergonomics rise from the maturity of the interaction devices and how they are used. Their physical parameters are not necessarily suitable for everyone, and they might need improvements to be used for longer periods of time (e.g. a VR headset). The cognitive load may also increase if there are a variety of interaction devices to be used. The execution of work tasks may change radically from the original (e.g. welding in real life vs. welding with VR devices, S1), and training good practices in a virtual environment does not necessarily ensure good ergonomics in the real world (e.g. S2). Another still unsolved issue is simulator sickness/cybersickness, which is also important from an inclusion point of view: working in the metaverse should be possible for all people and not only for those who do not experience cybersickness. Remote working allows people to adopt many kinds of postures and possibilities to vary them, but at the same time, it creates a space where no one is following how people are working. People may adopt poor postures or work overtime that may lead to sick leaves. This location-independent way of working may also provide challenges for workers to access appropriate interaction devices. Cognitive load may increase if workers are responsible of monitoring several entities simultaneously.

4.6 Safety

Working remotely is expected to increase the safety of the personnel who do remote work, but it is also considered a risk for operations and workers at the factory. The remote control of robots and operations is regarded as a safety issue in all the scenarios, particularly when Olivia was working near the remotely operated robot on the factory floor. When not being present at the factory, workers may miss the tactile examination and overview of the situation beyond the scope of the camera.

In S1, Paul using a treadmill while working was seen as a safety concern, as the VR headset may make it difficult to observe the real world and increase the threat of falling of the treadmill. On the other hand, in the S3 illustration, working from the sofa may increase the risk of decreased vigilance or even falling asleep. A virtual environment could improve safety as safety-critical operations can be rehearsed first, but it also raises concerns. It can be pondered whether the skills needed in the real factory can be reliably learned in a virtual environment. The researchers were also concerned about whether using a virtual training environment and a virtual working environment for remote operations are clearly separated from each other, to stay aware when one operates in the real factory and thus needing to be especially careful.

In addition to remote work causing safety risks at the factory, there may appear faults within the metaverse system. When doing remote operations, the latency and disruptions of the network connection were also identified as potential problems. The instability of the network could harm operations, such as lifting objects or cause delays between the metaverse and the operations in the real factory. The role of AI was identified as two-fold: as potentially increasing safety by preventing human mistakes and as a concern if it was used without human involvement, for example, if work permission was admitted by mere AI.

4.7 Ethics

As a new concept, the metaverse raises a range of ethical questions. The ethical key principles of privacy, autonomy, dignity, reliability, inclusion and benefit to society (Ikonen et al., 2009) were all covered in the comments. Even though the use of the metaverse may include elements that support ethics, such as possibilities for remote work and the personalised pace of learning fostering inclusion, it still raised more ethical questions and challenges.

In the metaverse scenarios, it was unclear whether the employer, subcontractor, worker or the mediating metaverse system is responsible in case of faults or accidents. In the first scenario, the extensive responsibility of one operator was seen as a concern – both from the perspective of the workload for the operator as well as for the safety of the other workers. The possibility to remotely access the metaverse and "teleport" to any part of it when needed may expand the entities monitored by one worker. In S2, the concern of responsibility was related to collaboration between remote worker Jose and on-site worker Olivia, which introduces new questions in defining the division of work as well as in considering the safety of workers at the factory. In addition, the increased communication with avatars was commented on from the perspective of decreasing in-person communication, which was seen as problematic, especially during a recruiting process and when starting to work in a new workplace. Moreover, when working mainly remotely, the probability of problems related to loneliness, exhaustion and ergonomics increases.

The increased data collection of workers raised privacy concerns. For example, locating the workers as avatars may be useful information, but it may also be considered unnecessary tracking of workers. Thus, it is important to define who can see the detailed information related to workers and for what purpose. On the other hand, when co-working with a remote colleague, very detailed information may be needed for fluency of work as well as for safety. From the perspective of companies, the use of the metaverse raised a threat to data security if the data is widely shared.

The role of AI raised questions about responsibility and ownership issues. An important question is how the use of AI will be regulated and who defines the ethical conduct for its use (e.g. a state, a company or individual workers). In S3, AI as the sole approver of Laura's exam for receiving the work permission raised concerns. To be ethically acceptable, a human recruiter should be involved in the process.

From the perspective of the work communities and the variety of workers, issues related to inclusion were brought up. How to ensure that the metaverse can be utilised by all workers, including the older generation? If remote work is enabled by an employer, how can worker equality be ensured when defining which work tasks can be remotely operated, what kind of equipment the workers can use and whether they can have the control devices for robots in their home.

4.8 Summary of human factors and ergonomics aspects

Table 1 summarises the main findings of the scenario analysis related to user experience, usability, usefulness, user acceptance, ergonomics, safety and ethics. It describes possible HF/E related opportunities and challenges of the industrial metaverse.

Table 1: Summary of opportunities and challenges from the HF/E point of view in the industrial metaverse.

Topics	Opportunities	Challenges
User experience	- Personalised experience with various interaction tools - A feeling of presence with extended immersion - A feeling of freedom with increased flexibility in choosing where and when to work	- How smooth and natural it would feel to collaborate and interact with avatars - An overwhelming experience with too much sensory information - Supporting the feeling of a smooth workflow - Supporting the feeling of control - Maintaining the sense of the actual work environment
Usability	- Improved usability with personally preferred interaction tools - Better overview of the factory compared to traditional control rooms - Machines adjust their behaviour according to the human worker	- The interaction tools may not be intuitive to use - Lag or latency issues may affect the usability - The physical environment and IT security at home may limit the possibilities to use some interaction devices

		- Operating machines remotely may be challenging and lack sensory feedback - Dual learning challenge to learn both to use metaverse and the actual work tasks
Usefulness	- Enables remote work and collaboration - Visual view of the factory and processes may increase efficiency - Easy to reach external experts - Can support recruitment and training	- Is the metaverse too heavy a solution for tasks that could be carried out with simpler means? - Cost vs. benefit - Requires a sufficient IT infrastructure (connectivity and security) in all places of work (i.e. remotely)
User acceptance	- Remote work as such may increase acceptance - For young generations, the acceptance may be higher as they are familiar with virtual environments - Possibility to demonstrate and try out work and thus find a job suitable for oneself - Enables personally adapted pace of studying and learning	- It is not thoroughly known how it actually feels like to work in the metaverse - Acceptance of AI-based systems - User acceptance of interaction with avatars may be limited
Ergonomics	- Versatile interaction devices/means of manipulation - May make access easier for all with different capabilities and skills - Proactivity to maintain well-being	- Technology is not mature enough, e.g. may create cybersickness - How to ensure a good working posture in multi-location work - Most appropriate interaction tools may not be available at home
Safety	- The use of AI could increase safety by preventing human mistakes - Training first in a virtual environment may improve work done in safety-critical operations	- Safety issues in remote control of robots and operation - Mixing of real and virtual environments may increase the possibility of accidents - Disruptions in the network connection - Faults within the "metaverse system"
Ethics	- Some elements may support inclusion, e.g. the personalised pace of learning and the possibility for remote work	- Privacy threats for workers and companies - Equality of workers when some work remotely and some at the factory; isolation in remote work - Responsibilities may be unclear, e.g. in case of accidents - Division of work tasks between workers and robots/AI

5 Discussion

The industrial metaverse is a part of the wider metaverse development where the boundary between the virtual and physical world is becoming more blurred: new economic and social systems will be formed, e.g. new markets, cultures, norms and regulations (Lee et al., 2021). It will change how industrial work is done, what kinds of ecosystems and business models exist and how sustainability values can be implemented. This paper has both practical and scientific implications.

5.1 Practical implications

This section describes practical and general implications based on the study findings related to technology maturity, cognitive load, novel work practices, organisations, business aspects and sustainability.

The experts in our study were concerned whether the interaction devices are mature enough to allow long-term working in the metaverse. Therefore, the devices should be designed to be used by people of all sizes, ages and abilities, and they should support a smooth workflow. To date, research in Industry 4.0 technologies has not considered technology users profoundly (Neumann et al., 2021). In the XR domain, the current generation of VR headsets causes less cybersickness, but some intense symptoms remain (Caserman et al., 2021). Another technology related issue is that how people learn to use the systems to be able to work in the metaverse? Is this know-how taught by the employer or learned in the school?

Cognitive and mental capabilities of workers were mentioned in the results. In the industrial metaverse, there can be a large amount of data presented which can create an overwhelming experience if there is too much sensory input. Therefore, it is important to consider which data is important for workers in their current work situations and how it should be visualised so as not to overload them. Also in here, the individual needs and preferences of the workers should be taken into account. Artificial intelligence will be a key enabler in the metaverse (Huynh-The et al., 2023) and needs to be designed to support workers rather than increasing confusion and the mental load. Novel technologies and ways of working may also create stress and frustration if workers do not know how to work in the industrial metaverse.

The change metaverse brings to industrial work needs to be addressed. Many of the enabling technologies already exist (Lee et al., 2021), and therefore, the major change will be based on the entity of the enabling technologies and what it will make possible regarding new work practices. The changes that Industry 4.0 is bringing to factory floor work have been addressed in (Romero et al., 2016, Kaasinen et al., 2022). The metaverse facilitates even wider changes in industrial work and available jobs, especially regarding remote work and training. The location-independent way of working could provide new challenges for physical and cognitive ergonomics. In workplaces, it is easier for a company to follow and ensure good HF/E standards, but it may become a challenge if people are working from several locations. Additionally, who should be responsible of providing the worker with sufficient connectivity in the remote location? Another key point is to understand how cyber-physical human-machine teams work together. This is important in order to avoid accidents that may occur due to people working together remotely.

Organisational aspects were identified as one topic to consider in utilisation of the industrial metaverse. Kadir et al. (2019) point out that the importance of the HF/E research at upper organisational levels should be taken into account more strongly when implementing Industry 4.0 solutions. Collaboration and social interaction will have new forms. The concept of the metaverse can transform how people socialise and do other activities (Lee et al., 2021). It is important to consider how it feels to work with avatars and cyber-physical systems. People should also feel they are part of the work community even though it might be different from how it is understood today. When designing work tasks in the industrial metaverse, it is important to pay attention to the inclusion of people and ways to take account of the diversity of the workforce (e.g. culture, language, skills and capabilities). When going forward in the development of the industrial metaverse, it is not enough to focus only on the design of HF/E issues regarding a certain technology. There is a need to take a systemic approach to the design (Lee et al., 2021, Kaasinen et al., 2019, Kadir and Broberg, 2021, Neumann et al., 2021) [10, 35-37, 48, 55] and consider simultaneously how processes and ways of working are changing. (Lee et al., 2021, Kaasinen et al., 2019, Kadir and Broberg, 2021, Neumann et al., 2021, Reiman et al., 2021, Breque et al., 2021)

The experts of the study pointed out open issues related to business models and ecosystems in the industrial metaverse. There can be ecosystems, manufacturing companies and small enterprises operating in the industrial metaverse with different kinds of business models. In addition, it is not yet clear whether there will be only one metaverse or several and how different kinds of metaverses (e.g. industrial, commercial) are connected. The concept of the metaverse still requires standardisation of the virtual economy (Lee et al., 2021) as well as principles for software interconnection and user teleportation (Mystakidis, 2022). Security and privacy are key points from both the business and individual perspectives (Lee et al., 2021). The metaverse can provide a new kind of collaboration platform for companies and individual experts. For example, it can allow experts to provide their services in the industrial metaverse, even globally. Parallel to the general metaverse development, the metaverse as a collaboration platform facilitates a new kind of service market where individual experts and companies can provide various services to a wide customer pool. Similarly, the metaverse will provide new kinds of possibilities for recruitment and training.

Due to the used HF/E framework, sustainability issues were not identified broadly during the scenario analysis. However, it is important to consider green issues (European Commission, 2021, Breque et al., 2021) when utilising industrial metaverse. Working in the industrial metaverse can decrease the need for travelling and therefore be beneficial for the environment. However, a smoothly functioning metaverse would include a massive amount of data, but processing and managing it is not necessarily sustainable in the long term.

5.2 Scientific implications

This paper contributes to scientific theories such as sociotechnical systems theory (Trist and Bamforth,1951) and approaches such as human-cenred design (ISO 9241-210, 2019) and Industry 5.0 (Breque et al. (2021) by introducing three industrial metaverse scenarios in which the human is important part of the system. The created scenarios can be used in the research and development of metaverse applications for industry. Additionally, the presented summary of opportunities and challenges from the HF/E point of view (Table 1) can be applied when creating new research questions and identifying challenges to be solved. Many industrial metaverse papers have been published recently. However, this paper is one of the first papers to address industrial metaverse from the HF/E point of view and therefore, it enhances the understanding of worker's role in the industrial metaverse.

5.3 Study limitations and future work

The concept of the industrial metaverse is still emerging and it is not fully understood nor defined yet. For this reason, a scenario-based approach was adopted due to its ability to present new systems and designs in future contexts (Stanton, 2017). The scenarios were created by HF/E experts with several years of experience. However, these experts were recruited from the same research institute. The larger number and variety of HF/E experts could have increased the soundness of the scenarios. The HF/E researchers were selected to do the HF/E evaluation task due to their broad knowledge of HF/E topics (e.g., user experience, safety, ethics). The experts from the industry could have provided additional views to the evaluation, however, they may have lacked thorough understanding of the HF/E topics.

When describing the future scenarios, the purpose was to describe realistic and futuristic applications of the metaverse in industrial work. Nevertheless, it is difficult to balance between futuristics visions and realistic capabilities: some technology and non-technology enablers may be realised in five years and some may take over 20 years. It can be possible that the selected HF/E framework and the low number of scenarios do not comprehensively introduce all the topics related to HF/E in the industrial metaverse.

In the future, the topic should be studied in real-life industry work context to fully understand what it means to work when both physical and virtual presence are possible and can be integrated in various ways. With the real-life use cases, opportunities and challenges of working in human-technology-AI teams in hybrid environments could be revealed in more detail. In future research, the created scenarios could be enhanced to include also organisational aspects and wider changes in working life. Additionally, the focus could be broadened to include larger systems and processes as well as working in multiple metaverse factories.

6 Conclusions

The discussion of the metaverse concept in manufacturing has reached wider attention. The purpose of this paper is to start a discussion on human factors and ergonomics (HF/E) in the industrial metaverse. It is essential to have human-centricity in mind when designing and developing a new kind of human-technology interaction. It can be seen that, even though the fourth industrial revolution has been around for a while, there is still a need for more comprehensive HF/E research actions.

This paper presents three co-created work scenarios for the industrial metaverse. Based on the scenarios, HF/E issues that may emerge in the industrial metaverse were identified. The main HF/E challenges originate from the change of work and the ways to collaborate in mixed reality human-technology teams (i.e., human cyber-physical systems). In addition to work change and human aspects, new business models and sustainability viewpoints should be thoroughly considered. A holistic and multi-disciplinary approach should be deployed when going forward with the industrial metaverse concept.

The findings of this study can be used as a starting point when considering HF/E issues in the industrial metaverse. Both the research community and the manufacturing industry can use the findings to gain an understanding of the opportunities and challenges as well as development needs regarding the industrial metaverse. In addition, the results can be utilized in other areas such as construction industry, transportation and smart cities.

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