XR5.0: Human-Centric AI-Enabled Extended Reality Applications for Industry 5.0

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***Abstract*—Applications for Extended Reality (XR) are rapidly expanding across a wide range of industries, including gaming, entertainment, and healthcare. Accompanying this trend is the field of digital manufacturing, which encompasses a broad range of applications such as quick product design, remote maintenance, production process simulation, employee safety, and training. Industrial personnel may benefit from ergonomic and user-friendly cyber-representations of production processes using XR applications, particularly in the industrial arena. These cyber-representations are utilized to create augmented environments for training, simulation, and testing. The wave of Industry 5.0 (I5.0) applications that are certain to be human-centric and emphasize trustworthy human-machine collaboration cannot be supported by current systems because of several issues, such as the requirement for individualized XR visualizations and new methods for world-building, content production, and flow control aspects of XR systems. The XR5.0 project is presented in this publication with the goal of addressing these issues and offering a revolutionary Person-Centric and AI-based XR paradigm that will be customized to the needs and characteristics of I5.0 applications. The project outlines the organizing concepts and guidelines for utilizing XR in I5.0 applications, with a focus on the creation of cutting-edge "XR-made-in-Europe" technology that complements human-centered manufacturing techniques and upholds European ideals. The associated applications consider the workers' environment through the incorporation of human-centered digital twins (DTs), which make up the "digital image" of the workers. This allows for the simultaneous design and implementation of an innovative fusion of cutting-edge AI paradigms and XR technology. The added value of the XR5.0 project is discussed, and potential use cases and user journeys are analyzed, leading to a discussion of the project's revolutionary benefits and additional steps that should be taken.**

I. INTRODUCTION

For over a decade there is a proliferation of Extended Reality (XR) applications for digital manufacturing, in a wide range of use cases (UCs) like rapid product design, remote maintenance, simulation of production processes, training, and employee safety [1]. XR-based immersive technologies merge the physical and virtual worlds to create new environments in which users can interact with digital content in more natural and intuitive ways. XR encompasses a range of technologies, including virtual reality (VR), augmented reality (AR), and mixed reality (MR). All XR technology takes the human-to-PC screen interface and modifies it, either by immersing the users in the virtual environment (VR), and adding to, or augmenting, the user's surroundings (AR), or performing both (MR).

For many years, the word "XR" has been in use. The first mention of it dates to Charles Wyckoff's patent application in the 1960s for his silver-halide "XR" film, which was meant to capture extraordinarily intense light occurrences, such nuclear explosions [2]. The phrase has gained use more lately as gadget manufacturers find it difficult to articulate the various display modifications they are utilizing. Some XR examples may be found in the world of gaming, movies, or healthcare, as well as retail and shopping among others. Both AR and XR offer players distinctive and engaging experiences in the realm of gaming [3]. AR games allow players to engage with their surroundings in novel ways by fusing digital aspects with the real world, like in Pokémon GO. However, XR includes a variety of immersive technologies, offering a wider variety of gaming experiences. To develop immersive movie experiences, the entertainment sector has also embraced AR and XR technology in the context of movies [4]. AR films improve the experience of the audience by superimposing interactive features or extra information on top of the video. With the use of XR technology, audiences can further immerse themselves in the movie's environment, experiencing a first-hand viewpoint and greater sense of immersion. Another industry that gains from advances in AR and XR technologies is healthcare [5]. To increase accuracy during treatments, medical personnel can utilize AR applications to superimpose digital information, such as real-time vital signs and diagnostic data, onto a patient's body. A wider range of uses is possible with XR technology, such as immersive training for medical personnel and virtual therapy sessions. AR and XR technologies improve the user experience in the retail and shopping industries [6] by providing immersive and customized shopping experiences. With AR applications, consumers may virtually arrange furniture in their homes or see things in their surroundings. They can even obtain product details by only scanning the product itself. As a more comprehensive technology, XR can provide virtual shopping experiences, enabling users to interact with products in fully digital surroundings and browse through virtual stores.

Especially in the industrial domain [7], XR applications provide industrial workers with ergonomic and user-friendly cyber-representations of production processes, which are used to construct augmented environments for testing, training, and simulation. They help manufacturers improve production quality and flexibility, while boosting employee safety. However, cutting-edge XR apps are developed with a "one-size-fits-all" approach that disregards the unique needs of each worker. As such, they are inadequate to support the new wave of Industry 5.0 (I5.0) applications, which are human-centric and prioritize reliable human-machine collaboration. I5.0 calls for XR visualizations that consider the traits, abilities, and environment of the manufacturing worker, as well as the particulars of how he or she interacts with equipment, automation systems, and cyber-physical production systems [8]. The development of such person centric XR is challenging from a technical and technological perspective, as it requires new approaches to the world-building, content production and flow control elements of XR systems. It is also challenging from the organizational and deployment perspective, since XR for I5.0 must adhere to European values (e.g., trustworthiness, data sovereignty, security/safety/privacy by design), including emerging regulations [9] (e.g., General Data Protection Regulation (GDPR), Artificial Intelligence (AI) Act).

With that in mind, considering the lack of human centered XR systems in industry, the limited integration of AI in XR systems, the lack of personalized XR solutions, the lack of AI-enabled human-machine interfaces, as well as the limited trust, privacy, interpretability, and compliance, the purpose of this manuscript is to present the XR5.0 project that aims to build human-Centric AI-enabled XR applications for the I5.0 Era. The goal of XR5.0 is to create, present, and verify a brand-new Person-Centric and AI-based XR paradigm that is specifically suited to the needs and characteristics of I5.0 applications. The project intends to give guidelines and blueprints for the use of XR in I5.0 applications in this direction, with a focus on the creation of cutting-edge "XR-made-in-Europe" technology that complements human-centric manufacturing technologies and upholds European ideals. Based on the integration of human-centered digital twins (DTs) [10], which make up the "digital image" of the worker, the XR5.0 apps are customized to consider the traits and context of the worker. Simultaneously, the objective of XR5.0 is to create and execute a distinct fusion of cutting-edge AI paradigms and XR technologies promoting human-AI- interaction, such as explainable AI (XAI) [11], Active Learning (AL) [12], Generative AI (GenAI) [13], and Neurosymbolic learning [14]. To provide industrial personnel with ergonomic and customized training on common industry-related procedures, the XR5.0 technologies are intended to be integrated with a cloud-based XR training platform for associated applications.

The rest of this manuscript is organized as follows. Section II provides the current technological status in several domains in relation to key XR-related technologies, introducing how the XR5.0 is advancing beyond the current state of the art. Section III introduces the main components that are going to be implemented and integrated towards realizing the XR5.0 vision, while section IV introduces some examples of user journeys and scenarios in which XR5.0 can be applied to. Section V discusses our concluding remarks, also introducing our further actions and steps.

II. Related Work & Ambition

A. *Reference Architectures/Models for XR in Industry 5.0*

I5.0 is a relatively new concept with few widely accepted standards and reference models. State of the art frameworks that can serve as a starting point for implementing I5.0 principles include: (i) The "5C" framework proposed by the Japan Institute of Standardization, which emphasizes the integration of human workers with advanced technologies, and the importance of considering both cyber and physical systems in the design and operation of industrial processes [15]; (ii) The "Social-Technical Systems" (STS) approach [16], which emphasizes the importance of considering both technical and social factors in the design of industrial systems; (iii) Industrial Reference Architectures [17] such as the Industrial Internet Reference Architecture (IIRA) of the Industrial Internet Consortium (IIC) and the RAMI 4.0 (Reference Architecture Model I4.0) of the German Electrical and Electronic Manufacturers' Association (ZVEI). IIRA and RAMI specify technological building blocks and structuring principles for the development of I4.0 applications, yet do not emphasize the human-centricity and sustainability functionalities of I5.0. Nevertheless, the above-listed reference models do not consider the integration of Industrial Automation functionalities with XR environments and cyber-representations. Hence, there is a lack of standards-based reference models for I5.0 applications that integrate XR. Existing reference models/frameworks provide guidelines for the development of digital manufacturing applications in-line with I5.0 implementation principles [18], yet they make no provisions for the development and deployment of immersive XR environments on top of these applications.

In this context, XR5.0 will design and implement an XR-enabled reference architecture (RA) for I5.0 that will facilitate the development, deployment, and operation of person-centric, AI-based XR applications, including new forms of human-machine interaction and collaboration. This reference model will empower a novel standards-based approach to the design and development of XR environments for I5.0 applications. It will emphasize the integration of human-centric AI modules with XR environments towards driving the creation and deployment of personalized XR cyber-representations for human-AI applications. In this direction, the reference model will specify structuring principles and integration points between trusted AI and robotics technologies (e.g., XAI) robotics and XR environments, to facilitate new forms of human-machine collaboration and decision making. Systems compliant with the reference model will be interoperable with legacy I4.0 systems and technologies, to benefit from existing knowledge and frameworks (e.g., the functional domains and the robust security, safety and data protection features of IIRA). Scalability and flexibility aspects will be considered to ensure that the model is adaptable to the evolving needs of different industries and UCs.

B. *Human-Centric Digital Twins of Industrial Workers*

I5.0 DTs must be adaptable to the workers' characteristics and preferences. In this direction, there are state-of-the-art DTs that embrace the characteristics of industrial workers

[19]. Such worker-centric DTs empower the development of functionalities that are tailored to the needs and preferences of the operators. This is in-line with recent studies that have focused on the implementation of XR technology in manufacturing settings with a clear emphasis on the operator [20]. However, very few works investigate how virtual content must be shown to the user. For instance, information filtering based on users' location and task is performed using a region-based approach [21]. As another example, hierarchical clustering has also been used to control the number of labels presented to users [22]. Moreover, the adaptation of virtual contents based on the environment has been proposed, considering illumination, target distance, and noise [23]. Also, different levels of detail in content presentations were suggested for adaptive AR applications [24]. Furthermore, MR and information gathered from the environment have also been used to interact with adaptive MR interfaces, which leverage information about the industrial environment, the tasks, and cognitive load [25]. The latter information tends to be highly dynamic and, in several cases, fast changing, which makes the task of content and interface adaptation challenging. Despite these works, there is still a lack of disciplined and integrated approaches for the implementation of human-centric DTs, yet they represent a very useful tool for adapting XR environments to the needs of the industrial users [26].

In this context, XR5.0 will develop human-centric DTs that produce faithful digital images of the workers to drive the development of highly personalized, yet trusted and regulatory compliant XR applications. It will extend the state of the art in the modelling of DTs with human parameters and digital models suitable for XR content development and personalization. In this direction, the project will extend the Clawdite platform [27] to develop human-centric DTs for highly realistic digital images of workers. It will collect and analyze workers' context, such as fatigue and emotional status, in addition to static traits like height, weight, and digital skills, moving beyond personalization to enable adaptive and real-time customization of the environment based on the workers' current state and performance.

C. Active Learning and XR Integration

AL uses human knowledge to ease the machine learning (ML) algorithm's learning process. As such AL systems can support a wide array of I5.0 UC that involve thrusted interactions between humans and AI systems [28]. In practice, AL systems are commonly used to facilitate the labelling of the data instances that are utilized for training the ML model. AL is one of the most powerful demonstrations of the Human-in-the-Loop paradigm's effectiveness [29], as AL systems lead to improved performance and accelerate the acquisition of knowledge for ML systems. Many recent works have focused on improving the learning performance of popular deep learning algorithms (e.g., Convolution Neural Networks (CNNs) and Long-Short Term Memory (LSTM)) based on their integration AL frameworks. There is also research on the incorporation of Generative Adversarial Networks (GANs) into AL [30]. Recently, there have been also works on reframing AL as a reinforcement learning paradigm. Also, there are AL scenarios in industrial environments (e.g., [31], [32]). Nevertheless, none of the above listed works attempts the integration of AL with formalized knowledge descriptions, which is a setback to using AL outcomes in XR environments.

XR5.0 will expand the state-of-the-art in AL by formalizing and realizing the integration of this ML paradigm with XR environments. AL systems that use XR visualizations to interact with human workers and solicit their feedback in tasks like data labelling will be implemented. To this end, XR5.0 will produce formalized knowledge about popular industrial tasks (e.g., product design, quality control, predictive maintenance). Specifically, XR5.0 will research & design ontologies that will translate concept graphs (e.g., semantic knowledge graphs (SKGs) into XR content and visualizations). Leveraging such knowledge models, XR5.0 will translate knowledge acquired through querying experts and/or acquiring proofs from external data sources to XR visualizations in the context of the industrial process at hand.

D. Neurosymbolic Learning and XR Integration

Nowadays, Neuro-symbolic AI systems are in their early stages of development and support with quite simple integrations between their AI/statistical and symbolic/rule-based parts. For example, [33] describes an image classifier combined with reasoning from text data. Another example of additional integration is provided by [34], which permits the replacement of a node in the probabilistic inference tree of a symbolic machine learning system (ProbLog) with a neural network. Recent works such as Logic Tensor Networks (LTN) [35] can also translate logical statements into the loss function rather than into the deep neural network architecture. The potential of integrating Neurosymbolic learning with MR interfaces is outlined in recent works [36], yet it has not been implemented. Overall, there is a lack of XR environments that are designed and deployed to foster human and AI systems collaboration on problem solving and industrial tasks.

XR5.0 will enable humans to engage in Neurosymbolic learning interactions through XR interfaces. Specifically, XR5.0 will design and develop XR visualizations that will enable humans to engage in a commonsense human centered reasoning, which will complement AI/ML outcomes for a set of popular industrial UCs that involve the human in the loop. The integration between XR environments and Neurosymbolic learning systems will result in higher workers' productivity and increased worker satisfaction for I5.0 cases.

E. Generative AI for XR-enabled Industrial applications

Recently, there has been a surge of interest in GenAI applications, particularly Large Language Models (LLMs) and their integration with XR applications. LLMs have demonstrated remarkable reasoning capabilities, enabling them to take on specific roles and outperform existing state-of-the-art methods in various fields [37]. Their conversational abilities, especially when fine-tuned for chat applications like ChatGPT, combined with integration into XR devices, can enable unprecedented levels of personalization and adaptability to end-user needs and application contexts which are prerequisites in I5.0 [38]. Additionally, specialized LLMs have showcased the ability to generate diverse content, including images and 3D models, from human text prompts, further enhancing their potential in creating immersive XR experiences [39]. Recently, there has been a surge of interest in GenAI applications (e.g., ChatGPT [37]), as well as in their integration with XR applications. One of the most promising research areas is the use of generative adversarial networks (GANs) for creating realistic 3D models and environments [38]. GANs can generate new data that is like available data, which empowers the creation of realistic virtual environments for XR applications [39]. Moreover, there is ongoing research on the use of reinforcement learning (RL) to improve the performance of GenAI in XR. RL algorithms enable the AI to learn from experience and adapt to changing environments, which is essential for creating interactive virtual environments [40]. Other recent developments include the use of ML to enable real-time rendering of XR environments [41]. These works can drive the generation of human-centric content and interfaces for I5.0 applications (e.g., Metaverse like product simulations [42]), yet this potential remains unexplored.

XR5.0 will use GenAI to improve the effectiveness, the ergonomics and the trustworthiness of I5.0 applications based on two complementary directions: (i) The use of GenAI for creating immersive virtual environments and realistic 3D models for training, guidance, simulation, and design. In this direction, GenAI techniques for popular industrial applications (e.g., generative product design) will be integrated with the XR content management platforms of the XR5.0 partners; (ii) The integration of ChatGPT-like generative interfaces to ease the interaction between industrial systems and workers. To this direction, XR5.0 will enhance existing general-purpose language models (e.g., Open AI's model [43], Google's META's PaLM Llama and Vid2Seq [44] models) with ad-hoc data and knowledge about industrial UCs utilizing Retrieval Augmented Generation (RAG) methods, to enable the GenAI agents to delivery proper contextual information to the workers. XR5.0 will leverage data efficient AI techniques (e.g., few-short learning) to train conversational agents using the enriched data corpus. XR5.0 will also consider the user's digital image to deliver user-centric immersive environments and conversational interactions. Overall, the XR and GenAI integration will result in ergonomic environments that reduce the risk of errors and increase worker's satisfaction, including low-skilled ones.

F. XR and eXplainable AI Integration

XAI is a core element of AI-based I5.0 applications as it fosters transparency, trustworthiness, human-centricity, and overall acceptance of AI applications by humans. As a result, the superimposition of explanations over XR visualizations is one of the most prominent cases of XAI/XR integration in UCs that are deployed in XR environments. For instance, there are works that provide virtual reality visualization of deep neural networks [45] and others that use XAI to drive the development of AR content [46]. Other cases of XAI/XR integration, include the development and use of immersive interfaces for training non-experts in the operation of ML models [47]. These UCs represent simple visualizations of explanations that focus on the outcomes of single state machines for industrial UCs (e.g., product classifications in quality control or remaining useful life calculations). They are destined to provide enhanced insights on AI outcomes to enable workers to handle uncertainty and to support them in their decision making.

XR5.0 will advance the state of the art in XAI/XR integration based on the development of XR visualizations for sophisticated process-wide explanations of I5.0 tasks. To this direction, XR5.0 will develop mechanisms for visualizing counter-factual explanations (i.e., to analyze what-if scenarios), while integrating industrial process related metadata (e.g., contextual information about the process) to increase accuracy and alleviate environmental uncertainty in the workers' decisions. Moreover, XR5.0 will benefit from XAI integration to improve the effectiveness of human-AI collaboration as part of the earlier analyzed Neurosymbolic learning and AL paradigms.

G. Augmented Intelligence based on XR Technology

Augmented Intelligence combines human intelligence with AI to improve industrial decision making in supply chain management, predictive maintenance, and quality control. Augmented intelligence can greatly benefit from agile and reconfigurable automation systems such as human-robot collaboration (HRC) [48]. Within these systems, XR technologies present new possibilities for user interaction with simulated environments, expedient information/knowledge retrieval, and anytime/anywhere learning [49]. Human communication involves multimodal [50] social interaction dynamics that produce a variety of patterns, such as the entrainment of repeating behavioral cycles among partners. Handling tasks involving human and robot interaction is a desirable feature in industrial applications [51]. In the past human-robot interaction was achieved through voice [52], gestures [53], and brain-computer interfaces [54]. However, the communication between humans and robots based on these modalities is not intuitive, fast, or flexible yet. Using XR can increase communication between humans and machines during the design, commission, and operation phases [55].

XR5.0 will research XR systems with three (3) interfacing components (menu interface, controller interface, and gesture interface). Users will be able to combine different interaction paradigms allowing for a multi-modal interaction including a GenAI modality. This multimodality will allow users to seamlessly switch among different types of interaction technologies, which will expand the accessibility of computing to non-specialist workers. Two versions of XR interfaces will be considered: (i) A 'lightweight version covering a smaller area of operation and used in sitting positions, and (ii) A 'heavier' version leveraging multiple tracking sensors to cover a larger area for walking users. For a seamless collaborative user experience, both robots and humans will be aware of each other's current actions and location. A shared environment will be implemented, allowing collocative experiences. Experiments will be deployed to quantitatively measure the effect of human engagement in AI decision making. Thus, XR5.0 will demonstrate AI with a more active jurisdictional or even executive role in HRC and human-AI interactions.

H. *Training* based on XR Technology

VR, AR, and MR training environments provide clear benefits in terms of safety (e.g., [56]), ergonomics, and cost-effectiveness, which is the reason why they are commonly used in industrial tasks such as assembly (e.g., [57], [58]), construction [59], and maintenance (e.g., [60]). However, most training applications provide poor integration of AI interfaces and techniques, and do not factor the context of the worker in the delivery of the content. This is a setback to providing personalized and adaptive training to operators. Moreover, the lack of human-centered approaches neglects the importance of addressing human factors such as emotions, cognitive load, and attention span during training. These limitations highlight the need for a more holistic and human-centric approach to operator training.

XR5.0 will deliver a configurable, cloud-based, personalized training platform. Rather than providing a one-size-fits-all content, the training platform will produce AI-based variations of training assets to match the needs of different workers' profiles and environmental settings. This will be available for both off-the-job and on-the-job training. Off-the-job training, typically conducted through VR, allows for immersive learning without real-world risks, making it ideal for mastering new equipment or procedures. On-the-job training, integrated with XR, blends real and virtual elements in the workplace, enhancing spatial awareness and supporting real-time decision-making. This allows workers to refine their skills without interrupting production. The platform will also incorporate information from the human-centered DTs and the digital image of the worker, to ensure that the training content is properly customized to the users' needs. By doing so, the platform will boost the human-centered concept of I5.0.

IV. XR5.0 Overview

A. *Overall Concept*

XR5.0's main goal is to develop a person-centric AI-based XR paradigm tailored to I5.0 applications. XR5.0 will set European XR platforms in the forefront of I5.0 offering the below features:

1) Person-Centric Extended Reality for I5.0 Applications: The project will integrate human-centered DTs [61] and Human-Machine Interfaces (HMIs) to enable the use of XR applications that consider the context and needs of the human worker. XR5.0 will not deliver the usual "one-size-fits-all" content and workflows. Rather XR5.0 applications will offer personalized content and workflows, that will be customized to the needs, skills, and context of the end-users. The XR5.0 solutions will streamline professionals' training and learning processes, as well as improve interactions among humans, machines, AI-systems, and robots. To this direction, XR5.0 will leverage advanced interfaces such as GenAI and prompt engineering [62]. Most importantly, the person-centric XR technologies of the project will be empowered by the human-centric DTs, which will construct the worker's digital image.

2) Effective, Transparent, Trustworthy, XR-compatible AI: XR5.0 will blend XR technologies with advanced AI/ML paradigms that foster transparent and trustworthy interactions among humans and AI systems. Specifically, it will converge XR environments with human-centered AI models such as AL, GenAI, XAI, and Neurosymbolic AI. This convergence will empower novel XR environments that visualize recommendations, classifications, and explanations to provide workers with access to enriched, detailed, and more accurate

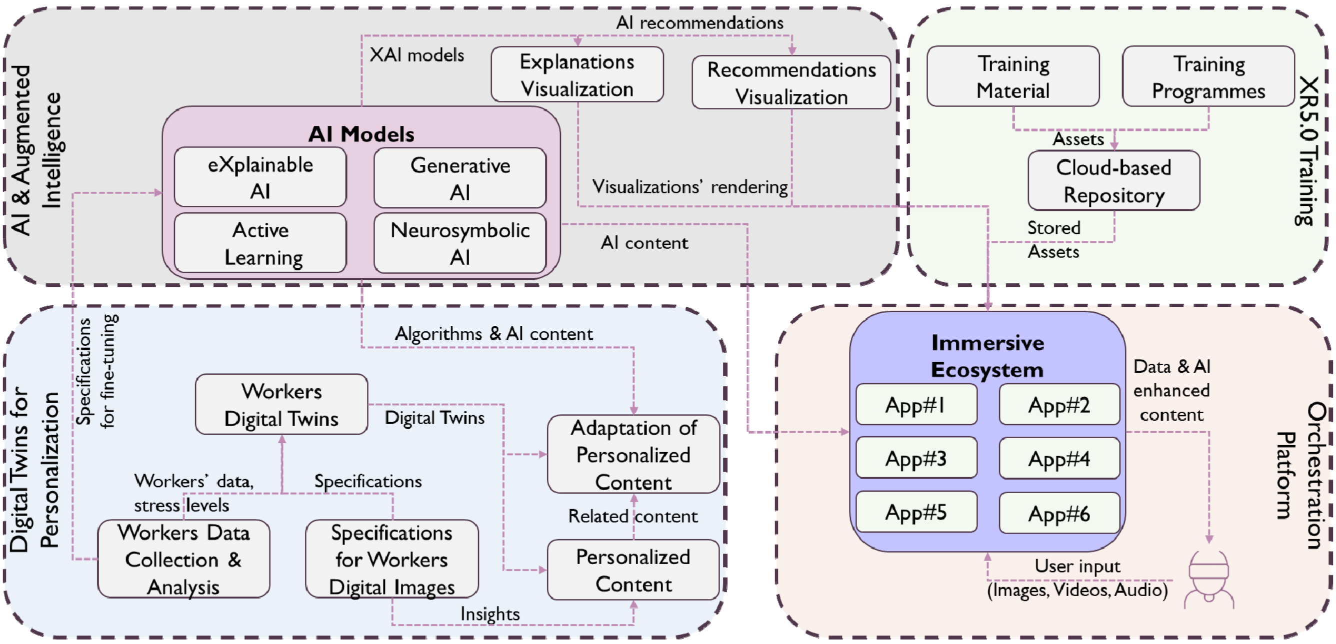

Fig. 1. XR5.0 Interacting Components Overview

information. Such settings will boost the safety, transparency, and trustworthiness of the respective XR systems. Moreover, they will increase the effectiveness of human-AI interactions. Emphasis will be paid on novel XR-AI integrations in the above areas, such as the visualization of counterfactuals (XAI-XR integration), the formalization of knowledge for effective AL interactions (AL-XR integration), as well as the production of highly personalized content and interactions (GenAI - XR integration). Furthermore, XR5.0 will provide enabling infrastructures for real-time inference and execution of AI models on edge devices towards low latency and high responsiveness environments that will deliver more immersive and interactive experiences.

3) Designing and Implementing Person-Centric AI enhanced XR Solutions: Leveraging the project's technologies, XR5.0 will deliver AI-based, person-centric XR solutions. In this direction, several enterprise scale platforms will be enhanced with XR5.0 technologies to support the AI-based and human-centric features of I5.0. Specifically, XR5.0 will deliver a training platform that will incorporate content and workflows tailored to the characteristics and needs of the worker.

B. XR5.0 Interacting Components

From a technical infrastructure perspective, XR5.0 will be empowered by cloud/edge infrastructures that will enable the implementation of novel real time AI UCs and XR rendering services. The latter will be applied in various industrial conformations offering enhanced decision making and support. The overall concept of the XR5.0 is illustrated in Fig. 1, in which the different interacting layers can be visualized, including the layers of: (i) Digital Twins for Personalization, (ii) AI & Augmented Intelligence, (iii) XR5.0 Training, and (iv) Orchestration platform.

At the heart of the XR5.0 platform, there are the:

1) Digital Twins for Personalization: This layer focuses on human-centered solutions such as Human-Centric DTs integrated to I5.0 tailored XR platforms. The *Specifications for Workers Digital Images* will firstly design and implement digital representations of the industrial workers, notably representations that capture their main characteristics. These digital representations (i.e., "digital images") of the workers will enable the construction of human-centric DTs. Each digital image will capture static, semi-static and dynamic characteristic of the industrial worker such as physical characteristics (e.g., height, weight), role on the shop floor, digital skills, fatigue levels, and emotional well-being. This will lead into the creation of a detailed set of specifications for creating worker digital images that can be seamlessly integrated into XR applications to enable the personalisation of XR functionalities, content, flows, and virtual worlds. Then, the *Workers Data Collecton & Analysis* will harness and manage data from a range of sources, such as enterprise systems (e.g., Human Resources Management Systems (HRMS) and ERPs), sensors, wearables, and other contextual information, in ways that will respect GDPR guidelines and ethical considerations. It will enable the extraction of meaningful insights from the collected data towards continuous refinement and personalisation of XR experiences, collecting workers' data and stress levels. The *Workers Digital Twins* will gather the aforementioned specifications and workers'-related data, focusing on designing and implementing human-centric DTs that accurately represent individual workers and their unique traits, behaviours, and contexts. The DTs will integrate the data and insights obtained, creating faithful digital images of the workers, along with suitable interfaces for integration with XR technologies. The *Personalized Content* focuses on developing tailored content for individual workers in the context of XR applications. It involves designing and creating personalised XR experiences, such as simulations, training modules, and virtual environments that take into account each worker's unique characteristics, skills, and preferences gathered from the developed DTs and the gathered workers' specifications. At this end, the *Adaptation of the Personalized Content* will develop mechanisms for dynamically adapting XR content based on the individual needs, intentions, and context of the industrial worker, developping algorithms and techniques that modify and adjust XR experiences in real-time, considering all the layers' generated input.

2) AI & Augmented Intelligence: This layer includes scientific activities focused on AI paradigms for trusted and human-centric collaboration between workers and AI systems, as well as integrating these paradigms into XR environments. These also include Perceptive, Naturalistic HMIs enabling unified access to XR5.0 capabilities for designing, developing, deploying, monitoring, and reconfiguring Human-AI systems. The HMIs will also offer multi-modal, ergonomic visualizations, dashboards, and XR environments that will be adjustable to the considered blueprints and UCs, always considering the gathered specifications of the workers' and their DTs of the previous layer. In more detail, the *eXplainable AI* part will integrate and blend in the XR solutions of the project, AI models that foster trustworthy human-AI collaboration for I5.0 applications. It will develop transparent, understandable, and adaptable AI systems that can effectively communicate with human users and provide personalised, yet trusted recommendations. It will build on guidelines and tools for ethical and responsible AI to ensure the regulatory compliance and trustworthiness of the XR5.0 AI systems. Human-centred XAI models will be developed, along with infrastructures that support their integration into XR environments. The *Active Learning* and *Neurosymbolic AI* parts will integrate XR-enabled AL techniques that involve humans in the machine learning process for better and faster results with XR interfaces, notably interfaces that enable naturalistic interaction among humans and AI. Furthermore, it will be integrated Neurosymbolic AI into XR-based industrial applications. The latter integration will combine deep learning and symbolic reasoning to create more robust and explainable models, which will be useful in complex and safety-critical I5.0 applications. The *Generative AI* part will be based on powerful open-source generative models (e.g., OpenAI's GPT, Google's PaLM, Transformers API) and prompt engineering, which will enable content generation and the development of user-friendly interfaces for human users (e.g., chat, voice to voice) in I5.0 contexts. The outputs of the GenAI models will be rendered in XR environments allowing for user-friendly immersive experiences. Then, the *Explanations* and *Recommendations Visualizations* will integrate the AI/XAI explanations into XR environments towards increased transparency and interpretability guaranteeing that the content produced by the AI models will be rendered in the target XR device/platform in real-time, ensuring that the positioning of the XAI visualizations meet the users' needs.

3) XR5.0 Training: This layer considers an AI-enabled, highly personalised XR-based training platform. The platform will allow industrial enterprises and workers to visualize processes in XR environments and navigate across them while being guided by a virtual training instructor. It will provide intelligent, human-centric training applications for I5.0 UCs. More specifically, *Training Materials* and *Training Programmes* will be developed tailored to specific industrial UCs and designed to enhance the operator's skills and knowledge in operating and maintaining complex equipment and processes. It will gather, classify, and document traditional training materials per job task (e.g., technical orders for replacing an equipment or performing an operational test), difficulty level, and industrial domain (e.g., aircraft maintenance). At this stage, the *Cloud-based Repository* will store and manage all this content in the form of assets, addressing security and privacy issues associated with cloud-based training asset management and ensuring compliance with ethical and legal requirements.

4) Orchestration platform: This layer includes an *Immersive Ecosystem* to enable seamless integration and coordination of XR assets, rendered visualizations, AI content, and applications, as well as devices supporting XR-enabled training of operators, as provided from the aforementioned XR5.0 layers. Moreover, it will address challenges of interoperability, performance, and scalability associated with the integration of heterogeneous XR devices and assets. It will enable real time and device-agnostic streaming of AR/VR applications to a wide variety of mobile XR devices through efficient and effective use of cloud/edge computing resources, also integrating AI-based visualizations.

C. Related Scenarios & User Journeys

The XR5.0 paradigm will facilitate the creation of many pilot applications in the fields of AI-driven product design, asset maintenance that is both remote and intelligent, worker training, product assembly assistance, and troubleshooting aid and instructions. Realistic manufacturing environments will host the deployment and demonstration of these applications. Below, a set of potential scenarios and user journeys are described to showcase the benefits of XR5.0 (Fig. 2):

1) Personalized, Multi-Modal, AI-Enhanced Workers' Training: When assembling a complex product, a production worker or specialist must pick up a new procedure. They can receive instruction in a highly customized, multi-model environment that combines virtual and physical elements with the aid of XR5.0's training platform. The setting replicates the actual manufacturing process while taking into account the context of the workers, which includes their traits, abilities, emotional state, and more. Additionally, the environment incorporates a broad range of AI-based intelligence capabilities, including real-time generating feedback on the user's activity within the applications and explanations for different aspects of the process. The factory employees' training in this setting will minimize the assembly process' learning curve while also significantly enhancing their learning experience and job satisfaction. This will then show up in the employee's general performance, productivity, and skill improvement.

2) AI-based Sustainable-by-Design Products/Production: A manufacturing product manager or an industrial plant manager seeks to maximize a product's sustainability. In line with the Circular Economy Action Plan (CEAP) of the European Commission, 80% of the sustainability improvements are likely to come from the design of green and eco-friendly products based on a Sustainable-by-Design (SbD) production approach. XR5.0 gives the manufacturing management the ability to see a multitude of product choices in a setting similar to a metaverse, hence promoting SbD. The latter is made feasible by the inclusion of GenAI with XR5.0 support. The factory manager may quickly audit hundreds of production configurations based not just on their look but also on their sustainability features and carbon impact by using XR5.0 technology to visualize them [63]. In addition, XR5.0 has the ability to visualize explanations, including counterfactuals, which helps managers analyze what-if scenarios and make better decisions. Employee productivity rises as a result of this strategy, which also improves decision-making skills and ultimately advances sustainability.

3) Effective Mass Customization based on AI and XR: In this case, a product designer must use a Made-to-Order strategy to develop a customized product for a particular client. The designer will be able to generate numerous design possibilities by using a GenAI model thanks to XR5.0. Real-

Fig. 2. XR5.0 Related Scenarios & User Journeys

time feedback from the XR environment will enable the designer to make quick adjustments and raise the caliber of the finished product.

4) Personalized Remote Instructions and Support in Maintenance Processes: A machine builder's skill is needed to maintain a sophisticated piece of machinery that a maintenance manager must perform. These days, scheduling lengthy travels during the engineer's availability necessitates the physical attendance of the machine builder's engineer for the majority of the maintenance procedure. This makes the process expensive, time-consuming, and environmentally unfriendly. With XR5.0, an on-site technician can receive personalized remote instruction from the machine specialist, negating the need for travel. In an XR environment, the remote guidance is visualized using appropriate material and instructions that are customized to the technician's skill level. Above all, XR5.0's AI and customization capabilities enhance the default instructions by adding individualized data, notifications, help, and contextual justifications. These characteristics let the technician perform maintenance and repairs in a timely, safe, and effective manner. This scenario delivers significant benefits to the manufacturing enterprise, the technicians, and the Original Equipment Manufacturer (OEM), towards increased productivity and reduced costs.

V. Discussion & Concluding Remarks

XR5.0 aims to contribute to the development of innovative, world-class, made-in-Europe, virtual world platforms based on the XR platforms and technologies. The latter platforms for virtual worlds will be enhanced with AI and Human Centric DTs technologies to support I5.0 solutions. The pathway to realizing this impact includes the development of the XR5.0 technological results, their integration and validation in several pilots, as well as the scale up of their use by industrial enterprises in Europe and beyond. In this manuscript it was presented that XR5.0 can provide novel technologies for virtual world development that will feature personalization features based on the worker's digital image, human-centered trustworthy interfaces for I5.0 applications, as well as a rich set of AI-based intelligence features. These technologies will enable hundreds of solution integrators to develop novel ergonomic and highly personalized solutions. What is more, XR5.0 will boost the competitiveness of the XR vendors and automation solution integrators of the project. It will enable them to become the world's first providers of person-centric AI-based XR technology, thus elevating their offering in the global XR market and their potential to increase their market share. At the same time, XR5.0 technology will enable multiple industrial enterprises and providers of automation solutions to develop, integrate, deploy, and operate the next generation of AI-based XR solutions, which will generate a niche within the XR5.0 market. In addition, the XR5.0 virtual worlds will improve the social performance of popular industrial applications for processes such as maintenance, assembly, training etc. This social performance will be benchmarked in the scope of XR5.0 based on parameters like workers' productivity and satisfaction. XR5.0 will scale up this impact based on a proliferation of XR5.0 deployments that will achieve similar performance as the project's benchmarks.

The implementation of XR5.0's intended functionality based on scenario-driven business and technical requirements is one of the next steps. While the overall XR5.0 interdependencies will be regularly adjusted, these features will be put through functional stress testing within the framework of the XR5.0 pilot sites, which mirror the demands of several EU countries, from Germany to Switzerland and Portugal to Greece. Performance assessments that focus on the usefulness, usability, and functionality of the XR5.0 offers will also be considered. The extracted results will be shared with external stakeholders (such as XR vendors/integrators, Manufacturing automation vendors/integrators, Industrial Enterprises in Manufacturing, AI Vendors and Solution Integrators, Industrial Workers, I5.0 & AI Policy Makers and Regulators) whose services will be facilitated. The extracted results will also be continuously monitored and evaluated. Furthermore, they will be integrated, tested, and adapted in the context of proprietary external domains' platforms and applications, such as [64], [65], [66], [67], [68], and [69].

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