Virtual Engineering: Hands-on Integration of Product Lifecycle Management, Computer-Aided Design, eXtended Reality, and Artificial Intelligence in Engineering Education

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Engineering education at the Institute for Information Management in Engineering integrates product lifecycle management (PLM), computer-aided design (CAD), eXtended reality (XR), and artificial intelligence (AI) to enhance learning and prepare students for modern challenges. Our interdisciplinary approach, emphasizing digital twins and virtual twins, fosters immersive, hands-on experiences. This paper reviews our strategies, comparing them with global initiatives, highlighting the transformative impact of our curriculum on preparing future engineers for complex industrial environments.

Keywords: Artificial intelligence, Engineering education, eXtended Reality, Product lifecycle management, Virtual engineering

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1 Virtual Engineering

Virtual engineering (VE) is the holistic, continuous, cross-linked (process view) and integrated (system view) support of the entire product life cycle (PLC) regarding coordination, evaluation, and verification of results of all partners with use of immersive eXtended reality (XR) technologies, including augmented reality (AR) and virtual reality (VR). VE refers to the use of software environments, knowledge-based systems, and product data management to create integrated design and manufacturing processes for new products [1].

The main objective of VE is merging the physical and virtual (i.e., computer-generated) engineering environments. This facilitates realistic human-machine collaboration within the reality-virtuality continuum. In education, virtual environments allow students to carry out their own practice and obtain an experience very close to the real one and many virtual environments provide technical results similar to those obtained in a real practice [2]. Thereby, VE helps to explore and shape tomorrow's reality and future technologies in the engineering domain.

In the contemporary landscape of engineering education, there is a pressing need to move beyond traditional and even digital paradigms to embrace more holistic and immersive approaches. At KIT's Institute for Information Management (IMI), we champion the concept of "virtual engineering," which not only aligns with this vision but also redefines it. To understand the transformative power of VE, it is essential to contrast it with the digital engineering paradigm. Digital engineering often sees engineers working in isolation, focusing on individual tasks. The emphasis is on completing specific tasks rather than broader decision-making. Information technology stands at the core, driving processes and solutions which are often not real-time and may lack immediate applicability. The interaction is primarily through two-dimensional graphical user interfaces, leading to a WIMP (Windows, Icons, Menus, Pointer) mentality.

On the other hand, VE, as conceptualized by IMI, offers a paradigm shift. It promotes collaborative efforts, emphasizing teamwork and shared objectives. The focus is on broader decision-making processes rather than just task completion. It puts people at the core, recognizing the value of human insight and intuition. Solutions are immediate,

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Figure 1. Overview of the areas of responsibility of the PLM [3].

relevant, and applicable in real-time scenarios. It prioritizes natural, intuitive interactions, moving away from traditional GUIs to tangible user interaction with digital information. This approach champions intuition and immersion as the primary drivers of effective human-machine collaboration.

VE transcends the limitations of the digital engineering paradigm, merging our present reality with the vast potential of a computer-generated world. It offers an environment where we can explore, shape, and apply the technologies of tomorrow in a manner that is both intuitive and collaborative. At IMI, our commitment to VE is unwavering. We see it as more than just a teaching methodology; it is a philosophy that reshapes how we approach engineering challenges, collaborate, and envision the future. This paper delves into our journey with VE, highlighting its impact, our successes, and the lessons we have learned along the way.

2 Application of Virtual Engineering Concepts in Education

2.1 Product Lifecycle Management

Product lifecycle management (PLM) deals with approaches to product-related and cross-company information management. The objective is to create continuous processes throughout the entire product lifecycle, starting with requirements and specifications and ending with product recycling (see Fig. 1) [3].

During this, employees and in particular engineers are supported in their daily work so that the "time to market" can be shortened, development costs reduced, and product quality increased. To achieve these goals, IT system solutions such as enterprise resource planning (ERP), computer-aided design (CAD), supply chain management (SCM) or customer relationship management (CRM) solutions are at the heart of PLM. A critical success factor in the implementation of the PLM approach is the efficient orchestration and targeted use of these IT system solutions in the business processes of an organization.

In the literature, PLM software is generally described as an approach which has the potential to enable users to simulate real-life situations and prepare future professionals for industry and real-life business cases. This complex topic has to be taught in higher education, the state-of-the-art on the topic of PLM in higher education is presented in the following.

Bedolla et al. [4] stated that there is no comprehensive review that fully captures how PLM is taught across higher education institutions globally; only few partial studies are available, a complete and thorough analysis is lacking. But according to Chang and Miller [5] PLM courses are more focused on the processes rather than practicing of PLM.

A study about educational strategies of United States universities in the context of PLM can be found. Gandhi [6] shows that at one university a Research and Development Program for the topic of PLM was developed, although details about the lecture are not given. Another university presents a center for PLM education, trying to develop coursework for existing masters in engineering and management programs.

Regarding the actual teaching programs of universities, several examples could be found. The survey in [4] furthermore reveals that PLM courses in Italy are predominantly offered at the Master's level, mainly part of programs in management engineering, mechanical engineering, and computer science, same could be observed in France. In many cases, PLM is addressed within broader courses with a duration between 6 and 64 h in France, such as drawing, industrial plants, and management. Interesting is that 25 out of 40 Italian courses do not contain software usage to support their teaching activities.

A PhD Program from a US university in mechanical engineering includes a design group project, focusing on product development aspect, during which the students require PLM knowledge and use CAD software [6]. An example of industry-university collaboration is an 18-h internet-of-things (IoT) innovation workshop for employees, trying to gain real-world experience with state-of-the-art technology solutions and application platforms, using various software-tools [7].

Hochschule Düsseldorf presented the module PLM and service management and offers students a practical module which includes lectures and practical exercises. The module also ensures practical application and industrial contribution. The work is done in a team and covers all areas from design to end-of-life [8]. Another industry-university collaboration is presented by the Purdue University PLM Centre of Excellence Program in the United States, which is directed by Dr. Nathan Hartman and the taught part supported by Boeing [9]. In this program, the industry (e.g., Boeing, Cummins, Rolls-Royce, General Motors) and the academia work together on real-life challenges and projects. Companies such as Siemens, Dassault, and PTC are also involved as vendors. In the program three main areas (3D modeling, relational design, and manufacturing process planning) are covered. Interactive exercises and also group discussions are used to teach the concepts and to discuss

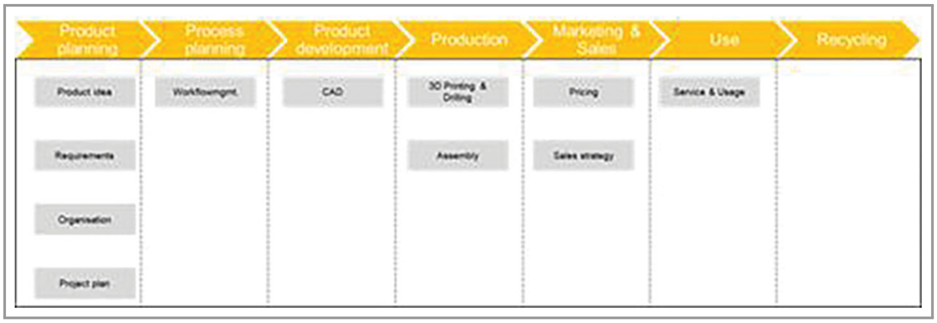

Figure 2. Procedure and tasks within the PLM-CAD workshop.

practical real-life projects. Each main area is done in 8 weeks and the material delivery is within 2 h of virtual lectures and 2 h of virtual laboratory sessions (weekly). The program is managed and supported by academic staff at Purdue and Boeing.

An example of more covered aspects of PLM is a course at a university in Switzerland [10], which is divided into three major components: a physical product, a business environment, and the relevant IT landscape. The physical product is constructed using LEGO, Arduino, and 3D-printed parts. Despite the simplicity of these technologies, the setup incorporates all relevant organizational aspects, processes, and IT tools typically found in a modern, up-to-date company, including ERP, PLM, configurators, and CAD systems. The processes examined in this setup include design and development, sales, production, and maintenance.

The given examples showed that there are different approaches to teaching PLM in higher education, advantages and opportunities of them commonly are: usage of various software tools, group projects, application in multiple disciplines such as mechanical engineering, real-life relevance of content for the gap between theory and reality, and incorporation of different aspects of PLM.

Within the framework of the "PLM-CAD workshop", the IMI pursues the goals of introducing students to the PLM approach in a risk-free experimental environment as part of and in an interdisciplinary team, and of testing the targeted use of IT system solutions. The PLM-CAD workshop is offered every semester for bachelor students of industrial engineering, computer science, and mechanical engineering. The idea of the PLM-CAD workshop is to go through the approach of PLM in project groups by setting a practical project and to develop a prototype. The unique selling point of the PLM-CAD workshop is the interdisciplinary approach, the wide range of IT system solutions that can be used, and a high practical component, e.g., through the use of 3D printing processes and the milling of components. These resources (3D printer, PLM systems, and milling machine) are necessary to offer the PLM-CAD workshop and to provide practical insights into PLM. The course includes a validation of the prototype in both the real and virtual environment. Furthermore, the applied methods and approaches are oriented towards current research in the field of PLM, virtual reality (VR), and virtual product development.

Contents of the course:
The PLM-CAD workshop begins by providing basic knowledge of PLM and CAD and explains the learning objectives and assignment for the semester. Students are given a hands-on assignment and are tasked with developing a prototype using milled parts, 3D printed parts, and LEGO mindstorms [11]. The process of the PLM-CAD workshop, as depicted in Fig. 2, has been established over the past semesters, but is undergoing continuous improvements and adjustments. The following explanations refer to the assignment from the winter semester 2022 and 2023.

The students had the task to design a telepresence robot in an interdisciplinary team and to start by establishing a fictitious company, defining roles and responsibilities, and elaborating three potential product ideas as illustrated in Fig. 3.

The functional requirements, quality requirements, and general conditions for the prototype (e.g., dimensions, weight, and functionalities) are determined during a fictitious interview with the teaching staff (in the role of a client)

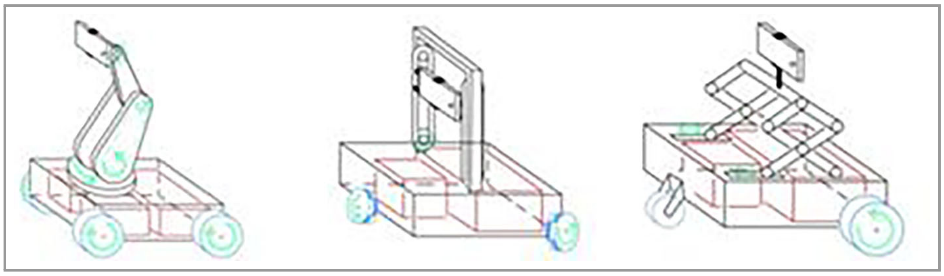

Figure 3. Three product ideas for the implementation of a telepresence robot.

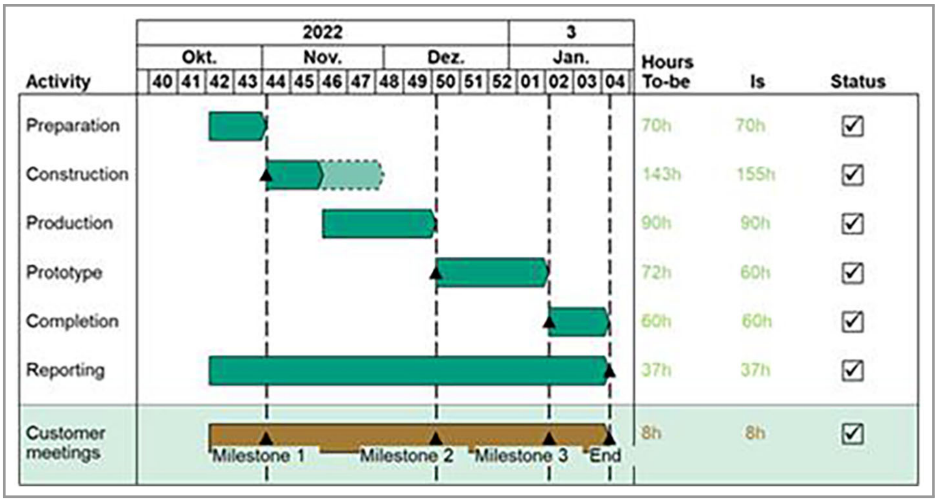

Figure 4. Example project plan of a project group.

and finally documented by the groups. The interview must be prepared by the groups so that the right questions are asked to elicit requirements. Missing requirements can lead to the prototype being overengineered or not meeting the needs of the eventual clients.

In addition, a project plan is developed by the groups so that both time, 120 h per student, and personnel planning is in place for each phase of the project. Regular milestone meetings are held to report on the progress of the project and to compare the planned target and actual hours, as detailed in Fig. 4.

Validation and review of project progress takes place in various formats. Out of a total of three milestone presentations, one presentation takes place digitally. The prototype is analyzed in VR and the final design is discussed in a pitching format. Finally, after the project plan is completed, the process definition takes place. During this, development and release processes are defined, modeled, and finally decided. This serves to accelerate development processes in the group and to define responsibilities. In the course, the 3D experience platform [12] is chosen as the software solution for process modeling.

After deciding on the final product idea, the selected design is realized in 3D experience. All team members learn how to use a CAD system regardless of their prior experience. A general idea in the workshop is for everyone to get in touch with the different aspects of the whole process. Introductions to the systems are given to the students, nevertheless they also must learn by themselves and improve their skills accordingly to their ideas. The full benefits of the software system can be used. For example, versioning of the individual components and assemblies is maintained in the system. Collaborative, synchronous or asynchronous work with several designers is possible. In the system documents are created, which would be important for the purchase and/or the camp of a company, e.g., the parts lists are provided. The stock can then be constantly checked for completeness of all required parts.

The design is validated both virtually and later in real life. After completion, the design is examined and discussed in a VR cave automatic virtual environment (CAVE). The assembly is projected onto multiple white walls, with the VR glasses it becomes three-dimensional, it can be moved manually or you can walk around your design. The CAVE offers the advantage that, on the one hand, a "look and feel" for the product is created. Customers can be included in this session, in this case the supervisor, to show the current state and, on the other hand, errors in the design can be easily identified in VR and requirements can be checked virtually. The common view on the large virtual model also facilitates group discussions, as well as the exchange among different groups.

In the workshop, the process of product development is considered from start to finish, therefore the ideas are to be transferred into reality. For this purpose, some parts are prepared for production using computer-aided manufacturing (CAM). At least one component will be 3D-printed and at least one other will be manufactured using milling by the group members. Therefore, the workshop provides experience in manufacturing technology.

A prototype of the product, as a mix of standard and in-house manufactured parts, is assembled, whereby an assembly instruction is provided. The requirements for the product can be tested in reality by means of the prototype. For the beginning to end process an instruction manual for the product is created.

The participants of the workshop have diverse backgrounds, including students from various study subjects like mechanical engineering, computer science, and industrial engineering represented and mixed in the groups. The workshop is also interdisciplinary in that not only typical mechanical engineering skills such as CAD, CAM, and manufacturing skills are tested, but areas of the mechatronic system are also explored. The products can be equipped with motors and sensors, which can be controlled via a standard controller. A new addition to the workshop is the function to control them via a self-written online tool, which requires programming skills.

At the end of the workshop, the prototypes are presented to an audience with no prior knowledge of the workshop. This presentation is based on a marketing presentation, where potential customers, who have no knowledge about product development, should be convinced of the product. A poster and a commercial for the product are also created.

The still quite new topic of artificial intelligence (AI) application has not yet been integrated as an official component in the workshop. However, AI approaches were partially used by individuals, e.g., to design a company logo, to generate a basic code for the controller or for text-to-speech approaches for a commercial. The official integration of this topic to the course could be the next step to improve our education.

To summarize, the PLM-CAD workshop can be seen as an extensive practical application of PLM, which is completed in an interdisciplinary manner using various software tools in a team. It therefore has overlapping features with various courses from related education programs as previously presented, or even combines them in one course, such as mapping of further parts of the product life cycle as strong focus in the course or content with real-life relevance. In contrast to the courses presented, the manufacturing of a product is further supplemented by 3D-printed and milled parts. With 120 h per student, the PLM-CAD workshop is also one of the more extensive courses found and the only one using immersive technology like XR.

2.2 Extended Reality

Building upon the foundation laid by our PLM and CAD courses, our educational approach is further enriched by the incorporation of XR technologies.

XR technologies, encompassing VR, AR, and mixed reality (MR), are increasingly being integrated into engineering and product design education. These technologies have the potential to transform traditional educational practices by creating immersive and interactive experiences that allow students to engage deeply with complex concepts. XR technologies have proven especially valuable in facilitating the exploration of sustainable design principles [13], although the integration of XR into educational practices remains an area in need of further research and development [14].

One significant approach to integrating XR in education is the “teaching factory” paradigm, which blends real-world industrial challenges with academic learning [15]. This approach aligns with the emerging concept of Industry 5.0, where human-centric and personalized education models are emphasized. XR technologies are particularly effective in enhancing remote and collaborative learning environments, which are becoming increasingly important in modern education systems. The concept of “personalized perception,” where XR is used to create tailored learning experiences based on individual student preferences and abilities, exemplifies the shift from mass education to personalized, adaptive learning environments.

Despite the potential benefits of XR technologies, there are several challenges that need to be addressed. The integration of XR into educational settings faces technical difficulties, including latency issues and the need for seamless human-machine interfaces [16]. Moreover, the successful adoption of XR requires robust support systems, including both social support (e.g., from colleagues) and technical assistance [14]. Faculty members generally express positive attitudes toward XR due to its potential to enhance student engagement, improve visualization, and foster greater interactivity, but institutional support and adequate infrastructure are essential for its effective implementation.

The application of XR in engineering education has a long history, with early adopters utilizing VR for data visualization and the enrichment of teaching materials to enhance information comprehension [17, 18]. VR has been particularly influential in fields such as building and construction, where it has been used to improve educational outcomes through immersive simulations [18]. Historically, the deployment of VR in education relied on complex and expensive hardware setups, such as CAVE systems [19]. These systems, though costly and operationally challenging, have been integrated into the curricula of several educational institutions [20].

Recent advancements in technology have introduced more accessible and versatile XR devices, such as the Microsoft Hololens, Meta Quest Pro/3, and Apple Vision Pro. These devices, along with tablets and smartphones, are now increasingly used in educational contexts to blend virtual data with physical environments, providing a more interactive and immersive learning experience [21–23].

Digital twins (DTs), which are increasingly being used in combination with XR technologies, offer significant opportunities for both industry and education. DTs enable users to interact with real-time, virtual representations of physical systems, thereby enhancing visualization and providing more immersive learning experiences [24]. In educational settings, DTs can be integrated with VR to create intelligent, interactive classrooms, allowing students to engage with complex processes in a controlled, virtual environment [25]. This integration of DTs and XR not only improves the effectiveness of training programs but also supports the development of personalized and adaptive learning environments [26].

The seamless integration of XR technologies is central to our VE curriculum. This enables students to not only visualize their designs but also interact with them in a comprehensive and immersive manner. Students can manipulate a virtual prototype of a complex machine, conduct an on-site visit virtually, or even traverse a simulated factory floor, experiencing first-hand the implications of their design decisions. XR technology has positive cognitive and pedagogical benefits in engineering education, which ultimately improves the students' understanding of the subjects, performance and grades, and education experience [27].

The incorporation of XR technologies revolutionizes traditional engineering design methodologies by enabling VTs, as an intuitive interface to the digital representations of cyber-physical systems. At IMI, we have been developing an open-source VR framework, i.e., "PolyVR" [28], for over a decade. This tool forms an integral part of our education and projects, providing a platform for immersive, experiential learning scenarios that greatly enhance the depth and quality of our engineering education. Utilizing our VR framework, the students can implement their VR projects, such as VTs, within one semester and simulate real-world processes in a virtual environment. With frequent expansions and improvements, PolyVR continues to evolve, staying in stride with advancements in technology and research. Although our primary focus lies on PolyVR, we also utilize industry-standard XR engines such as Unity, Unreal Engine, and Godot in our practical courses to provide a diverse range of tools and experiences for our students.

Alongside our software developments, we have integrated a range of cutting-edge XR hardware to support immersive learning. Devices such as the Microsoft Hololens 1 and 2, Meta Quest 2 and Pro, and HTC Vive 1 and Pro are used extensively in our XR applications. These devices enable students to engage with both virtual and physical elements seamlessly, thereby enriching their learning experiences. Additionally, tablets and smartphones are employed in various applications where mobile AR is beneficial, ensuring that students can access and interact with XR content in diverse environments. Our approach to VE incorporates concepts for model-in-the-loop (MiL), hardware-in-the-loop (HiL), software-in-the-loop (SiL), and human-in-the-loop processes. This offers a comprehensive and holistic approach to engineering education, recognizing the interconnectedness of human, machine, and software components in modern industrial processes. The subsequent sections will provide example XR applications from our education, research, and industry projects.

2.2.1 Virtual Twins

One of our research projects, incorporating the human aspect, was the development of a virtual simulator for teaching car driving [29]. Therefore, we integrated a physical car into the virtual driving simulation to deliver the haptics of a real car. Communication from and to the car controls was achieved via the CAN bus system. An intelligent tutoring system was developed for this driving simulator which supervises the progress of the students to deliver customized teaching scenarios such as specific repetitions and individualized assessment of learned skills. From this project, we further adapted various underlying simulation modules for a virtual tunnel boring machine (TBM) simulator [30]. One of the major challenges in human-centered simulation environments such as interactive VTs is the necessity of real-time capability. The whole environment must react to human input in real time. One of the outlying features to support this problem for the simulator is a combination of hardware- and software-in-the-loop approaches to incorporate the real programmable logic controller (PLC) of the TBM. Following this approach, realistic scenarios can be set up for training machine operators. Machine faults and errors will be displayed the same as on the physical machine due to the same program on the PLC as on the construction site.

Our latest use case is the development of a co-simulation of a flow rig stemming from the process industry. In this setup the PLC was not deployed in the simulation. Instead, the virtual scene was coupled to an external simulation software, namely, SIMIT[1] by Siemens. While we use this setup for training and educational purposes, the overarching research goal is the automatization of tedious, often manual steps in the product development process and the acceleration of the needed commissioning both in virtual as well as in physical form.

The virtual form of the commissioning process is a novel strategy of combining front loading effects to quicken trouble shooting in virtual form before the system is physically assembled. The effort of virtual commissioning (VC) promises to reduce errors in the assembly and accelerate programming and debugging steps on the side of implementing machine control code such as PLCs. VC projects typically rely on these three approaches: MiL, SiL, and HiL either separated or sometimes in combination [31]. Our work focuses on an SiL approach with SIMIT responsible for the facility simulation, in contrast to the TBM use case with the PLC running as an extension of the co-simulation in tandem with the VR software [30, 32]. Specifically, in the chemical and process industry DTs are heavily pushed through VC [33–36].

For the communication protocols, differences, advantages, and disadvantages in the context of "Industry 4.0" and "Internet of Things" are often discussed. The typical choice lies between the options of OPCUA[2] and MQTT[3]. While OPCUA is a very secure and reliable technology, MQTT promises more bandwidth and lower latency as well as variable quality of service layers to tune between performance and data checks. In our research, MQTT was chosen as a data exchange protocol.

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[1] SIMIT by Siemens: https://www.siemens.com/de/de/produkte/automatisierung/industrie-software/simit.html

[2] OPC UA – from automation pyramid to information network: https://iebmedia.com/technology/iiot/opc-ua-from-automation-pyramid-to-information-network

[3] OASIS MQTT Standard: https://docs.oasis-open.org/mqtt/mqtt/v3.1.1/mqtt-v3.1.1.html

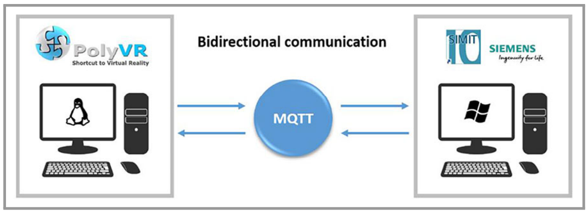

Figure 5. Simulation setup of co-simulation architecture.

In contrast to the majority of VR applications, which are developed in gaming engines like Unity[4] or Unreal Engine[5], in our research the open-source VR-authoring tool PolyVR[6] for VE was used due to PolyVR's ease of use for engineering specific tasks. The applied methods and algorithms are transferable if rewritten in the respective engines' programming language.

The combination of the virtual scene and an external simulation coupled through the communication protocol MQTT forms a co-simulation. The flow rig simulation consists of a flow simulation running in SIMIT in real time. Included in the water circulation layout are several sensors and actuators. Fig. 5 and Fig. 6 display the states of the virtual flow rig and SIMIT simulation while the co-simulation is running. The figures depict a situation during which the pump is fully opened, and one outlet valve is half opened. The water is expected to flow from the source tank on the right side to the target tank on the left side. The states of pump and outlet valve can be observed on the control panels on the virtual side and in SIMIT within the simulation schematic which indicates that the water flows through them. The measured flow rate of sensors can be seen on the corresponding sensor control panels. When the opening of one of the limiter valves is changed to a small value, the flow rate is decreased, and the water level in the target tank increases slower than before.

Through the combination of the interactive environment and the externally running simulation a better understanding can be transferred to the learning user. Errors and faults can be detected through the simulation in earlier time frames and accelerate the commissioning process.

While previous studies have demonstrated the potential of integrating DTs with XR technologies for educational purposes [24], our work advances this field by addressing the specific challenge of real-time capability in human-centered simulation environments. Unlike the general applications discussed in the literature [13], our approach emphasizes practical implementation through the integration of HiL and SiL processes. Moreover, in contrast to the more traditional preference for OPCUA in related work [37], our selection of MQTT as a communication protocol demonstrates our focus on optimizing performance and reducing latency, critical factors for real-time educational simulations. This emphasis on practical, real-time interaction clearly differentiates our work from existing studies that often remain theoretical or focus on conceptual frameworks.

2.2.2 Extended Collaborative Work

The digital transformation is reshaping our understanding of the workplace by offering new possibilities for conducting teamwork while being less dependent on time and location, i.e., when and where we work [38]. This evolution is fostering a renewed perception of collaborative work where the traditional face-to-face interactions are increasingly complemented, if not replaced, by digital interfaces.

A pivotal aspect of this transition is understanding the role of humans in an increasingly digitalized and automated setting. This shift emphasizes the human capability to interact with digital data. XR emerges as an intuitive interface in this regard, acting as a bridge between humans and cyber-physical systems.

In the "Virtual Reality Practical Course" [39] students learn to implement immersive experiences with real data from the physical world. For instance, in the "RoboTwin II" [40] project a group of students implemented a collaborative remote chess game experience. As illustrated in Fig. 7, a remote player could play a chess game with a co-player in the laboratory using a robot to perform the chess moves on the physical chess pieces.

Fig. 8 shows the VT representation of the chess robot system in the laboratory including the current state of the chess pieces and the robot kinematics. The remote player can interact with the DT to perform game moves in the laboratory. For the design of the chess pieces the students used their experience from our CAD workshops to create a special design for the chess pieces, as depicted in Fig. 8. The chess piece design could be optically distinguished by the optical object recognition methods and be magnetically interacted by the robot end-effector.

If we adapt the DT concepts to human-involved processes, we can virtually represent holistic human-in-the-loop processes, like in cyber-physical manufacturing. In the ongoing project XIRCON [41], the goal is to support human operators during reconfiguration processes of production systems using XR and thereby to reduce the downtime of manufacturing systems significantly. Our research projects involve the digitalization of physical processes performed by human operators, e.g., guidance processes during remote maintenance. As depicted in Fig. 9, CAD specifications can be imported into the XR environment and be operated like with their physical counterparts.

Sensors of XR systems allow us to track human operations and to reconstruct the work processes at any time [42, 43]. This allows a new kind of co-local and remote

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[4] Unity: https://unity.com/pages/more-than-an-engine

[5] Unreal Engine: https://www.unrealengine.com/en-US/unreal-engine-5

[6] PolyVR Source: https://github.com/Victor-Haefner/polyvr

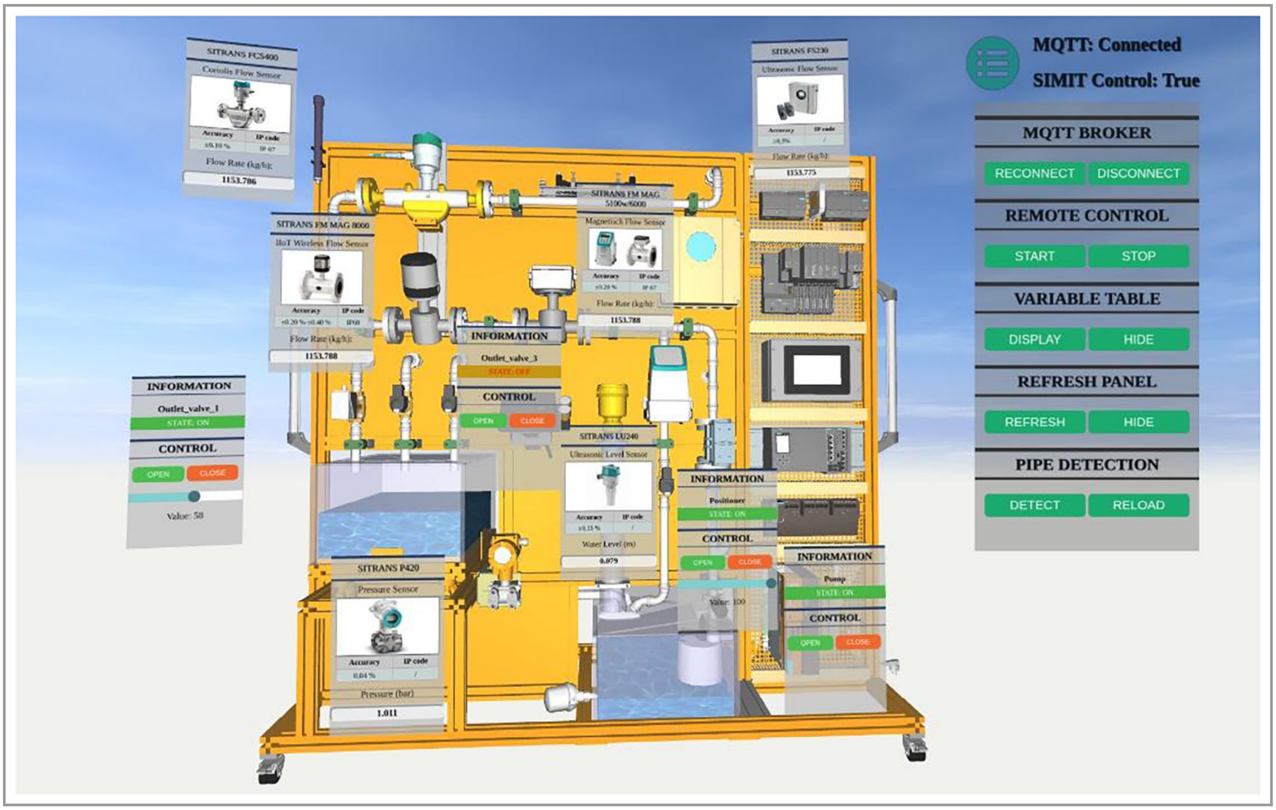

Figure 6. Result of the virtual twin in PolyVR.

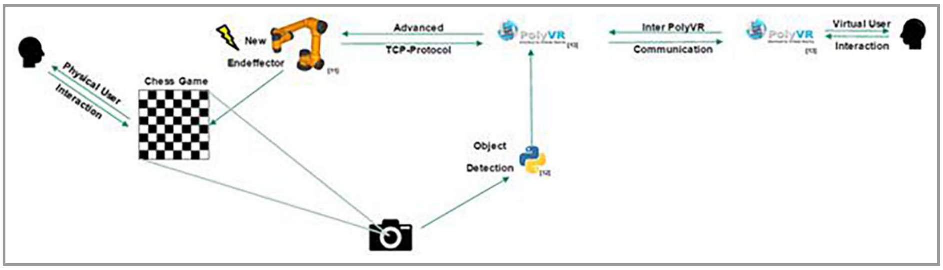

Figure 7. Overview of the collaborative chess robot system in the RoboTwin II project of the Virtual Reality Practical Course.

collaboration with 3D information like locations and position of 3D objects and human behavior. Fig. 10 depicts VR and AR applications which facilitates an efficient and intuitive creation of assembly manuals by simply demonstrating the construction process. The procedure can be exported into recordings which can be replayed at any time, visualizing a virtual avatar which is demonstrating the assembly steps.

Recent research opportunities include the design of courses involving groupwork on DTs. In particular, it is interesting to investigate the differences of avatar-to-avatar collaboration between remote students and face-to-face

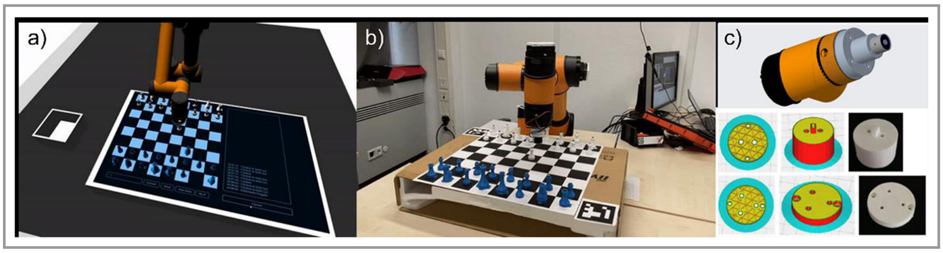

Figure 8. Implementation of the RoboTwin II student project: a) virtual twin of the chess co-bot, b) chess co-bot at the IMI laboratory, c) CAD design and 3D print preview of the electromagnetic end-effector.

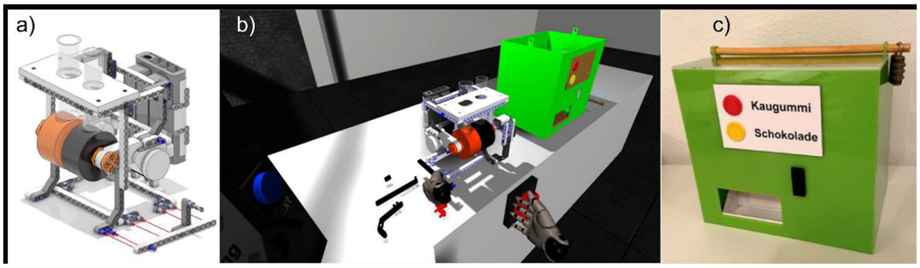

Figure 9. Candy dispenser student project: a) CAD design, b) VR assembly manual, c) physical candy dispenser from the PLM/CAD workshop.

collaboration between co-local students during their work with DTs [44].

In conclusion, the integration of XR technologies is reshaping both the professional and educational landscapes. While we have established significant advancements, many research opportunities for XR in professional education remain [45], promising to further melt the digital and physical worlds.

While the literature often discusses the potential of XR for enhancing collaborative work and human-machine interaction [15], our research goes further by demonstrating practical applications, such as the RoboTwin II project, which provides a concrete example of how XR can facilitate remote collaboration in an educational setting. This project contrasts with the more theoretical discussions found in other studies [14], by showing how XR technologies can be effectively applied to real-world educational scenarios, enhancing both learning and collaboration. Additionally, our focus on avatar-based collaboration in VR and AR environments offers new insights into how these technologies can replicate or even enhance traditional face-to-face interactions. This specific emphasis on comparing remote and co-local collaboration adds a layer of practical relevance that is often missing in broader discussions of XR's potential [16].

2.3 Artificial Intelligence

AI impacts every aspect of our lives, including the field of engineering. With 70 % of companies worldwide planning to adopt AI [46, 47], it is essential that current advancements and developments in the field are integrated into educational curriculums.

Recently, a new phenomenon has emerged: most exercises can now be solved using large language models (LLMs) such as ChatGPT [48].

This is already apparent, GPT-4 exhibits impressive performance in various disciplines. For example, it achieved 70 % on advanced cardiovascular life support (ACLS) exams [49], highlighting its potential application and risk in medical training. In a different study using the National Board Medical Examiners dataset (NBME-FreeStep-1) – a dataset from a United States non-profit organization that assesses health care professionals – the model performed on par with a third-year medical student [50], further highlighting its capabilities in the field of medicine. Furthermore, in the legal context, ChatGPT achieved an average grade of C+ in the University of Minnesota Law School exams, earning a low but passing grade in all four assessed courses [51]. In the field of computer science, GPT-4 achieved a score of 24 out of 40 on an "Algorithms and Data Structures" exam at the University of Tübingen in Germany [52]. These results indicate ChatGPT's high proficiency in solving complex problems and demonstrate the potential risk.

As educators, our response to this must be thoughtful, innovative, and informed. Therefore, several potential effects this trend can have on students must be considered.

The use of LLMs for education can be a double-edged sword. On the one hand, it can be an invaluable tool for education [53], helping students understand complex concepts and providing instant assistance with exercises. It can stimulate curiosity, foster engagement, and make learning more accessible and personalized [54]. Moreover, it could help students to familiarize themselves with the current trend of AI and its applications. On the other hand, it could

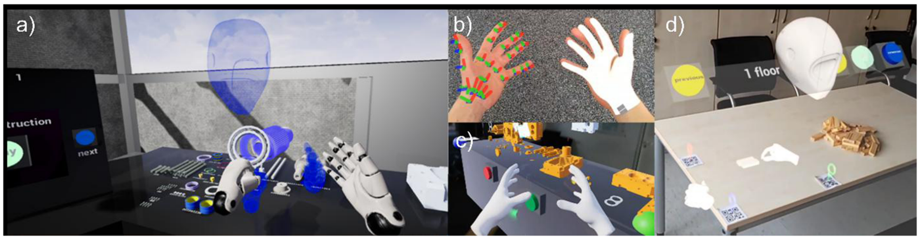

Figure 10. Virtualization and intuitive documentation of human processes: a) VR view, b) hand tracking, c) virtual hands based on the hand tracking, d) AR view.

potentially reduce students' reliance on critical thinking and problem-solving skills, particularly if used as a shortcut for completing exercises rather than a tool for comprehension [55]. It is also contended that employing LLMs at a professional level is similar to plagiarism [56]. In addition, the ease with which solutions can be found could foster an environment of less effort and more dependence, which could be detrimental in the long run.

A review of how LLMs are being integrated into engineering education identifies that LLMs are primarily used for tasks like code generation, problem-solving, and content creation in disciplines like software engineering, mechanical engineering, and chemical engineering [57]. The review emphasizes the need for clear roles for both students and educators, tailored strategies for different disciplines, and continuous evaluation of LLMs' impact on learning outcomes. Key challenges include handling inaccuracies in LLM outputs and ethical concerns.

Another article explores the integration of LLMs into chemical engineering education, specifically focusing on how these models can be utilized for problem-solving and model-building in core courses [58]. This involves using LLMs to assist students in solving typical chemical engineering problems, such as calculating efficiencies, solving thermodynamic equations, and simulating chemical processes or how to construct models of a steam turbine cycle or simulate reactions within a chemical reactor. These virtual models allow students to manipulate variables, explore different scenarios, and gain a deeper understanding of the principles behind these processes. By leveraging LLMs, students can receive step-by-step guidance, generate code, and access explanations that help them better understand and solve complex engineering problems.

Furthermore, one article explores the integration of LLMs into system modeling and simulation courses [59], highlighting their use in assisting MATLAB programming tasks and interdisciplinary knowledge acquisition. LLMs were used to provide real-time programming assistance, guide mathematical logic analysis, and support personalized learning paths. The study demonstrates that LLMs improved students' understanding of complex concepts, enhanced their programming skills, and increased engagement. Challenges include the occasional inaccuracy of LLM-generated solutions and the need for prompt engineering to improve interactions with LLMs.

In summary, related studies show that LLMs are typically being integrated into engineering education to assist with tasks such as code generation, problem-solving, and content creation. They enhance learning in disciplines like software, mechanical, and chemical engineering by providing real-time guidance and support for complex concepts and programming tasks. However, challenges such as inaccuracies in LLM outputs and ethical concerns need to be addressed.

2.4 Future Directions

In response to this, educators could use AI as a teaching aid instead of a solution provider. They could focus on teaching the underlying principles and algorithms that AI uses, to ensure that students not only use the tools but understand how they work. Furthermore, they could implement a balanced approach to technology usage, combining traditional methods with AI-assisted ones to nurture a generation of students who are not only tech-savvy, but also strong critical thinkers.

Finally, to keep the field of education effective and relevant, ongoing pedagogical adaptation and frequent evaluation of teaching methods are essential. The goal should be to incorporate advancements like LLMs in a way that enhances education and fosters a deep understanding of computer science among students, preparing them for the demands of a constantly evolving technological world.

2.5 Development of Technical Systems

As such, we at IMI have initiated a new course aimed at exploring the use of AI for the development of AI applications in engineering. The primary objective of this course is to devise an AI-based method such as a neural network for providing early recommendations for finite element method (FEM) analysis. In the course, it is postulated that companies have systematically archived historical simulation parameters and results. This data repository is assumed to be capable of providing insights, serving as a source of information to effectively train our AI model. Simulating the behavior of a structural component often presents significant temporal challenges, necessitating a more efficient approach to this process.

To leverage AI's predictive capabilities, this course explores the utilization of diverse variables as input parameters for the AI model. Therefore, the goal of the course was to develop a neural network for the prediction of FEM results, as depicted in Fig. 11.

The input variables I_1 to I_n include material properties, product dimensions, input coordinates, and different forces such as pressure. The AI model is designed to learn and establish relationships from this data, enhancing its ability to predict the outcomes O_1 to O_n representing, e.g., von Mises stress, displacements, and output coordinates.

It is worth noting that many of the students do not have prior knowledge in AI or FEM analysis. As a result, the course was designed to teach both principles simultaneously, integrating LLMs at various stages to facilitate a quicker immersion into the subject.

Since the course started in April 2023, the primary LLM in use was OpenAI's ChatGPT. In future iterations of the

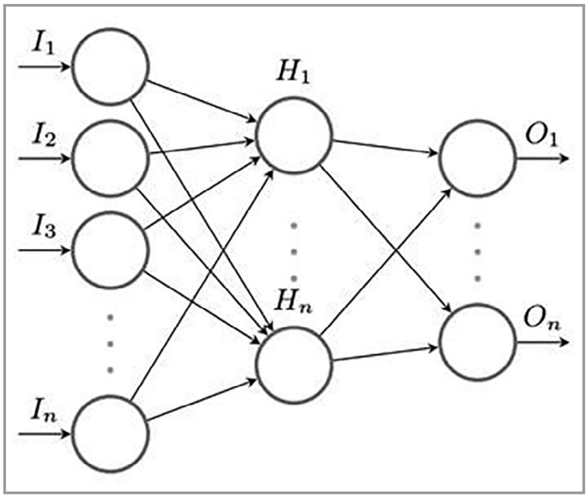

Figure 11. Simplified illustration of a neural network developed for predicting FEM results.

course, it will be interesting to observe students utilizing various LLMs, such as Metas open-source model Llama2 [60] or Googles Gemini [61].

Fig. 12 illustrates the workflow students adopted for this course. Initially, students had high expectations of ChatGPT, often seeking complete results. However, they quickly realized its limitations and began refining their interaction strategies with ChatGPT.

In addition, the students concurred that it did not offer fully functional answers at the outset. However, after a few trials, it did supply several necessary imports and a ground framework. This framework served as a starting point for the students, allowing them to modify and expand the code, thus eliminating the need to begin from scratch.

Subsequently, the students are required to comprehend the supplied code and assess its performance for the given use case. They then needed to suggest general enhancements to the neural network, like refining the import function to incorporate the structure with its connections, instead of merely relying on the x, y, z coordinates.

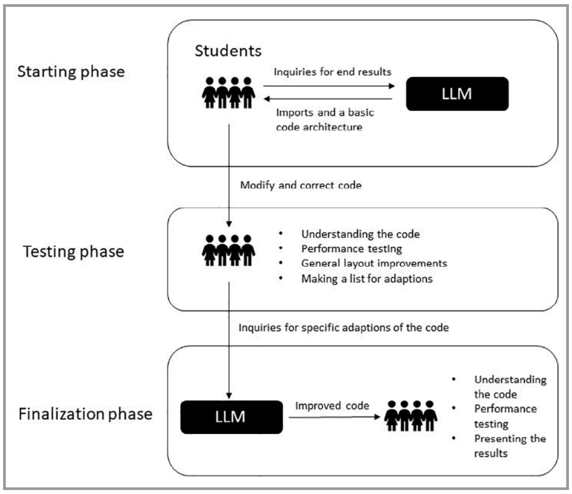

Figure 12. Workflow of the students with LLMs.

In the succeeding phase, students forwarded a list of proposed modifications to ChatGPT, which in turn furnished an improved version of the code. This enhanced code must be understood anew, and final adjustments must be carried out. In conclusion, the students must present the results, a step that ensures their understanding of the work accomplished during the course.

The objective of this procedure is twofold. First, it aims to educate students about the fundamental aspects of AI and FEM. This knowledge forms the foundation upon which more advanced concepts and applications can be built. Second, the procedure is designed to teach students how to interact effectively with LLMs such as ChatGPT. For example, the students learned that more specific inquiries work significantly better when using LLMs.

In conclusion, the course aims to equip students with the skills to effectively utilize sophisticated AI tools while also fostering a deeper understanding of their functionalities and potential real-world applications. This course sets itself apart by not only teaching AI concepts but also by integrating AI tools into the learning process, providing a hands-on approach that distinguishes it from other courses with different focuses.

3 Conclusion and Outlook

Our commitment to advancing VE through an integrated approach to PLM, CAD, XR, and AI has proven to be a transformative force in engineering education. By seamlessly blending the physical and virtual worlds, we offer a holistic and immersive educational experience that prepares students for the demands of modern industry. Our curriculum not only challenges traditional engineering methodologies but also introduces innovative concepts such as VTs and real-time co-simulation, which enhance learning outcomes and foster collaboration. As we continue to explore this rapidly evolving field, we remain dedicated to pushing boundaries, shaping the next generation of engineering solutions, and redefining how we tackle engineering challenges and envision the future.

The dynamic nature of VE ensures its continuous evolution. One emerging intersection is its potential role in advancing sustainability. The contemporary challenges of climate change, resource limitations, and environmental degradation necessitate a scientific approach to sustainable solutions. VE, with its inherent capabilities for simulation, modeling, and predictive analysis, is poised to play a pivotal role in these applications.

Future research and pedagogical endeavors at IMI will focus on the integration of sustainability principles within the VE framework. This could, for example, involve a systematic exploration of resilient and adaptive systems, emphasizing their alignment with ecological constraints and natural processes. A key focus will be the comprehensive assessment of product lifecycles, incorporating principles from the circular economy and leveraging renewable and ecological design methodologies in our virtual models.

The potential implications of this integration are vast. While it is conceivable that sustainability will become an intrinsic component of VE, the exact nature and depth of this integration remain subjects of ongoing research. At IMI, we are committed to spearheading this inquiry, ensuring that our methodologies are not only grounded in scientific principles but also oriented towards the potential sustainable futures they could potentially facilitate.

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Abbreviations

AI	artificial intelligence
ACLS	advanced cardiac life support
AR	augmented reality
CAD	computer-aided design
CAM	computer-aided manufacturing
CAN	controller area network
CRM	customer relationship management
DT	digital twin
ERP	enterprise resource planning
FEM	finite element method
HiL	hardware-in-the-loop
IMI	Institute for Information Management in Engineering
IoT	internet-of-things
LLM	large language model
MiL	model-in-the-loop
MQTT	message queuing telemetry transport
OPCUA	OPC Unified Architecture
PLC	programmable logic controller
PLM	product lifecycle management
SCM	supply chain management
SiL	software-in-the-loop
TBM	tunnel boring machine
VC	virtual commissioning
VE	virtual engineering
VR	virtual reality
XR	eXtended reality

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