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Development Of An Adaptive Augmented Reality Qualification System For Manual Assembly And Maintenance

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Abstract

The manufacturing industry is facing various challenges today - globalization, fast-moving sales markets, short product life cycles, individualization, mass production and diversity of variants are trends that will continue or even increase in the future. Speed and flexibility in production are thus becoming important success factors for companies. To meet the demands of the market, there is a growing necessity to deploy employees flexibly within the production process. This increases the need for additional qualification of workers. By overlaying reality with virtual cues, Head-mounted displays (HMD) can present information in a situation-specific and location-linked manner. Data glasses also offer a high and convertible degree of support through the possibility of providing different media forms while both hands are available at the same time. Augmented Reality (AR) guidance systems are already available on the market and are suitable as permanent assistance systems, but only to a limited extent for qualification aspects. An industrially applicable qualification software that collects expert knowledge from skilled workers and then makes it available to new or inexperienced employees in an adaptive way that promotes learning is currently not available. This paper therefore presents the development of the software AQUA, which taps internal expertise with low effort and creates training courses that convey learning content to learners without over- or under-challenging them.

Keywords

Augmented reality; Adaptive manufacturing; Knowledge management; Assembly; Maintenance

1. Introduction

While automatic and semi-automatic production are particularly suitable for the manufacturing of only a few variants and high quantities [1], manual assembly offers the flexibility for producing smaller quantities with a high diversity [2]. Currently, the qualification for assembly or maintenance tasks often takes place by means of the "on the job" measure "demonstrate - imitate", in which already experienced employees train new workers directly in line. Since the learning process takes place during series production, this can lead to overstressing due to time pressure [3]. In order to meet cycle times, there are frequent interruptions during the learning processes. The qualification can therefore have gaps [4] and furthermore the quality and duration of the learning processes can vary greatly between employees [3]. In addition to demonstration and imitation, classic media such as paper instructions support qualification processes. However, these make it difficult to transfer theory into practice [2]. Augmented reality-based qualification systems are promising as cognitive transfer between instruction and execution can be minimized [5]. HMD are becoming more common in

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industry, as well as in fields such as medicine, military, and sports, as both hands remain free [2]. Various studies have already demonstrated that the execution of assembly processes is faster with the help of AR guidance systems and lead to a lower error rate [6] [7] [8] [9]. These guidance systems are already available on the market and are suitable as permanent assistance systems, but only to a limited extent for qualification as they guide with the same support through assembly and workers thus remain dependent on the system. For this reason, the distinction between cognitive guidance/assistance and training/qualification systems is important [10]. In particular, given the different display capabilities of HMD, there is a lack of scientific guidelines on how a universal user interface should look like. Furthermore, existing training systems for HMD lack scalability making economical use impossible so far [2]. The goal of the project "Adaptive Augmented Reality based qualification – AQUA" is to develop and evaluate an adaptive AR qualification system for HMD to train employees in manual assembly and for maintenance tasks. The software should optimally support learners taking into account their learning progress and thus differentiate itself from AR guidance systems. In addition, the system adapts to diverse assembly processes by integrating new work instructions and learning content with as little effort as possible. In this way, the initial creation effort for AR trainings reduces in particular to ensure acceptance. In addition, the training creation should/must be possible for practical authors (e.g. supervisors, technicians) without programming knowledge. The AQUA software taps expert knowledge from experienced practitioners, bundles this knowledge and then prepares it for inexperienced employees in order to support them in learning in the best possible way.

2. Augmented Reality based qualification systems

The contemporary technological landscape at the intersection of Augmented Reality (AR) and qualification within the realm of production represents a dynamic field marked by substantial advancements [11]. Koteleva et al. [12] provided an exploration of AR's utility in skill acquisition and training by showing an example of combining AR with the maintenance of oil pumps. Their work highlighted AR's ability to create training environments that improve knowledge retention and hands-on experience. Werrlich et al. [13] developed an AR training system for HMD in which the number of AR functions reduces as learning progresses. The authors investigated the advantages and disadvantages of HMD-based training compared to training conducted using trainers. They showed ten percent fewer picking errors and five percent fewer assembly sequence errors for the HMD group compared to the human trained group. However, the HMD group required 60 percent more time for training. The authors suggested that the HMD subjects first had to familiarize themselves with the interaction modalities and functions of the new system. In 2020, Werrlich confirmed his assumption [14]. These works collectively spotlight AR's transformative potential in the context of AR-based qualification systems. However, they do not highlight the challenges of seamlessly integrating AR into production workflows and the crucial factor of user acceptance. While AR technology holds promise for industrial training, solving practical issues also becomes essential for its successful adoption.A recent trend is the fusion of AR with Artificial Intelligence (AI) and Machine Learning (ML) techniques [15]. AI-driven AR might personalize training experiences, adapt content dynamically based on individual performance, and even predict skill gaps proactively. This fusion promises to revolutionize workforce qualification by tailoring training regimens precisely to the needs and capabilities of each worker. However, the literature does not yet show any existing prototypes in this area, but only talks about the possibilities of this fusion. The AQUA project aims to change this. Another aspect that has received limited attention in existing literature is the incorporation of experiential knowledge from subject-matter experts. The infusion of ML into AR systems may optimize content delivery in the future, but it often falls short in capturing the nuanced insights and practical wisdom that experienced trainers and experts bring to the training process. The expertise of human trainers, who understand the contextual intricacies of production processes, is crucial in not only conveying information but also in imparting tacit knowledge that goes beyond what can be explicitly programmed into AI algorithms. This human element, where trainers impart their wisdom and adapt training on the fly based on the unique challenges of each learner, remains an area that warrants further exploration.

3. Methodology

The implementation of expert knowledge in adaptive learning environments play an overriding role for AQUA. Paramythis & Loidl-Reisinger [16] provide an appropriate statement here. "A learning environment is considered adaptive if it is able to observe/monitor the activities of its users, interpret them based on specific knowledge models, derive user preferences and needs from the interpreted activities, map them appropriately in associated models, and finally, based on the existing knowledge and the subject matter at hand, dynamically facilitate the learning process". The research questions arise from this definition:

- How can industrial companies implement an adaptive expert knowledge and AR-based qualification system into their structure?
- What does an AR-based qualification system look like and what data needs to be collected during the learning process to ensure adaptivity?
- How can the system interpret/learn from the collected data (ML) to improve the individual's learning?
- Does the system improve learning over traditional qualification methods and is it monetarily profitable?

The initial phase involved conducting a requirement analysis between application partners and researchers to establish shared objectives and fundamental principles for AQUA. Table 1 shows the results:

Table 1: AQUA requirement analysis

common goals	**core principles**	**in scope**	**out of scope**
▪ Increasing flexibility of the workforce ▪ Relief for trainers ▪ Enable independent maintenance of skills ▪ Up-to-date training documentation ▪ Standardization of training content ▪ Overcoming language barriers ▪ Avoidance of over- and under-challenging	▪ Simplicity and usability of software are more important than functional scope ▪ Implementation of expert knowledge ▪ Fun in learning and creating trainings	▪ Viewing AR-trainings ▪ Creation and modification of training instructions on HMD ▪ Exclusive use for offline training ▪ Preventive and reactive training ▪ Training of defined linear manual processes	▪ Hardware development ▪ Training on moving objects ▪ Simultaneous training of several persons ▪ Connection to production IT ▪ Quality inspection through data glasses

3.1 Implementation of AQUA into companies structure

A method to use especially at the beginning of software projects is the sketching of case diagrams – they are suitable for modelling the system structure. Use case diagrams show relations between actuators, main use cases and system boundaries [17]. Figure 1 shows the developed structure for AQUA and answers the first research question.

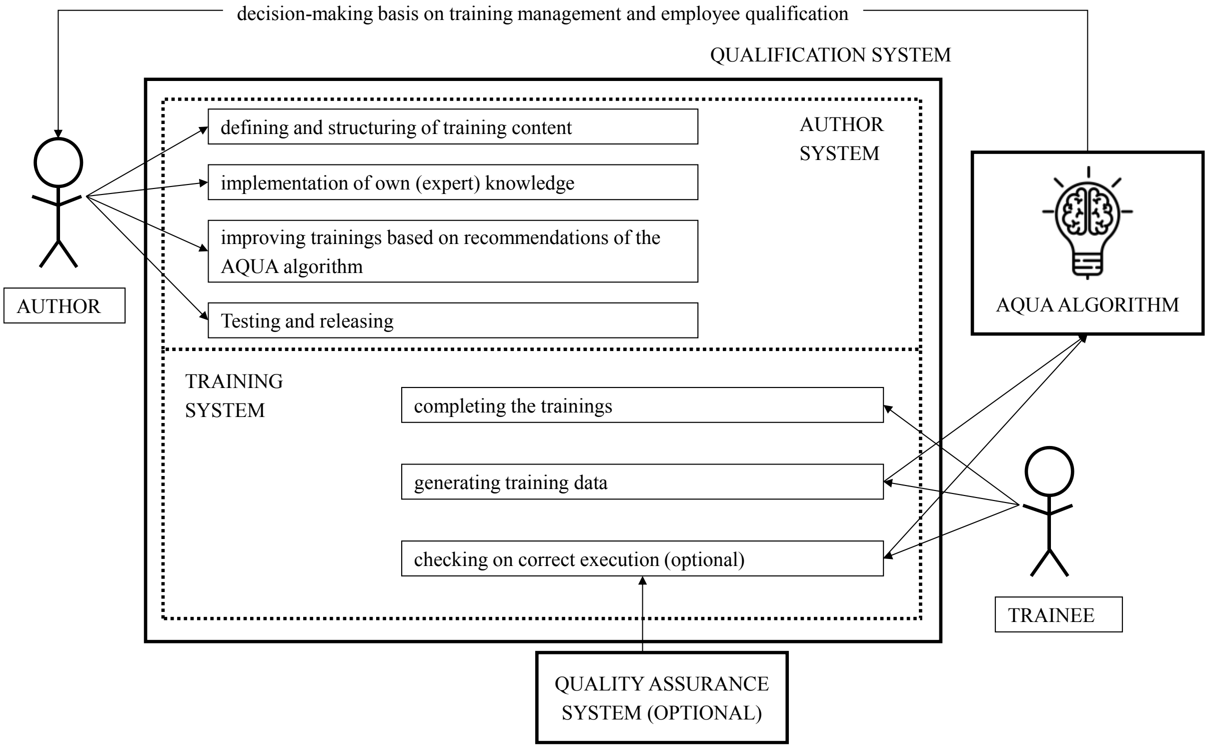

Figure 1: AQUA qualification method

Authors and trainees are actors. The use cases for authors are defining and structuring of training content, implementation of own knowledge, improving trainings based on the AQUA algorithm and testing/releasing. The use cases for trainees correspond to the execution of the training. The training system has an optional input for external quality assurance systems. Since the system must ensure general applicability, we refrain from permanently integrating a special testing system for one specific case. After knowing how to implement an adaptive AR-based qualification system into a manufacturing companies structure (Figure 1), the next research question is what an AR-based qualification system should look like (Figure 2). Therefore now follows the development of the AQUA User interface.

3.2 User Interface

The Cognitive Load Theory describes a branch of learning theory that investigates the functioning of the human memory system and thus derives guidelines for the design of teaching materials in order to effectively use and expand the information in the long-term memory. In the learning of new facts, however, the short-term memory plays an essential role, as it enables and influences the absorption of information into the long-term memory [18]. Hattie & Yates [19] describe, that especially the use of different media is conducive to efficient learning. Mayer [20] also supports this hypothesis. The authors further advocate active learning. According to their findings, passive observation is particularly ineffective when the learning content includes movement sequences. Furthermore, passivity carries the risk of distraction as well as purely superficial learning. For AQUA, the User Centered Design method according to DIN EN ISO 9241-210 forms the basis for designing the training and authoring area. The method goes through several iterations and creates various designs. The application partners evaluate the designs with the researchers by means of qualitative and semi structured interviews. Figure 2 shows exemplarily the result for the AQUA training area. The media forms provided are text, safety instructions, additional (textual) information, images, videos and position markers. The trainee can freely choose between these media forms in his training and combine them as desired for his particular work task. In addition, the trainer/author is also free to choose which media forms he or she makes available to the learner for the respective work tasks.

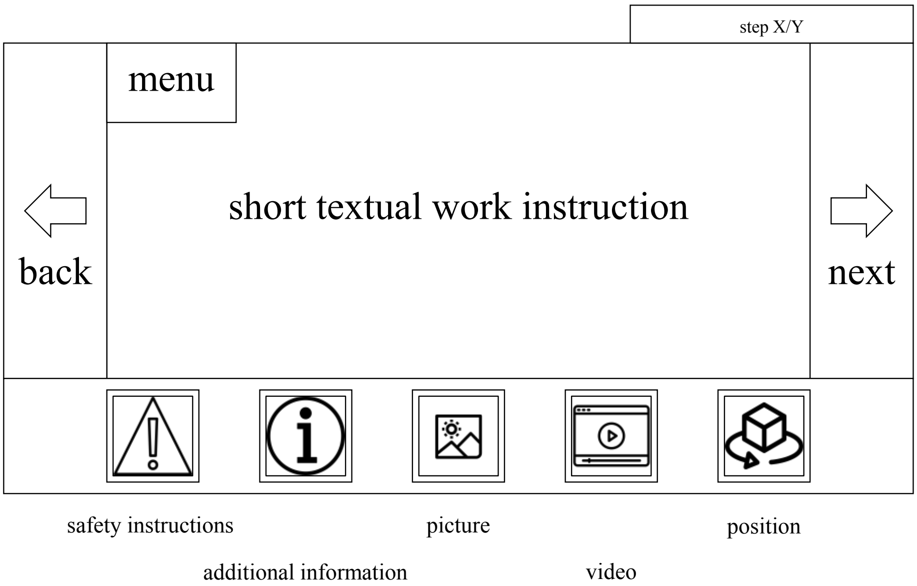

Figure 2: AQUA user interface

A central finding in the AQUA project is that authors only disclose their own experiential knowledge if they accept the system and enjoy using it. Therefore, the author area is deliberately very simple and accessible. Authors work exclusively with HMD - they can record images and videos directly, set the position markers and implement texts, for example, by voice input. In addition, the author creates and saves trainings on the data glasses directly at the assembly/maintenance object and edits/improves them if necessary without additional software or computer. The entire AQUA software can be controlled using hand gestures and speech. AQUA provides ten basic rules for authors to create adaptive AR-training instructions. The rules are, among others, taken from guidelines for effective communication from the military [19] [21]:

- Use the 1st and 2nd person (I/you)
- Use active instead of passive
- Put important content in front
- Use dynamic verbs instead of nominal
- Avoid adjectives if possible
- Be concise, but not too concise - do not use superfluous words
- Do not use foreign words or abbreviations if possible
- Record short videos (max. 20 sec) and short trainings (max. 15 min)
- Point out possible dangers and always share your tips and tricks
- Make every single media form as self-explanatory as possible

The HMD for AQUA is Microsoft HoloLens 2 (HL2). Fraunhofer IGCV chose HL2 after a market research as a suitable. It offers many different interaction options and can provide the necessary media forms. Hand tracking, which is possible on HL2, makes interactions feel very real, ensuring a high level of user-friendliness. The 3D development platform is Unity3D. The programming language used is C#. In order to make the various positioning objects appear in the right places, the software module Vuforia Image Targets supports the project. Using this library, a QR code acts as coordinate origin for positioning the individual elements. The Mixed Reality Toolkit provides various functions for AQUA to interact with 3D elements in a virtual space. Figure 4 shows a developer at the company LUDO FACT with digitally inserted user interface of the AQUA software. One of the Use Cases for LUDO FACT in the project is the debugging of their robotic system. The robot places and sorts game boxes on various conveyor belts. Employees then place the game pieces, instructions, dice, etc. on the belts. The robot unit can be in various states of malfunction. LUDO FACT implemented a wide variety of suppression measures for the respective fault scenarios in AQUA. The person responsible for the plant recorded the AQUA app as an expert author. Since then, inexperienced employees have been able to get the system up and running again independently with AQUA in the event of a malfunction.

Figure 3 AQUA practical example at the company LUDO FACT

3.3 Training data collection

While an employee is training, he generates training data. This data includes individual assembly times, data on the media forms used and, if applicable, data from the optional quality assurance system. The required support levels derive from the selected media forms. In order to draw conclusions from qualitative media form data to quantitative support level data, 41 employees of the applying companies in the AQUA project rated the support level of the available media forms with regard to assembly and maintenance from 1 (very low support) to 5 (very high support). Table 1 shows the result of the survey.

Table 2: AQUA derivation degree of support

	short instruction	long text	image (photo)	video	AR position
respondent 1	1	2	3	4	1
…	…	…	…	…	…
respondent 40	2	3	1	4	3
respondent 41	2	2	2	5	3
total	82	97	77	180	113
average	**2,00**	**2,37**	**1,88**	**4,39**	**2,76**

The average values of the individual media forms form the basis for calculating the level of support per work step in the further course of the project. If a trainee uses several forms of media in one assembly step, the values add up accordingly. The performed trainings generate the following data for the AQUA algorithm (Figure 4):

- assembly function [22], complexity [23] and competence according to REFA [24]
- execution durations
- media form usage
- applied degree of support
- quality (optional)
- additional human help (e.g. by trainer) necessary

Figure 4 illustrates the recording of the training data graphically:

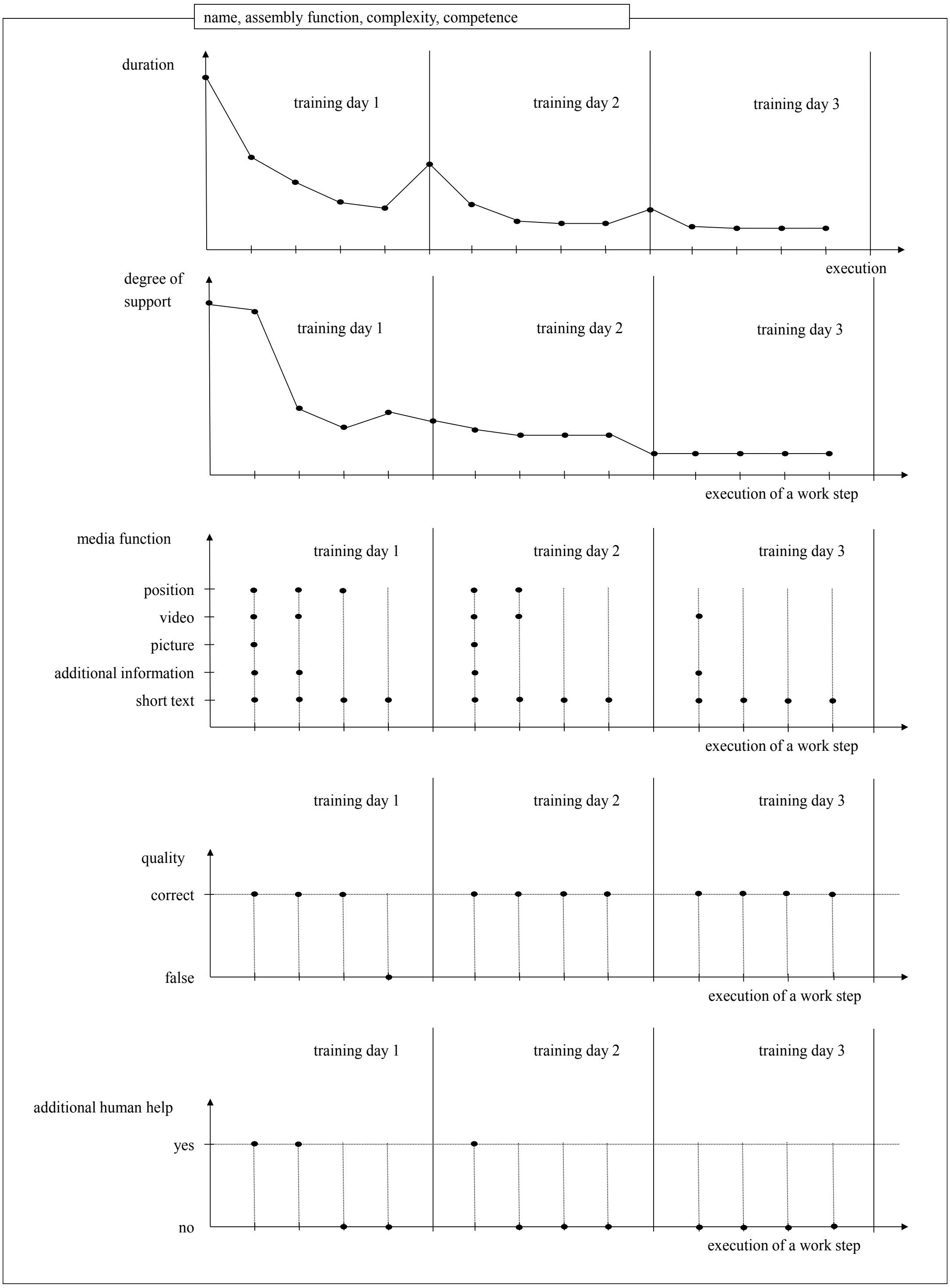

Figure 4: AQUA training data

4. Conclusion

In conclusion, this paper presents AQUA, a software designed to bridge the gap between experienced production workers and less-experienced beginners through the innovative use of augmented reality. AQUA not only captures the valuable expertise of seasoned employees but also delivers it to novices without overwhelming or underutilizing them. This approach has the potential to revolutionize workforce training and knowledge transfer in manufacturing settings. The development of AQUA marks a significant milestone, with implementation and testing at three partnering companies. Initial feedback from these trials has been promising. The complexity of the systems integration, for example, is very low. Installing the AQUA app on the data glasses takes about five minutes. Authors can create trainings offline and, if required, download them from the HMD to company computers via Microsoft Device Portal. The training of an expert author by the developers takes about 30 minutes. Once an author has created and edited a few training sessions with the help of a researcher, he or she can use both the data glasses and the app independently and generate new training sessions very quickly.The AQUA project is currently conducting a long-term study of the companies using the system. The continuously emerging data train the AQUA algorithm so that it can draw conclusions about the quality of the created trainings as well as the learning success of the test persons. In addition, after collecting enough training data, AQUA draws conclusions between assembly functions and media forms and can make recommendations based on it when creating future instructions. The further course of the project includes a comparison of learning success between the AQUA system and comparable training methods (video or oral explanations). Furthermore, the project aims to evaluate the economic viability of AQUA by conducting a comprehensive cost-benefit analysis. This assessment will not only consider the initial investment required for implementation but also the long-term advantages in terms of reduced training time, increased productivity, and enhanced knowledge retention.

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Biography

Maximilian König (*1990) studied industrial engineering at the University of Augsburg. Since 2018, he has been working as a research associate in the field of cognitive assistance systems at Fraunhofer IGCV. He leads various research projects and is doing a doctorate at the University of Augsburg.

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Maik Heller (*1975) has been Production Manager at ZF's plant in Aschau am Inn since 2017. He is responsible for the production of inflators, injection mouldings, igniters and spare parts. Before that, he was 30 years in leading positions at Boge, NXP, Phillips and VW.

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Prof. Dr.-Ing. Johannes Schilp (*1976) has held the Chair of Production Informatics at the University of Augsburg since 2015. He is also head of a main department at Fraunhofer IGCV, head of the Innovation Advisory Board of the Swabian Chamber of Industry and Commerce, and, among other honorary activities, an advisory board member of the German Assembly Congress.