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RESEARCH ARTICLE

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Teaching agile hardware development with an open-source engineering simulator: An evaluation with industry participants

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Abstract

Educational games are increasingly used to teach Agile development approaches to practitioners. Most of these training modules simplify the development environment, for example, by using LEGO bricks or playing cards. This oversimplification has been shown to result in limited transferability of learning to industrial practice. Furthermore, there is a lack of teaching modules that specifically address the challenges of applying Agile to physical products. In this paper, we present an open-source educational game that realistically simulates a hardware development project to teach Agile principles. Over 2 days, participants design, manufacture, and test modifications for a physical wire bending machine within an authentic engineering and production setting. The training mimics the typical roles, processes, and tools of industrial engineering teams to reflect the challenges of Agile hardware development. The module was evaluated with 44 industry professionals regarding perceived learning and user reaction. A combination of quantitative and qualitative methods was used for the experimental evaluation. The results showed a positive learning effect as the participants' average agreement with Agile principles increased through the training. Concerning user reaction, respondents reported a high degree of relevance, interaction, and confidence, indicating that the realistic simulation of the hardware development appropriately balanced the degree of realism with simplicity. The study showcases the opportunities of properly aligning game components to provoke learning situations targeted by the instructors. It contributes to the extant literature by providing a design framework (product, process, setting, and instruction) and open-source access to the tools used for implementation.

KEYWORDS

agile development, agile training, educational game, engineering simulator, serious games

1 | INTRODUCTION

New product development (NPD) is facing an unprecedented rise in uncertainty and volatility due to the accelerated pace of technological innovations and changing market demands [38]. Firms are required to deliver new products with more customer value faster than ever to stay competitive [35]. Agile development approaches offer the promising potential to address these fundamental challenges in NPD [8]. The term Agile refers to a group of NPD methods that emphasize short, iterative development cycles to reduce uncertainty and rapidly create customer value [4]. For the development of software, Agile has become the industry standard, with Scrum being the most widespread framework [11]. For physical products, however, the industrial adoption and scientific coverage of Agile hardware development (AHD) are still in their infancy [5]. Hardware-specific restrictions inhibit the direct transfer of Agile frameworks and methods from the software domain [32]. This includes, for instance, the lead time and costs that are required to build physical prototypes. Numerous case studies showed that Agile methods and tools often need to be adapted to address the characteristics of physical products (e.g., [26]). As a result, firms in the mechanical engineering and manufacturing industry have only begun to rebuild their processes and organizational structure toward AHD in recent years [31]. In a recent survey, Atzberger et al. [3] showed that the biggest hurdle to AHD adoption is related to establishing a distinct AHD mindset within an organization. The survey mentioned knowledge transfer and training for employees and managers as critical factors for establishing a joint understanding of Agile. These findings are in line with a study by Gandomani et al. [18]. In their publication, the authors reiterated that education plays a critical role in the Agile transformation process. They concluded that inadequate and nonpractical Agile training (e.g., theoretical courses) leads to several negative outcomes, such as unrealistic expectations, lack of deep understanding of Agile values, and low confidence. The study recommended focusing more on practical courses instead of the prevailing theoretical ones. Therefore, it can be summarized that there is an imminent need for more engaging approaches in the field of Agile teaching and education.

Within this contribution, we present an open-source educational game for transferring the principles of AHD into industrial practice. A hardware development project is realistically simulated over 2 days using a variety of technology-based tools and systems. The approach outlined in this study is in clear contrast to previous studies on Agile training [15, 28, 33, 37, 39], which oversimplified the development environment by using LEGO bricks, playing cards, or paper. Furthermore, it was evaluated with industry participants, as opposed to the aforementioned publications, which relied on university students.

The remainder of this manuscript is structured as follows. Section 2 presents an overview of related work in the research field of game-based learning and Agile teaching. Section 3 introduces our training module. The research methodology and results of the evaluation with industry professionals are presented in Sections 4 and 5, respectively. After a discussion of the potential and limitations of our approach (Section 6), we conclude with an outlook on future research opportunities in the field of interactive Agile training (Section 7).

2 | BACKGROUND AND RELATED WORK

In recent years, there has been an increasing shift in engineering education toward more interactive and practical education modules [21]. The motivation behind this trend is to better prepare learners for tasks and challenges they would face in real-world situations. Game-based learning and serious games (SGs) in particular have received great attention from scholars and practitioners alike. The term SG refers to full-featured games for nonentertainment purposes [10], which are increasingly adopted for teaching and training [12]. By embedding game elements such as roleplay or scenarios into an educational context, an immersive and engaging learning environment can be created [9]. Benefits include improved learning motivation, increased task engagement, and the promotion of specific skills such as problem-solving or collaboration [6]. Therefore, the learning outcomes of SGs are not restricted to the cognitive domain but can also include affective and behavioral learning [20]. The increasing availability and effectiveness of new information and communication technologies greatly facilitate this development [2].

Game-based learning has also been increasingly implemented in the field of Agile education. In their literature review, Rodriguez et al. [30] listed 22 SGs for teaching Agile. LEGO-based games are one prevailing type of SG [25, 28]. In these pieces of training, teams were asked to build structures during multiple sprints using LEGO bricks [25, 28]. In both cases, LEGO blocks were specifically used to remove the complexity of the development process through simplification. A similar approach can be seen within the Scrumia [39], Origami [33], and PlayScrum [15] training, which used handicraft materials or playing cards. Again, the process of developing, building, and testing is greatly simplified through the choice of material. The idea is to prevent unwanted technical challenges that may overwhelm students, resulting in them not following the process correctly [37]. Further training types include analog and electronic board games, virtual environments, and classroom games [30]. A large study by Steghöfer et al. [37]. investigated the opportunities and limitations of teaching Scrum to over 450 students using LEGO workshops. The interactive approach led to a high degree of student engagement and enabled instructors to react to emerging learning opportunities in real time. Still, the authors reported limited transferability of learnings to later, real-world projects. They attributed this to the fact that the LEGO workshop experience is considerably different from industrial practice. In addition, students within their study reported that "mapping from building a LEGO city to actual development activities is not clear" and that they often changed the process in later projects.

These findings highlight that there are still limitations associated with the current state of educational games for teaching Agile. The first limitation is the lack of teaching modules that specifically address the challenges of AHD. This is because almost all of the existing training is targeted at Agile software development or Agile methods in general [30]. As mentioned before, applying Agile for physical products requires significant adaptation due to the restrictions inherent in hardware product development (e.g., lead times and costs of physical prototyping). As presented in Omidvarkarjan et al. [26], AHD benefits from the application of adapted prototyping strategies such as feature separation, increased parallelization, and flexible switching of manufacturing processes. By doing so, time-consuming and costly hardware iterations can be accelerated, parallelized, or even prevented. Current educational games hardly cover those aspects due to the choice of material (e.g., LEGO, playing cards), resulting in limited transferability of learning to industrial practice, as reported in [37].

As shown in the literature review by Rodríguez et al. [30], the second limitation is that the majority of Agile training is developed for the university context, such as in the form of lectures or engineering courses. Furthermore, the evaluation of teaching modules is mostly conducted with students. It is therefore unclear how applicable existing Agile training modules are within an industrial context and how transferable the obtained results are to the experienced practitioners in the industry.

3 | TRAINING MODULE DESCRIPTION

To address the aforementioned limitations, this study presents a training that chooses an alternative educational strategy. The goal is to reflect the challenges of applying AHD more realistically than existing training studies while at the same ensuring an appropriate level of difficulty and user experience. For the remainder of this paper, this teaching concept is referred to as the engineering simulator (ES). Figure 1 displays the overall structure of the ES and its four main components: product, process, setting, and instruction. Similar to learning factories in the field of production and operations management education [1], these four elements represent the main design parameters that educators can tune to customize the learning experience and transfer the learning goals. In the following section, the training module is described using this classification.

3.1 | Learning goals

The goal of this training is to transfer the principles of Agile for the development of physical systems. Concerning Bloom's taxonomy [19], the objective of the ES is therefore to cover the first three layers of the affective domain, meaning that participants receive, respond to, and value the Agile principles after completing the ES. The specific learning goals can be found in Table 1. The seven Agile principles considered in this study were derived from prior publications [20, 21]. The set of

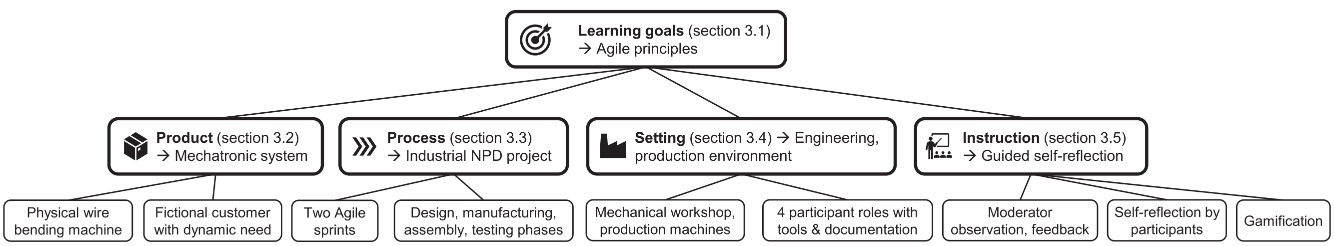

FIGURE 1 Overview of the ES structure. ES, engineering simulator.

principles is not meant to be an exhaustive list of all aspects of the Agile mindset; the goal was rather to include those principles that fit the constraints of the ES. Besides transferring the principles of AHD, the training aims to provide participants with practices and techniques that allow them to apply the AHD approach to hardware products. Specifically, these techniques include prototyping strategies such as separate feature testing, parallel prototyping of subsystems, and switching of prototyping media to minimize lead time and cost [26].

3.2 | Product

Within the context of the ES, the participants were confronted with the following practical development challenge. As part of a fictional company, they were tasked with modifying an existing wire-bending machine so that it could bend three-dimensional structures. At the beginning of the training, the product was only capable of bending in two dimensions. Figure 2a shows the initial machine that was provided to them. It was specifically developed for this training. As a mechatronic device, it is representative of products developed by firms in the mechanical engineering industry. Since industrial products are oftentimes developed in sequential product generations, the technical task of the presented training builds on the improvement of an existing design. The goal was to illustrate that AHD can also be beneficial for such applications. The wire bender consists of laser-cut wood and metal panels, machined components, and prototyping electronics (microcontrollers, motors, and a solenoid actuator). It is highly modular to enable quick disassembly and modification of components. The particular design of the wire-bending machine allows for only one realistic solution in the scope of this training (using two gears as depicted in Figure 2b), limiting the variety of gameplay scenarios. Furthermore, several intentional design pitfalls are included to provoke desired participant behavior and learning situations. For instance, support bars are hidden within the machine. If these are overlooked by the team, it can lead to a nonfunctional solution and missed sprint goals. Through the application of early and frequent testing as mandated by the learning goals, the participants can overcome these intentional pitfalls.

TABLE 1 Learning goals of the ES.

No.	Agile principle
1	Frequent interactions
2	Customer involvement
3	Test-driven development
4	Self-organizing teams
5	Accommodating change
6	Iterative progression
7	Continuous improvement

Abbreviation: ES, engineering simulator.

3.3 | Process

The process of the ES mimicked the real-world procedure of industrial NPD projects. Two Agile sprints were conducted, each with planning, review, and retrospective events. During these execution sprints, the participants modified the wire bender by planning, designing, fabricating, and testing new components, similar to the industrial process of hardware development. The team could freely decide how they wanted to invest the time that was provided to them. The sprint was concluded with a retrospective session, during which moderators provided feedback based on observations made during the sprint. The team was also asked to share their impression of what aspects of Agile they perceived to have adopted more or less successfully. The execution

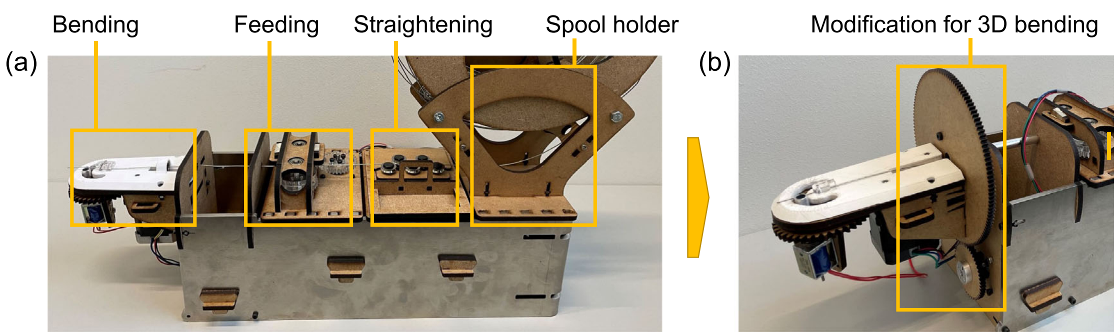

FIGURE 2 (a) Initial state of the 2D wire bending machine and (b) modified wire bender with the third bending axis. 2D, two-dimensional.

sprints were framed by an initial kickoff with a concise theoretical introduction to the principles of Agile, a tutorial task to familiarize the participants with the wire bender, and a closing reflection session (Figure 3). During the reflection, the participants presented the major concepts that they had learned. In addition, measures to translate the Agile principles into the participants' daily work were discussed.

During the development of the training module, the course was also conducted with more than two sprints. Nevertheless, it turned out that the biggest change in participant behavior was observed between the first and the second sprint. As a result, it was decided to limit the training to two sprints in total, and also to comply with the limited availability of the target group (i.e., industry professionals).

3.4 | Setting

The setting of the ES imitated an industrial engineering and production environment. The teams were provided with a variety of tools and equipment, such as a laser cutter, tool trolleys, or computer workstations. Four different team roles were used within the context of this ES, representing the typical disciplines involved in the industrial development of physical products (Table 2). Each role had its set of tools, responsibilities, and documentation, requiring the team members to collaborate to solve the development challenge.

Figures 4 and 5 display the two main toolchains of the ES. The featured software tools were selected and designed in such a way that they required minimal prior knowledge but at the core still resembled typical tools used in the industry. A drag-and-drop CAD system was used to design parts for the wire-bending machine. Although simplified, in essence, it resembled the tools used in the industry. With the help of custom templates, participants were only required to implement minor adaptations, limiting the complexity and time effort of this activity. Once finished, the designs were exported for production planning. Finally, the parts were fabricated using a laser cutter and plywood boards.

Apart from designing parts for the wire bending machine, the teams were asked to program bending sequences (Figure 5). This was done with a custom, simplified version of G-code that is also used for controlling industrial machines. For the ES, the code was utilized to control three motors (one for each axis) and a solenoid actuator. Through a web-based user interface, participants could wirelessly forward the commands to the machine to control electronics, allowing for rapid testing.

The design and manufacturing of physical parts were specifically included in the training design since these steps typically represent the biggest hurdles concerning short, test-driven iterations. Although 3D simulation tools can help to validate hardware designs, uncertainty related to the manufacturing process and materials (e.g., tolerances, deviations of material properties) can occasionally only be addressed through physical testing.

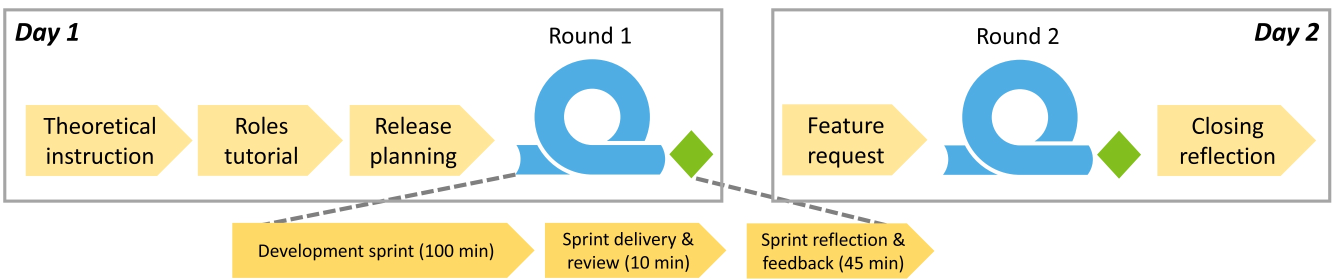

FIGURE 3 Training schedule.

TABLE 2 Role description (adapted from [27]).

Role	Responsibilities	Tools
Mechanical design	Design of laser-cut parts	Drag and drop CAD from Tinkercad (www.tinkercad.com)
Manufacturing and assembly	Setup and execution of laser cut jobs, assembly of mechanical components	Tool trolley, laser cutter
Programming	Transfer of bending patterns into machine code	G-code equivalent, web-based graphical user interface
Enabling and testing	Facilitation of team collaboration through moderation	Kanban board, a toolkit of Agile practices

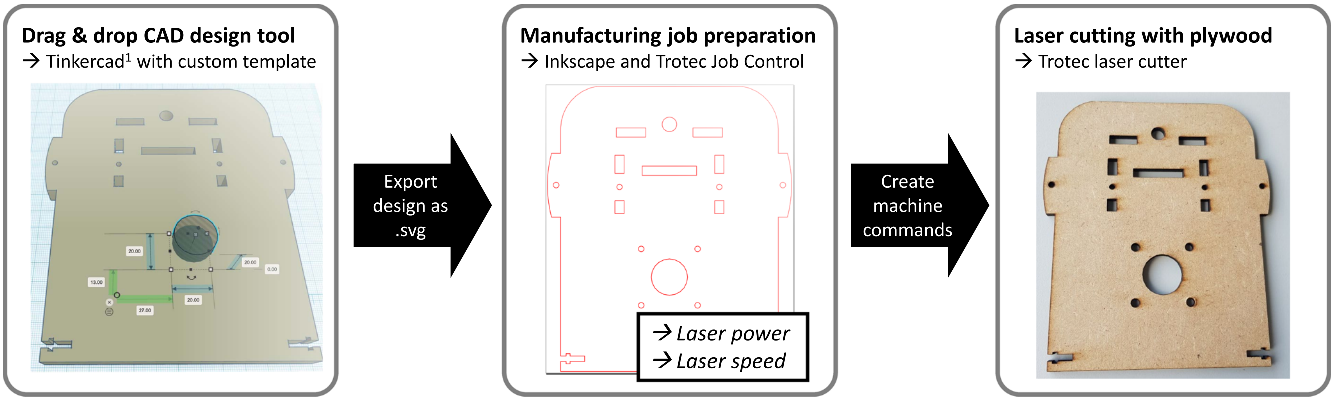

FIGURE 4 Design and manufacturing toolchain of the ES. ES, engineering simulator.

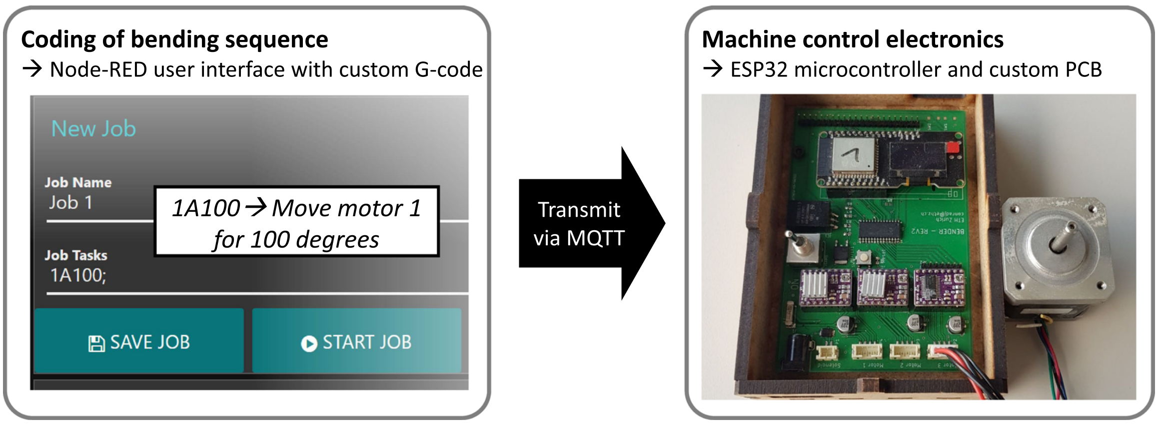

FIGURE 5 Programming toolchain of the ES. ES, engineering simulator.

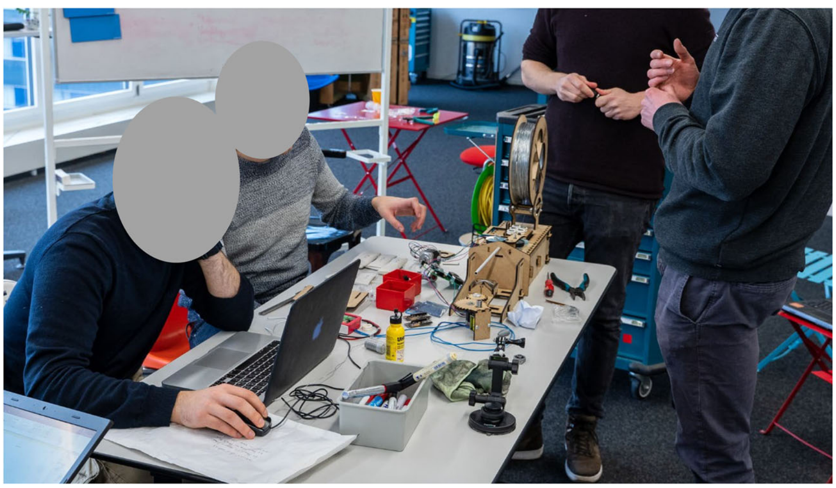

FIGURE 6 Participants working on the ES while being observed by a moderator. ES, engineering simulator.

3.5 | Instructions and moderation

The ES builds on individual and team-based self-reflection as the main learning mechanisms. For this reason, the formal instruction was kept to a minimum, with moderators mostly observing during the two execution sprints and only intervening if necessary (see Figure 6). This oftentimes led to a failed first sprint, where iteration goals were not met. With the help of open-ended questions, experiences, and learnings were discussed with the participants during the sprint retrospective. The moderator suggested concrete practices to improve the development approach, for instance, by providing a case study as a specific example. The participants were free to choose what recommendations to implement.

To further drive participant involvement and immersion, the ES utilized various game elements, such as a point system [22]. A reward (bonus points) was provided for early delivery of parts, while inefficient use of resources (e.g., manufacturing time and materials) was penalized with a point deduction. Further game elements included storytelling and roleplay, for instance, through the inclusion of a fictional customer. To include an element of adaptive challenge [16], the moderators could demand a feature request (limitation of the maximum height of the machine) after the first sprint based on the team's performance. By conducting the training with multiple teams at the same time, a sense of competition was created.

3.6 | Linking ES elements to learning goals

As presented in the previous sections, the four main elements of the ES were designed to imitate the real-world practice of industrial NPD teams. Special focus was given to aligning the four components in such a way that they specifically provoked learning opportunities related to the learning goals. For the principle *interact frequently*, the following section elaborates on how the design of the ES contributes to the transfer of Agile principles. The goal is to showcase how educators can customize the learning experience through the design and alignment of ES structure (Figure 7).

Agile greatly emphasizes collaboration between stakeholders through frequent interactions, opposing traditional development approaches that often build on extensive documentation such as requirement lists [14]. To transfer this principle, the ES provoked learning situations where participants could experience and reflect on the importance of interacting frequently. Concerning the *setting*, for instance, the workstations of the four participants were intentionally placed physically far apart from each other. As part of the *instruction*, the team was encouraged by the moderator to rearrange the workplace layout to fit their needs. In most of the cases, the participants moved closer together, since the physical distance inhibited direct exchange and interaction. This highlighted the benefits of colocation, as mandated by AHD [24]. In addition, essential information (such as data sheets or customer requirements) was intentionally spread across the *documentation* of all team roles. The participants were therefore again required to exchange information through frequent interactions to progress as a team. Overall, the structure of the *product* (mechatronic system, consisting of hardware, software, and electronic components) and the inherent *process* (design, manufacturing, assembly, and testing phases) required team collaboration due to the design of participant roles.

4 | RESEARCH METHODOLOGY

As described in Section 3, the experiment aimed to evaluate the viability of ES for training Agile in industrial practice. Similar to other studies in the field of educational games for Agile [30], this analysis investigated the potential for participant learning and discusses feedback regarding user reactions. To guide this evaluation, the study focused on the following two research questions (RQs):

- RQ1: Can principles of AHD be transferred to industry professionals with an ES?
- RQ2: How do participants react to the ES in terms of usability and user experience?

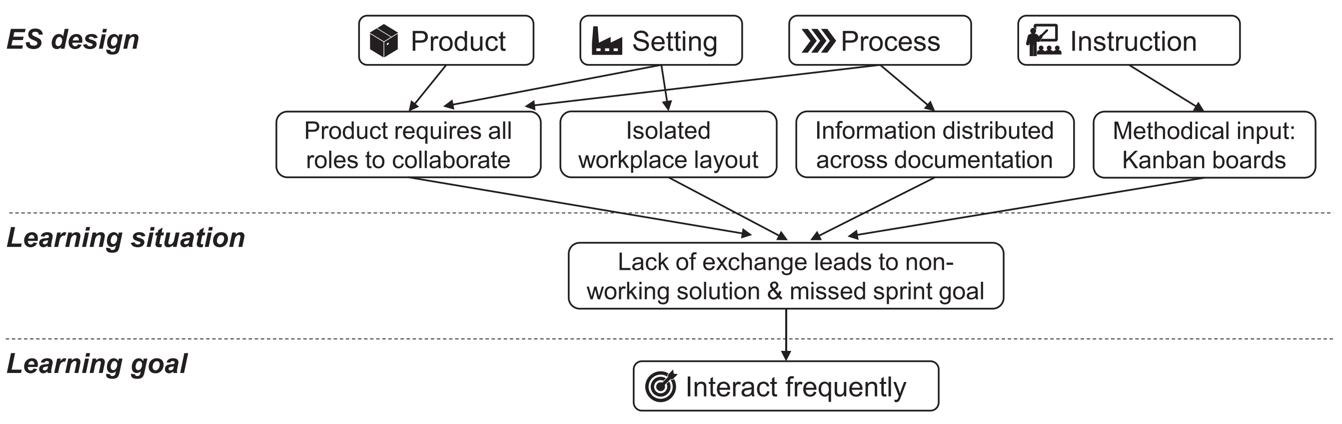

FIGURE 7 Linking of ES design, learning situation, and learning goal for the principle *interact frequently*. ES, engineering simulator.

Due to the novelty of the educational approach in the field of AHD, a mixed-methods research framework was used to answer the RQs. As shown in Figure 8, the study combined quantitative and qualitative methods to expand on findings and explain quantitative results through qualitative evidence. The individual research methods are described in the following sections.

4.1 | Perceived learning: Quantitative evaluation with pre-post survey

A combination of existing questionnaires was used to evaluate the participants' perceived learning. In this study, learning refers to the extent to which participants change their attitude towards the principles of Agile, therefore representing the second level of Kirkpatrick's framework [19]. Previous studies have shown that the field of measuring Agile is still relatively immature [7]. The various existing surveys are based on how their authors perceived the methodology, which may vary, as there are numerous conceptions of what Agile entails. In this study, a combination of three existing questionnaires was used to cover the learning goals of the ES. The three original surveys were Perceptive Agile Measurement [34], Team Agility Assessment [23], and Objectives Principles Strategies [36]. We mapped the items from the different surveys onto the learning goals of this training. The ones with the highest fit were selected for the compilation and slightly customized to harmonize the wording of all items. The resulting questionnaire was comprised of 25 items, representing statements that reflected certain characteristics of the various principles (see Appendix A).

For every item, the participants were asked to state their agreement on a 5-point Likert scale (1 = strongly disagree to 5 = strongly agree). The same questionnaire was provided to the participants before and after the training. Using descriptive statistics (means and standard deviations), the average change of agreement to the Agile principles was analyzed. The data were separated into two groups to distinguish between two levels of prior experience regarding Agile:

- **Low practical experience**: Participants who did not have more than 1 year of practical experience in working with Agile concepts, methods, or principles ($n = 19$).
- **High practical experience**: Participants who had more than 1 year of practical experience working with Agile concepts, methods, or principles ($n = 25$).

4.2 | Perceived learning: Qualitative content analysis of participants' reflections

A qualitative content analysis of the participants' learning was used to support and contextualize the quantitative assessment of the combined questionnaire. Following RQ1, the goal of the qualitative evaluation was to describe and illustrate the learning acquired by the participants. The methodology used in this study was based on Ref. [26].

After finishing the training and filling out the surveys, the participants were asked to write down their personal top three learnings on sticky notes. They did so independently from each other. The transcribed notes act

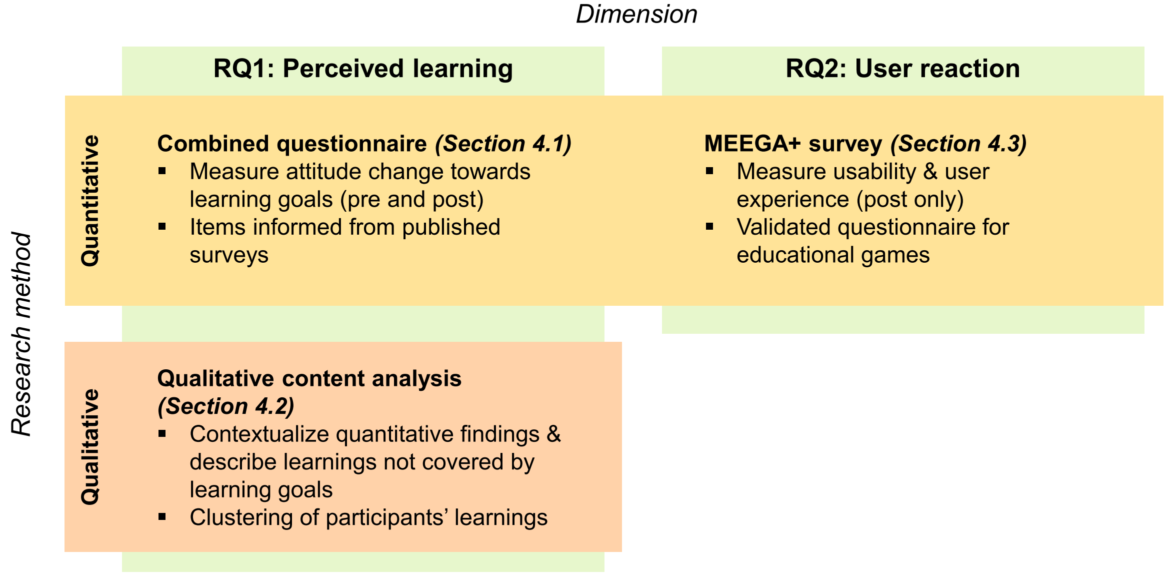

FIGURE 8 Research framework for the evaluation of the ES. ES, engineering simulator.

as the main source of data for the qualitative content analysis. In the first deductive phase, the items were allocated to the predefined learning goals (Agile principles from Section 3.1). In the second phase, inductive category development was conducted for all remaining items. In a series of multiple iterations, topical themes not covered by the predefined learning goals were derived. Within this paper, the focus lies on these *other learnings*, as the description of the predefined learnings would be mostly a repetition of the Agile principles. The goal is to illustrate and clarify the entire scope of learning conveyed by the ES by providing actual quotes from the respondents.

4.3 | User reaction: MEEGA+survey

Within Kirkpatrick's framework, the term "reaction" refers to the extent to which participants are satisfied when partaking in a training program [19]. While a positive reaction does not necessarily relate to high learning results, exciting and attractive training keeps users engaged. This study applied the Meega+ survey [29] for the evaluation of participants' reactions. The standardized questionnaire evaluates the quality of an educational game concerning the subcomponents of usability and user experience. It was also used for the evaluation of Scrumia training [39]. The questionnaire consists of 27 items with response options ranging from strongly disagree (−2) to strongly agree (2) on a 5-point Likert scale. Participants completed the questionnaire after finishing the training. The results were analyzed and discussed using descriptive statistics (medians and frequencies of responses).

4.4 | Sampling

As opposed to other training in the field of Agile teaching, this evaluation was conducted with industry professionals ($N = 44$). This included engineers, project managers, and team leaders from more than 15 different firms, mostly from the mechanical engineering and manufacturing industries. Most of the participants (60%) had a business background but worked in a technical or cross-disciplinary function within their firm. The rest of the sample was from engineering sciences such as mechanical, electrical, and software engineering (40%). At the time of the assessment, most of the participants (over 90%) stated that they had theoretical knowledge about Scrum. In addition, more than half of the group (57%) had more than 1 year of practical experience working on Agile development projects. All of them participated voluntarily. The evaluation was conducted anonymously. The training took place in Zurich, Switzerland; Ditzingen, Germany; and Pasching, Austria on six different occasions.

5 | RESULTS

5.1 | Perceived learning: Quantitative evaluation with pre-post survey

Figure 9 displays the results of the pre–post-survey. The respective changes in the average agreement are summarized in Table 3. For both groups (experienced and inexperienced with Agile), the average agreement toward the Agile principles increased during the training, except for *test-driven development*, which remained unchanged for participants with high practical experience. This result indicates that the ES has a positive influence on internalizing Agile principles in most cases. When comparing these changes, the gain in the average agreement was larger for the group with low practical experience for every learning goal (ranging from 0.30 to 0.38) compared to experienced participants (ranging from 0.00 to 0.36). Thus, it can be concluded that the learning effect of the ES is larger for the inexperienced group.

Within the group with low practical experience, the principles *frequent interactions*, *customer involvement*, *continuous improvement*, and *test-driven development* showed the largest gains on average agreement, while *self-organizing teams* and *iterative progression* experienced the smallest increases. For the experienced group, *customer involvement* exhibited the largest gain. In contrast, principles such as *self-organizing teams*, *iterative progression*, and *test-driven development* showed very little or no increases at all for this group.

5.2 | Perceived learning: Qualitative content analysis of participants' reflections

A qualitative content analysis provided further detail regarding the participants' learnings. Whenever possible, quotes and supporting moderator observations are provided.

One major recurring learning was related to the *general understanding of Agile*. Respondents expressed that "Agile does not need to be Scrum" and that one should focus on "pragmatism rather than following a process." With regard to specific Agile frameworks or methods, it became clear to participants that Agile might

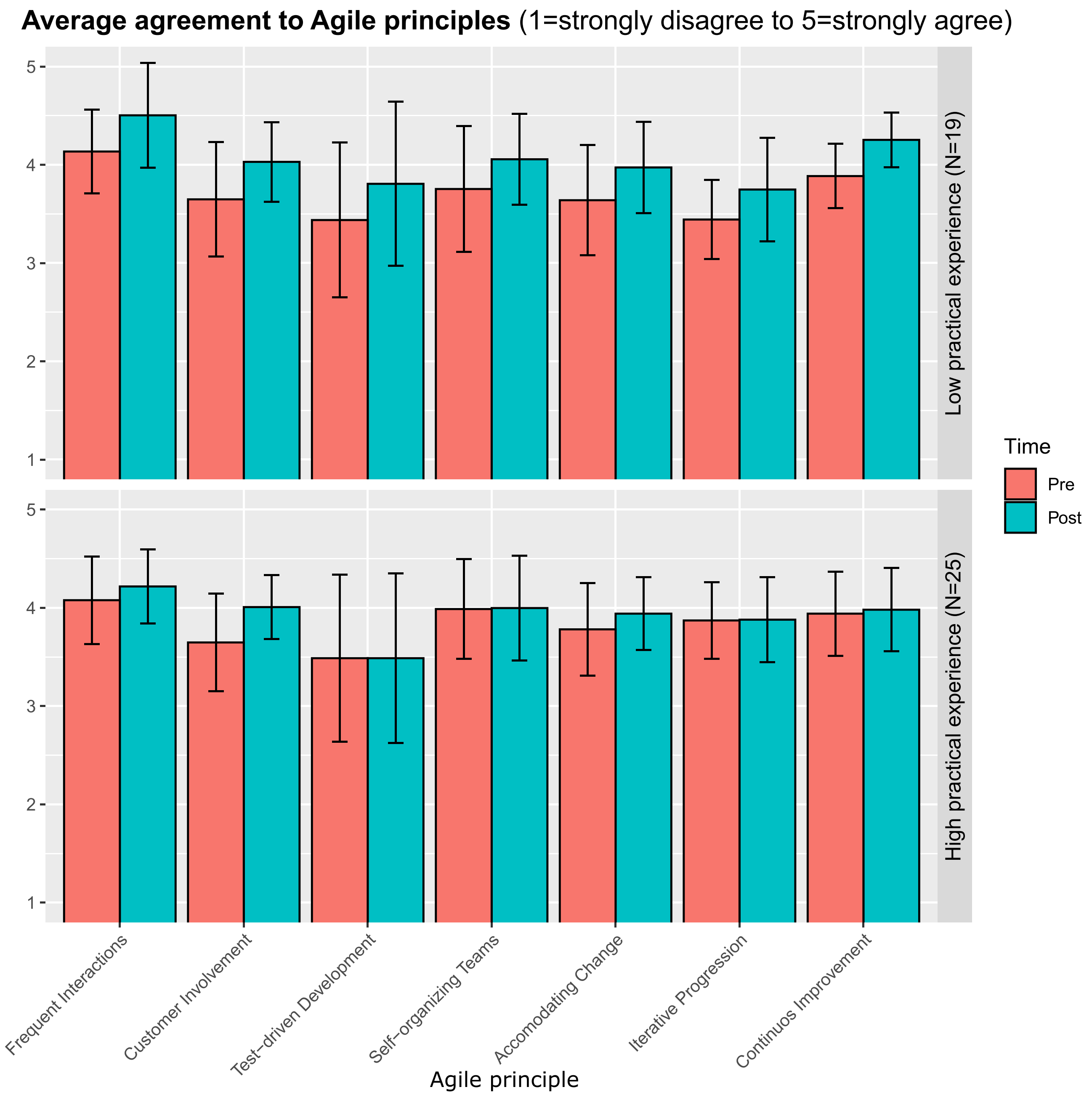

FIGURE 9 Change on average agreement and standard deviations concerning practical experience with Agile.

TABLE 3 Change in average agreement for the principles concerning practical experience with Agile.

Agile principle	Delta for low practical experience (<1 year) ($n = 19$)	Delta for high practical experience (>1 year) ($n = 25$)
Frequent interactions	0.37	0.14
Customer involvement	0.38	0.36
Test-driven development	0.37	0.00
Self-organizing teams	0.30	0.01
Accommodating change	0.33	0.16
Iterative progression	0.31	0.01
Continuous improvement	0.37	0.04

require adaptation to the respective context ("adapt Agile method for us"). Failure to do so may lead to struggles, as summarized by the following statement from a respondent: "The only thing standing in the way of Agile development at [Company X] is the Scrum method." Furthermore, participants expressed that *specific Agile practices and concepts had become clearer* through practical application within the ES. Statements such as "Kanban boards are a good idea," "time boxing works," and "I have learned to use a retro properly" indicate that the applied context of the ES was beneficial even if such practices were already known from theory.

Regarding the *application of Agile for physical products*, participants noted that "Agile is relevant for hardware" and that "hardware can embrace Agile." Still, the respondents recognized that the viability of an Agile approach depended on influencing factors, such as the availability of "a cheap/digital way to prototype" and "the task complexity and the disciplines involved." Within this context, *planning* was repeatedly mentioned as a possible means to facilitate the iterative development of physical products. The participants remarked that "planning is essential" for AHD, and one should "plan enough time for planning" so that the "tasks are clear before execution." Tasks should be structured and distributed "so they can be done in parallel" with work packages being "interlocked within a team." Still, participants reported that spending the right amount of time planning can be challenging ("Spend enough time on project planning, but not too much"). They picked up on the point that planning activities should ideally be conducted by the entire team by "setting the sprint goal together (the entire time)." To ensure a common understanding of the joint plan, the participants noted that one should "explicitly go through the sprint goal within the team after planning."

In addition to the aforementioned items, learnings not directly related to Agile were also reported by the participants. Some respondents felt that they received better *insight into the other roles involved in a typical hardware development project*. For example, according to a participant with a nontechnical background, they were able to "experience the perspective of software developers as [a] hardware engineer," and they concluded that "engineering is complex and not easy."

5.3 | User reaction: Meega+ survey

Figures 10 and 11 show the results of the user reaction surveys for both groups combined ($N = 44$).

The five-point Likert scale ranged from −2 (strongly disagree) to 2 (strongly agree). When possible, the results are detailed with observations made by the moderators.

User feedback regarding the *usability* of the ES is displayed in Figure 10. According to the authors of the Meega+ survey [29], this dimension can be separated into the subdimensions of *learnability* and *operability*. Regarding *learnability*, participants were not entirely certain whether things needed to be learned before interacting with the ES (median = 0). This was consistent with moderator observations of some participants struggling with the tools at the beginning of the training. The CAD system especially required some experimentation before the participants were able to use it to its full extent. This indicates that a learning curve is present regarding the tools employed in the ES. Participants agreed that the actual process of learning the tools was easy (median = 1) and that most people would be able to do so (median = 1). Several participants mentioned that the dedicated tutorial task as part of the training process helped to improve the learnability of the tools. Regarding

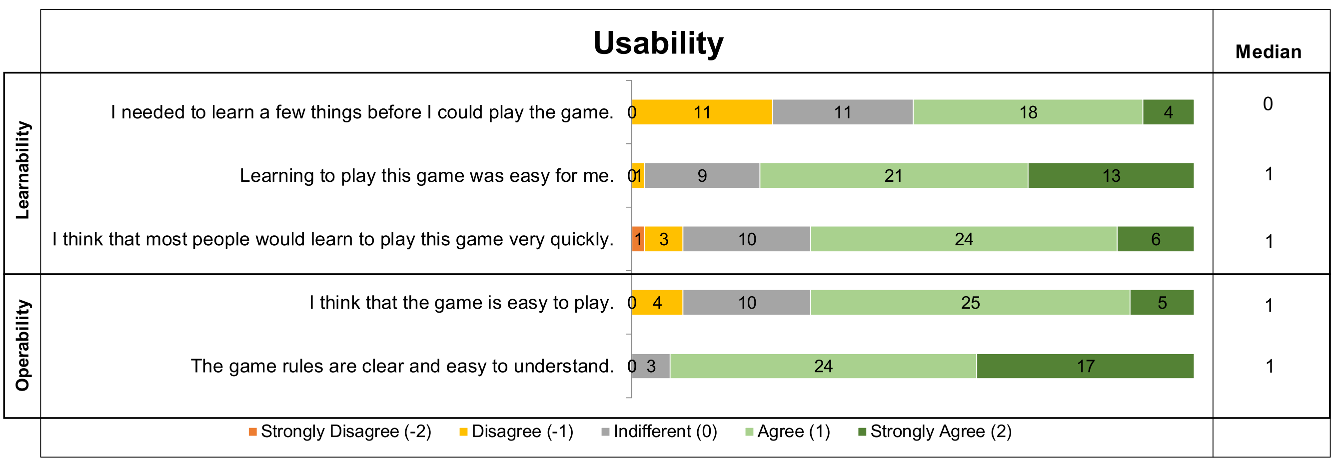

FIGURE 10 Results from Meega+ survey for usabilit y (plot created using the design template by [29]).

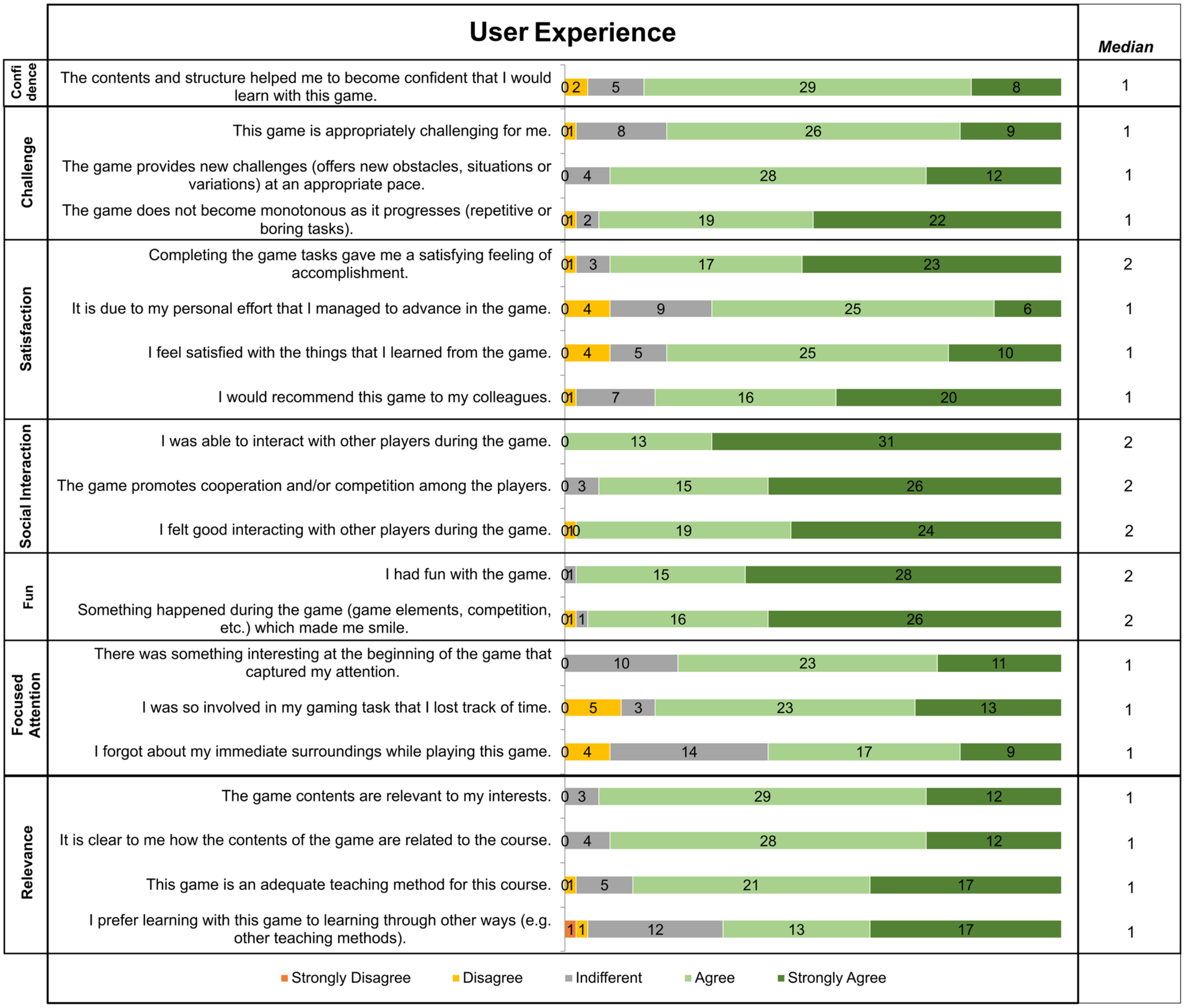

FIGURE 11 Results from the Meega+ survey for user experience (plot created using the design template by [29]).

operability, respondents deemed the ES to be easy to play once familiarized (median = 1), and they felt that the rules were clear and easy to understand (median = 1).

Apart from *usability*, the Meega+ survey also assessed the *user experience* of a training module. Here, the results were again generally positive, with medians mainly ranging between 1 and 2 (Figure 11). The subdimensions of *social interaction* and *fun* received the highest ratings (median = 2 for both). This result indicates that respondents enjoyed themselves during the training and that interaction was very much present (median = 2). Regarding *satisfaction*, most players felt satisfied with the information that they learned from the game (median = 1). They also indicated that they would recommend it to others (median = 1). Again, the quantitative findings are consistent with the conceptual design of the ES and moderator observations. By deliberately distributing crucial information and tools to the different roles, the teams were required to intensively collaborate to complete the task. We conducted the training with multiple teams in parallel, which automatically led to a sense of competition between the teams. As almost all teams managed to complete the task in the end, a sense of accomplishment was visible for most of the participants.

The majority of participants perceived the ES to be appropriately *challenging* (median = 1). This indicates that the complexity of the tools and system was neither too high nor too low for the respondents. This can also be seen in the high degree of *confidence* felt by the participants (median = 1). The ES managed to capture the *attention* of the participants (median = 1), which again is in line with moderator observations of teams working on their systems even during the lunch break.

The content of the ES was rated as *relevant* (median = 1), with multiple participants highlighting the similarity of working with the wire bending machine and products in their daily work. The respondents acknowledged that the ES represents an adequate teaching method for AHD (median = 1) and that they would prefer this method compared to other ways of teaching (median = 1).

6 | DISCUSSION

Within this section, the main contributions of the study are discussed. Furthermore, threats to validity are presented.

6.1 | Theoretical and practical implications

This study contributes to the extant literature in two ways. As its first contribution, the manuscript presents a novel educational game that addresses the challenges of AHD through the realistic simulation of hardware development. As described in the related works section, there is a lack of training emphasizing this specific context. In addition, this study used industry professionals for the evaluation as opposed to university students as in existing research.

Concerning RQ1, the results of the experiment show that our approach of realistically simulating hardware development is capable of transferring a broad range of learning outcomes. It can be used to promote the understanding of softer aspects, such as Agile principles and mindset, which traditional, lecture-style instructions rarely convey [18]. Within the evaluation, this was reflected by the increase in average agreement with the Agile principles covered by our training module. In addition, the ES helps to intensify theoretically acquired knowledge through practical application. In our case, this includes more specific concepts and practices, such as Kanban boards or retrospectives, as reported by the participants. The learning effect was visible for both experienced and inexperienced users, with the increase being larger for the latter group.

Concerning RQ2, the usability and user experience of the ES were rated positively, indicating that the realistic simulation of the hardware development process is not too complex or difficult to interact with. The evaluation showed a high degree of relevance to the industrial participants since their everyday practice was realistically reflected in a simplified way. The complexity of the technical system, together with the engineering process, tools, and setting, created a situation mirroring real-life situations in hardware development. In this context, the selection and design of appropriate technological tools were important, as they allowed for balancing the necessary simplicity with the complexity of the simulation. Prototyping technologies proved to be especially useful for the design of our ES. By utilizing readily available tools such as microcontrollers, frameworks such as NodeRED and laser cutters, an authentic yet accessible learning environment was created.

As a second contribution, this study presents a framework (product, process, setting, and instruction) that describes how the design of an ES contributes to achieving the desired learning goals. As seen in the description of the training module, the alignment of the four components provides various opportunities to provoke the educator's intended learning situations. The featured tools, including open-source access to the source data, are presented in detail. This enables practitioners and scholars to replicate and adapt the presented training module to their individual needs. An adapted version of this specific ES has already been used for design support validation in the context of distributed product development [13, 17], highlighting the relevance of our educational approach for other learning domains.

Concerning practical implications, we do not deem the ES to be a replacement for existing training in the field of Agile education. Conventional modules such as Scrum certification classes are much more scalable and provide learners with the necessary theoretical foundation. Similarly, the existing educational games that build on LEGO or other simplification techniques are capable of teaching Agile in a general context. We see the presented ES as a complementary supplement for the specific setting of hardware development. Instructors can use it as a dedicated tool to highlight the challenges of AHD in a controlled environment, allowing them to be there when the methodology is applied and to react to the participants' behavior if necessary.

6.2 | Threats to validity

Several threats to validity are present within this study. They are discussed in the following using the classification of [40].

6.2.1 | Internal validity

Internal validity is related to the extent to which an experimental outcome (in this case, perceived learning and user reaction) can be causally explained by the treatment. We are aware that the single-group design represents a major threat to internal validity. Due to practical reasons, it was not possible to include a control group in the experimental evaluation. The sample group of industry professionals had very limited availability, limiting the total sample size. Furthermore, it was not possible to process a portion of the sample group with an alternative treatment, since other training from the literature [15, 25, 33, 39] could not be recreated based on the information given in the publications. For these reasons, the evaluation is limited to providing a first, exploratory assessment of the presented teaching approach without a direct comparison to other instructional strategies. Considering that most of the related work is evaluated with students, we prioritized practical relevance by selecting industry participants.

There are several extraneous factors in the context of the experimental evaluation. The first one is related to varying degrees of participant skill level and prior knowledge that may influence the outcome. We tried to mitigate this by randomly allocating participants to teams. Furthermore, the pre–post analysis differentiates between high and low prior experience. In addition, there is the threat of moderator influence on team performance and ultimately learning and user experience. By using a standardized moderation script with consistent instructions and having the same moderator for all evaluations, we tried to minimize the influence of this extraneous factor.

6.2.2 | Construct validity

Construct validity is concerned with the extent to which an observation relates to the underlying theory. Within this context, the quantitative evaluation of perceived learning represents a threat, since it builds on a nonstandardized questionnaire. To address this, the items were informed by tested surveys published in the literature. Furthermore, the analysis of participant learning included multiple sources of data by combining quantitative and qualitative methods. The qualitative evaluation was mainly based on participants' self-assessments and personal reflections. There is the possibility that respondents willingly or unconsciously provided a distorted impression. We tried to account for this by ensuring anonymity and including open-ended comment opportunities for participants.

6.2.3 | External validity

External validity refers to the extent to which experimental results can be generalized [40]. By sampling industry professionals instead of students and imitating real-world settings and processes as closely as possible, the ES is by design highly relatable to industrial practice. To further increase external validity, we pooled participants from multiple firms and organizations.

7 | CONCLUSION AND OUTLOOK

Teaching Agile is becoming increasingly more engaging. This study presented a novel training module that realistically simulates a hardware development project to transfer the principles of AHD. In contrast to existing educational games in the field of Agile, the presented teaching module realistically reflects the challenges of applying Agile to physical systems. This is done by mimicking the typical roles, processes, and tools of industrial engineering teams. The evaluation conducted in this publication indicates that this approach can transfer principles of Agile to industry professionals.

For both experienced and inexperienced participants, a positive affective learning outcome was observed in the form of increased agreement with Agile principles. A high degree of relevance, interaction, and confidence was reported by the participants, underlining the general applicability of the approach. The evaluation highlights the opportunities of aligning game components to provoke instructors' targeted learning situations. This study contributes to the extant literature by providing a design framework (product, process, setting, and instruction) and open-source access to the tools and systems used for implementation. Instructors and scholars can build on these resources to adapt the presented training or create their modules.

In the future, we aim to investigate the long-term effects of the presented training by conducting follow-up assessments with the participants. The goal would be to investigate whether they have transferred the learnings to their professional work and how much they adhere to these learnings. Moreover, a direct comparison with existing Agile training would be of great interest.

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DATA AVAILABILITY STATEMENT

"The data that support the findings of this study are openly available in the following repository at https://gitlab.ethz.ch/pdz/agile-engineering-simulator."

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APPENDIX A

Table A1

TABLE A1 Questionnaire items: Perceived learning survey.

Agile principle	Survey item	References
Frequent interactions	Frequent meetings should be conducted as it provides the quickest way to notify other team members about problems.	[35]
	The team should work in a physical environment that fosters collaboration.	[36]
	The team should be colocated.	[36]
	Team members should communicate and collaborate with their colleagues.	[37]
Customer involvement	Developers should be able to contact the customer directly without any bureaucratical hurdles.	[35]
	A requirement should not be regarded as finished until its acceptance tests (with the customer) is passed.	[35]
	When the development scope cannot be implemented due to constraints, the team should hold active discussions with the customer on what to finish within the development iteration.	[35]
	The customer should pick the priority of the requirements when planning development iterations.	[35]
Test-driven development	The team should integrate development results continuously.	[35]
	A product feature should be developed to pass a predefined test case.	[35]
	Test plans should be created before the developers start designing the product feature.	[37]
Self-organizing teams	The team should lead the communication; communication should not be managed	[36]
	The team should have administrative control over their development environment	[36]

TABLE A1 (Continued)

Agile principle	Survey item	References
	The team members should be able to determine, plan, and manage their day-to-day activities under reduced or no supervision from the management.	[37]
	Management should support the self-managing nature of the teams.	[37]
Accommodating change	The product features should be reprioritized when new features are identified.	[37]
	Only high-level product features can be identified at the start of development.	[37]
	The changes requested by the customers should be accommodated.	[37]
Iterative progression	The team should rather reduce the development scope than delay the deadline.	[35]
	At the end of a development iteration, the team should deliver a potentially shippable product.	[35]
	The team should have small and frequent releases of development results.	[36]
	Development iterations should be of a consistent fixed length.	[36]
Continuous improvement	The team should regularly inspect and adapt the overall development process	[36]
	Practices that worked well during the development iteration should be used again in the future.	[37]
	Practices that did not yield the expected results should be discontinued in future development iterations.	[37]

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