Integration of Simulation-based Training for Welders

Benjamin Knoke*, Klaus-Dieter Thoben

BIBA – Bremer Institut für Produktion und Logistik GmbH, University of Bremen, Hochschulring 20, 28211 Bremen, Germany; **kno@biba.uni-bremen.de*

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Abstract. Simulation-based training for welders is continuously gaining importance. However, research on the integration of welding simulators into existing structures and processes is still scarce. In order to contribute towards a greater understanding, this paper collects concepts from areas with a long history of simulation-based training, such as medicine and aviation. These concepts are applied to provide a structured evaluation of two case studies that were conducted within two pioneer organisations. It was observed that certain levels of physical and functional fidelity were necessary for experienced trainers to accept welding simulators. Currently, the expected features are best provided by welding simulators based on augmented reality. Optimal results were yield in groups of 3-4 trainees, when every trainee is engaged into the simulation with a certain role (welding, correcting, filming, taking notes). Simulation-based training can be successfully applied towards a range of skills that includes technical and functional expertise training, problem-solving and decision-making skills, as well as interpersonal and communications skills.

Introduction

Vocational education and training in the field of welding is currently undergoing a transformation through the integration of simulation-based training. Although the transformation is gaining momentum from advances in multimedia technologies, the implementation of simulation-based training is still in its infancy. Much less research is available than in areas with a long history of simulation-based training, such as the medical sector.

In order to contribute towards a greater understanding of the possibilities that these simulation technologies have to offer, this paper discusses the applicability of find-ings from other sectors towards simulation-based train-ing for welders.

For an educated design and the integration of simulation technologies for welders, it is necessary to understand the benefits and relevant characteristics of training simulations. Although it seems that a training simulation simply improves the closer it comes to reality, the relation is instead more complex [1]. Not only can unnecessary details increase the costs of simulators [2] [3], they also bear the risk to divert the focus from the intended training [4]. Therefore, Shirts (1992) recommends to ‘look past the details to the essence of reality’ [4].

This paper discusses concepts that contribute to the success of simulation-based training in various sectors, such as simulation fidelity, definition of training objectives, and benefits of simulation technologies. The currently available welding simulators and two case studies are analysed to investigate the current state-of-the-art and the applicability of the aforementioned concepts into welding training.

1 Related Work

1.1 Simulation Fidelity

Early research initiated by Thorndike & Woodworth in 1901 argued that a simulated environment must have the same elements and surface features than its real counterpart in order to allow a transfer of problems [5] and to evoke engagement of the trainee [6]. This demand influenced the definition of the term ‘simulation fidelity’ in the middle of the 20th century. Simulation fidelity is used to describe the degree to which the real operational equipment or situation is resembled by a simulator [1] [2].

Subsequent studies indicate that the correlation between simulation fidelity and training effectiveness relies on multiple dimensions. Initially, Kinkade and Wheaton (1972) defined three dimensions of simulation fidelity [7]:

- *Equipment fidelity*: the degree to which the simulator looks and feels like the original operational equipment.
- *Environmental fidelity*: the degree to which the simulator resembles the sensory stimulation and control feel of the original task situation.
- *Psychological fidelity*: the degree to which the trainee perceives the simulator as a duplicate of the original operational equipment and task situation.

This definition has been refined by Fink and Shriver (1978), who defined two key dimensions [8]:

- *Physical fidelity* as the degree to which a simulation represents the appearance and feel of the original equipment (previously: equipment fidelity).
- *Functional fidelity* as the degree to which the original stimulus and response options are implemented in the equipment (previously: environmental fidelity).

Hays (1980) emphasises the use of the terms physical and functional fidelity [9]. He also states that psychological fidelity and corresponding approaches can be derived from physical and functional fidelity and should therefore be discarded. Although physical fidelity and functional fidelity also show interdependencies, the functional fidelity of a training simulation is mainly considered to determine its performance [10] [11].

Although the term fidelity is widely used since its introduction, Hamstra et al. (2014) argue that the differentiation between functional and physical dimensions is not made consistently across literature [12]. The authors also emphasise the importance of functional task alignment (functional fidelity) over physical resemblance (physical fidelity), which is always determined in context of the underlying instructional goals [12].

The knowledge to differentiate between important and unnecessary fidelity is one of the key objectives during the design of simulation-based training, because minimal costs can only be achieved by selecting just the fidelity that is necessary to meet the training objectives [13].

The conclusions drawn for the methodology of this paper are (i) to distinguish between physical from functional fidelity, (ii) to analyse if the importance of functional over physical fidelity can be confirmed for welding simulators, and (iii) to benchmark functional fidelity in consideration of specific training objectives. Approaches to describe the skills that can be achieved through simulation-based training are described in the following section.

1.2 Skills that can be trained through simulation-based training

The main objective of training is the acquisition, improvement or testing of skills [14] [15] [16]. The skills that can be trained through simulations have been classified by Lateef (2010) into three main types [16]:

- Technical and functional expertise training.
- Problem-solving and decision-making skills.
- Interpersonal and communications skills or team-based competencies.

A similar categorization has been published by Larnpotang et al. (2013), who defined a skills triangle to emphasise the possible training of multiple dimensions in a single training simulation, as shown in Figure 1 [17].

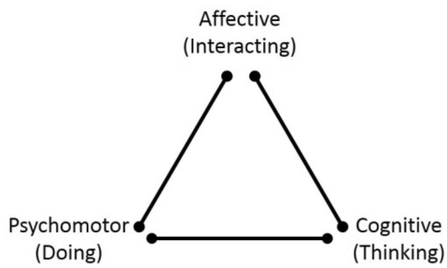

Figure 1: The skills triangle of simulation-based training [17].

In addition to an improved acquisition of skills, higher fidelity in simulation-based training can offer several benefits in comparison to regular training.

1.3 Features and uses of fidelity in simulation-based training

Issenberg et al. (2005) conducted an extensive literature review on the features and uses of successful high-fidelity medical simulations with the following results, sorted by weight [18]:

- Feedback is provided during learning experience
- Learners engage in repetitive practice
- Simulator is integrated into overall curriculum
- Learners practice with increasing levels of difficulty
- Adaptable to Multiple Learning Strategies
- Capture Clinical Variation
- Operate in a controlled Environment
- Individualised Learning
- Defined Outcomes and Benchmarks
- Simulator validity

Although the study has been conducted in the medical field, the results are expected to be applicable as a framework to examine the features and uses of fidelity in training simulations of welders.

1.4 Simulation technologies in welding simulators

Simulation technologies can be defined as materials and devices created or adapted to solve practical problems and create simulations [19]. The current key simulation technologies in welding are virtual and augmented reality. During the past decade these technologies were applied to create welding simulators and made the transition towards practical application [20] [21]. The commercial solutions that are currently available are listed in Table 1.

Manufacturer	Product	Characteristics
GSI SLV Halle	GSI SLV Halle Schweißtrainer	Real low-power arc for melt run, requires shielding gas
Seabery	Soldamatic	Augmented Reality over an artificial workpiece
Fronius International	Virtual Welding	Virtual Reality, artificial workpiece in fixed position for haptic feedback
Lincoln Electric	VRTEX	Virtual Reality, artificial workpiece in fixed position for haptic feedback
123 Certification	ARC+	Virtual Reality, no haptic feedback
EWM Hightec Welding	EWM Virtual Welding Trainer	Virtual Reality on screen, no headgear, no haptic feedback

Table 1: Overview on available welding simulators.

All of the listed simulators rely on optic measurement to capture the position and movement of a welding torch or electrode. The measured characteristics include stick out, work angle, travel angle, travel path, and travel speed.

The listed welding simulators differ greatly in physical and functional fidelity, as well as in price. Currently, the augmented reality system (Soldamatic) seems to be dominant, which has also been observed within the two case studies that are described in the following section.

2 Application of Welding Simulators

Within the course of the German research project 'MESA – Medieneinsatz in der Schweißausbildung' (media applications in welding training), two diverse case studies have been conducted to analyse the implementation of welding simulators in industrial practice. The case studies include a plant for the construction of car chassis of a car manufacturer and an organisation for joint training of metal processing SMEs.

2.1 Case study 1: Car chassis manufacturing plant

The first case study was conducted at a car chassis manufacturing plant of a German car manufacturer. On average, 50 trainees periodically perform a welding training with a duration of four weeks. This includes mostly apprentices, but also advanced training sessions and individual coaching for employees.

The introduction of welding simulators started with two VRTEX-systems that were mostly used as demonstrator and had low impact on the practical training. In 2015 four Soldamatic systems have been purchased. The decision to change the system was made due to the considerably lower price and a better physical and functional fidelity of the simulation. The augmented reality system was preferred due to a more robust mode of operation and constraints of motion sickness through limited environmental perception within the virtual reality simulation. It was observed that VRTEX-systems create strong electromagnetic fields and are prone to failure, if positioned within 4-5 metres of other sources of electromagnetic fields or each other.

In collaboration with the simulator manufacturer, an individual workpiece was integrated in the simulation to enable the welding training along a curved outline on a control arm that is actually manufactured within the chassis plant and used in welding training. The control arm was replicated as a plastic workpiece with reference markers. It is used within the welding training to increase the simulators acceptance among the trainers through an increased connection to reality and to save resources.

Each simulator is used by a group of 3-4 trainees. After the initial enthusiasm fades, it is considered important to engage every trainee in the simulation through a specific task. While one trainee welds within the simulation, the second trainee analyses an external screen of the simulation and communicates corrections. The third trainee films the process and focusses on ergonomic aspects. To make the posture more visible, a white adhesive strip is vertically taped on the back of the first trainee. If present, an optional fourth trainee is instructed to fill an evaluation sheet.

After an initial scepticism and fear for their occupational safety, the simulators are now greatly appreciated by all welding trainers. They see the simulators as an easy way to provide individual feedback that is not contested by the trainees. To further increase the acceptance among experienced welding trainers, it is important to state that the simulation should not be seen as a perfect replication. The physical fidelity is lowered through characteristics such as a low travel speed that is considered to be more like ‘Tai-Chi’ by the trainers. However, the trainers generally observe a ‘significant learning effect’ through the simulation-based training, implicating a high functional fidelity.

2.2 Case study 2: Joint training organisation

The second case study concerns a regional joint training organization that trains apprentices and experienced employees for 65 metal processing SMEs in central Germany.

The practical welding training is usually conducted in groups of three trainees. In addition to the 15 welding booths, the organization purchased one ARC+-system in 2013 and also one Soldamatic-system in 2016. Complaints were made that the ARC+-system is rather fragile and had to be sent to Canada multiple times for repairs. Also it allows less customization than the Soldamatic-system and provides no haptic feedback through lack of a physical workpiece.

The simulators have been integrated into basic welding training for beginners. The objectives were to ensure an ergonomic posture, train the correct parameters, such as travel speed and work angle, and to generate direct and individual feedback. The simulation-based training resulted in ‘much better results’ during the trainees’ first workpieces and a focus on ergonomic aspects that was not possible in the conventional welding booths, due to blinds and personal safety gear. The welding tasks can be reset quickly and do not require the preparation of workpieces, leading to much faster exercises and a steeper learning curve. A time saving of up to 40-50% through a combination of simulation-based and conventional training was observed to teach basic welding skills to beginners. The trainers also noticed an increased level of engagement during the group sessions in simulation-based training. This appears to be linked to the gamification aspect of the simulations, as trainees contest each other for higher scores.

In addition to training, the mobile design and operational safety of the simulators also allows to use them to attract attention on local trade fairs and in events for occupational orientation.

3 Discussion of Results

During the following discussion, the concepts described in Section 2 are evaluated in consideration of results from the two reported case studies.

3.1 Fidelity requirements

A certain level of *physical fidelity* appears to be beneficial in order to support the integration of simulators into existing structures and processes. The case studies showed that an experienced welding trainer is more likely to approach a simulator that resembles traditional welding equipment. Therefore, the processing equipment of the most successful welding simulators is integrated into cases of traditional welding equipment and applies a similar set of controls.

Although the welding simulators perform well for their intended purpose, an experienced welder requires 3-5 ‘test runs’ in order to generate good results on a welding simulator. This shows a certain lack of *functional fidelity* that is usually accepted, if the difference between simulation and replication is explained to the welder. The level of acceptance is higher if the simulator is seen as equipment that allows to train skills that be transferred into welding.

3.2 Skills that can be trained through welding simulators

The positive learning effect through (partial) integration of simulators in the training of welders has been proven in multiple studies [22] [23] [24] [25] and was also observed in both case studies. The skills that can be trained through welding simulators are described in the following along the three main categories [16].

Technical and functional expertise. Technical and functional expertise comprises the main objective of practical welding training. The key parameters that are monitored by all welding simulators are stick out, work angle, travel angle, travel path, and travel speed.

In addition to the parameters that impact the weld, welding simulators have shown great potential in training of an ergonomic posture. Instead of isolated training in welding booths, where welding apprentices are mostly rated by their results, simulation-based training can be conducted under supervision or in groups to put the focus on the process. Currently, ergonomic training is not directly implemented in welding simulators, but both case studies showed great interest and applied work-arounds. Group training and video recording can be applied to create awareness for posture during welding training.

Problem-solving and decision-making skills. The current state-of-the-art welding simulators create complex simulations that depend on various parameters, such as voltage, current, shielding gas type and flow rate. These parameters have to be configured for training sessions and trainees can also experiment with the outcomes of parameter manipulation without suffering serious safety constraints.

The simulations can be applied to provide a link from theory to practice and support classroom situations through combination with an external video projector, e. g. in vocational training schools.

Most simulators include some ability to display learning material and conduct tests. However, this function has not been used within the case studies, because the simulators are usually operated in groups of 3-5 trainees, which contradicts traditional test situations.

Interpersonal and communications skills. In comparison to traditional training, the simulators are usually used in small groups of trainees. Within the chassis manufacturer plant, each group member was given a specific task during the individual training sessions (welding, correcting, filming, taking notes), which led to an increase in communication and team-work. Both case-studies also reported informal competitions between the trainees as a positive effect that increases engagement.

Furthermore, the welding sector is characterised by a relatively high level of cultural diversity, which can cause language barriers. Visualisations and multi-language support are implemented in most simulators and can be applied to facilitate the teaching of technical terms.

Overall, skills in all three categories are impacted by training with welding simulators. However, interaction and communication are merely seen as a corollary of psychomotor and cognitive skills.

3.3 Features and uses of fidelity in simulation-based training

The features and uses of fidelity in simulation-based training that have been defined by Issenberg et al. (2005) within the medical sector [18] are discussed in consideration of the characteristics of welding simulators and the performed case studies.

Feedback is provided during learning experience. All of the currently successful welding simulators include feedback concerning the monitored parameters that can be shown during welding sessions. They also feature an evaluation screen that shows the course of parameters along the weld after completion.

In combination with group work, the feedback feature was considered highly important in both use cases and is expected to be a main cause for skill improvement.

Learners engage in repetitive practice. The ability to quickly restart a welding session is seen as a great advantage over traditional training, which would require preliminary work, such as cutting and grinding of the workpiece. Instead, simulation-based training sessions can be repeated under identical circumstances within the press of a button.

Simulator is integrated into overall curriculum. Multiple cases of successful implementation of welding simulators in vocational training are existing. However, the curriculum integration is still in a preliminary state and differs greatly between organisations in scope and evaluation.

The MESA-project is currently performing research towards a curriculum integration of welding simulators and cooperates with the German Welding Society (DVS) to develop a structured guideline.

Learners practice with increasing levels of difficulty. Implemented difficulty levels in welding simulations vary through more or less strict evaluation, variation of tasks, or (partially) turned off feedback during the exercise. The variation of feedback was considered helpful, but not necessary during the case studies. It has been characterised as a viable approach to further prepare beginners in advance of their first actual welding training.

Adaptable to Multiple Learning Strategies. Most welding simulators can be used in learning situations of single users or groups with or without the presence of instructors. The simulation is usually displayed within a head-mounted display that resembles a welding helmet, and a small screen that is placed on the processing unit. Through connection of external video equipment, the simulations can also be used in classroom settings.

Capture (Clinical) Variation. The high variation of products and processes that confront welders in industrial practice are difficult to transfer into simulation-based training and seem to be a general barrier for simulation-based training in production.

An integration of individual products showed to have a positive effect on the acceptance of simulation-based training, and to reduce waste during the production of those products. During the case study of the car chassis manufacturer, considerable effort was spent to integrate a specific control arm into the augmented reality simulation of the Soldamatic-system. However, a low-cost or short-term variation of workpieces remains impossible, as long as the systems rely on digital representations of workpieces and an on-the-fly digitalization is not implemented.

A promising feature of augmented reality-based simulators is that the simulation is integrated into the real environment. During the simulation of MAG welding, the Soldamatic-system enforces a certain position and orientation of the headgear and welding torch towards the workpiece. This allows to mount the workpiece into confided spaces or underneath a table to simulate extraordinary processes (e. g. Figure 2), such as the welding of pressure tanks or heat exchangers.

This can be applied to provide ergonomic assistance during constrained postures and to improve confidence towards complex task or unanticipated events (as in [16]).

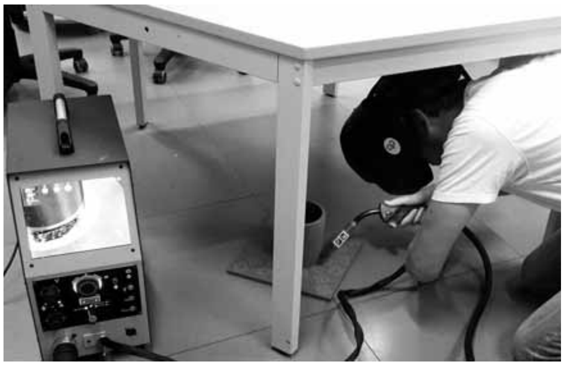

Figure 2: Welding simulation in confined spaces through Augmented Reality.

Operate in a controlled Environment. Welding simulators provide the possibility to train in groups and to freely variate process characteristics, which is usually not possible in conventional training due to safety constraints. Within the case studies, welding trainers expressed great delight towards the opportunity to provide support during the process and to improve consciousness for an ergonomic posture.

Individualised Learning. Individual requirements can be met through variation of time spent in the simulation and through adjustment of difficulty levels. Additionally, the simulators provide several sets of standard tasks with the most prominent types of manual welding processes: MIG, GTAW, and SMAW.

Defined Outcomes and Benchmarks. The task and benchmarks are clearly defined by all observed welding simulators and the monitored parameters are graded in percent that were achieved during the training sessions. However, beginners require a short introduction to the simulation to correctly interpret the provided feedback. A suitable tutorial is missing.

Also, welding trainers reported the neutral feedback through sensor data as a strong improvement over traditional training, where their feedback is sometimes either not taken seriously or causes unnecessary strain.

Simulator validity. The validity of welding simulators corresponds with their functional fidelity and has been proven in both use cases. System resilience was described as an important criteria by both use cases for their decision to purchase specific welding simulators.

4 Conclusion and Outlook

During the past decade, simulation-based training for welders continuously gained importance. Since extensive research on the integration of simulators has already been conducted in other areas, such as medicine or aviation, this paper reviewed established concepts to evaluate two case studies on the integration of welding simulators that were performed in pioneer organisations.

The evaluation proved that welding simulators are greatly appreciated by welding trainers, once certain requirements are met. The expectations towards physical fidelity mostly address intuitive controls that simulate those of conventional welding equipment. It was also observed to be important that welding simulators are presented as training equipment and not as a perfect replication of reality. Otherwise, experienced welders, who usually do not perform well on their first tries, tend to get upset and focus on system flaws.

In accordance with previous research, both case studies reported a 30-50% decrease in time that is necessary to develop basic welding skills, when simulators are integrated into welding training for beginners. Best results were achieved during simulation-based training in groups of 3-4 persons, when each person was engaged into the simulation through an individual task (welding, correcting, filming, taking notes), or during individual training with an instructor.

Most features and uses of fidelity that contribute towards the success of simulations in the medical sector, also apply for welding simulators. Though, the individuality of products and processes seems to be a general barrier towards the customization of simulations in production. A demand of customization showed, as one of the two organisations spent considerable effort to integrate a specific workpiece into a welding simulator.

A promising application of augmented reality is the opportunity to fit the available standard workpieces into confined spaces. This allows the simulation of complex welding tasks and the support of ergonomic postures with relatively low effort. Following research may include experiments to transfer welding simulations into specific environments, such as pressure tanks or heat exchangers.

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