Simulation in Produktion
und Logistik 2019
Matthias Putz & Andreas Schlegel (Hrsg.)
Wissenschaftliche Scripten, Auerbach 2019

Literature Review on Training Simulators in Manufacturing Processes

Literaturanalyse zu Trainingssimulatoren in Fertigungsprozessen

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Abstract: Training Simulators can be a beneficial addition to conventional training and are fundamental for training in areas, such as aviation, medicine, and military. While new applications emerge in conjunction with the development of human-machine interface (HMI) technologies, only a few applications for manufacturing processes are used in industrial practice. This study provides a literature review on simulation-based training in manufacturing processes and applies the definitions of DIN 8580:2003 for structuring the research. Although 204 applications were found, most focus on a small number of processes and the others rarely mature past the prototype stage. An analysis of the required efforts and expected benefits of simulation-based training is performed to investigate the observed distribution further.

1 Introduction

The ongoing transformation of production environments towards cyber-physical systems creates increasing demands towards the skills of workers and the vocational training to achieve those (Gorecky et al. 2014). The desired skill sets encompass technical and functional expertise, as well as application and process oriented skills (Ahrens & Spöttl 2015). Training simulations have been proven to be a viable approach to create and improve these skills, and are commonly applied in multiple areas (Lateef 2010, Larnpotang et al. 2013, Sohmer et al. 2014).

Simulation-based training has become an integral part in diverse sectors, such as medicine (Cook et al. 2011), aviation (Sullivan et al. 2011), or firefighting (Backlund et al. 2011), but only a few applications for manufacturing processes are used in industrial practice (Mujber et al. 2004). Literature states that the continuous development of technologies for the human-machine interface (HMI), such as Virtual Reality and Augmented Reality, is expected to enable new applications (Yuen et al. 2013, Barsom et al. 2016). Although technology development seems to lead towards new applications of simulation-based training, research that analyses this connection is scarce (Hamstra et al. 2014).

Against this background, the research aims to provide an overview of existing applications. Through the analysis of process characteristics, the results can support the identification of existing challenges and show the demand for new training simulators and advances in HMI technologies.

2 Methodology

Manufacturing is defined by DIN 8580:2003 as the production of workpieces of a geometrically defined shape. Manufacturing is performed in manufacturing processes, which alter the form, shape, and/or physical properties of a given material (Chryssolouris 2013, p.5). With this definition, processes that produce intangible results are excluded from the study, as well as preceding or supporting tasks, such as product design and maintenance.

The study applies the classification of DIN 8580:2003 to structure the research. The structure distinguishes between six main groups (primary shaping, forming, separating, joining, coating and finishing, and change of material properties), 42 groups, and 150 sub-groups. The research is performed on the sub-group level and through the search engines of *Google Scholar* and *Microsoft Academic*. The search was performed on both platforms with the terms “skills simulation”, “simulator training”, and “simulation-based training”, considering the first 50 results each. Elements that are not limited to manufacturing processes, such as “cutting” or “drawing”, were added the term “manufacturing” to provide suitable results.

3 Results

204 studies that describe training simulators in manufacturing processes have been identified during the research. The findings were aggregated to the group level, and the tables are limited to the five most cited publications of each group to keep the paper format. The process groups with more than five publications are in descending order: assembly (53), cutting with geometrically defined edge (45), welding (34), disassembly (28), and coating from liquid state (18).

The results include a brief description of the HMI design and an estimation of the maturity level that is based on the published content:

- The description of the HMI design includes abbreviations for Virtual Reality (VR), Augmented Reality (AR), Motion Capture (MOCAP), and Head-Mounted Display (HMD). The term “desktop application” is used for HMI designs that include a computer screen, mouse, and keyboard. “Haptic interface” describes complex haptic input and/or output devices, such as a welding torch that is augmented with sensors and actuators. An Operator Training Simulator (OTS) describes a simulator that physically resembles one or multiple workstations and is typically used for plant operation training. An embedded simulation is performed within a model or a real system that is used for the training purpose.
- The maturity level of each simulator is described in one of five states: unknown, theoretical, experimental, case study, and patented.

3.1 Primary Shaping

Only a few training simulators have been identified for processes of the main group *primary shaping* (Tab. 1). The simulators can be split into two groups by their skill focus. Those that focus on psychomotor skills for manual casting processes are in a rather experimental stage and employ AR or VR technologies as well as haptic interfaces. Simulators that focus on procedural operator skills are mostly designed as desktop applications and tend to resemble OTS.

Table 1: *Training simulators in primary shaping processes*

Group	Publication	HMI design	Maturity level
1.1. Liquid initial material state	Watanuki & Hou (2010)	AR on screen, haptic interface, keyboard	Experimental
	Watanuki & Kojima (2007)	VR cave, haptic interface	Experimental
	Iwamoto, et al. (2014)	AR HMD, haptic interface	Experimental
	Ravi (2014)	Desktop application	Case study
	Lee et al. (2013)	Desktop application, haptic interface	
1.2. Primary shaping of fibre-reinforced plastic	Shi et al. (2008)	Stereoscopic VR on screen, desktop application	Experimental
	Zhou et al. (2009)	Stereoscopic VR on screen, desktop application	Experimental
	Sun & Tsai (2012)	VR HMD, haptic interface	Case study
	Salazar (1994)	Desktop application	Theoretical
1.3. Pappy / mushy initial material state	Sacks et al. (2013)	VR Cave, haptic interface, audio	Case study
1.8. Gas initial material state	Liu et al. (2008)	Desktop application	Case study
1.9. Prototypes from ionized state	Tikasz et al. (1994)	OTS	Experimental

3.2 Forming

Training simulators in the main group *forming* are limited to rolling and bending processes (Tab. 2). All simulators for the operation of rolling mills are designed as OTS to simulate their complex interface terminals. The bending simulations include a simulator for machine operators (Fernández et al. 2011) as well as a simulator for manual rebar bending for the construction industry (Menon et al. 2017a).

Table 2: *Training simulators in forming processes*

Group	Publication	HMI design	Maturity level
2.1. Pressure Forming	Li & Winitsky (1999)	OTS	Experimental
	Bonavia (2016)	OTS	Unknown
	Cockerell et al. (1993)	OTS	Experimental
	Brickwedde et al. (2007)	OTS	Case study
	Zhao et al. (2006)	OTS	Unknown
2.4. Bending	Fernández et al. (2011)	Desktop application	Case study
	Menon et al. (2017a)	Desktop application, haptic interface, audio	Case study
	Menon et al. (2017b)	Desktop application, haptic interface, audio	Case study

3.3 Separating

The main group *separating* includes a larger number of simulators for machining centres, and disassembly processes, as well as rather isolated applications for sawing, grinding, lapping, blasting, and electrochemical machining (Tab. 3). Most of the machining centre simulations include multiple processes, such as turning, drilling, and milling. Some disassembly simulators are also used in assembly processes.

Table 3: *Training simulators in separating processes*

Group	Publication	HMI design	Maturity level
3.1. Separating	Higashi & Kanai (2016)	Tablet application, haptic interface	Case study
3.2. Cutting with geometrically defined cutting edges	Li et al. (2002)	VR on screen, haptic interface, audio	Case study
	Acal & Lobera (2007)	Desktop application	Experimental
	Crison et al. (2004)	Desktop application, haptic interface	Case study
	Yao et al. (2007)	Desktop application, audio	Experimental
	He & Chen (2006)	Desktop application, haptic interface, audio	Experimental
3.3. Cutting with geometrically non-defined cutting edges	Balijepalli & Kesavadas (2003)	Desktop application, haptic interface, audio	Case study
	Li et al. (2017)	Desktop application, haptic interface	Case study

	Bolick et al. (2010)	VR on screen, desktop application, haptic interface, audio	Patented
3.4. Non-conventional machining	Kozak (2013)	Desktop application	Theoretical
3.5. Disassembly	Belloc et al. (2012)	Tablet application	Use cases
	Abate et al. (2009)	VR HMD, haptic interface, audio	Case study
	Gutierrez et al. (2010)	VR on screen, MOCAP, haptic interface	Experimental
	Ferrise et al. (2013)	1: VR on screen, MOCAP, haptic interface; 2: AR on screen, desktop application, haptic interface	Case Study
	Sportillo et al. (2015)	VR HMD, MOCAP, audio	Case Study

3.4 Joining

The main group *joining* includes a large number of assembly and welding simulators, as well as a single soldering application (Tab. 4). While the welding simulators have a strong focus on psychomotor skills, the assembly simulators have a more heterogenic design and range from complex data glove interfaces to desktop applications that convey procedural knowledge. Most of the simulators that are labelled as assembly simulators span across multiple process groups and also include screwing and clipping, which are part of the *press fitting* group. Some of these simulators are also used for disassembly.

Table 4: *Training simulators in joining processes*

Group	Publication	HMI design	Maturity level
4.1. Assembling / 4.3. Press Fitting	Westerfield et al. (2014)	AR HMD, model, audio	Case study
	Bhatti et al. (2009)	VR HMD, MOCAP, haptic interface, audio	Case study
	Xia et al. (2012)	VR cybersphere, MOCAP, haptic interface	Case study
	Wang et al. (2016)	AR HMD, MOCAP, haptic interface, embedded simulation	Case study
	Jia et al. (2009)	VR HMD, haptic interface, audio	Case study

4.6. Welding	White et al. (2011)	VR HMD, haptic interface, audio	Experimental
	Batzler et al. (2016)	AR HMD, haptic interface, audio, embedded simulation	Patented
	Albrecht (2015)	VR on screen, haptic interface	Patented
	Peters et al. (2016)	Desktop application, haptic interface, audio	Patented
	Becker & Pfeifer (2017)	VR on screen, haptic interface, audio	Patented
4.7. Soldering	James et al. (2019)	Desktop application, haptic interface, audio	Case study

3.5 Coating and Finishing

The findings within the main group *coating and finishing* are limited to simulators for coating processes from liquid state. They include 14 simulators for industrial spray painting applications, one for printing, and three for calligraphy simulation that can be categorized as a labelling process (Tab. 5).

Table 5: *Training simulators in coating and finishing processes*

Group	Publication	HMI design	Maturity level
5.1. Coating from liquid state	Shilkrot et al. (2015)	Embedded simulation, desktop application, haptic interface	Case study
	Wang et al. (2006)	Desktop application, haptic interface	Case study
	Yang et al. (2007)	VR on screen or AR HMD, haptic interface, audio	Experimental
	Konieczny et al. (2008)	VR HMD, haptic interface	Case study
	Kruse (2009)	VR on screen, haptic interface	Patented

3.6 Change of Material Properties

Although process simulation is commonly applied for process analytics within the main group *change of material properties*, only a single publication contains an intended use for operator training (Connaghan et al. 2004). It focusses on industrial irradiation equipment and describes a mathematical model that is implemented as a desktop application with a theoretical application in end user training.

4 Discussion

The research shows that a larger number of publications are limited to a small number of processes. The processes with more than five publications in descending order are: assembly (53), cutting with geometrically defined edge (45), welding (34), disassembly (28), and coating from liquid state (18). The prominence of these processes is certainly a strong factor for the implementation of simulation-based training, but it is likely not the only indicator. Else, training simulators for process groups such as tension compression forming or press fitting would have been identifiable. Salazar (1994) argues that the decision for simulation-based training is made by technical directors and production managers that are not interested in the chosen simulation model but want to increase production and quality, reduce energy consumption, and in general aim to achieve an economic benefit. This point of view implies a trade-off between required efforts and expected benefits that can be used as a proprietary framework to explain the uneven distribution among the manufacturing processes. The identified factors focus on measurable effects and disregard subjective criteria, such as the intention to use innovative media for advertising purposes.

4.1 Benefits from Simulation-based Training

The factors that benefit the use of training simulators in manufacturing have already been analysed in previous research (Knoke et al. 2018), to be based on research from aviation (Farmer et al. 1999) and medicine (Lateef 2010). In combination with findings from the reviewed literature, they can be condensed to the following:

- *Economic benefit:* The potential savings through simulation-based training rise with the training costs within the original system. These costs usually are created by the use of consumables and equipment, as well as the required presence of experts (Menon et al. 2017b). The costs scale with the amount of training that is required. Thereby, processes that involve a large workforce provide an increased opportunity for simulation-based training (e. g., assembly, disassembly). Desktop applications can be used to further decrease the costs and enable scalability of training (Gilles et al. 2006).
- *Risk reduction:* Simulation has an increased benefit if training in the real system inherits risks that may result in loss of health or equipment. This is often connected to the requirement of personal protective equipment, which is a barrier to apply the training in certain settings, such as classrooms, and creates another opportunity for simulators.
- *Higher training frequency:* The volume of exercises that are possible within a given time frame can be increased through simulation. Especially, if training in the real system is interrupted due to set-up and post-processing (e. g. welding, spray painting), or if the training focus is on the set-up phase and the training is interrupted by longer processing times (e. g., machining, additive manufacturing).
- *More precise feedback:* The ability to receive objective feedback while performing the training is a benefit for simulation-based training that is not given in most real systems (e. g., welding). This also provides opportunities for standardisation and quality control. It is particularly relevant for processes, whose result is greatly depending on operator skill (Iwamoto et al. 2014). With

skill dependency rises the importance of well-qualified employees especially if an automation of the process is difficult.

4.2 Required Efforts for Simulation-based Training

The benefits that are gained through simulation-based training are offset by the effort that is required for its implementation and operation. This effort is caused by:

- *Initial costs:* Training simulators often involve costly technology or may be related to substantial development costs. Hence they require a certain investment of finances and personnel (Sun & Tsai 2012).
- *Scenario creation and individualisation costs*: Training simulators that are developed for a specific scenario or are bought off the shelf may result in additional costs for customisation (Sacks et al. 2013).
- *Extended qualification requirements*: The operation of a training simulator requires a skill set that differs from traditional training (Ravi 2008). Trainer and trainee usually have to be able to interact with digital media and have basic troubleshooting skills. The costs during operation are expected to be lower than those of traditional training.

In addition to these factors, some applications face barriers due to technology constraints. In the past, digital simulation models had to be simplified because of limited computing performance or visualisation possibilities (Li & Winitsky 1999). Currently, some users avoid AR or VR technologies because of potential simulator sickness or related issues (Sun & Tsai 2012).

5 Conclusion and Outlook

204 applications of simulation-based training for manufacturing processes have been identified and categorized by the structure of DIN 8580:2003. Most simulators focus on a small number of process groups. These are assembly (53), cutting with geometrically defined edge (45), welding (34), disassembly (28), and coating from liquid state (18).

The balance between the required efforts and expected benefits provides presumably the basis for decision-making on the implementation of simulation-based training. In general, it is expected that the future progression of HMI technologies will benefit new applications. The influence of technology development and the underlying factors will be subject to further research being a key component in the development of a framework that supports the decision-making on the implementation of simulation-based training in manufacturing.

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