Implications of human-machine interface (HMI) technologies for the applicability of training simulators in manufacturing

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M.Sc. Benjamin Knoke

Hauptreferent: Prof. Dr.-Ing. Klaus-Dieter Thoben

Korreferent: Prof. Dr. Dr. h. c. Georg Spöttl M. A.

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Zusammenfassung

Trainingssimulatoren sind zentraler Bestandteil für die Ausbildung in Bereichen wie Luftfahrt, Medizin und Militär. In der industriellen Praxis werden jedoch nur wenige Anwendungen für das Training von Fertigungsaufgaben eingesetzt. Obwohl mit der Entwicklung von Technologien der Mensch-Maschine Schnittstelle (HMI) neue Anwendungen entstehen, sind die Ursachen und Zusammenhänge, insbesondere für die industrielle Fertigung, nur wenig erforscht.

Das Ziel dieser Dissertation ist es, die Auswirkungen von Mensch-Maschine-Schnittstellen (HMI) Technologien auf die Anwendbarkeit von simulationsbasiertem Training für Fertigungsaufgaben zu identifizieren. Dafür wird im Rahmen dieser Dissertation das Modell der Anwendbarkeitsfaktoren aufgestellt.

Ein Trainingssimulator wird für eine bestimmte Aufgabe als anwendbar definiert, wenn seine Implementierung aufgrund von Vorteilen gegenüber konventionellem Training gerechtfertigt ist. Daher können HMI Technologien die Anwendbarkeit von simulationsbasiertem Training beeinflussen, indem sie die Erzielung von Vorteilen gegenüber konventionellem Training ermöglichen. Anwendbarkeitsfaktoren werden in diesem Zusammenhang als Eigenschaften des ursprünglichen Trainingsprozesses definiert, die das Training nachteilig beeinflussen und in einer Trainingssimulation vermieden oder reduziert werden können. Über die Anwendbarkeitsfaktoren lässt sich für eine spezifische Arbeitsaufgabe demnach ein potenzieller Mehrwert einer Trainingssimulation bestimmen. Die Erreichbarkeit dieses potenziellen Mehrwerts ist wiederum von den verfügbaren HMI Technologien abhängig.

Zur Bestimmung von Anwendbarkeitsfaktoren und zur Überprüfung der aufgestellten Thesen wird eine systematische Literaturanalyse zum simulationsbasierten Training in Fertigungsprozessen durchgeführt und nach den Definitionen der DIN 8580:2003 strukturiert. Auf dieser Basis wird eine Methode zur Analyse von Arbeitsaufgaben entwickelt und in vier Anwendungsstudien überprüft: Schweißen, Zerspanen, Kleben und additive Fertigung.

Die Evaluation hat gezeigt, dass der potenzielle Mehrwert von Trainingssimulatoren für eine bestimmte Aufgabe mit einer Anwendbarkeitsfaktoren beschrieben werden kann. Die Evaluierung ergab auch mehrere Beispiele für potenzielle Vorteile, die aufgrund der Beschränkungen der verfügbaren HMI Technologien nicht erreichbar waren. Diese Beispiele zeigten, dass die HMI Technologien aufgrund ihres Einflusses auf die Differenz zwischen potenziellem und erzielbarem Mehrwert einen Einfluss auf die Anwendbarkeit von simulationsbasiertem Training in der Fertigung haben. Die Beispiele zeigen technologische Herausforderungen auf, die ein Entwicklungspotenzial für HMI Technologien aufzeigen können und einen Mehrwert für die entwickelte Methode darstellen.

Abstract

Training simulators are a central part of training in areas such as aviation, medicine, and the military. In industrial practice, however, only a few applications are used to train manufacturing tasks. Although new applications are emerging with the development of human-machine interface (HMI) technologies, the causes, and effects, especially for manufacturing, constitute a research gap.

This thesis aims to identify the impact of human-machine interface (HMI) technologies on the applicability of simulation-based training for manufacturing tasks. For this purpose, the model of applicability factors is defined in the context of this dissertation.

A training simulator is applicable for a specific task if advantages over conventional training justify its implementation. Therefore, HMI technologies can influence the applicability of simulation-based training by enabling achievable benefits over conventional training. Applicability factors are defined in this context as characteristics of the original training task that adversely affect the training and can be avoided or reduced in a training simulation. The potential benefit of a training simulation can therefore be determined for a specific work task via these applicability factors. The achievability of this potential benefit depends on the available HMI technologies.

A systematic literature analysis on simulation-based training in manufacturing is carried out and structured according to the definitions of DIN 8580:2003 to determine applicability factors and to review the current state-of-the-art. On this basis, a method for work task analysis has been developed and tested in four application studies: welding, machining, gluing and additive manufacturing.

The evaluation has shown that the potential benefit of training simulators for a specific task can be assessed with applicability factors. The evaluation also revealed several potential benefits that were not achievable due to the limitations of available HMI technologies. These examples showed that the HMI technologies impact the applicability of simulation-based training in manufacturing due to their influence on the difference between potential and achievable benefits. The examples highlight technological challenges that can indicate a potential for the development of HMI technologies.

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List of abbreviations

AR	Augmented Reality
CNC	Computer Numerical Control
HAZOP	Hazard and operability
HMD	Head-mounted display
HMI	Human-machine interface
OTS	Operator Training Simulator
PPE	Personal protective equipment
TIG	Manual tungsten inert gas
VR	Virtual Reality

1 Introduction

1.1 Motivation

The demographic trends in Germany lead to increasing demand for skilled workers (BA 2019). New vacancies are difficult to fill as the ongoing transformation of manufacturing 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 skillsets encompass technical and functional expertise and application- and process-oriented skills (Ahrens & Spöttl 2015). Training simulations have proven to be a viable approach to create and improve these skills (Lateef 2010, Larnpotang et al. 2013, Sohmer et al. 2014).

In addition to possible applications towards the development of skills required within Industry 4.0, training simulations can increase the efficiency and effectiveness of vocational training in manufacturing (Gonzalez-Franco et al. 2017). Multiple benefits are attributed to simulation-based training over conventional training on the job. A literature study concluded the benefits of high-fidelity training simulations in the medical sector (Issenberg et al. 2005). Among other benefits, simulation-based training enables:

- To provide feedback during the learning experience,
- Repetitive practice,
- Variation of difficulty levels,
- To operate in a controlled environment.

Simulation-based training has become an integral part of diverse areas, such as medicine (Cook et al. 2011), aviation (Sullivan et al. 2011), and firefighting (Backlund et al. 2011). However, only a few applications 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). However, research that focuses on the requirements towards simulation-based training in manufacturing is scarce (Hamstra et al. 2014). This scarcity motivates the questions, why only a few applications for simulation-based training in manufacturing exist and what characteristics constitute a task that can benefit from integrating training simulators. Further questions are how emerging HMI technologies may lead to new applications and how a potential benefit of simulation-based training can be achieved in industrial practice.

1.2   Introduction to the research problem

A training simulator is defined within this research as applicable towards a specific task if its implementation is justified because of its benefits over conventional training. This definition is complemented by the notion that the benefit of training simulators over conventional training cannot be guaranteed for manufacturing tasks in general but must be determined for each task individually.

This dissertation focuses on the research gap created by the lack of knowledge on how the benefits of training simulators can be identified for manufacturing tasks. The availability of HMI technologies must have implications on the achievable benefits of training simulators because their development and increasing maturity enables new applications (Yuen et al. 2013, Barsom et al. 2016). A methodology to assess the benefits of training simulators for specific tasks must also consider HMI technologies' implications.

Frameworks that support the systematic development of simulators and consider the implications of HMI technologies are scarce (Nazir et al. 2015) and non-existent for applications in manufacturing. Available frameworks mostly stem from military applications (Farmer et al. 1999) or medical applications (Issenberg et al. 2005). These areas have a long history of simulation-based training and are often used to prevent a potential loss of life (Vega 2002). Therefore, the frameworks in these areas were designed under the premise that simulation-based training is always a worthwhile endeavour. These frameworks guide the development of training simulators but provide no methodology to assess if simulation-based training is applicable for a specific task.

1.3   Research goal and research methodology

This dissertation aims to fill the identified research gap by developing and evaluating a methodology for a systematic task analysis. The methodology is expected to support the identification of factors that have implications for the applicability of simulation-based training for individual tasks in manufacturing under consideration of the implications of HMI technologies.

This research goal is divided into multiple sub-goals described in the following together with the methodology that is applied to achieve them:

- *To identify the state-of-the-art on simulation-based training in manufacturing.* The state-of-the-art will be achieved through a systematic literature analysis of pre-existing training simulators and the structure of DIN 8580:2003 with a focus on the applied HMI technologies.
- *To analyse the factors that have implications for the applicability of simulation-based training towards manufacturing tasks.* A methodology for a sys-

tematic assessment of these factors is developed in two steps: At first, factors that are described in frameworks from other areas are collected to develop a categorisation; during the second step, the factors described in the publications of the literature analysis are aggregated and sorted into the categories.

- *To aggregate and enable an application of the knowledge that is gained from the research*. A methodology is developed to assess the implications of HMI technologies on the applicability of simulation-based training for manufacturing tasks.
- *To evaluate the research*. An evaluation is performed by applying the tasks analysis methodology in three scenarios and evaluating the results through expert interviews. Subsequently, the research hypotheses are discussed against the evaluation results.

Training simulators are complex technical systems that are applied under didactic considerations. The interdisciplinary nature of their application requires the scope of this dissertation to be narrowed down to meet its objectives. Therefore, the following aspects are considered out of scope:

- This dissertation cannot claim to provide holistic instructions on designing training simulators in all production processes, which commonly includes *engineering, software development, and workplace design*. Instead, the intention is to support an assessment if simulation-based training is applicable to a manufacturing task and provide focused insights on general technological design aspects, respectively, the selection of HMI technologies regarding the characteristics of the original task.
- A large share of available literature on simulation-based training stems from *occupational science* and focuses on proving didactic concepts. Although these publications are considered viable input for this research, didactic concepts are considered out of scope for this dissertation. Nevertheless, some benefits of simulation-based training that facilitate certain methods such as trial-and-error may have didactic implications.
- This dissertation focuses on the analysis of existing technologies and their applications on a conceptual level. *Technology design or the development of new applications* cannot be achieved within the given boundaries.
- The implementation of training simulators can have *stakeholder-related benefits* such as increased motivation. *Stakeholder-related benefits* are described where applicable, but an intensive analysis of these factors is not within the scope of this research.

1.4   Structure of the dissertation

The structure of the dissertation follows the sub-goals described above and is structured into six chapters:

- The first chapter contains the motivation and a first introduction to the research problem and goals. It also describes the general structure of the dissertation.
- The second chapter is used to provide a more detailed description of the research problem. Important concepts of this dissertation are described to define the scope further.
- The third chapter summarises a state-of-the-art analysis of training simulators in manufacturing and their HMI design.
- The fourth chapter explains the development and structure of the methodology to analyse the potential use of training simulators in manufacturing tasks. The chapter also includes the definition of research hypotheses and concludes with a detailed description of the methodology.
- The fifth chapter covers the application of the framework in case studies and an evaluation of the results supported through expert interviews.
- The sixth chapter summarises and concludes the dissertation.

2   Problem statement and terminology

The second chapter includes a detailed description of the problem statement and the terminology that is used within the dissertation, as well as key for the following chapters.

2.1   Terminology and introduction of key concepts

The dissertation applies terminologies and concepts that have previously been interpreted in a broad range of fields. The wide distribution has led to various definitions that differ depending on the authors' perspectives. The following subsections are used to define the terminologies and concepts that were used throughout the presented research.

2.1.1   Manufacturing, manufacturing process, and tasks

Manufacturing is defined by DIN 8580:2003 as the production of workpieces of a geometrically defined shape. Manufacturing is performed by a manufacturing system, which consists of an arrangement and operation of machines, tools, material, people, and information (Cochran 1999, p.5).

This research follows the notion that although production and manufacturing both included in the creation of products, the terms can be distinguished. Manufacturing only involves converting raw materials into tangible workpieces, whereas production can also include intangible services such as maintenance (Hitomi 2017).

Manufacturing can be subdivided into *manufacturing processes*, which alter a given material's form, shape or physical properties (Chryssolouris et al. 2013, p.5). DIN 8580:2003 describes a structure that distinguishes between six main groups of manufacturing processes (primary shaping, forming, separating, joining, coating, and finishing, and change of material properties).

A manufacturing process is a sequence of pre-established operations intended to produce a specific part (Rodriguez & Souza 2010). A *task* is defined as a specific execution of a predefined operation (Vasil & Notick 2013). A specific execution of a manufacturing process can be described as a task, a sub-task, or a sequence thereof.

2.1.2 Human-Machine Interface (HMI) technologies

A *human-machine interface (HMI)* is defined as all the hardware and software mechanisms that exchange information and actions between a human user and a machine in an interactive system to accomplish a specific task (Iannessi et al. 2018, McRuer & Jex 1967). The schematic composition of the HMI is visualized in Figure 1.
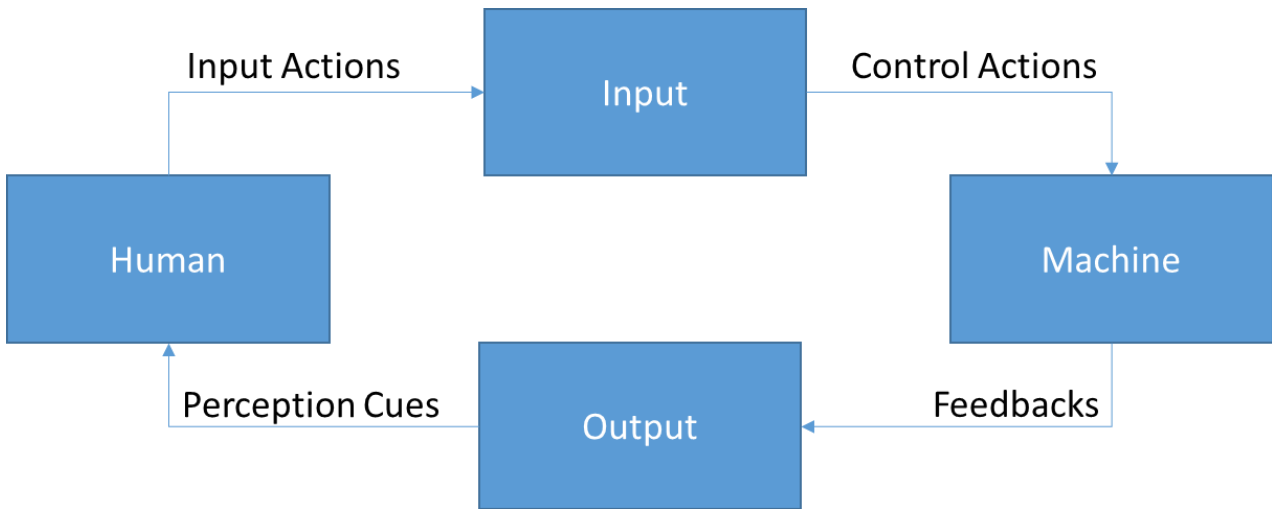
Figure 1: Schematic composition of the Human-Machine Interface (Valla et al. 2020, McRuer & Jex 1967, Johannsen 1993)

HMI technologies are all devices involved in the transfer and presentation of information and commands within a human-machine system and can be described as a specific form of information technology (cf. Björk 1999). HMI technologies can be classified by their direction, which is either input, output, or bidirectional. Another classification is related to the modalities of HMI technologies as described in the following subsection.

2.1.2.1 Modalities of HMI technologies

In training simulator design, perception cues are output signals that the trainee can interpret. The purpose of perception cues can either provide instructional support or help the trainee interpret the simulated reality (Paige & Morin 2013). Perception cues can be conveyed to the trainee through various modalities, as shown in Table 1 (Farmer et al. 1999).

The perception cues conveyed by the simulation are usually intended to resemble the perception cues given in the original system. A high convergence of these cues is defined as cueing realism and is a key factor for the functional fidelity (see subsection 2.1.6) and the learning effect of a training simulation (Farmer et al. 1999).

Table 1: Taxonomy of non-instrumental cues (Farmer et al. 1999).

Visual		Auditory	
Monocular	**Binocular**	**Monoaural**	**Binaural**
Accommodation (distance)	Stereo-vision	Loudness	Time differences
Known size (distance)	Interocular rivalry	Echoes	
Occlusion (distance ranking)		Spectral composition	
Linear perspective		Speech	
Texture			
Shading			
Shadows			
Aerial perspective			
Colour			
Optic flow/motion parallax			
Vestibular	**Tactile**	**Kinaesthetic/ somatosensory**	**Smell**
Sacculus utriculus	Skin pressure sensing	Joint position sensing	Olfactory signals
Semi-circular canals	Skin temperature sensing	Muscle extension and force sensing	
		Internal pressures	

For this research, the modalities are limited to the main categories. Vestibular cueing and smell cueing are discarded as they convey little process-related information in manufacturing applications. Tactile cueing and kinaesthetic/somatosensory cueing are merged into haptic cueing.

It is also possible to describe the modality of input actions. Although haptic interaction is highly bidirectional, haptic input devices are the prevalent input modality in simulator design (Perret et al. 2013). Haptic input devices include generic devices such as keyboards, controllers, or switches, but some simulators also use physical models or highly individual peripherals.

2.1.2.2 Virtual Reality

Virtual Reality (VR) can be defined as a human-machine interface (HMI) technology that conveys an immersive, interactive, computer-generated experience in which a person perceives a simulated environment in real-time (Mandal 2013).

Earlier definitions referred to VR as an immersive system that allowed the user to use natural head and hand movements to interact with the computer-generated environment (Jayaram et al. 1997, Hanwu & Yueming 2009).

Some newer definitions are less specific and describe systems that visualise three-dimensional objects on larger screens as VR systems (Beier 2000, Hanwu & Yueming 2009), classified as non-immersive VR (Rebbani et al. 2021). Immersive VR can be distinguished from traditional media by substituting the primary sensory input with data received produced by a computer (Bekele et al. 2018, Heim 1998). Thus, it removes the ability to interact with the real world (Rebbani et al. 2021).

2.1.2.3   Augmented Reality

Augmented Reality (AR) is a technology that enables augmentation of objects in the real world with virtual objects and information, is interactive in real-time, and visualises links between real and virtual objects in three dimensions (Azuma 1997, Chicchi Giglioli 2015). Thereby, AR enhances the view of a real-world environment with computer-generated and virtual information (Carmigniani et al. 2011). Common AR devices are head-mounted displays (HMDs), handheld displays, or projection displays (Azuma 1997).

2.1.3   Skills

Skill can be defined as the ability of an individual to apply knowledge to complete of tasks (Chryssolouris et al. 2013). Therein, skills require a composition of ability and knowledge. They can be distinguished by their relevance towards certain tasks and their composition of ability and knowledge.

A commonly used categorisation of skills distinguishes between three types of skills (Bloom 1956, Lateef 2010):

- *Psychomotor skills (Doing):* Technical and functional expertise training

- *Cognitive skills (Thinking):* Problem-solving and decision-making skills

- *Communication skills (Interacting):* Interpersonal skills or team-based competencies

These categories have been used and modified in various publications. For example, Chryssolouris et al. (2013) distinguish between perceptual-motor skills, procedural skills, cognitive skills, time-sharing skills, and team skills.

Although a task usually requires skills from multiple categories, it can focus on a certain category. For this research, it is important to distinguish between psychomotor and cognitive skills. The training of psychomotor skills is typically related to more demanding requirements regarding HMI technologies than cognitive skills training (Madhan Kumar et al. 2020, cf. Sbernini et al. 2018).

Interpersonal and communications skills are rarely trained with devices that can be characterised as training simulators. Some training approaches involve game-based learning to reduce inter-personal barriers and create an enjoyable atmosphere (Bodnar & Clark 2017). Many publications that describe methods for developing interpersonal skills stem from occupational sciences and are not within the scope of this research.

2.1.4   Training

Training is a planned activity aimed at modifying skills through the application of experience and education (Milhem et al. 2014). The main objective of training is to acquire, improve, or test skills (Gaba et al. 1998, Gupta et al. 2008, Lateef 2010).

Transfer of training is defined as applying skills on the job, which have been learned during training (Cheng & Ho 2001, Baldwin & Ford 1988, Xiao 1996).

2.1.5   Training simulators

Simulation is the experimental manipulation of a model to observe its dynamic behaviour (Krallmann et al. 2013). It is a technique to replace and amplify real experiences with guided ones in an interactive fashion (Lateef 2010).

A *training simulation* is a simulation that is intended for training (Yuviler-Gavish et al. 2013). Training that utilises training simulations can be defined as *simulation-based training* (Al-Elq 2010). Training simulators are implementations of simulation models that are used for training purposes. This implementation may consist of hardware and software components.

The HMI design with its applied HMI technologies is a formative characteristic of training simulators. Its relevance is reflected by multiple taxonomies of training simulators that are based on the HMI design (Maran & Glavin 2003, National Research Council 1996, Kneebone 2003). This research uses a taxonomy that is based on Kneebone (2003) and divides training simulators into:

- *Model-based simulators:* Physical models that simulate can be used in training, although models as inanimate objects provide no or only limited feedback.

- *Computer-based simulators:* Computer simulations that enable training by emulating a real system's input and output behaviour. Computer-based simulators can be further divided into desktop applications and Virtual Reality simulators. Virtual Reality has emerged as a technique to increase the immersion of computer-based simulations.

- *Hybrid simulators:* Hybrid simulators combine physical models and computer simulations. Hybrid simulators are usually applied to provide an enhanced haptic interaction while also conveying sensor-based feedback. Augmented Reality is commonly used to augment physical models with computer-based information and feedback.

Embedded training simulators are a specific form of hybrid simulators integrated into the real system and use its HMI, which is common practice in CNC machining (Wasfy et al. 2005).

Operator Training Systems (OTS) are another specific type of training simulator. An OTS is usually a computer-based or hybrid simulator that simulates the control system of an industrial plant (Patle et al. 2019).

2.1.6   Functional and physical fidelity

Since the emergence of simulation-based training, the performance of training simulations is expected to depend on their *fidelity*, the degree to which they resemble the original environment (Thorndike, E. L. & Woodworth 1901; Hays & Singer 1989).

Through the technology-enabled introduction of high-fidelity training simulations during the 1970s, it became apparent that the performance of simulation-based training does not directly scale with the fidelity of simulators. Instead, a multidimensional approach to fidelity is usually applied to describe the relationship between training performance and simulation fidelity. Since then, most studies have viewed *functional fidelity* and *physical fidelity* separately. *Physical fidelity* is defined as the degree to which a simulation represents the look and feel of the original equipment. *Functional fidelity* is defined as the degree to which stimulus and response options of the simulation represent those of the original equipment (Kinkade & Wheaton 1972, Miller 1974).

While *physical fidelity* depends on the simulations' resemblance to the original equipment, the *functional fidelity* of a training simulation can only be measured considering the specific performed task (Hamstra et al. 2014). A high level of *functional fidelity* requires interactivity of the simulated scenarios and functional alignment with the tasks that are to be trained. *Functional fidelity* has a significant

influence on the transfer of training and the general performance of simulation-based training (Maxwell 2016).

2.1.7 Applicability factors

Applicability factors have been used in related research to assess the applicability of certain methods or tools (cf. Arunachalam 2014, p. 42, Onori 2002).

Within this research, *applicability factors* are defined as task-related factors that impact the applicability of simulation-based training for manufacturing tasks. Applicability factors are characteristics that are inherited by training tasks, adverse for training, and may be avoided or reduced in simulation-based training (Knoke & Thoben 2021). These applicability factors are related to a potential benefit of the training task that may be achieved by implementing simulation-based training.

2.2 Problem statement and research hypotheses

The research is structured by research hypotheses used to detail the problem statement introduced in section 1.2. The research hypotheses are also used to structure the discussion in section 5.7.

A training simulator is defined within this research as applicable towards a specific task if its implementation is justified because of its benefits over conventional training. This definition implies that simulation-based training can have certain characteristics that may create a better training experience than training in the real system (see Lateef 2010). Accordingly, an applicability assessment of a training simulator requires the ability to identify its benefits and the effort required for its implementation.

For this research, the benefits of training simulators are further divided into potential benefits and achievable benefits. The potential benefit is defined as the benefit of the ideal training simulation compared to conventional training and is an inherent attribute of a specific task. An achievable benefit is the fraction of a potential benefit that can be achieved in practice. The achievable benefit can be limited by technical, financial, or organisational constraints.

The effort required to implement simulation-based training is usually determined as part of a cost-benefit analysis (Asche et al. 2018). The implementation effort is a highly variable and an individual characteristic of manufacturing systems and cannot be determined universally. Because the implementation effort and financial or organisational constraints are not a property inherited by a training simulator, the scope of this research is limited to assess the achievable benefit under consideration of the technical constraints.

The scope of this research and the addressed research gap is described further in the following research hypotheses.

H1: The potential benefit of training simulators varies between manufacturing tasks

This research is based on the hypothesis that multiple factors determine the potential benefit of a training simulator and that the composition of these factors depends on the simulated tasks. If this is true, then the potential benefit must also vary between manufacturing tasks.

Research on the factors that are relevant to the applicability of simulation-based training is scarce. Established methodologies for the design of training simulators typically stem from areas where training simulators have a strong historic background, and their feasibility is rarely questioned. Therefore, available research from these areas provides only a little information on the benefits of training simulators (see Farmer et al. 1999; Maran & Glavin 2003; National Research Council 1996; Hays & Singer 1989). The benefits described in these publications are used as a baseline to analyse task-related factors in section 4.2.

This hypothesis implies that the applicability of simulation-based training is not a binary attribute but a continuum that differs between tasks in manufacturing.

H1.1: The potential benefit of training simulators is related to characteristics of the original task that are adverse for training

The hypothesis that the potential benefit of training simulators varies between manufacturing tasks leads to the question of how this potential benefit can be assessed. Training can only be improved with simulations if training in the original system is not perfect. Accordingly, the original training must have certain adverse characteristics for the training experience to allow a training simulation to have a potential benefit compared to the original system.

This relation motivates the questions of how characteristics of an original manufacturing task that are adverse for training can be identified and how a training simulation must be designed to leverage the potential benefits.

The decision to focus on the "negative" characteristics was taken to direct the focus on the original task, facilitating the development of a task analysis methodology. Farmer et al. (1999) take a similar approach by describing practical reasons for simulation-based training via restrictive properties of the original system.

H2: The achievable benefit of training simulators for manufacturing correlates with the available potential of HMI technologies

The available potential of HMI technologies implicates the achievable benefit of training simulators for manufacturing tasks. HMI technologies are considered crucial for skill development because their selection determines the user interaction, which includes the information presented by the technical system (Chung et al. 2009). HMI technologies and the achievable benefit of training simulators can be linked through the concept of fidelity, which HMI technologies have a major impact on (see Yuen et al. 2013, Bouchner 2015).

The functional fidelity determines the possible training results, whereas the physical and psychological fidelity influence the technology acceptance of trainers and trainees (Alessi 2000, Hathaway & Cross 2016). The HMI design must also be considered a major driver of costs (Seth et al. 2011).

This hypothesis raises the question of how the implications of HMI technologies for the achievable benefits of training simulators can be described.

H3: A structured analysis can determine the implications of HMI technologies for the applicability of simulation-based training for specific manufacturing tasks

Knowledge of the available potential of HMI technologies and the relevant characteristics in a manufacturing task is required to determine the achievable benefits and their impact on the applicability of simulation-based training. This hypothesis serves as a placeholder for a structured evaluation of a task analysis methodology intended to deliver the required information.

H4: The task analysis methodology can be used to identify factors that cause training simulators to be not applicable

If the task analysis methodology can determine the implications of HMI technologies for the applicability of simulation-based training, it may also be used to identify the factors that hinder its implementation. An assessment of technology-based barriers would enable the task analysis methodology to identify demands or development potential for HMI technologies.

3 State-of-the-art on simulation-based training in manufacturing processes

The third chapter contains a systematic analysis of the state-of-the-art in training simulators for manufacturing. The analysis focuses on the applied HMI technologies.

3.1 Methodology

The classification of DIN 8580:2003 is applied 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 of manufacturing processes. The research is performed on the subgroup level and through the search engines of Google Scholar and Microsoft Academic. The terms "skills simulation", "simulator training", and "simulation-based training" are used on both platforms and in combination with the groups and subgroups, considering the first 50 results each. Processes that are not specific to manufacturing, such as "cutting" or "drawing", were supplemented with the term "manufacturing" to yield a higher ratio of relevant results.

The literature review includes publications that either describe the development or application of training simulators in manufacturing processes. In this context, *training simulators* are defined as implementations of simulation models used for training purposes (see subsection 2.1.5). This implementation may consist of hardware and software components.

Some applications are included that focus not on the execution of the task but its set-up. This focus can be found in some automated settings, such as CNC machining with predominantly automatic execution.

Publications are included multiple times within the tables if they describe multiple distinguishable training simulators or if the training simulators are intended for multiple process groups.

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, or physical properties of a given material (Chryssolouris 2013, p.5). With this definition, processes that produce intangible results and preceding or supporting tasks, such as product design and maintenance, are excluded from the study. The definition also excludes mining and excavation work as well as woodcutting. Although training simulators for these purposes have been developed (Odegard et al. 2013, Millheim 1986, Pickens et al. 1993), they are not used on workpieces of a geometrically defined shape.

The results include a brief description of the HMI design that is based on the published content:

- The description of the visual HMI includes abbreviations for Virtual Reality (VR), Augmented Reality (AR), Operator Training Simulator (OTS), and head-mounted display (HMD). An OTS describes a simulator that physically resembles one or multiple workstations and is typically used for plant operation training. The term "desktop application" is used for simulators that are software products and can be used in combination with arbitrary personal computers or tablet computers. The visual HMI is labelled as "unknown" if the visual interface design is not described within the publication or the description was not accessible during the research.
- The haptic HMI is categorised into:
  - *Generic peripheral devices.* The category of generic devices includes prevalent peripheral devices for computer systems. These devices are not always specified within the publications. The commonly used haptic input devices are mouse, keyboard, touch screens, and gamepads or joysticks. Haptic output devices in this category are limited to force feedback that is implemented in gamepads or joysticks.
  - *VR controllers:* Some implementations of Virtual Reality rely on handheld motion controllers that are located by the systems base stations to collect information about the motions of the trainee and typically also allow force feedback.
  - *Specialised peripheral devices:* Specialised peripheral devices are devices that are not commonly distributed. These devices have either been developed together with the application or are niche technology, such as wired gloves, 3D mouses, or light pens. Some training simulations use haptic input devices embedded into the real system or modelled to simulate the original equipment physically. The haptic interface of the simulator can also use the interface of the real system if it includes sensors that detect the input.
  - *Unknown:* Some training simulations use haptic input devices embedded into the real system or modelled to simulate the original equipment physically.

The results are presented in the following sections thematically within the structure of DIN 8580:2003 and chronologically, focusing on the HMI technologies.

3.2   Findings

The findings of the literature analysis are sorted by their manufacturing process and supplemented with an analysis of HMI technologies used in their design.

3.2.1   Training simulators for manufacturing processes

The findings resulted in 204 applications that were aggregated to the group level of DIN 8580:2003. The aggregation was performed because some simulators are applicable across multiple sub-groups, such as the simulators of machining centres. Assembly and disassembly training simulators are an exception. Twenty-one training simulators were described to be applicable for assembly and disassembly training. These simulators have been counted for both groups. Process groups with more than five publications are in descending order: assembly (53), cutting with geometrically defined edge (45), welding (34), disassembly (27), and coating from liquid state (18).

3.2.1.1   Primary shaping

Only a few training simulators have been identified the main group *primary shaping* (Table 2). The simulators can be split into two categories by their skill focus. Those that focus on psychomotor skills for manual casting processes are somewhat experimental and employ AR or VR technologies and haptic interfaces. Simulators that focus on procedural operator skills are mostly designed as desktop applications and OTS.

Table 2: Training Simulators in Primary Shaping Processes

Group	HMI design	Publication
1.1. Liquid initial material state	AR, specialized periphery	Watanuki & Hou (2010)
	VR, specialized periphery	Watanuki & Kojima (2007)
	AR, specialized periphery	Iwamoto, et al. (2014)
	Desktop application, generic periphery	Ravi (2014), Lee et al. (2013)
1.2. Primary shaping of fibre-reinforced plastic	VR, generic periphery	Shi et al. (2008), Zhou et al. (2009)
	VR, specialized periphery	Sun & Tsai (2012)
	Desktop application, generic periphery	Salazar (1994)
1.3. Pappy / mushy initial material state	VR, generic periphery, audio	Sacks et al. (2013)
1.8. Gas initial material state	Desktop application, generic periphery	Liu et al. (2008)
1.9. Prototypes from ionized state	Desktop application, specialized periphery	Tikasz et al. (1994)

3.2.1.2   Forming

Training simulators in the forming main group are limited to rolling and bending processes (Table 3). All simulators for the operation of rolling mills are designed as OTS to simulate sophisticated interface terminals. The bending simulations include a simulator for machine operators (Fernández et al. 2011) and a simulator for manual rebar bending within the construction industry (Menon et al. 2017a).

Table 3: Training Simulators in Forming Processes

Group	HMI design	Publication
2.1. Pressure Forming	Desktop application, specialized periphery	Li & Winitsky (1999), Bonavia (2016), Cockerell et al. (1993), Brickwedde et al. (2007)
	Unknown, unknown	Zhao et al. (2006)
2.4. Bending	Desktop application, generic periphery	Fernández et al. (2011)
	Desktop application, specialized periphery, audio	Menon et al. (2017a), Menon et al. (2017b)

3.2.1.3 Separating

The main group *separating* includes a larger number of simulators for machining centres and disassembly processes, as well as somewhat isolated applications for sawing, grinding, lapping, blasting, and electrochemical machining (Table 4). Most of the machining centre simulations include multiple processes, such as turning, drilling, and milling. Some disassembly simulators are also used in assembly.

Table 4: Training Simulators in Separating Processes

Group	HMI design	Publication
3.1. Separating	Desktop application, generic periphery	Higashi & Kanai (2016)
3.2. Cutting with geometrically defined cutting edges	Desktop application, generic periphery	Acal & Lobera (2007), Antonietti et al. (2001), Arshad et al. (2008), Arthaya et al. (2010), Batista, et al. (2009), Chang (2010), Chen (2012), Fang et al. (2011), García Plaza et al. (2011), Gilles et al. (2006), Hanwu & Yueming (2009), Hwang (1989), Koh et al. (2010), Li et al. (2005), Ong et al. (2002), Seo et al. (2000), Suh et al. (2003), Valvo et al. (2012), Valvo et al. (2012), Wasfy et al. (2005), Xiong & Liu (2011)
	Desktop application, generic periphery, audio	Yao et al. (2007)
	Desktop application, specialised periphery	Akshay et al. (2013), Crison et al. (2004), Crison et al. (2005), Hon (1996), Li et al. (2002), Li et al. (2011), Lin et al. (1996), Lin et al. (1999), Lin et al. (2002), Muthupalaniappan et al. (2014), Noguez & Huesca (2008)
	Desktop application, specialised periphery, audio	He & Chen (2006)
	Desktop application, unknown	Bi et al. (2009), Kalwasiński et al. (2010)
	Physical model, specialised periphery	Xudong & Lizhi (2016), Yamaguchi et al. (2013), Fu & Wang (2014)
	AR, specialised periphery	Monroy Reyes et al. (2016)

	VR, generic periphery	Boer et al. (1997)
	VR, VR controller	Fang et al. (1998)
	VR, specialised periphery	Hashimoto (2011), Jose et al. (2014), Jose et al. (2016), Liang et al. (2012)
3.3. Cutting with geometrically non-defined cutting edges	Desktop application, specialised periphery, audio	Balijepalli & Kesavadas (2003)
	Desktop application, specialised periphery	Li et al. (2017)
	VR on screen, specialised periphery, audio	Bolick et al. (2010)
3.4. Non-conventional machining	Desktop application, generic periphery	Kozak (2013)
3.5. Disassembly	Desktop application, generic periphery	Belloc et al. (2012), Chang et al. (2010), He & Wu (2008), Iacob & Popescu (2013), Li et al. (2003), Li et al. (2008), Wang et al. (2012)
	Desktop application, specialised periphery	Brough et al. (2007), Gutiérrez et al. (1998), Hassan & Yoon (2010), Iglesias et al. (2007), Jihong (2000), Murray & Fernando (2004), Ogasawara et al. (1998)
	AR, specialised periphery	Ferrise et al. (2013)
	VR, specialised periphery	Al-Ahmari et al. (2016), Abate et al. (2009), Corvaglia (2004), Ferrise et al. (2013), Gutierrez et al. (2010), Ishii et al. (1997), Wang & Yang (2011), Xia et al. (2012)
	VR, specialised periphery, audio	Sportillo et al. (2015)
	Unknown, unknown	He & Wu (2009), Ikonomov & Milkova (2004), Xie et al. (2019)

3.2.1.4   Joining

The main group *joining* includes various assembly and welding simulators and a single soldering application (Table 5). While the welding simulators have a strong focus on psychomotor skills and predominantly use AR or VR HMDs, 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 labelled as assembly simulators span across multiple groups and include screwing and clipping, which are part of the *press fitting* group. Twenty-one of these assembly simulators can also be used for disassembly training.

Table 5: Training Simulators in Joining Processes

Group	HMI design	Publication
4.1. Assembling / 4.3. Press Fitting	Desktop application, generic periphery	Belloc et al. (2012), Chang et al. (2010), Gupta et al. (2001), Kealy et al. (2006), Okumoto et al. (2009), Wang et al. (2012)
	Desktop application, specialised periphery	Abate et al. (2009), Brough et al. (2007), Ferrise et al. (2013), Ferrise et al. (2013), Gutiérrez et al. (1998), Hassan & Yoon (2010), Iglesias et al. (2007), Jihong (2000), Murray & Fernando (2004)
	AR, specialised periphery	Boud et al. (1999), Funk et al. (2017), Gavish et al. (2011), Hořejší (2015), Peniche et al. (2012), Wang et al. (2016), Webel et al. (2013), Webel (2011)
	AR, specialised periphery, audio	Westerfield et al. (2015)
	VR, generic periphery	Jiang et al. (2016), Müller et al. (2016), Sousa et al. (2008), Yao et al. (2006)
	VR, specialised periphery	Onda et al. (1997), Adams et al. (2001), Al-Ahmari et al. (2016), Boud et al. (1999), Carlson et al. (2015), Corvaglia (2004), Gallegos-Nieto et al. (2017), Gavish et al. (2011), Gutierrez et al. (2010), Hoedt et al. (2017),

		Jiang et al. (2016), Jiang et al. (2016), Sportillo et al. (2015), Wang & Yang (2011), Xia et al. (2012)
	VR, specialised periphery, audio	Bhatti et al. (2009), Jia et al. (2009)
	VR, unknown	Schenk et al. (2005)
	VR, VR controller	Langley et al. (2016), Ordaz et al. (2015), Peniche et al. (2012), Stork et al. (2012)
	Unknown, unknown	He & Wu (2009), Ikonomov & Milkova (2004), Lu et al. (2012)
4.6. Welding	Desktop application, specialised periphery	Kreindl & Glanseck (2014), Kreindl et al. (2008)
	Desktop application, specialised periphery, audio	Peters et al. (2016)
	Desktop application, VR controller	Wallace et al. (2016)
	Physical model, specialised periphery	Denison (1984), Matherne (1998)
	Physical model, specialised periphery, audio	Penrod et al. (2016), Schow (1979), Schow & Abrams (1975)
	AR, specialised periphery	Barrera et al. (2015), Kobayashi et al. (2001), Kobayashi et al. (2003)
	AR, specialised periphery, audio	Batzler et al. (2016), Okimoto et al. (2015)
	VR, specialised periphery	Albrecht (2015), Chambers et al. (2012), Fast et al. (2004), Fast et al. (2012), Jo et al. (2011), Peters et al. (2011), Wang et al. (2006a), Wang et al. (2009), Yang et al. (2010)
	VR, specialised periphery, audio	Becker (2016), Becker & Pfeifer (2017), Byrd et al. (2015), Choquet (2008), McLaurin & Stone (2012), Stone et al. (2013), Stone et al. (2011), White et al. (2011), Zboray et al. (2014)
	VR, VR controller	Ordaz et al. (2015)
	Unknown, unknown	Wu (1992)
4.7. Soldering	Desktop application, specialised periphery, audio	James et al. (2019)

3.2.1.5   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 categorised as a labelling process (Table 6).

Table 6: Training Simulators in Coating and Finishing Processes

Group	HMI design	Publication
5.1. Coating from liquid state	Desktop application, generic periphery	Yin et al. (2005)
	Desktop application, specialised periphery	Bayart et al. (2005), DiVerdi & Song (2014), Fujimoto et al. (2017), Lin et al. (2004), Matsumoto et al. (2016), Shilkrot et al. (2015), Vandoren et al. (2008), Wang et al. (2006b)
	VR, specialised periphery	Ebensberger et al. (2008), Konieczny et al. (2008a), Konieczny et al. (2008b), Kruse (2009), Valmiki & Rajamani (2013)
	VR, specialised periphery, audio	Lee et al. (2010), Yang et al. (2007), Zboray et al. (2013)
	VR, VR controller	Kim et al. (2007)

3.2.1.6   Change of material properties

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

3.2.2 Application of HMI technologies

The research showed a wide range of HMI technologies that were applied in the identified training simulators. Although one publication argued the possible benefit of olfactory feedback (Lee et al. 2010), all simulators were limited to haptic, visual, and auditory interfaces. The literature analysis has not identified a kinaesthetic interface or a motion system that moves the trainee and seems unnecessary for any manufacturing training simulator.

The most notable differences between competing simulators lie within their design of visual and haptic interfaces. While the visual interface has a stronger impact on the physical fidelity of the training simulation, the haptic interface usually influences its functional fidelity. The identified simulators show a broad range of interfaces.

3.2.2.1 Visual interfaces in manufacturing training simulators

The visual interface of training simulators is usually used to convey the output of the simulation to the user. It can therefore have a major influence on the perceived physical fidelity of the training simulation.

The application of HMI technologies can be categorised into physical models, desktop applications, Augmented Reality applications, and Virtual Reality applications. The distribution of these technologies does change over time (Figure 2). While computer technology was in its infancy, physical models were the only way to implement simulation-based training in manufacturing. The rising availability of computing power led to an increased share of desktop applications supplemented by Virtual Reality and Augmented Reality interfaces once the maturity of the respective technologies increased.

The chronological distribution shows a drop in 2018 that can likely be attributed to the time it takes for a publication to be uploaded, indexed, and included in the top search results of the search engines.

NUMBER OF IMPLEMENTATIONS IN TRAINING SIMULATORS OVER TIME
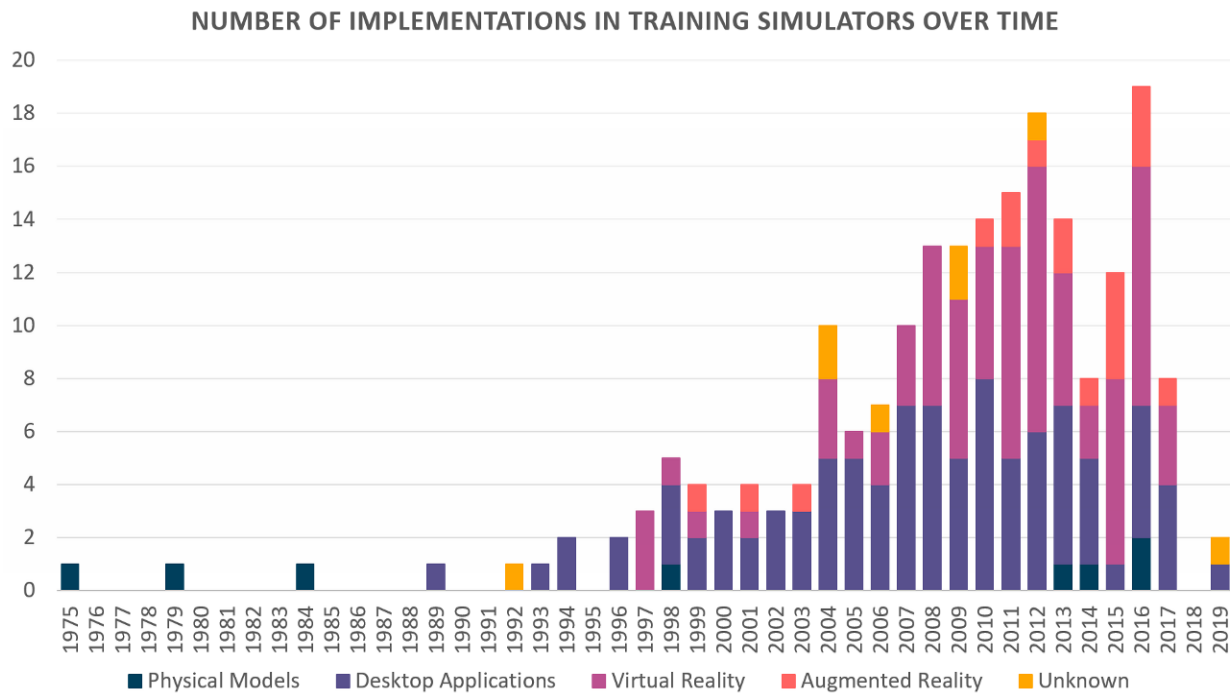
Figure 2: Application of HMI technologies for visual output in manufacturing training simulators over time

The effort put into the design of simulators can differ significantly, even within the same category. Simulators that rely on Virtual Reality range from commercial Virtual Reality headsets to complex systems, such as a Virtual Reality cybersphere (Xia et al. 2012).

Some training simulators also implement a visual HMI technology as an input device. This input mechanism is usually complementary to a Virtual Reality headset and realised through motion tracking of the trainee with an optical scanning system and subsequent image processing (Ordaz et al. 2015, Ferrise et al. 2013, Gutierrez et al. 2010, Sportillo et al. 2015).

3.2.2.2 Haptic interfaces in manufacturing training simulators

Haptic interfaces are used to simulate the haptic input and output behaviour of the original systems and, therefore, have a major impact on the immersion and the perceived functional fidelity of a training simulator (Samur et al. 2007). They are also the most efficient method of training psycho-motoric skills (Morris et al. 2007, Chandran et al. 2018).

Haptic interfaces are usually categorised by their interaction technique or the sensory cue that they can emit (Samur et al. 2007). However, for this research, a more technologic-centric approach is favoured. The identified manufacturing training simulators' haptic input or output devices are categorised into generic peripheral devices, VR controllers, specialised peripheral devices, and unknown devices.

NUMBER OF IMPLEMENTATIONS IN TRAINING SIMULATORS OVER TIME
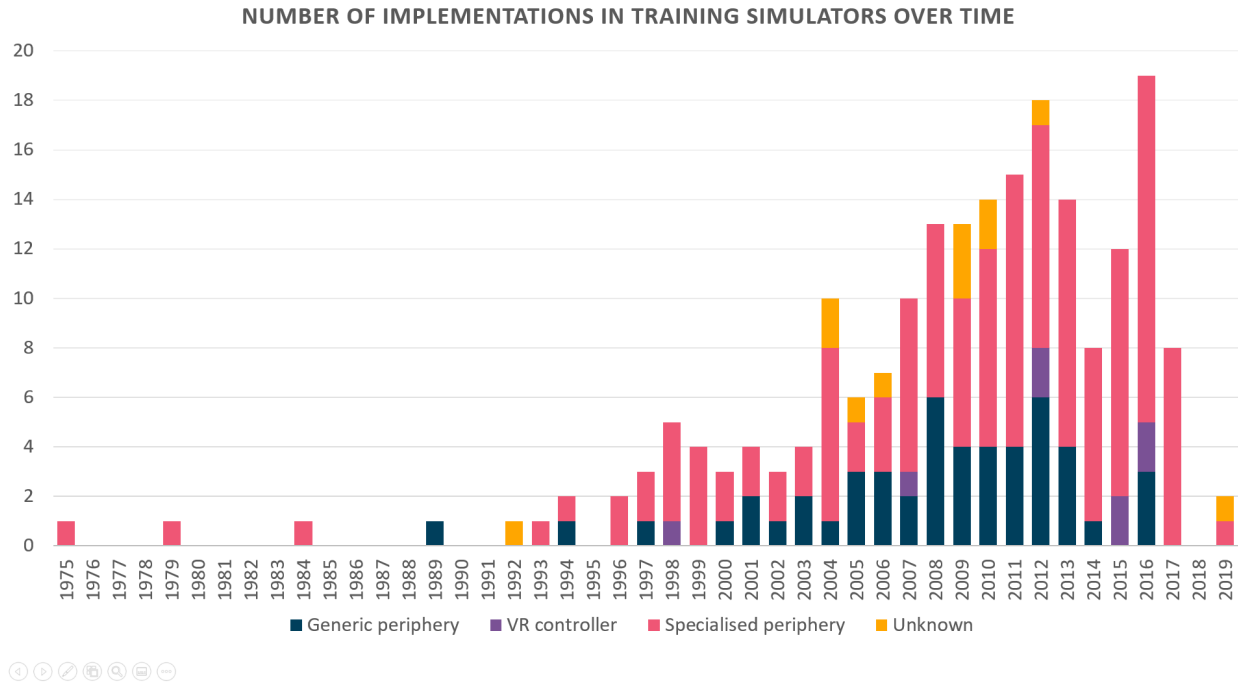
Figure 3: Application of haptic HMI technologies in manufacturing training simulators over time

The distribution of haptic interfaces over time (Figure 3) shows that the integration of specialised periphery has been an ongoing part of training simulators in manufacturing. It implies a focus on psycho-motoric skills that justifies an integration of costly technologies. However, it appears that the availability and maturity of visual HMI devices have a stronger influence on the feasibility of a training simulator. Nevertheless, the haptic interface design has a strong impact on the simulator's costs and scalability. Simulators that rely solely on generic devices can be easily distributed to a wider audience (Ravi 2014). Implementations that require specialised peripheral devices such as physical models are usually more costly to develop or obtain. Many simulators are realised with individual haptic interfaces, often required for a sufficient functional fidelity and a major driver of costs that hinder a wider implementation into industrial practice beyond the laboratory stage (Xia 2012).

3.2.2.3   Auditory interfaces in manufacturing training simulators

The auditory interfaces of the identified manufacturing training simulators are solely used as output devices. Although communication with a teacher or simulator operator could be classified as a bidirectional auditory interface, the system boundary within this research is limited to the technical system. The auditory interface appears to be of less importance to the simulation. Only 40 of the identified applications stated the use of auditory feedback. The interface is usually implemented with a speaker system, while some applications were designed to be used with headphones.

4 Development of the task analysis methodology

The literature analysis that has been described in chapter 3 shows that most publications are limited to a small number of groups. The 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 prominence of these groups is certainly a strong factor for the implementation of simulation-based training, but it is likely not the only indicator. Else, training simulators for groups such as tension compression forming or press fitting would have been identifiable.

The literature analysis has confirmed that training simulators can achieve a benefit in vocational training for manufacturing. However, the identified applications address a relatively small selection of similar manufacturing tasks.

This chapter develops a task analysis methodology to assess the achievable benefit of simulation-based training in manufacturing. The development starts with the definition of functional requirements.

4.1 Functional requirements towards the task analysis methodology

The development starts with an analysis of functional requirements towards the task analysis methodology. Requirements can be categorised into functional and non-functional requirements. Functional requirements state the actions to be performed by the methodology, while non-functional requirements state how the actions are performed (Veena et al. 2020).

The analysis of functional requirements is performed to ensure that the task analysis methodology inherits the functionalities required to fulfil its purpose.

The task analysis methodology aims to evaluate the research hypotheses, which are described in section 2.2. This purpose leads to the complex functional requirement that the task analysis methodology shall assess the implications of HMI technologies for the applicability of simulation-based training in manufacturing tasks. Following the research hypotheses, the complex functional requirement can be further disaggregated into the following functional requirements. The syntax of these functional requirements is based on Hull et al. (2005).

R1: The task analysis methodology shall be applicable to manufacturing tasks with psycho-motoric and cognitive skill focus

The task analysis methodology must apply to an array of different manufacturing tasks to evaluate the research hypothesis H1 and enable an analysis of different manufacturing tasks. The literature analysis showed that the HMI design of training simulators strongly depends on their skill focus. Regarding the focus of this research and the categorisation of skills established in section 2.1.2, the task analysis methodology must apply to training simulators with psycho-motoric skill focus and training simulators focusing on cognitive skills.

R2: The task analysis methodology shall include individual task characteristics in the analysis

The research hypothesis H1.2 requires the task analysis methodology to include characteristics that differ between tasks. These task characteristics are inherent to the original tasks and adverse for training.

Some of the publications that have been identified in the literature analysis describe the benefits and limitations of training simulators for individual manufacturing tasks. These benefits and limitations can derive a pool of individual task characteristics, which can be included in the task analysis methodology.

R3: The task analysis methodology shall include an HMI design outline in the analysis

Research hypothesis H2 requires the task analysis methodology to allow statements regarding the implications of HMI technologies on training simulators for manufacturing tasks. The implications of HMI technologies are related to their potential because of their impact on the functional fidelity of training simulators (see subsection 2.1.6). Therefore, the task analysis methodology must include the available potential of HMI technologies in its assessment.

A complete specification of training simulators is not within the scope of the task analysis methodology. However, HMI design outlines are a crucial element for an evaluation of the research hypothesis. Therefore, the definition of an HMI design outline must be supported by the task analysis methodology.

R4: The task analysis methodology shall have a structural framework

The task analysis methodology is intended to provide a framework that allows for a structured analysis of the implications of HMI technologies for the applicability of

training simulators for manufacturing tasks. The purpose of the structure is to improve the usability and consistency of the task analysis methodology (cf. Hernandez-Matias et al. 2006).

R5: The task analysis methodology shall enable the identification of all relevant factors regarding the benefits of simulation-based training for manufacturing tasks

For research hypothesis H4, the output of the task analysis methodology must include all relevant factors that determine whether simulation-based training is beneficial to the analysed training tasks. In combination with information on the hindering technology-based factors (R3), potential benefits that cannot be achieved due to technical limitations may enable identification of demands or development potential for HMI technologies, adding benefit to the task analysis methodology.

4.2 Scope of the task analysis methodology

A quantified assessment of the applicability of simulation-based training for manufacturing tasks would require a cost-benefit analysis (cf. Asche et al. 2018). Quantification of costs and benefits such as improved adaptability would require a detailed analysis and may only be expressed as an estimated number or may only be determined during application. A quantified comparison of costs and benefits before implementing simulation-based training would be either incomplete or impractical due to the impact of intangible factors. The costs of simulation-based training are a highly individual figure that provides no basis for transferable findings.

Therefore, the scope of the task analysis methodology is limited to provide a structured approach to identify the relevant task-related factors that impact the applicability of simulation-based training for manufacturing tasks. These factors are further referred to as applicability factors (see subsection 2.1.7). If research hypothesis H1 is confirmed, these applicability factors impact the potential benefit of simulation-based training that differs greatly between tasks and manufacturing systems. Against this background, the task analysis methodology will support the identification of applicability factors for manufacturing tasks and, in combination with an HMI outline, allow a qualitative assessment of the potential benefit, which can be the basis for subsequent cost-benefit analysis (cf. Moor & Andrews 1992, p. 351-354, Boardman et al. 2017).

Decision support systems developed to introduce innovative technologies also emphasise the importance of qualitative factors (Keen 1981, Şen et al. 2009). It is suggested that the required investments are often less important compared to the actual usage of new technology (Devaraj & Kohli 2003), which is influenced by

the technology acceptance of its users and the perceived usefulness (Chin & Lin 2016, p. 640).

The proposed methodology provides a structure for a task analysis. In its purpose, the developed task analysis methodology is similar to a feasibility study, which is generally performed to assess if a concept can be shaped to be relevant and sustainable for a specific task (Bowen et al. 2009, p. 453). In the context of this research, the task analysis methodology aims to support the decision to determine which benefits are achievable with a training simulator given the available potential of HMI technologies.

4.3   Methodology structure

Requirement R4 requires the task analysis methodology to have a structural framework to improve its usability and consistency. An individual structural framework is developed because a task analysis methodology that fits the requirements does not exist in literature. The intended task analysis methodology is similar to a feasibility study. Feasibility studies usually aim to determine if it is possible to develop a concept for a specific task, how much it would cost if it can be operated, if it would be accepted among its stakeholders, and if there is evidence of performance (cf. Weller et al. 2015, Harris et al. 2013). Feasibility studies are usually focused on specific applications.

The methodology structure is based on the approach to Training Media Selection by Farmer et al. (1999) and the holistic feasibility study framework by Khoong & Ku (1994). It consists of the following steps:

- Identification of task-related applicability factors.
- Definition of HMI design requirements for each applicability factor and consolidation of the requirements into an HMI design outline. The HMI design outline should meet as many requirements as possible and aim to achieve:
  - Sufficient levels of functional, physical, and psychological fidelity.
  - The training objectives of the original training task.
- Consolidation of achievable benefits and HMI design outline

The structure of the task analysis methodology can be applied to manufacturing tasks. The steps of this methodology are described in the following subsections. A summary of the task analysis methodology is provided at the end of the chapter (subchapter 4.7).

4.4 Identification of factors that impact the applicability of training simulators

The next step towards the methodology development is collecting factors that impact the applicability of simulation-based training to manufacturing tasks. Because no holistic source could be identified, these applicability factors are aggregated by comparing literature from other areas with the applicability factors described in the publications identified in the literature review (chapter 3.2).

4.4.1 Related work on applicability factors from other areas

In this subsection, related work from other areas is analysed regarding the description of applicability factors.

4.4.1.1 Applicability factors for military training simulators

Farmer et al. (1999) published research that stems from the military research project "Military Applications of Simulator and Training concepts based on Empirical Research" (MASTER). They distinguish between practical and didactic reasons for simulation-based training. The practical reasons for simulation-based training are (Farmer et al. 1999, p. 61):

- Training in the real systems is too dangerous,
- There is insufficient time available in the real system,
- The circumstances required for training do not occur frequently enough,
- The possibilities for training are restricted by environmental regulations related to noise, pollution, or other causes.
- Safety regulations preclude the execution of tasks or manoeuvres.

The didactic reasons are described as (Farmer et al. 1999, p.62):

- Control of the type and timing of training events presented and, hence, the learning experiences offered to the trainee(s). This control enables the provision of more learning experiences per unit of time and the planned distribution of learning experiences,
- Adapting the training task to the performance of the trainee(s),
- Providing augmented cueing and feedback, i. e., cues and feedback extrinsic to the (training) task,
- Registering and diagnosing trainee performance, e. g., for debriefing or administrative purposes,
- Automating the process of training and instruction and consequently improving efficiency.

The authors also describe negative factors that hinder simulation-based training (Farmer et al. 1999, p. 61-62). These factors are:

- The achievable fidelity of a training simulator is limited. This limitation can negatively impact:
    o The acceptance as a training device by trainees and instructors,
    o The transfer of skills from simulation-based training to the real system is hindered.
- The costs of training simulators can be very substantial and may exceed the costs of the real system. These costs include:
    o Procurement costs of training simulators,
    o Costs of operating and maintaining training simulators.

Similar statements have been made by Carey & Rossler (2020) and Hays & Singer (1989, p. 18), who stress that the physical and functional fidelity of a simulator determines its potential for effective learning.

A comparison of the described practical and didactic reasons shows a heterogenous frame of reference. The practical reasons are based on training flaws in the real system, while the didactic reasons are described as improvements enabled by simulation-based training.

4.4.1.2   Benefits of medical training simulators

Simulation-based training in the medical area has been developed as an alternative to the traditional apprenticeship training (Maran & Glavin 2003). Therefore, training simulators are compared to on-the-job training, in which medical apprentices learn their profession by assisting medical professionals in real medical procedures. Against this background, Maran & Glavin (2003) Issenberg et al. (2005), and Bradley (2006) list benefits of simulation-based training:

- Providing feedback
- Allowing repetitive practice
- Integrating within curriculum
- Providing a range of difficulties
- Being adaptable; allowing multiple learning strategies
- Providing a range of clinical scenarios
- Providing a safe, educationally supportive learning environment
- Active learning based on individualised needs
- Defined outcomes
- Simulator validity as a realistic recreation of complex clinical situations

The authors do not list any negative factors regarding the implementation of simulation-based training. Albeit Maran & Glavin (2003) stress the importance of simulator fidelity, especially when the training focuses on complex skills.

4.4.1.3   Benefits of simulation-based training in marine training

The National Research Council (1996, p.52-53) published insights on simulation-based training in mariner training. The design of training simulators in this area ranges from software applications to simulation models or OTS that resemble the bridges of large marine vessels. The motivation for the use of simulation-based training is described as:

- Increased safety
- Lesson repetition
- Recording and playback
- Flexibility
- Multiple tasks and prioritisation
- Training on new technologies
- Peer interactions
- Cost-effectiveness

The initial costs are described as a major downside of training simulators. If low-cost simulations on desktop computers are used, the training quality is reduced because available cues and interactions between trainees are limited (National Research Council 1996, p.55).

4.4.1.4   General rationale for the use of training devices

In a book that investigates the role of fidelity in training system design, Hays & Singer (1989, p. 16-17) describe the rationale for using training devices in general. They distinguish between hardware centred issues and instructionally based issues. The hardware centred issues are (Hays & Singer (1989, p. 16):

- Training devices allow the practice of dangerous situations without risks,
- Costs can be reduced by avoiding the use of consumables during practice,
- It can be more reasonable to employ a dedicated training device than to interrupt the use of a complex system, such as a commercial plane or a nuclear power plant.

The instructionally based issues are factors that concern the quality or efficiency of training (Hays & Singer 1989, p. 17):

- Performance measurement enables the trainer to provide accurate feedback and individualised instructions,
- Instructional flexibility is gained through possible variations in difficulty,
- The risk-free environment enables a trial-and-error approach,
- The training process is not bound to a specific sequence,
- It is possible to replace some of the instructor's functions with a training device.

The authors argue that training devices may not be efficient or effective if the physical and functional fidelity do not meet the requirements for effective learning (Hays & Singer 1989, p. 18).

4.4.2 Development of a categorisation for applicability factors

The identified sources for collecting applicability factors on simulation-based training stem from different fields and individual perspectives. The applicability factors are described in heterogeneous formats:

- Farmer et al. (1999) base the description of practical reasons on restrictive properties of the original system, whereas the description of didactic reasons is based on the achieved benefits. The factors from the medical area that are aggregated by Maran & Glavin (2003), Issenberg et al. (2005), and Bradley (2006) contain practical and didactic benefits that are conveyed through the implementation of simulation-based training.
- The National Research Council (1996) describes the motivation for simulation-based training by listing positive factors.
- Hays & Singer (1989) describe hardware centred issues and instructionally based issues that create the rationale for using training devices in general.

Although the identified sources stem from different fields and individual perspectives, the heterogeneous formats of the identified applicability factors implicate a lack of a standardised structure. Literature does not provide a fitting categorisation, because as stated in the problem description (subsection 2.2), the applicability of training simulators is rarely questioned in established training simulator design frameworks.

The heterogeneity of the identified applicability factors can be compensated by assigning the applicability factors to training characteristics in the real system that are averse to training and may be removed or reduced by implementing simulation-based training.

A structure has been developed by combining a condensed description of the practical reasons for simulation-based training by Farmer et al. (1999) with a structure

for process quality factors that have been developed by Reinertsen (2009) and Rubin (2012), and a structure used by King et al. (2017) to describe general benefits of technology-based learning. This structure is intended to act as a framework for the identification of applicability factors (R4):

- *Training risks:* Possible hazards during training in the real system may cause risks to the trainee, the environment, or a potential loss of resources.
- *Training costs:* Training in the real system requires resources, creating costs that may be avoided or reduced in a training simulation.
- *Training availability:* The available training time in the real system is limited by the availability of training conditions. A training simulation could enable more time-efficient training.
- *Training transparency:* The trainee could benefit from additional or more direct feedback during training in the real system.
- *Training adaptability:* Training in the real system cannot be adapted to fit the training needs optimally due to rigid structures and task requirements.

An allocation of the identified applicability factors to the defined categories can be found in the annexe in Table 44. The next subsection contains a review of applicability factors described in the publications identified during the literature review (chapter 3) using the defined structure.

4.4.3 Task-related applicability factors for manufacturing applications

This subsection discusses the applicability factors of training simulators for manufacturing tasks that were reviewed in chapter 3. Several publications describe factors that have an impact on the applicability of simulation-based training. The applicability factors of each category are reviewed in the following subsections.

The applicability factors that have been aggregated from multiple areas were grouped into five categories. The publications on manufacturing did not present a factor that could not fit into any of these categories, although the descriptions of some factors overlap multiple categories.

4.4.3.1 Training risks

Simulation-based training has an increased benefit if training in the real system inherits risks that may result in loss of health or equipment. The obvious benefit of simulation-based training lies in removing or reducing the existing hazards through virtualisation or abstraction. The authors described avoidance of injuries (Sun & Tsai 2012), avoidance of damage to equipment (Iwamoto et al. 2014, Cockerell et al. 1993, Li et al. 2002, Hon 1996), avoidance of damaging interference with other parts of the system (Brickwedde et al. 2007, Shi et al. 2008), or general avoidance

of risks and increased safety (Gilles et al. 2006, Li et al. 2005, Wasfy et al. 2005, Crison et al. 2005) as benefits of training simulators.

If risks are part of the original system, training may require personal protective equipment. This requirement can be a barrier based on the process-related hazards and has an impact on the training adaptability and the barriers that stakeholders perceive. With the removal of risks, it becomes possible to apply a trial-and-error approach or perform the training in certain settings, such as classrooms, and create additional opportunities for simulators (Tikasz et al. 1994, Fang et al. 1998).

Simulation-based training can also switch from an error-free approach to a learning strategy that allows trial-and-error. If hazards can be simulated without risk and with a sufficient level of functional fidelity, they can benefit the learning effect (Sacks et al. 2013). An experience without risks can provide trainees with a general idea of a machine (Antonietti et al. 2001).

4.4.3.2 Training costs

Simulation-based training can be used to decrease training costs (Shi et al. 2008, Gilles et al. 2006, Fang et al. 1998, Batista et al. 2009, Li et al. 2005, Wasfy et al. 2005, Sun & Tsai 2012). The potential savings through simulation-based training rise with the training costs within the original system. These costs are usually caused by consumables and equipment and the required presence of experts (Menon et al. 2017b). Moreover, machines may not be able to create marketable products while they are used for training. Simulation-based training can reduce training costs by saving production time on the original machine and preventing costly breakdowns (Hon 1996).

The costs also scale with the time that is dedicated to training. Thereby, processes involving a large workforce or lengthy supportive tasks provide an increased opportunity for simulation-based training (e. g., assembly, disassembly).

4.4.3.3 Training availability

The time dedicated to effective training in a certain time frame can be increased through simulation-based training (Lee et al. 2013). An improvement is possible if training in the real system is interrupted due to supporting tasks, such as set-up and post-processing (e. g. welding, spray painting), or if the training focus is on the set-up phase and the training cycles are prolonged by the actual processing (e. g. machining, additive manufacturing). Tasks that do not contribute to relevant skills training may be fast-forwarded or skipped in a training simulation.

Simulation-based training is not necessarily depending on the availability of machines, tools, or auxiliary processes. Instead, a simulator can be designed to be usable independent from the availability of other resources, which is usually a benefit compared to training in the original system (Sun & Tsai 2012). It can also enable training before starting a new production cycle and create an opportunity for training without trial production (Li et al. 2005).

4.4.3.4 Training transparency

The ability to receive objective feedback while performing the training benefits simulation-based training that is not given in some manufacturing processes (e. g. welding). The sensors integrated into training simulators can provide objective feedback and enable self-evaluation (Fang et al. 1998). The increased measurability also provides standardisation and quality control opportunities within the training progress (Hon 1996).

It is particularly relevant for processes whose results greatly depend on operator skill (Iwamoto et al. 2014). With a dependency on skills, the importance of well-qualified employees rises, especially if automation of the process is difficult (Iwamoto et al. 2014).

4.4.3.5 Training adaptability

The ability to adapt the training design to specific needs can significantly benefit simulation-based training compared to training in the original system (Fang et al. 1998). The authors of the identified publications expressed the desire to adapt the training design in numerous ways hindered in the real system.

Simulation-based training can be used to encourage and support autonomous learning (Fang et al. 2011). The digital media used in most simulators can be used to convey information on the learning progress. Thereby, the training can be designed to have prolonged autonomous learning sessions or require less guidance from trainers.

The training difficulty can be customisable towards individual learning preferences or prior knowledge (Fang et al. 2011). This customisation is usually achieved by providing more detailed feedback or a less strict performance evaluation for beginners and a more realistic challenge for advanced users (Liu et al. 2008). Simulation-based training can also be used to reduce the complexity of a process (Fernández et al. 2011). A simulation allows the trainer to focus on specific elements and their relations in a complex system or augment the simulation with additional information, such as machine theories or process-related knowledge (Fang et al. 1998).

Training group size is another parameter that can be easier to change with a simulated environment. Training in the real system is often performed by individuals or in small groups. While this is also possible with simulation-based training, the simulation can also enable training in classroom settings (Fang et al. 2011). Larger group sizes become possible through the use of digital media. The scalability of a training exercise can be increased beyond a classroom setting if the simulation is only dependent on software that can be duplicated on many desktops (Gilles et al. 2006) or if it can be accessed through a web-based application (Wasfy et al. 2005, Hon 1996).

4.4.4 Methods for the identification of applicability factors

The intended methodology aims to provide a structured approach towards the analysis of manufacturing tasks concerning the potential benefit of simulation-based training. The methodology is structured around the applicability factors that have been identified within the previous subsections. The factors are sorted into five categories:

- Training risks
- Training costs
- Training availability
- Training transparency
- Training adaptability

The proposed methodology uses a rating system for the significance (S) of the applicability factors. The values are: S=0 (insignificant), S=1 (low significance), and S=2 (high significance). The rating is intended to support the prioritisation of the derived HMI design requirements in case of conflicts.

The categories and their assessment methodologies for training tasks in manufacturing are described in the following subsections.

4.4.4.1 Analysis of training risks

If a training task inherits risks, it can be an incentive to transfer the training from the real system to a training simulation. However, the benefit of a reduced training risk can only be achieved if risks can be identified and mitigated by implementing simulation-based training. The assessment of the achievable benefit requires a risk analysis.

Only risks that are related to the training task should be considered relevant. Risks that stem from external hazards such as earthquakes are not related to the training task and cannot be mitigated with a training simulation.

A trainer, who is familiar with the manufacturing process, can usually identify the relevant risks attached to the training task. Nevertheless, a methodological approach can provide a defined structure to convey and externalise the knowledge. According to the training task, the risk assessment methodology should be chosen (cf. Crawley & Tyler 2015). If the training is performed in an extraordinarily complex manufacturing system, a detailed approach such as the hazards and operability study (HAZOP, see annexe 8.4) may be necessary. For more common training tasks, a condensed approach is usually sufficient. The condensed approach is based on steps 3-7 of the HAZOP methodology (cf. Crawley & Tyler 2015):

- Analyse the sub-tasks of the training task.
- Analyse each sub-task regarding possible deviations that may have negative consequences and impose a risk.
- If safeguards mitigate risks, analyse if a failure of these safeguards is possible.
- Assess the significance of each identified risk.

The risk assessment is based on the assumption that the training only causes harm if its execution deviates from the norm.

4.4.4.2 Analysis of training costs

The task-related costs relevant to the analysis can potentially be eliminated by transitioning from on-the-job training to simulation-based training. A widely used taxonomy distinguishes between three categories (Bhimani et al. 1999, p. 49):

- *Direct material costs* are linked to an individual product and related to materials, which will become part of the product.
- *Direct manufacturing labour costs* can be linked to an individual product and include the compensation of all manufacturing labour related to the product.
- *Indirect manufacturing costs* are all manufacturing costs that occur during the manufacturing of a product but cannot be causally linked to an individual product in an economically feasible way. Examples include power, supplies, waste disposal costs, and indirect materials.

Direct material costs are often avoided in simulation-based training. These savings are achieved by simulating the manufacturing process in a virtual environment and reducing or removing the physical transformation of input materials and consumables.

Although unsupervised training is usually not recommended, direct manufacturing labour costs may be reduced by simulation-based training if the original training

requires extensive mentoring. The training simulator can be designed to provide additional guidance and reduce the workload of the training personnel. This reduction is often realised through the use of digital media.

Indirect manufacturing costs can be categorised into variable overhead and fixed overhead (Bhimani et al. 1999). The variable overhead scales with production quantity and can usually be reduced through the introduction of simulation-based training. Nevertheless, indirect manufacturing costs are often fixed and difficult to influence through the implementation of simulation-based training.

During subsequent cost-benefit analysis, it should be considered that trainees trained on the job can also add value through their contribution to the creation of products. If simulation-based training removes their added value, it should also be reflected in a cost analysis. The gross training costs of German metalworkers for their companies in 2012 were estimated at €16.171 per trainee (Schönfeld et al. 2016, p.91) against generated returns of €9.185 this resulted in net costs of €6.986 per year (Schönfeld et al. 2016, p.91). However, these costs have no impact on the potential benefit of simulation-based training and differ significantly between manufacturing processes or companies. They should therefore be evaluated individually.

4.4.4.3 Analysis of training availability

As it is defined in section 2.1.4, training is always focused on the training of specific skills. When the necessary resources or conditions for training these skills are limited in the real system, simulation-based training can be beneficial. A task analysis should compare the training time to time spent waiting or on activities that provide no training experience towards the targeted skills to determine this factor.

Farmer et al. (1999) stated that it may not always be possible to train the desired skills when the training depends on specific circumstances that do not frequently occur in the real system. In manufacturing, setup time is a typical example of an auxiliary activity that increases the duration of a training cycle without providing a substantial training experience (Mitchel 1998, Badiru 2005). The setup time includes the entire time from stopping the manufacturing of one product until the manufacturing of the next product. It is the time required to change the manufacturing conditions, including stopping the present job and preparing the conditions for the start of the next job. (Shirahama 2001, p. 594).

The training objective in manufacturing is to enable a trainee to perform a certain manufacturing task. Although this ability may encompass sub-tasks performed during the setup time and during the run time, the training is usually focused on actions of the trainee that impact the manufacturing results. Three relevant cases can be determined for a training task:

- *Focus on setup time and run time:* Skills required during setup and run-time are critical for the result and require training.
- *Focus on setup time:* The setup time requires critical skills for the result and require training, such as the programming of a machine. The run time does not require skills relevant to the result and is spent waiting or on auxiliary actions.
- *Focus on run time:* The run time requires critical skills for the process result and require training such as the use of a tool. The setup time does not require skills that are relevant to the result.

A theoretical trivial fourth case can be constructed with a process that does not require any critical skills. However, in such a case, there is also no need for focussed training.

If the training focuses on either setup time or run time, the training cycle may be shortened with simulation-based training. Simulating a virtual workpiece makes it possible to skip or fast-forward time that does not train the desired skills.

Determining the training focus can help to identify whether a sub-task is relevant for training or not. Then, the significance of the time spent on activities without relevance to the training can be assessed.

4.4.4.4   Analysis of training transparency

A manufacturing process can be interpreted as the transformation of a product from one state to another (Wuest 2015). The transformation is based on deterministic causation/causalities (Pearl 2003) and deviates from the desired state to a certain degree, characterising the performance. Against this background, *training transparency* can be defined as the degree of difficulty to identify deviations from the desired product state caused by the trainee's actions in a training process.

If the process transparency is low, it is difficult to identify deviations from the desired state, and an average trainee cannot interpret the impact of mistakes on the performance. Because effective training requires feedback about trainee performance (Stacy et al. 2006), a trainee may require external feedback to identify the causalities that determine the performance. The transparency of a training task can also be at a level where it is difficult for a trainer to identify a trainee's performance.

Other causes for transparency factors can include situations that hinder the trainer from conveying the feedback. These situations can appear if the performance measurement is delayed because it requires testing procedures or the trainee performs the training task at a different location.

Training simulators are commonly designed with sensors. Sensors can add a benefit if the original training task has low transparency. Sensors are applied in training simulators to determine the trainee performance, which can then be conveyed as feedback through HMI technology to the trainee and trainer.

A transparency analysis of a training task can be performed by analysing the mistakes made by the trainee for each sub-task. The significance of these transparency factors can be assessed based on the impact of possible mistakes and the difficulty for the trainee to notice them. The analysis of these mistakes can be performed in conjunction with the risk analysis but should focus on the difficulty to determine the causalities of deviations.

4.4.4.5 Analysis of training adaptability

The training adaptability describes the ability of the trainer to change the characteristics of the training task according to individual needs or situational needs. The desire to implement changes to a training task can be based on various reasons, such as increasing the trainee's motivation, meeting certain training objectives, or accounting for external influences.

The objective to be cost-efficient or deliver a certain product and level of quality typically constrains the adaptability of training within a real manufacturing system. Because training in a simulated environment is not bound to the same restrictions as training in the original system, it is usually easier to change and can provide a potential benefit. Therefore, the adaptability factors of a training task can be determined by analysing the ability to change its characteristics to fit the training needs better.

The training experience can be changed in various ways. The identified applicability factors are used as a basis to structure the analysis of the adaptability of a training process:

- *The training requires non-portable objects:* Manufacturing is usually performed at defined locations and determines a certain time and space available for training. These requirements are mostly related to the use of heavy machinery or dependence on infrastructure. Approaches, such as mobile learning, build upon the benefits that can be gained by removing time and space barriers (Prieto et al. 2014). In addition to increased flexibility, mobile learning is considered an approach to increase trainees' motivation (Rodrigo 2011). Although a mobile design of training simulators is not always practicable, it is not necessarily hindered by environmental or safety regulations, which might impact the use of real manufacturing equipment at different locations. Mobile training simulators can also create an interactive

teaching unit at a vocational school, which might not have the funds to acquire the original equipment or create a portable and interactive experience for advertising purposes.

- *Personal protective equipment (PPE) is mandatory:* The training cannot be performed without PPE, limiting the adaptability of the training to other settings, such as classrooms or job fairs. It also raises the entry barriers.

- *The trial-and-error approach is impracticable:* A major benefit of simulation-based training is the ability to learn about the system behaviour through a trial-and-error approach. Although this factor is related to the risks or costs of the manufacturing process, some adjustments of process parameters are prohibited by rigid safety features and are not possible to perform in a real manufacturing system.

- *Autonomous training is restricted or impractical:* Autonomous training usually requires automation of instructions and feedback, which is often difficult to realise during training in the real system. Training simulators can be used to facilitate autonomous learning, which can be a benefit.

- *Difficulty cannot be adjusted:* The ability to change the difficulty level of a training process can significantly impact the perceived progress and increase the trainee's motivation (Kane et al. 2011).

- *Complexity cannot be reduced for training:* Similar to the difficulty level, it may be beneficial to reduce the complexity of the training task to improve the learning experience. A reduction of the complexity can be difficult to realise in the real system.

- *Additional information cannot be conveyed on site:* Augmenting the training task with additional information on the manufacturing process can improve the learning outcome. A training simulator that includes digital media can facilitate conveying additional information. The training simulation can include products manufactured in the future or train events, such as task-related emergencies that are not part of training in the real system.

- *Group size cannot be adjusted:* The Training group size can be usually changed easier in a training simulation than in the real system. Training in the real system often depends on access to workstations or tools. While this can apply to simulation-based training, the simulation may enable training in classroom settings (cf. Fang et al. 2011). Larger group sizes become possible through the use of digital media. The scalability of a training exercise can be increased beyond a classroom setting if the simulation only depends on the software that can be duplicated on many desktops (Gilles et al. 2006) or can be accessed through a web-based application (Wasfy et al. 2005, Hon 1996).

- *Blended learning cannot be implemented:* Blended Learning combines a wide variety of media integrated into conventional face-to-face activities (Mayadas & Picciano 2007). For the context of this research, implementation of Blended Learning implies the ability to perform task-related training

via digital media. Some training simulators enable the training of manufacturing tasks via web-based applications (Wasfy et al. 2005, Hon 1996).

After the applicability, factors have been identified, and their significance has been assessed, the HMI implementation can be outlined.

4.5 Outline of the HMI design

The assessment of applicability factors led to a list of undesired characteristics of the original training task. The next step of the methodology is to outline how each applicability factor can be resolved and how it relates to HMI design requirements. If an implementation of simulation-based training could resolve every applicability factor on the list, the complete potential benefit would also be achievable.

4.5.1 Definition of HMI design requirements

For a benefit to be achievable, the HMI implementation must provide sufficient levels of functional, physical, and psychological fidelity. Also, the training objectives of the original training process must be accomplishable. The proposed methodology in this step is to define HMI requirements based on the applicability factors and assess if any training objectives depend on the implementation. The HMI requirements are intended to facilitate the definition of an HMI design outline and serve as a link between the HMI design and the applicability factors. This link is required to assess the achievable benefit in the following steps.

Table 7: Exemplary definition of an HMI design requirement

Applicability factor	S	Related training objective	HMI design requirement
Drying time cannot be skipped.	2	The trainee is aware that the paint needs to dry before a new layer can be painted.	The training simulation shall include a time-skipping function for the drying time and provide feedback if ignored.

If a painting task requires the trainee to wait for the paint to dry, the waiting time can be identified as an applicability factor from the availability category. The waiting time limits the time available for training because the waiting time extends the training cycle without adding training experience. The waiting time is connected to the training objective that the trainee knows that the paint needs to dry before a new layer can be painted. The potential benefit could be achieved in the HMI design by implementing and visualising a time-skipping function and appropriate

feedback if the drying time is ignored. The proposed structure is shown in Table 7 using the example. The table matches the applicability factor, its significance S, the related training objective, and the derived HMI design requirement.

4.5.2 Consolidation of the HMI design outline

The proposed approach is to consolidate the identified HMI design requirements by combining similar requirements and removing inconsistencies. The outline describes via which HMI technology a training simulator could be implemented. If HMI requirements on the list contradict each other, a selection must be made.

The purpose of the HMI design outline is to provide a basis for analysing technological risk and assessing the achievable benefit. The HMI design outline should include a definition of the training simulator type (see subsection 2.1.5: model-based, computer-based, or hybrid simulator) and the key HMI technologies to achieve its purpose.

4.6 Analysis of technological risk and assessment of the achievable benefit

The final step of the task analysis methodology is to assess the achievable benefit. This assessment is based on the consolidated HMI outline and analysis of the technological risk.

4.6.1 Analysis of technological risk

In addition to the identified tangible and intangible factors, some applications of simulation-based training 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, computing performance is rarely a limiting factor for training simulators. Instead, content creation for virtual environments has become a significant limitation to the design of training simulations (Büttner et al. 2017, Zhang 2017, Liagkou et al. 2019, Scott et al. 2020). However, budget constraints still limit the effort that can be spent on the simulation model and the budget available for HMI technologies, which negatively impacts the functional fidelity of the training simulator.

The methodology is developed under the premise that it is always possible to develop a training simulator with low functional fidelity for any manufacturing process. The challenge is to analyse to what degree the functional fidelity depends on HMI technologies, which features are relevant to achieve, and if a training simulator has a chance to provide a benefit and be accepted among trainers and trainees.

A systematic analysis of the benefits of high fidelity for simulation-based training has been performed by Issenberg et al. (2005), who analysed 109 studies on medical training simulators. The authors identified features that have been developed for medical training but can be transferred to manufacturing processes. Some of the features are overlapping, but they allow systematic identification of technological challenges.

- *Feedback quality:* Feedback is critical for effective learning. However, the learned skills influence the demands towards HMI technologies, the quality of feedback, and their impact on the functional fidelity of the simulator. The feedback quality depends on the HMI design due to the following factors:
  - *Embodiment:* The embodiment of an HMI technology is determined by the distance between a tangible input device and the output of a reaction (Fishkin 2004). The embodiment of an HMI is a concept that has been developed for haptic interfaces and therefore is of higher relevance for training simulators that focus on psycho-motoric skills. It is beneficial for acquiring such skills if physical manipulation is perceived at the same location, as it would appear in the real system.
  - *Metaphor quality:* The metaphor of an HMI technology is the degree to which the simulated effect of a user action is analogous to the real-world effect of similar actions (Fishkin 2004). The applied metaphor's quality determines the effort required to transfer knowledge gained within the simulator to the real system. However, the design of good metaphors requires an effort that must be spent on the simulation model and the HMI design. This concept also focuses on the interaction with haptic interfaces and has a strong impact on the acquisition of psycho-motoric skills. It determines not only the functional feedback but also has an influence on the physical fidelity of a simulator and thus the technology acceptance among trainers and trainees.
  - *Time of feedback:* Feedback can be provided by the simulator, given by an instructor during the training sessions, or provided after the session by viewing a recording of the performance or interpreting a summary (Issenberg et al. 2005). Providing feedback in real-time creates a certain technological challenge for the simulator design. For tasks with procedural or cognitive focus, post hoc feedback may be enough, but simulators that aim to convey psycho-motoric skills strongly profit from direct feedback to allow the trainee to correct the handling or posture during the training.

The quality factors for feedback are most relevant for the acquisition of psycho-motoric skills. Haptic feedback that results in a good functional fidelity can require a significant effort to achieve (Kaluschke et al. 2018) and may be beyond the technical capabilities within a constrained budget. Instead, AR or VR technologies can be used to visually convey the feedback from haptic input in real-time and so that it

is easy to interpret and perceive at the correct location. However, these technologies are not without flaws, as some users avoid AR or VR technologies because of potential simulator sickness or related issues (Sun & Tsai 2012).

- *Curriculum integration:* A quarter of the studies analysed by Issenberg et al. (2005) stated that integrating simulation-based training in the standard curriculum is essential for the effective use of simulators. These findings are certainly transferable to manufacturing. The technology acceptance among trainers and trainees is higher if training simulators are not perceived as an experiment but as a permanent addition to the curriculum.

If a training simulator is intended as a lasting addition to the curriculum, it creates an additional challenge towards the HMI technology design. The simulators and their HMI technologies require a matured design and high resiliency for permanent integration.

- *Range of difficulty level:* The ability to exercise with variable difficulty settings can provide a benefit to simulation-based training. It allows adjusting to a trainee increasing skill levels and helps to prevent frustration or boredom. A range in difficulty can be provided through several measures, such as:
  - Allowing a selection from multiple tasks with varying difficulty.
  - Adjusting the evaluation strictness according to the desired difficulty level.
  - Providing support through aides that can be provided or reduced to create a variation in difficulty. These aides can be:
    - given by a trainer through intensive mentoring,
    - integrated into the simulator as cues such as visual references.

An increased effort towards the simulation model is required to select among multiple tasks or select the strictness of an automated evaluation. If integration of reference cues is intended, it has also to be considered during the HMI design.

- Multiple learning strategies: The training adaptability of a simulator is increased if it can be used in different settings, such as individual learning, small groups, and classroom settings.

The adaptability towards multiple learning strategies may require the HMI design to allow for the exchangeability of technologies. A small screen or a VR headset might be a feasible solution for individual learning or small groups, but a video projector might be a better choice for a classroom setting.

Another challenge that is related to training adaptability is to create a mobile training simulator. A possible benefit of simulation-based training is the opportunity to

provide a risk-free experience at job fairs or in schools. If the simulator is used in these settings, bulky HMI technologies such as a cybersphere should be avoided.

- *Task variation:* Training on customised products in specific processes or manufacturing systems can be desirable to increase immersion, identify with the product, or decrease the required transfer of learned skills. The customisation of a training simulation can be a significant challenge towards the simulation model and HMI design if training simulators are developed for a specific scenario or are bought off the shelf, the customisation results in additional costs, which should be considered during the decision making (Sacks et al. 2013).

The required effort depends on the HMI design. Exchange of products can be less difficult if the products or a simulated environment are solely virtual, and the models can be swapped by replacing their CAD data. A customisation results in additional costs if physical representations of the products exist or a process is to be modified beyond the initial simulation model design possibilities.

The costs are avoided if the products are no defined input of the simulation. The customisation of products can be part of the manufacturing process if the process has only bar stock as input material.

- *Simulation of hazards:* The functional fidelity of a training simulator is determined by its response to correct inputs and mistakes, similar to the original system. For each identified hazard of the training task, it should be considered how it is implemented into the simulation:
  - *Hazard continuance:* The hazard cannot be avoided and transfers from training in the original system to the training simulation. Erroneous input by the trainee may cause damages or physical harm.
  - *Hazard removal:* The hazard is removed or significantly reduced in the training simulation. Erroneous input by the trainee does not cause damages or physical harm.
  - *Hazard metaphor:* The hazard is removed or significantly reduced in the training simulation, but it is modelled within the simulation. Erroneous input by the trainee leads to the simulation of damages or physical harm.

Compared to errorless learning, training through a trial-and-error method is considered to allow for an easier transfer into practice (Jones et al. 2010) and achieves better results in perceptual-motor skills (Prather 1971). Trial-and-error learning in a controlled environment becomes possible through metaphorical hazards that are present in the original system. A hazard metaphor requires integrating feedback cues that are a metaphor of the damages or physical harm that would be the original system response to erroneous input.

A continuance of hazards should be avoided whenever possible. However, the benefit gained through a hazard metaphor has to be waged against the required effort for its implementation. The integration of feedback clues and the more detailed error detection and system behaviour is an additional challenge to the sensors of the simulator and the underlying simulation model.

- *Autonomous learning:* Training simulators can be used to automate instructions and feedback, which can reduce the workload of trainers (Hays & Singer 1989, p. 17). If the trainees can operate the simulator by themselves, they may engage in lengthened autonomous learning sessions. Autonomous learning requires an intuitive HMI design so that the instructions for the simulator use and the setup of exercises do not require too much training time. The HMI also needs to convey instructions and feedback that the trainees can interpret without a trainer. If an incorrect use of a training simulation is not prevented, independent learning can lead to misconceptions (Antonietti et al. 2001).
- *Use as a benchmark:* The ability to provide reproducible, standardised educational experiences are a feature of high-fidelity training simulators (Issenberg 2005). This ability is required if a training simulator is intended to benchmark the skills of a trainee. The validity of any tests made with a training simulator is limited by the required transfer of learning and the simulator's functional and physical fidelity.

Issenberg et al. (2005) also describe repetitive practice as a basic learning feature of high-fidelity medical simulations. However, this is less transferable to manufacturing. Training simulators in manufacturing should always allow for an easy reset and repeat of exercises. A reset can be more difficult in medical simulations when tissue is cut, biological organisms are involved, or the simulation includes interaction with patients.

The HMI design outline and the physical, functional, and psychological fidelity requirements enable an estimation of the technological risk. The risk analysis can be based on an analysis of the state-of-the-art in training simulators. For example, if similar applications have already been developed, the technological risk would be relatively low.

4.6.2   Assessment of the achievable benefit

The final step of the task analysis methodology is the assessment of the achievable benefit. This assessment is intended as a qualified estimation and input for a cost-benefit analysis regarding simulation-based training for manufacturing tasks. It is based on the rated applicability factors, the consolidated HMI outline, and an analysis of the technological risk. It should be checked for each applicability factor

with at least a low significance (S>0) if the HMI design outline, given the identified technological risk, can achieve the potential benefit. Possible outcomes are that a benefit from a specific applicability factor can or cannot be achieved, may be partly achieved, or that significant effort may be required to extend upon the current state-of-the-art.

In practice, this task analysis would be followed by a cost-benefit analysis. However, the calculation of costs is not in the scope of this research.

4.7   Summary of the task analysis methodology

The structure of the task analysis methodology can be further divided into a series of steps (Figure 4).
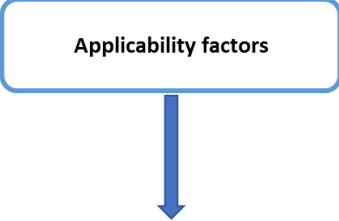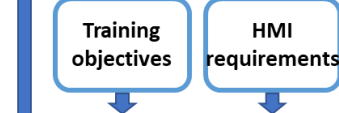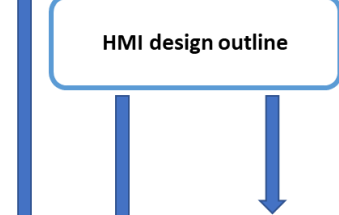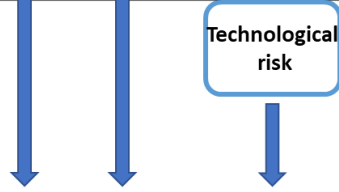
Step	Coverage	Results and dependencies	Additional Information
1. Identify task-related applicability factors	For each category	Applicability factors	Categories are: ▪ Training risks ▪ Training costs ▪ Training availability ▪ Training transparency ▪ Training adaptability
2. Assess significance (S)	For each applicability factor	Rated applicability factors	Significance levels are: ▪ 0: insignificant ▪ 1: low ▪ 2: high
3. Identify training objectives and HMI requirements	For each applicability factor with S>0	Training objectives / HMI requirements	▪ Group similar HMI requirements
4. Define HMI design outline	Aim to use each HMI design requirement	HMI design outline	▪ Prioritise HMI requirements that are based on applicability factors with S=2 ▪ Keep Training objectives
5. Assess technological risk	For the HMI design and each applied HMI technology	Technological risk	▪ Compare HMI design outline with state-of-the-art ▪ Check for similar applications
6. Assess achievable benefit	For each applicability factor with S>0	Achievable benefit	Achievement levels are: ▪ Yes ▪ Partly ▪ Research required ▪ No

Figure 4: Visualisation of the task analysis methodology

The *first step* is to identify the applicability factors that may have significance for the analysed training task. This analysis should consider the previously described categories and applicability factors:

- Training risks:
    o Each risk to health, resources, or the environment can be listed separately as an applicability factor.
- Training costs:
    o Each cost factor caused by tools, machines, consumables, or services necessary for the training task can be listed separately as an applicability factor,
    o Cost factor: Presence of a trainer,
    o Cost factor: Production downtime,
    o Cost factor: Indirect manufacturing costs.
- Training availability:
    o Each time that is not spent on training, but required in the original task, can be listed separately as an applicability factor,
    o Availability of resources.
- Training transparency:
    o Each mistake made by the trainee and might be difficult to recognise can be listed separately as an applicability factor,
    o Training is difficult to observe by the trainer,
    o Feedback is delayed.
- Training adaptability:
    o The training requires non-portable objects,
    o Personal protective equipment (PPE) is required,
    o Trial-and-error approach is impracticable,
    o Autonomous training is restricted or impractical,
    o Difficulty cannot be adjusted,
    o Process complexity is high and cannot be reduced for training,
    o Additional information cannot be conveyed on site,
    o Group size cannot be adjusted,
    o Blended Learning cannot be implemented.

The *second step* of the task analysis methodology is to assess the significance (S) for each identified applicability factor that applies to the training task. The proposed rating system for the significance uses the possible values of $S=0$ (insignificant), $S=1$ (low significance), and $S=2$ (high significance). The rated applicability factors indicate the potential benefit of simulation-based training for a specific training task.

The *third step* is to derive training objectives and HMI requirements from each applicability factor with at least a low significance ($S>0$). The training objectives to be identified in this step are desired training outcomes and related to these applicability factors. The purpose of defining the training objectives is to facilitate the creation of a training simulation that retains as many training objectives of the original system as possible. When translating applicability factors into HMI requirements, it is recommended to group similar HMI requirements together.

The *fourth step* focuses on the definition of the HMI design outline, which should provide a general idea of the training simulator and the applied HMI technologies. The HMI design outline is based on the training objectives and HMI requirements. If some HMI requirements are conflicting, those related to applicability factors with a higher significance should be prioritised.

The *fifth step* is to assess the technological risk of the outlined HMI design. This assessment should consider similarities between the HMI design outline and existing solutions and check if the HMI design outline could be realised given the available state-of-the-art and capabilities.

The *sixth step* is the assessment of the achievable benefit. It should be checked for each applicability factor with at least a low significance (S>0) if the HMI design outline, given the identified technological risk, can achieve the potential benefit. Possible outcomes are that a benefit from a specific applicability factor can or cannot be achieved, could be partly achieved, or that significant effort may be required to extend upon the current state-of-the-art.

5 Application and evaluation of the task analysis methodology

This chapter evaluates the task analysis methodology by applying it to four use cases and interviews with industry experts.

5.1 Selection of use cases

The purpose of the task analysis methodology is to evaluate the research hypotheses. To apply to requirement R1 and evaluate research hypothesis H1, the use cases must cover tasks with psycho-motoric and cognitive focus.

For research hypothesis H4 and requirement R5, the use cases should include applications where simulation-based training is already implemented and use cases where it is not.
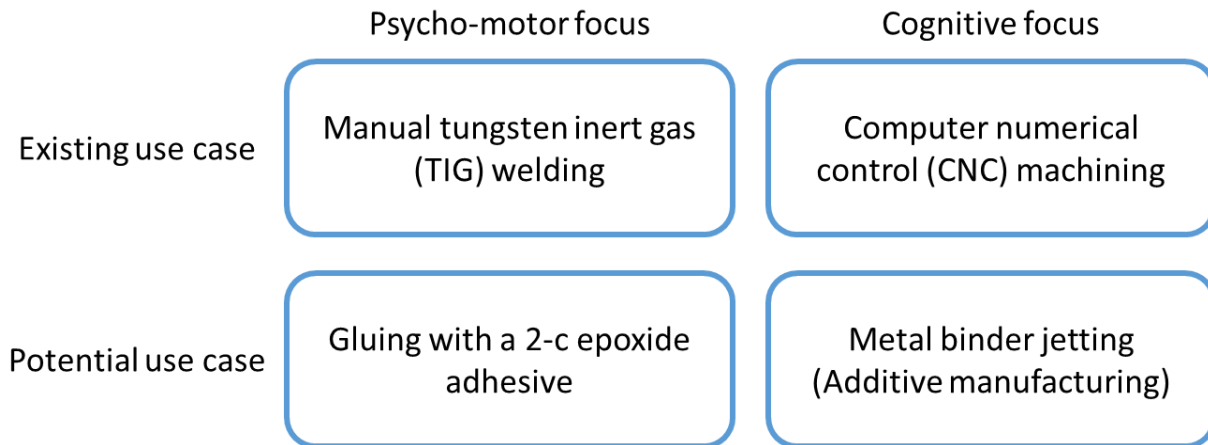
Figure 5: Use case selection overview

Four use cases are selected to meet the requirements. Two use cases with already existing simulation-based training are selected (existing use cases), and two without (potential use cases). Each pair consists of a task with a psycho-motoric focus and one task focusing on cognitive skills. The use case selection criteria are depicted in Figure 5.

5.2   Modelling approach and interview structure

The objective of the interviews is to identify and validate the characteristics of the training in the original system that impact the applicability of training simulators. These characteristics are defined as applicability factors.

The analysed manufacturing tasks are modelled in collaboration with interviewees. The interviews were performed to gain access to knowledge regarding the tasks and training procedures for the selected use cases. Therefore, the interviewees were required to be industry experts that conduct training in these tasks.

Each interviewee describes a training task used to create a task model and perform an initial analysis of the applicability factors. The analysis produces tables that contain an initial set of applicability factors. Guided interviews follow this initial analysis to expand, validate, and assess the significance of these applicability factors.

The interviews are conducted in the form of a guided interview. This approach has been chosen because it allows a focused but open validation of the initial task modelling and because it provides an approach that can be structured along with the available framework while also maintaining a high level of flexibility (Helfferich 2011).

A downside of guided interviews is the limitation of the guiding structure on possible answers (Helfferich 2011, Friebertshäuser & Langer 2010). The impact of

this limitation is reduced by using open questions and introducing the developed structure in the following steps. With this approach, the interviews are intended to leave as much open space for answers as possible (cf. Schmidt 2018, Helfferich 2011) while also providing a logical structure applied to all use cases.

In advance of the interviews, each interviewee has provided information on the analysed training task. This information has been used to create a task model consisting of a brief task description, a list of sub-steps, and the applied tools, machines, infrastructure, and consumables. The first step of the task analysis methodology has been applied to identify applicability factors for each task model. The interviews consist of a combination of deductive and inductive steps (cf. Witzel & Reiter 2012) intended to validate the task model, to expand the identified applicability factors, and to assess their significance for the second step of the task analysis methodology:

1. *Validation of the task model:* The interviews start with deductive and individual questions intended to clarify uncertainties of the task model and to check if the task model is correct.
2. *Open question on benefits of simulation-based training:* In this inductive step, the interviewees are asked the open question of how training simulators are providing (existing use case) or may provide (potential use case) benefits to the training task. Any applicability factors described but not identified in the initial analysis are collected and added to the table of a category, if possible.
3. *Focussed question on benefits of simulation-based training:* The initial question of how training simulators provide (existing use case) or may provide (potential use case) benefits to the training task is repeated for each category of applicability factors. Any applicability factors that were not identified in the initial analysis are added to the table of their respective categories.
4. *Assessment of the significance for each applicability factor:* The tables of applicability factors prepared in advance of the interviews and extended in steps 2-3 are then presented to the interviewees. In this deductive step, the interviewees are asked to assess the significance of each applicability factor's impact on the training quality. The rating is performed on a numeric rating scale with the possible values of 0 (insignificant), 1 (low significance), and 2 (high significance).

The interview outputs are validated and rated sets of applicability factors that can be used to analyse the achievable benefit for each task.

The first discussed use case is a training task for welding. Multiple training simulators for welding have been identified in the literature review (see subsection 3.2.1.4). The interviewee of this existing use case has already implemented simulation-based training.

5.3 Use case I – Manual tungsten inert gas (TIG) welding

The interview on the welding case has been conducted with two welding trainers working in technical vocational training in the automotive industry. Their company already applies simulation-based training in vocational welding training. The applied training simulator is the Soldamatic® welding training system.

The analysed task focuses on the manual tungsten inert gas (TIG) welding of a fillet weld between two aluminium plates (Figure 6). The training has a strong psycho-motoric skill focus because it requires coordinating a welding gun and filler material to create the weld.
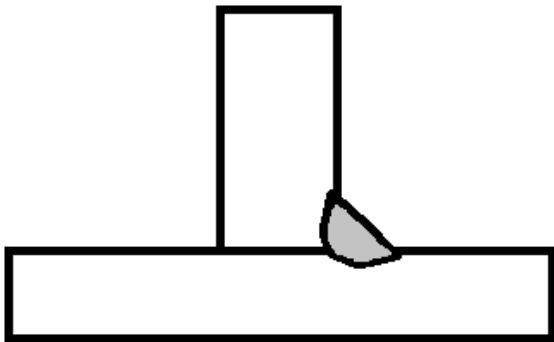
Figure 6: Schematic visualisation of a fillet weld

The interview started with individual questions that were intended to clarify uncertainties in the task analysis. The following statements were made:

- The training uses aluminium plates with varying thicknesses. Plates with a thickness of 1mm are very common.
- The plates are fixed in position with screw clamps and tack welds.
- A typical training task uses aluminium plates that are used multiple times. The aluminium plates can be reused up to four times.
- The wolfram electrode must be sharpened at the start of the welding training, and it may also be necessary to resharpen it during training.
- The training simulator is used for welding training and to benchmark the welding skills of new employees.
- Through cooperation with the simulator supplier, it is possible to digitalise individual products and use them in welding training.

The training task spans multiple sub-tasks from the tacking of the metal plates until they are separated again. The training requires PPE, which consists of welding gloves, a welding helmet, an apron, gaiters, and safety glasses for the cutting and grinding sub-tasks. The welding sub-tasks are performed in separated welding booths. The sub-tasks consist of:

- Sharpening of the wolfram electrode at an electrode grinding machine, if necessary.
- Activating and configuring the welding system for the task. The configurable parameters include voltage, current, and gas flow (argon).
- Tacking and fixation of the metal plates to fixate their position.
- Welding the fillet weld while repeating the following steps:
  - Welding while monitoring the most important parameters:
    - Position and orientation of the filler material,
    - Position and orientation of the welding torch,
    - Welding speed,
    - Filler metal feed.
  - Resharpening of the wolfram electrode at a bench grinder, if necessary.
  - Reconfiguring the welding system for the task, if necessary. The configurable parameters include voltage, current, and gas flow (argon).
- Deactivation of the welding system.
- Cooling the workpiece in water.
- Discussing the fillet weld with the trainer.
- Separating the metal plates with a press after multiple workpieces have been accumulated. The trainee does not perform this step.
- Cleaning the metal plates by grinding

The training task uses multiple tools and consumables that are listed in Table 8.

Table 8: Tools and consumables of the analysed welding task

Tools, machines, and infrastructure	Consumables
Welding booth with ventilation system and furniture	PPE equipment (welding gloves, a welding helmet, an apron, gaiters, and safety glasses)
Ventilation system	Wolfram electrode
Screw clamps	Metal plates
Electrode grinding machine	Protective gas (argon)
Welding system	Filler material
Press	Electricity

The interview continued with the identification of applicability factors.

5.3.1 Identification of applicability factors

A list of applicability factors was compiled in advance of the interviews by applying the first step of the task analysis to the task model. The resulting list is shown for each category in tables 9 to 13. The significance ratings were filled during step four of the interview. No new applicability factors were identified in steps two and three of the interviews.

The interviewees were asked why simulation-based training was integrated into the welding training and which benefits were gained. The following reasons were given:

- Welding training uses workpieces made from aluminium or costly alloys that are not required in simulation-based training.
- Real welding training requires preparation work that can be skipped in the simulation-based training, making it faster.
- Mistakes are more easily identified with a training simulator than in the real system.
- The training simulator lowers the entry barriers for initial training. It has less use for educated welders.
- The simulator can quickly assess welding skills, while an assessment with a real welding task would require more preparation.

The question of benefits gained from simulation-based training was repeated, focusing on each category of applicability factors. The following statements were made:

- **Training risks**: The main hazards of welding in the real system are vapours, high temperatures, and the electric current.
- **Training Costs:** Each trainee performs an average of 20-30 welds with each material. Because the reusability of the workpieces is limited, it becomes a significant cost factor.
- **Training Availability:** The availability of trainers is usually not a limiting factor in the current training environment.
- **Training transparency:** The trainees' performance in the real system is usually discussed after the weld is completed. On the contrary, the training simulator allows to evaluate mistakes in real-time, and training sessions can be rewatched. The system also provides feedback regarding the point of view.
- **Adaptability:** It is difficult to review welding mistakes on real workpieces with the training groups.

The last step of the interview was to discuss the rating of the identified applicability factors on a numeric rating scale with the possible values of 0 (insignificant), 1 (low significance), and 2 (high significance). The results are described in the following for each category.

5.3.1.1 Training risks

The significance of training risk factors is summarised in Table 9. The following statements support the rating:

- The welding training has not led to any serious accidents, which is supported by organisational measures and safety features of the applied equipment:
    - Automatic welding helmets prevent the typical arc eye injury.
    - Welding systems reduce the damage potential of electric current with automatic limitation of no-load voltage.
    - The risk of inhaling harmful ozone vapours is mitigated by a stationary ventilation system or ventilated welding helmets.
    - The welding system automatically enters a standby mode if it is not deactivated properly.
    - The sharpening of wolfram electrodes is performed with a dedicated electrode grinding machine that inherits no significant risk.
    - The separation of workpieces is performed in bulk by technical staff at a press.
- It is possible that spatter bypasses the personal protective equipment and causes minor burns to the trainee.
- In some cases, the trainees forget to properly cool the workpieces after their training session, which can also cause minor burns.
- The welding systems are sometimes damaged during training and have to be repaired or replaced. Damages are not a common occurrence but happen at an average of one welding system per year.

Table 9: Welding use case - Training risk factors with significance rating

Training risk factors	Significance
Risk of electric shock	0
Risk of faulty or wrongly used Personal Protective Equipment (PPE)	0
Risk of spatter bypassing the PPE and hurting the trainee	1
Risk towards other trainees or observers	0
Risk caused by improperly configured welding systems	0
Risk of damage to the welding system during training	1
Risk of exposure to ozone vapours	0
Risk of touching a heated workpiece	1
Risk of not deactivating the welding system after training	0
The trainee has an accident during the separation of workpieces	0
The trainee has an accident with the electrode grinding machine	0

5.3.1.2 Training costs

The significance of training cost factors is summarised in Table 10. The following statements support the rating:

- Concerning capital costs, the infrastructure is considered to be the biggest factor. It consists of the welding booth, the ventilation system, noise protection, power outlets, protective curtains, and other infrastructure.
- The press for separating workpieces is also a costly investment, but only one press is required for the course.
- The recurring costs of welding training are relatively low. Most recurring costs are caused by the cleaning and replacing PPE equipment, the aluminium plates, the protective gas, and a trainer's presence.
- The interviewees also expressed welding on car components as a major benefit of the training simulator. While welding on real car components would be too costly, these components can be simulated through a collaboration with the simulator manufacturer.

Table 10: Welding use case - Training cost factors with significance rating

Training cost factors	Significance
Cost factor: welding booth, ventilation system, noise protection, power outlets, protective curtains, and other infrastructure	2
Cost factor: Screw clamps	0
Cost factor: Machine for separation of workpieces	2
Cost factor: Electrode grinding machine	0
Cost factor: welding system	2
Cost factor: PPE (welding gloves, a welding helmet, an apron, and safety glasses)	1
Cost factor: wolfram electrode	0
Cost factor: aluminium plates	1
Cost factor: protective gas (argon)	1
Cost factor: filler material	0
Cost factor: electricity	0
Cost factor: presence of a trainer	1
Production downtime	0
Indirect manufacturing costs	0
Cost factor: Training on actual products is too costly	2

5.3.1.3   Training availability

The training is usually interrupted by waiting time to receive feedback from the trainer because the usual group size per trainer averages twelve trainees. However, the trainees usually use the time to discuss their results within the group so that the interviewees do not consider the waiting times wasted. The interviewees stated that the training is enclosed by supporting activities required to repeat the task but mostly irrelevant otherwise. The duration of the supporting activities times is highly individual. The schematic visualisation of supporting activities, training and waiting times is depicted in Figure 7.
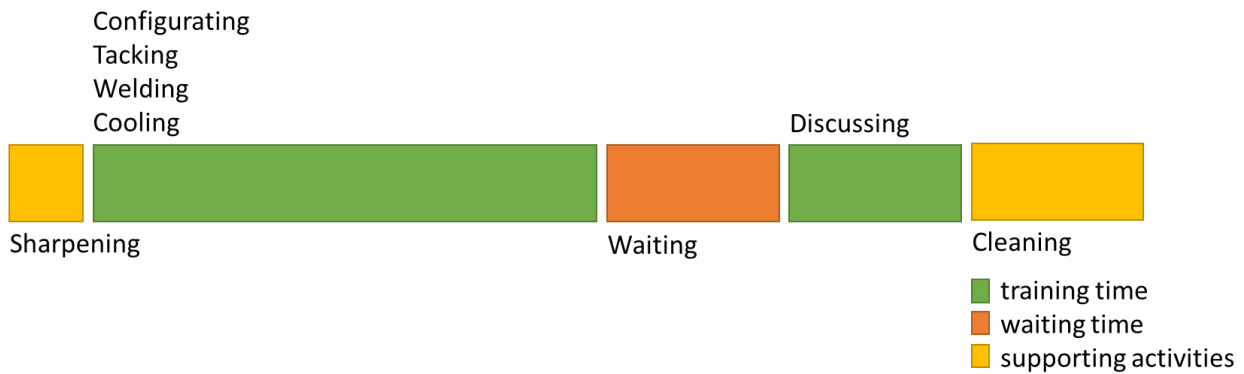
Figure 7: Welding use case - Schematic visualisation of training times (green) and waiting times (orange)

It is not feasible to skip the non-training times in the real system without impacting the result. However, the separation of the workpieces is performed by technical staff once a larger amount of workpieces has accumulated. Thereby, waiting times only have a minor impact on training availability. The training also requires multiple resources (trainer, equipment, welding booth, consumables), but their availability is not limiting.

Table 11: Welding use case - training availability factors with significance rating

Training availability factors	Significance
Supporting activities cannot be skipped	1
Waiting time cannot be skipped	0
Availability of technical staff	0
Availability of resources	0

5.3.1.4 Training transparency

During welding, trainees can make multiple difficult mistakes for them to notice without support from the trainer. Possible non-transparent mistakes are:

- The welding system has an integrated potentiometer to facilitate configuration, but mistakes during the voltage and current configuration commonly result in a non-ideal welding arc.
- The position, orientation, and movement of the filler material and the welding torch significantly impact the weld. Mistakes in handling the welding tools are difficult to identify and correct by trainees and require guidance by the trainer.
- Welding in a non-ergonomic posture does not directly influence the weld but significantly impacts long-term health. Trainees usually require guidance from a trainer to correct their posture.

- Although the training is performed in separate welding booths, the trainer cannot enter these booths to observe the trainee.
- If the wolfram electrode is not sharpened correctly, the trainees usually notice the irregular welding arc.

The significance of training transparency factors is summarised in Table 12.

Table 12: Welding use case - training transparency factors with significance rating

Training transparency factors	Significance
Non-transparent mistake: wolfram electrode not sharpened or has the wrong size.	0
Non-transparent mistake: welding system not configured properly	1
Non-transparent mistake: Wrong orientation, position, or speed of the filler material	1
Non-transparent mistake: Wrong orientation, position, or speed of the welding torch	1
Non-transparent mistake: Wrong gas flow	0
Non-transparent mistake: Non-ergonomic posture	2
Training is difficult to observe by the trainer	0
Feedback is delayed	0

5.3.1.5 Training adaptability

The existing safety measures and the required equipment result in limitations to the training design. The significance of training adaptability factors is summarised in Table 13. The following statements support the rating:

- The training requires non-portable objects such as the welding booth. A small benefit could be gained if the training could be performed at any location.
- Because welding requires personal protective equipment (PPE), it is not recommended to perform the training without it.
- A trial-and-error approach is impracticable in the real system because of the complex causalities and low transparency.
- Autonomous training could provide a benefit, but it would highly depend on the target group. Autonomous training is hindered in the real system by the need for the trainer to correct mistakes.
- Difficulty and process complexity cannot be adjusted in the training task, which is considered a major benefit of the training simulator.

- The trainer can provide additional information if required.
- The group size does not need to be adjusted.
- An integration of Blended Learning is not desired.

Table 13: Welding use case - training adaptability factors with significance rating

Training adaptability factors	Significance
The training requires non-portable objects	1
Personal protective equipment (PPE) is required	0
A trial-and-error approach is impracticable	1
Autonomous training is restricted or impractical	1
Difficulty cannot be adjusted	2
Process complexity is high and cannot be reduced for training	2
Additional information cannot be conveyed on site	0
Group size cannot be adjusted	0
Blended Learning cannot be implemented	0

5.3.2 Outline of the HMI design

The first step to defining an HMI design outline is to derive the HMI design requirements from the identified applicability factors (Table 14). Applicability factors that were rated as insignificant by the interviewees (S=0) are removed from the list.

Table 14: Welding use case - definition of HMI design requirements

Applicability factor	S	Related training objective	HMI design requirement
Risk of spatter bypassing the PPE and hurting the trainee	1	The trainee is aware of the spatter hazard	The training simulation shall include a virtual welding arc with spatter effects
Risk of damage to the welding system during training	1	The trainee is aware of possible damages to the welding system by spatters or directly by the welding torch.	The training simulation shall simulate damage a to welding system and the attached tubes caused by spatters or the welding torch.
Risk of touching a heated workpiece	1	The trainee is aware of heated surfaces	The training simulation shall include a virtual welding arc and provide feedback if the trainee handles a heated workpiece without tools or

			protection.
Cost factor: welding booth, ventilation system, noise protection, high-power outlets, protective curtains, and other infrastructure	2	No specific training objective	The training simulation shall include a virtual welding arc and remove the need for the infrastructure.
Cost factor: Machine for separation of workpieces	2	The trainee knows the relation between welding quality and the fracture pattern.	The training simulation shall include the option to create a virtual fracture pattern.
Cost factor: welding system	2	The trainee can configure the welding system.	The training simulator shall be modelled after a real welding system.
Cost factor: PPE (welding gloves, a welding helmet, an apron, and safety glasses)	1	The trainee is aware of the importance of PPE and knows how to use it.	The training simulation shall include a virtual welding arc and be usable with PPE as an optional setting.
Cost factor: aluminium plates	1	No specific training objective	The training simulation shall include a virtual welding arc and not consume the workpieces.
Cost factor: protective gas (argon)	1	The trainee can configure the protective gas stream.	The training simulation shall simulate the protective gas and provide feedback for a wrong configuration of the protective gas stream.
Cost factor: presence of a trainer	1	No specific training objective	The training simulation shall provide automated instruction and feedback to reduce the workload of the trainer
Cost factor: training on actual products is too costly	2	The trainee can perform complex welding tasks on various car parts	The training simulation shall be applicable to any workpiece without altering the workpieces.
Supporting activities cannot be skipped	1	The trainee can perform setup and cleaning tasks.	The training simulation shall include preparation and cleaning tasks.
Non-transparent mistake: welding system not configured properly	1	The trainee can configure the welding system for the task	The training simulation shall simulate the configuration options of a welding system.

Non-transparent mistake: Wrong orientation, position, or speed of the filler material	1	The trainee can control the orientation, position, and speed of the filler material	The training simulation shall provide feedback that allows for correcting the orientation, position, and speed of the filler material
Non-transparent mistake: Wrong orientation, position, or speed of the welding torch	1	The trainee can control the orientation, position, and speed of the welding torch	The training simulation shall provide feedback that allows for correcting the orientation, position, and speed of the welding torch
Non-transparent mistake: Non-ergonomic posture	2	The trainee can perform welding tasks ergonomically	The training simulation shall provide feedback that allows the trainee to correct towards an ergonomic posture
The training requires non-portable objects	1	No specific training objective	The training simulator shall be portable
A trial-and-error approach is impracticable	1	No specific training objective	The training simulation shall realistically simulate the consequences of mistakes without risk.
Autonomous training is restricted or impractical	1	No specific training objective	The training simulation shall automatically provide instructions and feedback
Difficulty cannot be adjusted	2	No specific training objective	The training simulation shall include an option to configure the evaluation strictness and the extent of feedback.
Process complexity is high and cannot be reduced for training	2	No specific training objective	The training simulation shall include an option to toggle the influence of individual welding parameters on or off.

In the next step, the identified HMI design requirements are consolidated by combining requirements that concern similar issues or objects and removing inconsistencies (Table 15). This step is performed to facilitate the definition of an HMI design outline.

Table 15: Welding use case – consolidation of HMI requirements

HMI design requirement	Consolidated HMI design requirement
The training simulation shall include a virtual welding arc with spatter effects	The training simulation shall include a virtual welding arc with: • spatter effects • possible damage to a virtual welding system and the attached tubes caused by spatters or the welding torch. • Optional use of PPE • No damage to the workpieces
The training simulation shall simulate damage to a welding system and the attached tubes caused by spatters or the welding torch.	
The training simulation shall include a virtual welding arc and remove the need for the infrastructure.	
The training simulation shall include a virtual welding arc and be usable with PPE as an optional setting.	
The training simulation shall include a virtual welding arc and not consume the workpieces.	
The training simulator shall be modelled after a real welding system.	The training simulator shall be designed after a real welding system and realistically simulate the consequences of configuration errors. Configuration options include: • Current • Voltage • Protective gas stream
The training simulation shall simulate the configuration options of a welding system.	
The training simulation shall simulate the protective gas and provide feedback for a wrong configuration of the protective gas stream.	
The training simulator shall be portable	The training simulator shall be portable
The training simulation shall provide automated instruction and feedback to reduce the workload of the trainer	The training simulation shall provide automated instruction and feedback • that allows for correcting the orientation, position, and speed of the filler material • that allows for correcting the orientation, position, and speed of the welding torch • that allows the trainee for correcting towards an ergonomic posture
The training simulation shall provide feedback that allows for correcting the orientation, position, and speed of the filler material	
The training simulation shall provide feedback that allows for correcting the orientation, position, and speed of the welding torch	
The training simulation shall provide feed-	

back that allows the trainee to correct to-wards an ergonomic posture	• with an option to configure the evaluation strictness and the extent of feedback
The training simulation shall automatically provide instructions and feedback	
The training simulation shall include an option to configure the evaluation strictness and the extent of feedback.	• with an option to toggle the influence of individual welding parameters on or off.
The training simulation shall include an option to toggle the influence of individual welding parameters on or off.	• if the trainee handles a heated workpiece without tools.
The training simulation shall include a virtual welding arc and provide feedback if the trainee handles a heated workpiece without tools.	• realistically and without risk.
The training simulation shall realistically simulate the consequences of mistakes without risk.	
The training simulation shall be applicable to any workpiece without altering the workpiece.	The training simulation shall be applicable to any workpiece without altering the workpiece.
The training simulation shall include preparation and cleaning tasks.	The training simulation shall include preparation and cleaning tasks.
The training simulation shall include the option to create a virtual fracture pattern.	The training simulation shall include the option to create a virtual fracture pattern

The consolidated list of HMI requirements shows that the training simulation must convey extensive feedback to the trainee in real-time. The training simulation needs to simulate the input and output behaviour of the original system to achieve sufficient functional fidelity. Because the training is focussed on psychomotor skills, specialised peripheral devices are required that are modelled after the welding system, the filler material, and the welding torch. In addition to these physical objects, the simulation should also include a physical workpiece. A combination of physical objects and extensive real-time feedback implies the design of a hybrid simulator, which can be realised with Augmented Reality (AR).

While a handheld AR device would be impractical, AR could be realised with an HMD or a projection-based system. A projection-based system would limit the possible geometries of the workpieces, while an HMD would interfere with an optional implementation of PPE. The AR system needs to visualise a virtual weld and welding arc on the workpiece and convey additional visual feedback to the trainee.

Audible cues, such as stuttering sounds or a variation in pitch, can provide important feedback regarding the configuration of welding parameters (voltage, current, gas flow) and the handling of the welding torch (cf. Lv et al. 2017). The training simulator should therefore include a speaker system for audio output.

The haptic interaction is characterised by the trainee's interaction with the welding torch, filler material, welding system, and workpiece. A common mistake in TIG welding training is that trainees bring the electrode in contact with the workpiece, resulting in the electrode sticking to the surface (Naik & Reddy 2018). Sticking to the surface could be implemented into the training simulator via an electromagnet in the welding torch that activates if contact is made during welding.

Based on the identified HMI requirements, the training simulator does not need to give out olfactory cues or transmit heat. Although, the consequences of touching heated surfaces could be simulated through visual and auditory cues.

The input devices require a complex camera array with subsequent image processing to detect the trainee's posture, the welding torch, the filler material, and the workpiece. The training simulation should create a virtual workpiece model via the camera array to apply to any workpiece. However, input by the trainer would be required to position the intended weld on the workpiece. The weld must be marked by non-permanent means such as coloured tape or configuration software on the virtual model. Also, the settings regarding current, voltage and the protective gas stream must be recorded.

The hardware should be integrated into a case modelled after a welding system and simulate its controls to achieve high physical fidelity. A compact design would also benefit the mobility of the system.

5.3.3 Analysis of technological risk and assessment of the achievable benefit

The final step of the proposed task analysis methodology is assessing the achievable benefit based on the identified applicability factors, the HMI design outline, and the technological risk.

5.3.3.1 Analysis of technological risk

Welding simulators are examples of simulation-based training in manufacturing that became possible through recent advances in HMI technologies (González-Linares et al. 2015). While the implementation into the vocational training of welders is still ongoing, strong benefits over conventional training have been observed within case studies (Okimoto et al. 2015).

Figure 8: Simulation-based welding training[1]

The outlined HMI design is similar to the Augmented Reality training simulator Soldamatic (Okimoto et al. 2015, Seabery Soluciones 2012, Knoke & Thoben 2017). The simulator is integrated into a case that is modelled after a welding system. The system includes an AR HMD designed similar to a welding helmet and uses two cameras positioned on the HMD. The AR system simulates a weld, welding arc, spatters, and a metal texture over predefined plastic workpieces. The system is portable and can be connected to external displays, as shown in Figure 8.

Integration of customised workpieces is possible but has to be performed by the system provider. The interviewees of the welding use case employ the Soldamatic training simulator for welding training and have collaborated with the system provider to integrate multiple custom workpieces into the simulation. The training simulator also includes various training materials to support autonomous learning sessions partially but cannot replace the need for a trainer.

The feedback quality is reported to be sufficient for learning. Although the visual feedback is projected directly in front of the trainee's visual field, the perceived embodiment matches the original system. The feedback is given in real-time and adjusted according to the difficulty level (Knoke & Thoben 2017).

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[1] Image provided by the German Federal Ministry of Education and Research

No existing training simulator for welding monitors the trainee's posture or produces a virtual fracture pattern. Haptic feedback is also not provided if the welding torch sticks to the workpiece.

In the analysed training environment, one trainer typically instructs a group of up to twelve trainees. The training simulators potentially decrease the workload for the trainer through sensor-based feedback but does not enable autonomous training. However, most training simulators using AR or VR technology also support external audio and video devices, enabling different settings, such as classrooms or presentations (cf. Knoke & Thoben 2017).

Because many requirements are already met by existing training simulators in industrial practice, the technological risk of achieving a training simulator for welding with sufficient fidelity is low.

5.3.3.2 Assessment of the achievable benefit

The analysis has produced various applicability factors that indicate a significant potential benefit of simulation-based training for manual welding tasks. The technical risk analysis has shown that most potential benefits are achievable with currently available training simulators. A summary of the achievable benefit for the welding use case is given in Table 16.

Table 16: Welding use case – Summary of the achievable benefit

Applicability factor	S	Achievable Benefit
Risk of spatter bypassing the PPE and hurting the trainee	1	Yes
Risk of damage to the welding system during training	1	Yes
Risk of touching a heated workpiece	1	Yes
Cost factor: welding booth, ventilation system, noise protection, high-power outlets, protective curtains, and other infrastructure	2	Yes
Cost factor: Machine for separation of workpieces	2	Work required
Cost factor: welding system	2	Yes
Cost factor: PPE (welding gloves, a welding helmet, an apron, and safety glasses)	1	Yes
Cost factor: aluminium plates	1	Yes
Cost factor: protective gas (argon)	1	Yes
Cost factor: presence of a trainer	1	Work required
Cost factor: Training on actual products is too costly	2	Yes
Supporting activities cannot be skipped	1	Yes
Non-transparent mistake: welding system not configured properly	1	Yes
Non-transparent mistake: Wrong orientation, position, or speed of the filler material	1	Yes
Non-transparent mistake: Wrong orientation, position, or speed of the welding torch	1	Yes
Non-transparent mistake: Non-ergonomic posture	2	Work required
The training requires non-portable objects	1	Yes
A trial-and-error approach is impracticable	1	Yes
Autonomous training is restricted or impractical	1	Yes
Difficulty cannot be adjusted	2	Yes
Process complexity is high and cannot be reduced for training	2	Yes

A fracture pattern or feedback on the posture of the trainee could provide a significant benefit over the existing systems. While the visualisation of a fracture pattern would be more demanding on the simulation model, sensor-based feedback towards a more ergonomic posture would require additional sensors because the existing training simulators do not capture information on the posture of the trainee beyond the position of the welding helmet.

5.4　　　　Use case II – Computer Numerical Control (CNC) machining

The Computer Numerical Control (CNC) machining case study has been conducted with the CEO of a training association for vocational training with over 60 member companies. The analysed training task of CNC machining is performed with a DMG MORI DMU 50 system (Figure 9).

Figure 9: The CNC machining system used in the training task[2]

The CNC machining system also has an embedded simulation functionality. A trainee can run a CNC program within the simulation to assess the outcome. In addition to one DMG MORI DMU 50 system, the company also uses twelve programming stations designed after the operator panel and used by trainees to write and simulate CNC programs.

The analysed task involves the CNC machining of the training workpiece "Lachplatte". The workpiece, which resembles a smiley, has a challenging geometry and has been specifically designed for training (Figure 10).

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[2] Image provided by C+P Bildung GmbH

Figure 10: CNC machining use case - Training workpiece[3]

The training task consists of multiple sub-tasks, including the preparation and quality control of the semi-finished goods. The sub-tasks are:

- Putting PPE on. Safety glasses, Coat. Safety shoes
- Deburring and measuring of semi-finished goods with dimensions of 120 x 80 x 20mm.
- Fixating the workpiece in the machine.
- Defining the zero point.
- Creating the CNC program.
- Executing the CNC program:
  - Milling a rectangular pocket (114 x 74 x 1mm),
  - Milling a rectangular pocket (35 x 30 x 3mm),
  - Milling two circular pockets (Ø 25 x 6mm),
  - Milling a circular pocket (Ø 30 x 6mm),
  - Milling a cavity (r=42mm x 15mm, angle=70°),
  - Milling two cavities (30 x 10 x 3mm),
  - Milling a cavity (40 x 10 x 6mm),
  - Milling a cavity (r=42mm x 8mm, angle=70°),
  - Milling three circular pockets (Ø 8mm).
- Reworking, deburring and measuring of the workpiece.
- Releasing and deburring of the workpiece.
- Performing quality control.

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[3] Image provided by C+P Bildung GmbH
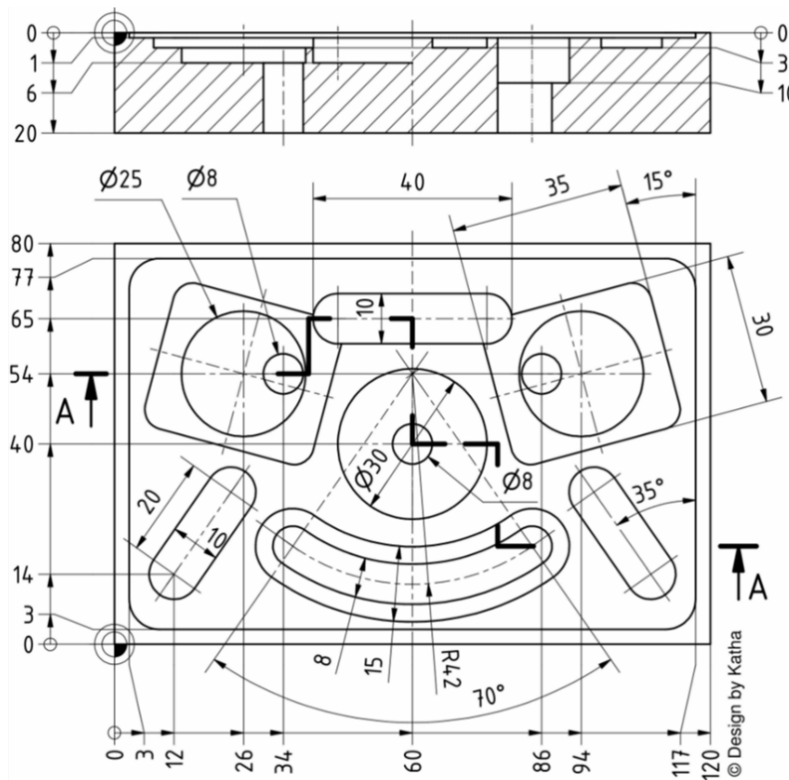
Figure 11: CNC machining use case - Technical drawing of the workpiece[4]

The training focuses on the cognitive skills required to create the CNC program and extract the necessary information from a technical drawing (Figure 11). The CNC program is created via the interface of the machining system. The program code is included in the annexe (subsection 8.6). The CNC machining task requires multiple tools and consumables that are listed in Table 17.

Table 17: CNC machining use case - Tools and consumables

Tools, machines, and infrastructure	Consumables
CNC machining system	Semi-finished good (120 x 80 x 20mm)
3D sensor	Electricity
Calliper	
Depth gauge	
Rasp	
Deburring tool	
PPE equipment (safety glasses)	
Milling head (Ø 12mm)	
Milling head (Ø 8mm)	

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[4] Image provided by C+P Bildung GmbH

The interview started with individual questions that were intended to clarify uncertainties in the task analysis. The following statements were made:

- The personal protective equipment (PPE) for the training task includes safety glasses, overalls, and safety shoes.
- The CNC program is written either on the machine, the programming stations, depending on the group size. Programs written with programming stations can be sent to the CNC machining system via the network.
- The trainees can switch between CNC programming languages of multiple providers (Heidenhain, Siemens).

The following subsection describes the identification and assessment of applicability factors.

5.4.1 Identification of applicability factors

A list of applicability factors was compiled in advance of the interviews by applying the first step of the task analysis to the task model. The resulting list is shown for each category in tables 18 to 22. The significance ratings were filled during step four of the interview. No new applicability factors were identified in steps two and three of the interviews.

The CNC machining training is partially performed with programming stations that have embedded training simulations. The interviewee was asked what benefits are gained from an integration of simulation-based CNC machining training. The following reasons were given:

- The CNC program code can be evaluated in a simulation before it is applied to the machine. This evaluation prevents errors and a potential crash.
- To reduce resource consumption.
- To increase the training effect.
- Only one CNC machining system is available. Therefore the programming stations are used for larger groups to train up to twelve trainees at once.

The interviewee was asked for each applicability factor category why training could be not ideal. The following statements were made:

- *Training risks:* If the milling head is moved too fast into the material or moved into the chuck, the milling head or the spindle can be damaged.
- *Training costs:* Material costs and machine running time are expenses of training in the real system.
- *Training availability:* Only one CNC milling machine is available, which is not enough for larger groups of trainees.

The last step of the interview was to discuss the rating of the identified applicability factors on a numeric rating scale with the possible values of 0 (insignificant), 1 (low significance), and 2 (high significance). The results are described in the following for each category.

5.4.1.1   Training risks

The significance of training risk factors is summarised in Table 18. The following statements support the rating:

- Missing or wrongly used Personal Protective Equipment (PPE) is a significant work safety risk.
- If the workpiece is not properly fixated, it results in defective goods.
- If the zero point is not calibrated correctly, the milling head or the spindle can be damaged.
- The machine has integrated collision detection, although it only recognises specific errors in the CNC program. Therefore, a faulty CNC program can result in damage to the milling head or spindle.

Table 18: CNC machining use case - Training risk factors with significance rating

Training risk factors	Significance
Risk of faulty or wrongly used Personal Protective Equipment (PPE)	2
Risk of injury during deburring	0
Risk of not properly fixated workpiece	1
Risk of wrongly calibrated zero point	2
Risk caused by a faulty CNC program	2

5.4.1.2   Training costs

The significance of training cost factors is summarised in Table 19. The following statements support the rating:

- The CNC machining system has been a significant investment.
- The 3D sensor and the milling heads are expensive yet fragile parts that are easily damaged during training.
- The costs of the semi-finished goods, electricity and indirect manufacturing costs are not negligible.
- The personnel costs for the trainer are a significant cost factor.

Table 19: CNC machining use case - Training cost factors with significance rating

Training cost factors	Significance
Cost factor: CNC machining system	2
Cost factor: recurring costs: 3D sensor	2
Cost factor: Caliper	0
Cost factor: Depth gauge	0
Cost factor: Rasp	0
Cost factor: Deburring tool	0
Cost factor: PPE equipment (safety glasses)	0
Cost factor: Semi-finished good (120 x 80 x 20mm)	1
Cost factor: Milling head (Ø 12mm)	1
Cost factor: Milling head (Ø 8mm)	1
Cost factor: Recurring costs: Electricity	1
Cost factor: Presence of a trainer	2
Cost factor: Production downtime	0
Indirect manufacturing costs	1

5.4.1.3   Training availability

The training focus is on the creation of the CNC program based on a technical drawing. The CNC programming is enclosed by activities essential to the task and considered an important part of training by the interviewee.

Figure 12: CNC machining use case - Schematic visualisation of training times (green) and waiting times (orange)

The only waiting time occurs when the trainee has to wait for the CNC processing to finish. The schematic visualisation of training and waiting times is depicted in Figure 12. It shows that waiting times are only a minor applicability factor. The most significant factor regarding the training availability is the availability of resources because only one CNC machining system is available. The applicability factors from the availability category and their significance rating are summarised in Table 20.

Table 20: CNC machining use case - Training availability factors with significance rating

Training availability factors	Significance
Supporting activities cannot be skipped	0
Waiting time cannot be skipped	1
Availability of technical staff	0
Availability of resources	2

5.4.1.4 Training transparency

The significance of training transparency factors is summarised in Table 21. During the training, trainees can make multiple mistakes that are difficult to notice without support from the trainer. The following statements support the significance rating:

- An unproperly fixated workpiece is usually noticed if it has a larger deviation.
- An improperly deburred workpiece may result in faulty fixation.
- Mistakes in the CNC program can be difficult to identify for the trainee without support from the trainer.

Table 21: CNC machining use case - Training transparency factors with significance rating

Training transparency factors	Significance
Non-transparent mistake: workpiece not properly fixated	1
Non-transparent mistake: semi-finished good has not been deburred	0
Non-transparent mistake: zero point has not been identified properly	0
Non-transparent mistake: mistake in CNC program	1
Non-transparent mistake: workpiece has not been deburred	2
Non-transparent mistake: improper measuring	0
Training is difficult to observe by the trainer	0
Feedback is delayed	0

5.4.1.5 Training adaptability

The existing safety measures and the required equipment result in limitations to the training design. The significance of training adaptability factors is summarised in Table 22. The following statements support the rating:

- The training task depends on the CNC machining system, which is very difficult to move.
- Autonomous training or a trial-and-error approach can have a positive effect on training. However, the risk of damages to the machine is too high if performed in the real system.
- Difficulty or process complexity cannot be adjusted in the real machine without changing the training task.
- Apart from the embedded simulation, the CNC machining system has no functionality to convey additional information on site.
- Implementing the CNC machining training in a Blended Learning concept would be beneficial if it could reduce the time that the trainee needs to be on site. This especially applies due to the ongoing pandemic.

Table 22: CNC machining use case - Training adaptability factors with significance rating

Training adaptability factors	Significance
The training requires non-portable objects	1
Personal protective equipment (PPE) is required	0
A trial-and-error approach is impracticable	1
Autonomous training is restricted or impractical	1
Difficulty cannot be adjusted	1
Process complexity is high and cannot be reduced for training	1
Additional information cannot be conveyed on site	1
Group size cannot be adjusted	0
Blended Learning cannot be implemented	2

5.4.2   Outline of the HMI design

The first step to defining an HMI design outline is to derive the HMI design requirements from the identified applicability factors (Table 23). Applicability factors that were rated as insignificant by the interviewee (S=0) are removed from the list.

Table 23: CNC machining use case - definition of HMI design requirements

Applicability factor	S	Related training objective	HMI design requirement
Risk of faulty or wrongly used Personal Protective Equipment (PPE)	2	The trainee can correctly use PPE and identify faulty equipment	The training simulation shall include a virtual machining simulation
Risk of not properly fixated workpiece	1	The trainee can properly fixate the workpiece	The training simulation shall include a virtual machining simulation and provide feedback regarding the fixation of the workpiece
Risk of wrongly calibrated zero point	2	The trainee can calibrate the zero point	The training simulation shall include a virtual machining simulation and provide feedback regarding the calibration of the zero point
Risk caused by a faulty CNC program	2	The trainee can create the required CNC program	The training simulation shall include a virtual machining simulation that is based on the CNC program created by the trainee
Cost factor: CNC machining system	2	No specific training objective	The training simulation shall not require a real CNC machining system
Cost factor: recurring costs: 3D sensor	2	The trainee can calibrate the zero point	The training simulation shall not require the positioning of a real 3D sensor
Cost factor: Semi-finished good (120 x 80 x 20mm)	1	No specific training objective	The training simulation shall not transform semi-finished goods
Cost factor: Milling head (Ø 12mm)	1	No specific training objective	The training simulation shall not require real milling heads
Cost factor: Milling head (Ø 8mm)	1	No specific training objective	The training simulation shall not require real milling heads
Cost factor: Recurring costs: Electricity	1	No specific training objective	The training simulation shall not involve the movement of heavy machine parts
Cost factor: Presence of a trainer	2	No specific training objective	The training simulation shall reduce the workload of the trainer
Indirect manufacturing costs	1	No specific training objective	The training simulation shall not occupy space on the shopfloor

Waiting time cannot be skipped	1	No specific training objective	The training simulation shall include a function to fast-forward the simulated machining
Availability of resources	2	No specific training objective	The training simulation shall not require a real CNC machining system
Non-transparent mistake: workpiece not properly fixated	1	The trainee can properly fixate the workpiece	The training simulation shall provide feedback if the workpiece is not properly fixated
Non-transparent mistake: mistake in CNC program	1	The trainee can create the required CNC program	The training simulation shall provide feedback if the CNC program contains a mistake
Non-transparent mistake: workpiece has not been deburred	2	The trainee can deburr the workpiece	The training simulation shall provide feedback if the workpiece has not been deburred
The training requires non-portable objects	1	No specific training objective	The training simulator shall be portable
A trial-and-error approach is impracticable	1	No specific training objective	The training simulation shall realistically simulate the consequences of mistakes without risk.
Autonomous training is restricted or impractical	1	No specific training objective	The training simulation shall automatically provide instructions and feedback
Difficulty cannot be adjusted	1	No specific training objective	The training simulation shall include an option to configure the evaluation strictness and the feedback during programming.
Process complexity is high and cannot be reduced for training	1	No specific training objective	The training simulation shall include an option to support the programming with a help function.
Additional information cannot be conveyed on site	1	The trainee understands the manufacturing process	The training simulation shall include an option to convey additional information on the manufacturing process
Blended Learning cannot be implemented	2	No specific training objective	The training simulation shall be designed as a web-based application

In the next step, the identified HMI design requirements are consolidated by combining requirements that concern similar issues or objects and removing inconsistencies (Table 24). This step is performed to facilitate the definition of an HMI design outline.

Table 24: CNC machining use case – consolidation of HMI requirements

HMI design requirement	Consolidated HMI design requirement
The training simulation shall include a virtual machining simulation	The training simulation shall include a virtual representation of a CNC machining system that: • performs according to the CNC program created by the trainee, • requires the positioning of a virtual 3D sensor to calibrate the zero point, • has the option to fast-forward the simulated machining, • realistically simulates the consequences of mistakes without risk.
The training simulation shall include a virtual machining simulation that is based on the CNC program created by the trainee	
The training simulation shall not require a real CNC machining system	
The training simulation shall not require the positioning of a real 3D sensor	
The training simulation shall not require real milling heads	
The training simulation shall not involve the movement of heavy machine parts	
The training simulation shall not occupy space on the shopfloor	
The training simulation shall include a virtual machining simulation and provide feedback regarding the calibration of the zero point	
The training simulation shall include a function to fast-forward the simulated machining	
The training simulation shall not require a real CNC machining system	
The training simulation shall realistically simulate the consequences of mistakes without risk.	
The training simulation shall be designed as a web-based application	The training simulation shall be designed as a web-based application
The training simulator shall be portable	
The training simulation shall provide feedback if the workpiece is not properly fixated	The training simulation shall include a virtual representation of the workpiece and task the trainee to fixate and deburr it virtually.
The training simulation shall include a virtual machining simulation and provide feedback regarding the fixation of the workpiece	
The training simulation shall provide feedback if the workpiece has not been deburred	
The training simulation shall not transform semi-finished goods	
The training simulation shall include an option to convey additional information on the	The training simulation shall include an option to convey addition-

manufacturing process	al information on the manufacturing process
The training simulation shall reduce the workload of the trainer	The training simulation shall automatically provide instructions and feedback
The training simulation shall automatically provide instructions and feedback	
The training simulation shall provide feedback if the CNC program contains a mistake	The training simulation shall provide feedback if the CNC program contains a mistake and include an option to enable assistance during programming.
The training simulation shall include an option to support the programming with a help function.	
The training simulation shall include an option to configure the evaluation strictness and the feedback during programming.	

The consolidation of HMI design requirements shows that most requirements involve the virtualisation of the machining process. Without dependence on the physical transformation of the workpiece, the training does not require the heavy machinery of the original system, thereby improving flexibility and resource efficiency.

The requirement of a web-based application contradicts a transformation of real objects such as the deburring of the workpiece. A web-based application would be preferable to save resources and achieve better availability, which was defined as a significant applicability factor. A web-based application implies the use of generic peripheral devices. The training focus lies on procedural knowledge and the cognitive skills for CNC programming. Thereby, a haptic interface with high physical fidelity is not required.

All consolidated HMI design requirements can be met with an animated CNC machining system in a virtual environment that is programmable and interactive. The interaction should include a virtual representation of the workpiece that can be fixated and deburred. The programming interface should include enabling a support function and accessing additional information on individual functions and the manufacturing process.

5.4.3   Analysis of technological risk and assessment of the achievable benefit

The final step of the proposed task analysis methodology is assessing the achievable benefit based on the identified applicability factors, the HMI design outline, and the technological risk.

5.4.3.1 Analysis of technological risk

The literature analysis has led to the identification of 45 applications for cutting with a geometrically defined edge. Most of these applications involve CNC programming, and some have been designed as web-based applications (Muthupalaniappan et al. 2014, Ong et al. 2002, Seo et al. 2000, Suh et al. 2003, Wasfy et al. 2005). The visual feedback of these training simulations differs from the feedback in the original system, as an often simplified representation of the workpiece is transformed and visualised on screen. However, simplified feedback has no negative impact on the functional fidelity of the simulation due to the focus on cognitive skills.

The application described by Wasfy et al. (2005) also includes a function to fixate the workpiece. A deburring function was not described in the identified training simulators for CNC machining but has been implemented by Jose et al. (2014) for a pipe-cutting training simulation.

Training tasks with individual workpieces can be achieved with a relatively low technological risk when comparing the CNC milling training to the previously described welding training. For a customisable experience, the training simulation is required to include a configuration for the semi-finished goods, which have a limited variance in their geometry. With the CNC program, the trainee provides information that can be interpreted by the training simulation system to shape individual workpieces.

The analysis of the available simulators shows that the creation of a CNC training simulator has a low technological risk.

5.4.3.2 Assessment of the achievable benefit

Most of the identified applicability factors are caused by the dependence of the training task on the CNC machining system. The analysis of the HMI design outline has shown that all applicability factors can be achieved with a web-based training simulation (Table 25). The technological risk can be considered relatively low because training simulators that provide the required functional fidelity have already been developed.

Table 25: CNC machining use case – Summary of the achievable benefit

Applicability factor	S	Achievable Benefit
Risk of faulty or wrongly used Personal Protective Equipment (PPE)	2	Yes
Risk of not properly fixated workpiece	1	Yes
Risk of wrongly calibrated zero point	2	Yes
Risk caused by a faulty CNC program	2	Yes
Cost factor: CNC machining system	2	Yes
Cost factor: recurring costs: 3D sensor	2	Yes
Cost factor: Semi-finished good (120 x 80 x 20mm)	1	Yes
Cost factor: Milling head (Ø 12mm)	1	Yes
Cost factor: Milling head (Ø 8mm)	1	Yes
Cost factor: Recurring costs: Electricity	1	Yes
Cost factor: Presence of a trainer	2	Yes
Indirect manufacturing costs	1	Yes
Waiting time cannot be skipped	1	Yes
Availability of resources	2	Yes
Non-transparent mistake: workpiece not properly fixated	1	Yes
Non-transparent mistake: mistake in CNC program	1	Yes
Non-transparent mistake: workpiece has not been deburred	2	Yes
The training requires non-portable objects	1	Yes
A trial-and-error approach is impracticable	1	Yes
Autonomous training is restricted or impractical	1	Yes
Difficulty cannot be adjusted	1	Yes
Process complexity is high and cannot be reduced for training	1	Yes
Additional information cannot be conveyed on site	1	Yes
Blended Learning cannot be implemented	2	Yes

Two potential use cases for training simulators have been analysed with the developed task analysis methodology. The results are described in the following subsections, starting with the use case on gluing.

5.5 Use case III – Gluing with a 2-c epoxide adhesive

The interview regarding a potential use case in a gluing training task was conducted with the deputy head of a training and technology transfer department and head of a training centre for adhesive bonding technology.

The analysed task "manufacture 4 lap shear test specimens with aluminium substrates using a 2-c epoxide adhesive" includes cleaning, sanding, gluing, and testing sub-tasks. The task is performed in small groups of two trainees.
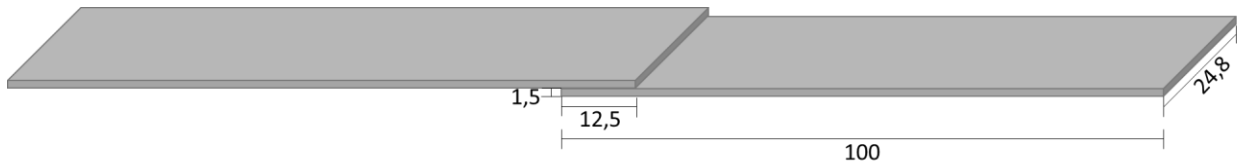
Figure 13: Visualisation of a lap shear test specimen

Four lap shear test specimens are created by joining eight aluminium workpieces (100×24,8×1,5 mm) with an overlapping length of 12,5 mm and an adhesive layer thickness of 0,2 mm (Figure 13).

The bond is created with the adhesive Araldite 2013-1. It is a two-component epoxy resin-based pasty adhesive applied with a double cartridge (Figure 14). The adhesive has a pot life of 50 to 80 minutes if 100 grams are mixed at 25°C. The mixing ratio of the components is 1:1. The adhesive may cause skin irritation, allergic skin reactions, serious eye irritation and damage, and is potentially harmful to the environment.

Figure 14: Double cartridge with glue (top) and static mixer (bottom)[5]

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[5] Image provided by Filzring OHG

The training task spans multiple sub-tasks, from cleaning the workpieces to testing the lap shear test specimens in a universal testing machine. The sub-tasks performed by the trainee are:

- Measuring the room temperature and relative humidity and logging it on the exercise sheet.
- Inserting the spacers into the positioning device to achieve an adhesive layer thickness of 0,2 mm.
- Cleaning of the eight workpieces with solvent and paper tissues.
- Waiting for five minutes of drying time.
- Grinding the workpieces in a cross-hatch pattern to prepare the surfaces.
- Cleaning of the eight workpieces with solvent and paper tissues.
- Waiting for five minutes of drying time.
- Logging the batch number of the adhesive and its expiration date on the exercise sheet.
- Inserting the double cartridge into the cartridge press.
- Attaching the static mixer to the cartridge press.
- Checking if adhesive exits from both chambers of the double cartridge.
- Disposing of the first exiting adhesive over the length of the static mixer as hazardous waste.
- Applying the adhesive evenly on one side of a workpiece and spreading it with a spatula.
- Joining the workpieces to form lap shear test specimens by attaching the positioning device with stripes of PTFE foil in between.
- Logging the time on the exercise sheet.
- Cleaning the spatula with solvent and paper tissues and disposing of the paper tissues as hazardous waste.
- Labeling of the workpieces.
- Waiting for 24 hours of drying time at room temperature.
- Measuring the overlapping length and width of each lap shear test specimen and logging it on the exercise sheet.
- Testing two lap shear test specimens with a universal testing machine while logging the maximum force, lap shear strength, and fracture pattern.
- Waiting for 24 hours, while the remaining two lap shear test specimens are submerged in a vat filled with water at 60°C.
- Testing the remaining two lap shear test specimens with a universal testing machine while logging the maximum force, lap shear strength, and fracture pattern.

The training task uses a universal testing machine for the lap shear tests and a range of tools and consumables listed in Table 26.

Table 26: Gluing use case – tools and consumables used in the training task

Tools and Machines	Consumables
Cartridge press	8 aluminium workpieces at 100×24,8×1,5 mm
Ruler	Double cartridge with glue: Araldite 2013
Positioning device	Static mixer
Spacer elements	Solvent
Spatula	Paper tissues
Calliper	Exercise sheet
Disposal bin for hazardous waste	Fibre pen (waterproof)
PPE (safety glasses, gloves, lab coat)	Abrasive paper
Heated vat	PTFE foil
Universal testing machine	Water

A task description was provided in advance that was used to perform the task analysis. The interview started with individual questions that were intended to clarify uncertainties in the task analysis. The following statements were made:

- All test samples are disposed of after the tests and are recycled together with scrap metal from other departments. The adhesive is not regarded as hazardous waste after it has hardened.
- The ageing process is performed in a vat that is 60°C in a ventilated drying oven. The oven is operated by technical staff.
- The training room is outfitted with a ventilation system to lower the risk of an allergic reaction.

5.5.1 Identification of task-related applicability factors regarding simulation-based training

In this subsection, the task-related applicability factors are analysed following the structure of training risks, training costs, training availability, training transparency, and training adaptability.

A list of applicability factors was compiled in advance of the interviews by applying the first step of the task analysis to the task model. The resulting list is shown for each category in tables 27 to 31. The significance ratings were filled during step four of the interview.

The interviewee was asked how an ideal training would differ from the current training while disregarding any specific implementation. Given the limitations imposed by the COVID-19 pandemic, it would be ideal if a Blended Learning approach could be implemented so that a larger part of the training could be conducted online. This statement led to the addition of the applicability factor "Blended Learning cannot be implemented" to the category "training adaptability". This newly identified applicability factor has also been added to the summary of the task analysis methodology (subsection 4.7). Because the gluing use case was analysed first, the new applicability factor has been applied to the other use cases as well.

The previous question regarding possible improvements of the current training was asked specifically for each category:

- **Training risks:** The adhesive may cause allergic reactions if it comes into contact with human skin or the exercise is not performed in a ventilated room.
- **Training costs:** The training uses expensive equipment, but running costs are otherwise not a significant issue.
- **Training availability:** Waiting times interrupt the training multiple times. Waiting times are required during the surface preparation and for the hardening and ageing of the adhesive, usually done overnight.
- **Training transparency:** It is difficult to assess the quality of an adhesive bond without a fracture pattern. The quality depends on multiple factors, such as how the cleaning is performed. Insufficient cleaning might leave a layer of fat on the surface within the scale of nanometres. Such a layer is difficult to identify but can have a great impact on the result.
- **Training adaptability:** The training requires personal protective equipment (PPE), the ability to dispose of hazardous waste, and a large room or a room fitted with a ventilation system.

The last step of the interview was to discuss the rating of the identified applicability factors on a numeric rating scale with the possible values of 0 (insignificant), 1 (low significance), and 2 (high significance). The results are described in the following for each category.

5.5.1.1 Training risks

The main hazard in the analysed system stems from the applied adhesive. According to the available safety information, it may cause physical harm if it comes into contact with human skin or eyes and environmental damage if it is not properly disposed of as hazardous waste.

Another hazard is the heating vat, which holds water and the lap shear test specimens at a temperature of 60 °C. At this temperature, water may cause burns within three seconds of contact with human tissue (DIN CEN/TR 16355:2012-09).

The training does not include the handling of sharp or heavy objects.

The significance of training risk factors is summarised in Table 27. The following statements support the rating:

- The major risk is that the trainees may not use the PPE as intended. This risk can include temporary removal of the PPE, bringing the rubber gloves into contact with the solvent, or touching their skin or eyes with the gloves.
- If the gloves and lab coats are used properly, there is only a low risk of bringing the adhesive into contact with unprotected skin.
- There are no uninvolved persons without PPE present in the training environment.
- The ventilation system mitigates the risk of inhaling fumes of the solvent or adhesive.
- The instructor makes sure that any contaminated paper tissues or leftovers of the adhesive are disposed of as hazardous waste, which reduces the risks.
- The heating oven is operated by technical staff, which also greatly reduces the risk of burns.
- The technical staff drains the water from the vats, and the samples quickly cool off. This action has not yet led to any burns, and the risk of this subtask can be considered insignificant.

Table 27: Gluing use case - training risk factors with significance rating

Training risk factors	Significance
Risk of the trainee not using the Personal Protective Equipment (PPE) as intended	2
Risk of the adhesive coming into contact with unprotected skin of the trainee	1
Risk of the adhesive coming into contact with unprotected skin of other persons	0
Risk of the adhesive not disposed of as hazardous waste	1
Risk of the trainee attempting to take the lap shear test specimens out of the heating vat without tools or protection	1
Risk of knocking the heated vat over	0

5.5.1.2 Training costs

The training task requires multiple tools and a universal testing machine used to test the shear tension of the created lap shear test specimens. The most expensive equipment includes the cartridge press, the positioning device, the PPE equipment, and the universal testing machine.

Various consumables are consumed in one or multiple training sessions. Of these consumables, the aluminium workpieces and the adhesive (Araldite 2013) are major cost drivers. Further training costs result from disposal fees because the adhesive must be disposed of as hazardous waste.

The training requires the presence of a trainer who supervises multiple groups.

The training does not result in any production downtime within the analysed manufacturing system. Further indirect manufacturing costs result from operating the heating vat and the universal testing machine but can be disregarded in this case.

The significance of training cost factors is summarised in Table 28. The following statements support the rating:

- The training requires expensive machines, tools, and other lab equipment, which results in significant capital costs. The major cost factors are the universal testing machine, the ventilation system, and the ventilated heating oven. The bonding units and the PPE are other cost factors with minor significance.
- Recurring costs are mainly caused by hazardous waste disposal. The adhesive is a minor cost factor.

Table 28: Gluing use case - training cost factors with significance rating

Training cost factors	Significance
Cost factor: cartridge press	0
Cost factor: ruler	0
Cost factor: positioning device	1
Cost factor: spacer elements	0
Cost factor: spatula	0
Cost factor: calliper	0
Cost factor: disposal bin for hazardous waste	0
Cost factor: PPE (safety glasses, gloves, lab coat)	1
Cost factor: heating oven	2
Cost factor: ventilation system	2
Cost factor: universal testing machine	2
Cost factor: 8 aluminium workpieces at 100×24,8×1,5 mm	0
Cost factor: double cartridge with glue: Araldite 2013	1
Cost factor: static mixer	0
Cost factor: solvent	0
Cost factor: paper tissues	0
Cost factor: exercise sheet	0
Cost factor: fibre pen (waterproof)	0
Cost factor: abrasive paper	0
Cost factor: PTFE foil	0
Cost factor: water	0
Cost factor: hazardous waste disposal	2
Cost factor: presence of a trainer	0
Cost factor: production downtime	0
Cost factor: indirect manufacturing costs	0

5.5.1.3   Training availability

The training is interrupted four times by waiting times. Waiting times are required for the solvent to evaporate (1 & 2), for the adhesive to harden (3) and for the submerged lap shear test specimens to moisten in the heating vat (4). The evaporation of the solvent requires a waiting time of five minutes, while the hardening and moistening require a waiting time of 24 hours. It is not feasible to skip the waiting times in the real system without negatively impacting the result.
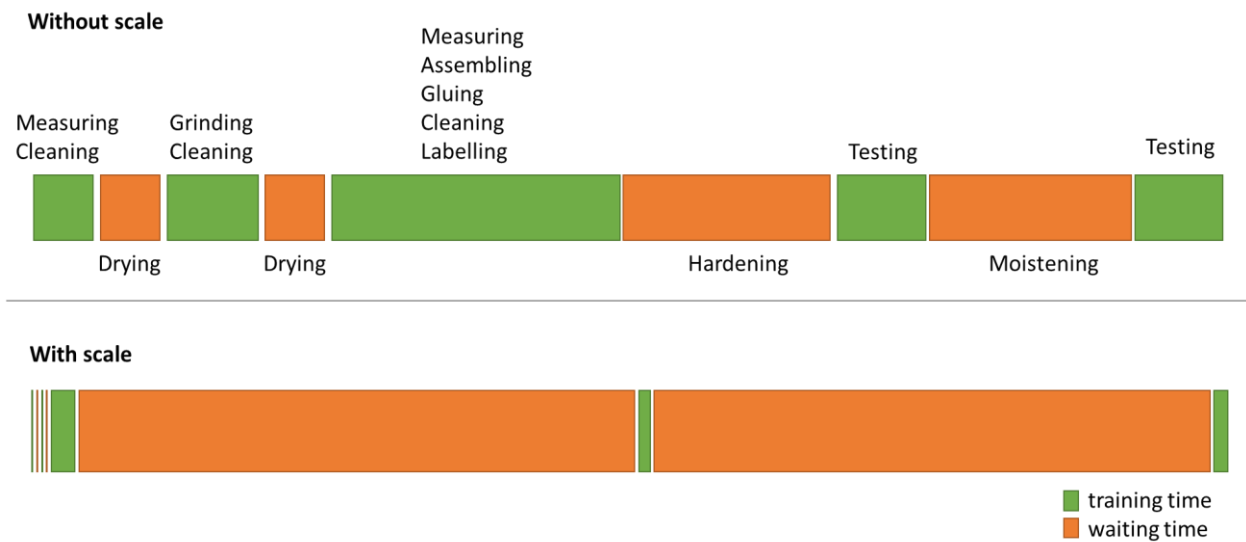
Figure 15: Gluing use case – schematic visualisation of training times (green) and waiting times (orange) without scale (top) and with scale (bottom)

The scaled approximation of training and waiting times (Figure 15, bottom) shows the significant duration of the waiting time that interrupts the training.

The training availability factors are summarised in Table 29. The following statements support the rating:

- The major waiting times stem from the hardening and ageing times with 24 hours each.
- The five minutes of waiting time that is required for the solvent to evaporate has a minor significance.

- The training requires multiple resources (experts, equipment, universal testing machine, consumables). The availability of these resources is not a limiting factor in the training.

Table 29: Gluing use case – training availability factors with significance rating

Training availability factors	Significance
Drying time (1)	1
Drying time (2)	1
Hardening time (3)	2
Ageing time (4)	2
Availability of resources	0

5.5.1.4 Training transparency

Most possible mistakes are difficult to identify. Especially the cleaning must be done correctly because insufficient cleaning can leave a layer of fat on the nanometre scale on the workpiece that is invisible to the naked eye.

The training itself can be observed easily by the trainer. There is no significant barrier that hinders the observation or communication by the trainer.

For the trainees, it is almost impossible to perform a self-evaluation of their actions until the lap shear test specimens are separated during the final testing and the fracture pattern can be analysed. The feedback is therefore delayed until the final steps of the training task.

The significance of training transparency factors is summarised in Table 30. The following statements support the rating:

- Room temperature and humidity have a major influence on the viscosity and the mixing of the adhesive.
- Insufficient cleaning can result in weak adhesion.
- If the solvent has not evaporated completely, the adhesive will not work as intended. However, the solvent is visible, and the mistake is not made in practice.
- The cross sanding has a minor impact on the adhesion.
- A faulty or expired adhesive can be an issue, although it rarely occurs.
- The adhesive does not work as intended if both components are not mixed correctly.
- If the workpieces are not joined correctly, it negatively affects the adhesion.
- The hardening of the adhesive is usually done overnight. If the adhesive is not hardened completely, it will impact the test results.
- The trainee is supervised by qualified staff while operating the universal testing machine. The universal testing machine is easy to use, and there is no significant risk to generate faulty test results.
- No barrier prevents the trainer from observing the training.
- The hardening and ageing times cause a significant transparency factor because the feedback stems from the testing and is delayed by one to two days.

Table 30: Gluing use case – training transparency factors with significance rating

Training transparency factors	Significance
Non-transparent mistake: Room temperature and humidity outside of the acceptable range	2
Non-transparent mistake: Insufficient cleaning	2
Non-transparent mistake: Solvent did not evaporate completely	0
Non-transparent mistake: Cross sanding was not performed correctly	1
Non-transparent mistake: The adhesive was faulty or expired	1
Non-transparent mistake: The adhesive was not mixed correctly	2
Non-transparent mistake: The adhesive was not applied correctly	2
Non-transparent mistake: The workpieces were not joined correctly	2
Non-transparent mistake: The adhesive did not harden correctly	1
Non-transparent mistake: The universal testing machine was not used correctly	0
Training is difficult to observe by the trainer	0
Feedback is delayed	2

5.5.1.5 Training adaptability

The significance of training adaptability factors is summarised in Table 31. The following statements support the rating:

- The possibility of performing the training at different locations and settings is significantly hindered by its dependence on heavy equipment and PPE requirements.
- A Blended learning approach would be beneficial, especially regarding the limitations caused by the COVID-19 pandemic. However, this is hindered by practical exercises and the required machines, tools, and equipment.
- A trial-and-error approach would also be beneficial. However, it is currently hindered by delayed feedback.
- The difficulty is fixed in the current training. In some cases, it would be beneficial if the difficulty could be increased, e. g., by using more viscose adhesives or by changing the specifications regarding the surface finish.
- The group size is limited to one or two trainees. A benefit could be achieved if a simulator would allow for more flexible group sizes.

Table 31: Gluing use case – training adaptability factors with significance rating

Training adaptability factors	Significance
The training requires non-portable objects	2
Personal protective equipment (PPE) is required	2
Trial-and-error approach is impracticable	2
Autonomous training is restricted or impractical	0
Difficulty cannot be adjusted	1
Process complexity is high and cannot be reduced for training	0
Additional information cannot be conveyed on site	0
Group size cannot be adjusted	1
Blended Learning cannot be implemented	2

5.5.2   Outline of the HMI design

The first step to defining an HMI design outline is to derive the HMI design requirements from the identified applicability factors (Table 32). Applicability factors that were rated as insignificant by the interviewees (S=0) are removed from the list.

Table 32: Gluing use case – definition of HMI design requirements

Applicability factor	S	Related training objective	HMI design requirement
Risk of the trainee not using the Personal Protective Equipment (PPE) as intended	2	The trainee can use PPE correctly	The training simulation shall simulate the adhesive and include PPE optionally
Risk of the adhesive coming into contact with unprotected skin of the trainee	1	No specific training objective	The training simulation shall simulate the adhesive
Risk of the adhesive not disposed of as hazardous waste	1	The trainee is aware that the adhesive must be disposed of as hazardous waste	The training simulation shall simulate the adhesive and train its disposal as hazardous waste
Risk of the trainee attempting to take the lap shear test specimens out of the heating vat without tools or protection	1	No specific training objective	The training simulation shall simulate the adhesive
Cost factor: positioning device	1	The trainee can use the positioning device to fix the positions of workpieces	The simulation shall not require a real positioning device
Cost factor: PPE (safety glasses, gloves, lab coat)	1	The trainee can use PPE correctly	The training simulation shall simulate the adhesive and include PPE optionally
Cost factor: heating oven	2	No specific training objective	The simulation shall not require a real heating oven
Cost factor: ventilation System	2	No specific training objective	The training simulation shall simulate the adhesive
Cost factor: universal testing machine	2	No specific training objective	The training simulation shall simulate the universal testing machine
Cost factor: double cartridge with glue: Araldite 2013	1	No specific training objective	The training simulation shall simulate the adhesive
Cost factor: hazardous waste disposal	2	No specific training objective	The training simulation shall simulate the adhesive and train its disposal as hazardous

			waste
Drying time (1)	1	The trainee knows that the solvent must evaporate before continuing	The training simulation shall simulate the cleaning of the workpieces and support a time-skipping function for the evaporation of the solvent
Drying time (2)	1	The trainee knows that the solvent must evaporate before continuing	The training simulation shall simulate the cleaning of the workpieces and support a time-skipping function for the evaporation of the solvent
Hardening time (3)	2	The trainee knows that the adhesive must dry before the bond can be tested	The training simulation shall simulate the adhesive and support a time-skipping function for its hardening
Ageing time (4)	2	The trainee knows how ageing affects the adhesive bond	The training simulation shall simulate the adhesive and support a time-skipping function for its ageing
Non-transparent mistake: Room temperature and humidity outside of the acceptable range	2	The trainee knows that temperature and humidity can affect the adhesive bond	The training simulation shall include an option to configure room temperature and humidity and provide feedback
Non-transparent mistake: Insufficient cleaning	2	The trainee can clean the workpieces	The training simulation shall provide feedback if the workpieces are not properly cleaned
Non-transparent mistake: Cross sanding was not performed correctly	1	The trainee can sand the workpieces	The training simulation shall provide feedback if the workpieces are not properly sanded
Non-transparent mistake: The adhesive was faulty or expired	1	No specific training objective	The training simulation shall simulate the adhesive
Non-transparent mistake: The adhesive was not mixed correctly	2	The trainee can operate the static mixer	The training simulation shall provide feedback if the adhesive is not properly mixed
Non-transparent mistake: The adhesive was not applied correctly	2	The trainee can apply the adhesive	The training simulation shall provide feedback if the adhesive is not properly applied

Non-transparent mistake: The workpieces were not joined correctly	2	The trainee can use the positioning device to fix the positions of workpieces	The training simulation shall provide feedback if the positioning device is not operated properly
Non-transparent mistake: The adhesive did not harden correctly	1	The trainee knows that the adhesive must dry before the bond can be tested	The training simulation shall simulate the drying time of the adhesive and provides feedback
Feedback is delayed	2	No specific training objective	The training simulation shall provide real-time feedback
The training requires non-portable objects	2	No specific training objective	The training simulator shall be portable
Personal protective equipment (PPE) is mandatory	2	The trainee can use PPE correctly	The training simulation shall simulate the adhesive and include PPE optionally
The trial-and-error approach is impracticable	2	No specific training objective	The training simulation shall realistically simulate the consequences of mistakes without risk.
Difficulty cannot be adjusted	1	No specific training objective	The training simulation shall include an option to configure the evaluation strictness and the extent of the feedback.
Group size cannot be adjusted	1	No specific training objective	The training simulation shall include an option to show a visual overlay on the workpiece that indicates liquids
Blended Learning cannot be implemented	2	No specific training objective	The training simulation shall be designed as a web-based application

In the next step, the identified HMI design requirements are consolidated by combining requirements that concern similar issues or objects and removing inconsistencies (Table 33). This step is performed to facilitate the definition of an HMI design outline.

Table 33: Gluing use case – consolidation of HMI requirements

HMI design requirement	Consolidated HMI design requirement
The training simulation shall simulate the adhesive and include PPE optionally	The training simulation shall simulate the adhesive and: • include PPE optionally, • train its disposal as hazardous waste, • support a time-skipping function for its hardening and ageing • provide feedback if it is not properly mixed • provide feedback if it is not properly applied
The training simulation shall simulate the adhesive	
The training simulation shall simulate the adhesive and train its disposal as hazardous waste	
The training simulation shall simulate the adhesive	
The training simulation shall simulate the adhesive and include PPE optionally	
The simulation shall not require a real heating oven	
The training simulation shall simulate the adhesive	
The training simulation shall simulate the adhesive and support a time-skipping function for its hardening	
The training simulation shall simulate the adhesive	
The training simulation shall simulate the adhesive and support a time-skipping function for its ageing	
The training simulation shall simulate the adhesive and train its disposal as hazardous waste	
The training simulation shall simulate the adhesive	
The training simulation shall provide feedback if the adhesive is not properly mixed	
The training simulation shall provide feedback if the adhesive is not properly applied	
The training simulation shall simulate the drying time of the adhesive and provides feedback	
The training simulation shall simulate the	

adhesive and include PPE optionally	
The simulation shall not require a real positioning device	The training simulation shall provide feedback if the positioning device is not operated properly
The training simulation shall provide feedback if the positioning device is not operated properly	
The training simulation shall simulate the universal testing machine	The training simulation shall simulate the universal testing machine
The training simulation shall provide feedback if the workpieces are not properly sanded	The training simulation shall provide feedback if the workpieces are not properly sanded
The training simulation shall simulate the cleaning of the workpieces and support a time-skipping function for the evaporation of the solvent	The training simulation shall simulate the cleaning of the workpieces and • support a time-skipping function for the evaporation of the solvent, • provide feedback if the workpieces are not properly cleaned
The training simulation shall simulate the cleaning of the workpieces and support a time-skipping function for the evaporation of the solvent	
The training simulation shall provide feedback if the workpieces are not properly cleaned	
The training simulation shall include an option to show a visual overlay on the workpiece that indicates liquids	The training simulation shall include an option to configure feedback to: show a visual overlay on the workpiece that indicates liquids, provide real-time guidance, simulate the consequences of mistakes without risk, be based on a configurable room temperature and humidity, adjust the evaluation strictness and the extent of the feedback.
The training simulation shall provide real-time feedback	
The training simulation shall realistically simulate the consequences of mistakes without risk.	
The training simulation shall include an option to configure the evaluation strictness and the extent of the feedback.	
The training simulation shall include an option to configure room temperature and humidity and provide feedback	
The training simulator shall be portable	The training simulator shall be portable
The training simulation shall be designed as a web-based application	

Some of the analysed HMI design requirements contradict each other and had to be removed during the consolidation. From a cost perspective, it would be beneficial to remove the positioning device. However, the manual operation of the position-

ing device is an integral part of the training experience and causally related to the training objective that the trainee can use the positioning device to fix the positions of workpieces. The best functional fidelity could be achieved with a physical positioning device, whose position is captured by positioning sensors or optical detection. The positioning device would be a specialised peripheral that also contradicts the design of the training simulation as a web-based application.

Psychomotor skills are an integral part of the training. Therefore, the HMI design outline should include physical objects. For a sensor-based evaluation of input actions, the training simulator needs to detect surface contaminations and the adhesive on the workpieces. The proposed training simulator detects these liquids via an optical scanner system. Feedback is projected directly on the workpieces via a projector to enable an Augmented Reality (AR) overlay (Figure 16).
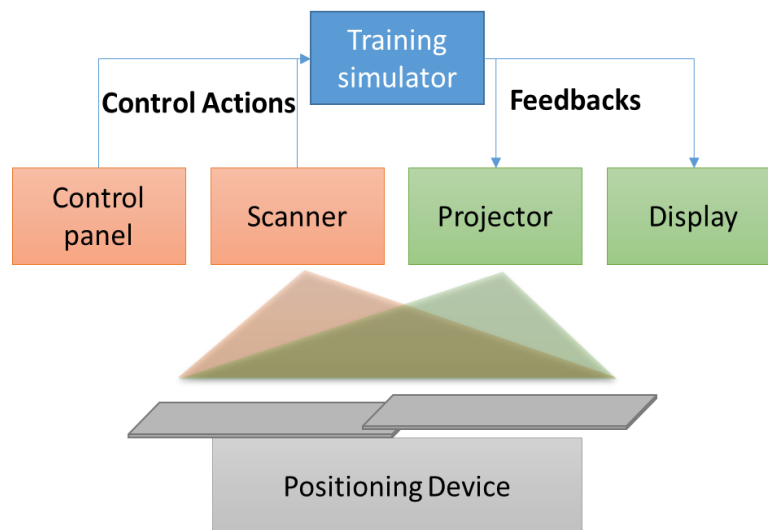
Figure 16: Gluing use case – Schematic visualisation of the proposed HMI design outline

After the trainer has configured the training task, the trainee reads the room temperature and relative humidity measurements from an integrated display. The trainee then follows the original task and puts the workpieces under the scanner, enabling the training simulator to detect the outcome of the cleaning and cross-sanding sub-tasks. If the functionality is activated via the control panel, an overlay highlighting contaminations or improperly sanded sections can be activated.

The proposed HMI design uses a non-functional gel that mimics the viscosity of the original adhesive. A cartridge press and spatula must be used to properly distribute the gel on the workpiece, which is controlled optically by the scanner. The positioning device is then used to fixate the workpieces in the intended position. Finally, the trainee can use the control panel to skip the drying time and simulate a lap shear test. The lap shear test results are calculated based on the input. Detailed

feedback is displayed that depicts deviations from optimal cross-sanding, cleaning, distribution of the adhesive, positioning of the workpieces, and drying time.

5.5.3 Analysis of technological risk and assessment of the achievable benefit

The final step of the proposed task analysis methodology is assessing the achievable benefit based on the identified applicability factors, the HMI design outline, and the technological risk.

5.5.3.1 Analysis of technological risk

The proposed HMI design relies on an optical scanning and image processing system to detect the position and surface structure of the workpieces and liquids and contaminations. Optical detection systems should detect particle sizes of up to 0,5-0,3μm (cf. Lilienfeld 1986), which would suffice for fat particles (Di Marzo 2016). If the detection of contaminations should exceed the hardware capabilities, the trainer could prepare the workpieces with a fluid that is easier to detect by the system.

Another challenge towards optical scanning is the positioning of the workpieces. Once the workpieces are fixated, only the surface of the bottom workpiece can be scanned from above. This limitation can be bypassed with either a more complex scanning system or requires the trainee to put the workpieces under the scanner after each sanding, cleaning, and distributing adhesive to enable the training simulator to detect the outcome.

A training simulator that teaches gluing tasks or similar applications has not been identified during the literature analysis. Therefore, and because of the challenges towards the scanning system, the proposed gluing training simulator has a relatively high technological risk.

5.5.3.2 Assessment of the achievable benefit

The proposed HMI design outline inherits a high technological risk and does not achieve all potential benefits (Table 34). The training simulator requires a real positioning device. The drying time of the cleaning sub-tasks has not been eliminated, and a variation of the group size or a Blended Learning approach is still impracticable.

A better result might be achievable with a Virtual Reality (VR) application. However, the haptic interface of a VR system might not provide the required feedback quality and, thereby, functional fidelity to train psychomotor skills.

Nevertheless, the proposed HMI design outline achieves most benefits by replacing the adhesive with a non-toxic gel, integrating sensor-based feedback, and removing the dependence on a ventilation system, universal testing machine, and heating oven.

Table 34: Gluing use case – summary of the achievable benefit

Applicability factor	S	Achievable Benefit
Risk of the trainee not using the Personal Protective Equipment (PPE) as intended	2	Yes
Risk of the adhesive coming into contact with unprotected skin of the trainee	1	Yes
Risk of the adhesive not disposed of as hazardous waste	1	Yes
Risk of the trainee attempting to take the lap shear test specimens out of the heating vat without tools or protection	1	Yes
Cost factor: positioning device	1	No
Cost factor: PPE (safety glasses, gloves, lab coat)	1	Yes
Cost factor: heating oven	2	Yes
Cost factor: ventilation System	2	Yes
Cost factor: universal testing machine	2	Yes
Cost factor: double cartridge with glue: Araldite 2013	1	Yes
Cost factor: hazardous waste disposal	2	Yes
Drying time (1)	1	No
Drying time (2)	1	No
Hardening time (3)	2	Yes
Ageing time (4)	2	Yes
Non-transparent mistake: Room temperature and humidity outside of the acceptable range	2	Yes
Non-transparent mistake: Insufficient cleaning	2	Yes
Non-transparent mistake: Cross sanding was not performed correctly	1	Yes
Non-transparent mistake: The adhesive was faulty or expired	1	Yes
Non-transparent mistake: The adhesive was not mixed correctly	2	Yes
Non-transparent mistake: The adhesive was not applied correctly	2	Yes
Non-transparent mistake: The workpieces were not joined correctly	2	Yes
Non-transparent mistake: The adhesive did not harden correctly	1	Yes
Feedback is delayed	2	Yes
The training requires non-portable objects	2	Yes
Personal protective equipment (PPE) is mandatory	2	Yes
The trial-and-error approach is impracticable	2	Yes
Difficulty cannot be adjusted	1	Yes
Group size cannot be adjusted	1	No
Blended Learning cannot be implemented	2	No

5.6　　　　Use case IV – Additive manufacturing (metal binder jetting)

Additive manufacturing has been added into the draft of DIN 8580:2020-01 within the primary shaping main group. Additive manufacturing was not included in DIN 8580:2003, which has been the basis for the literature analysis. Therefore, an additional literature analysis was performed. Additive manufacturing qualifies as a potential case because no simulation-based training applications have been identified within the additive manufacturing group.

The interview on the additive manufacturing case has been conducted with a project manager for additive manufacturing, who works at a research institution and offers vocational training.

A task description was provided in advance to extract a task model and perform the task analysis. The analysed task focuses on metal binder jetting. Metal binder jetting uses a metal powder that consists of particles below 70 µm and is fused with a binding liquid (binder). A heat treatment (curing) is performed as an additional step to harden the binder.
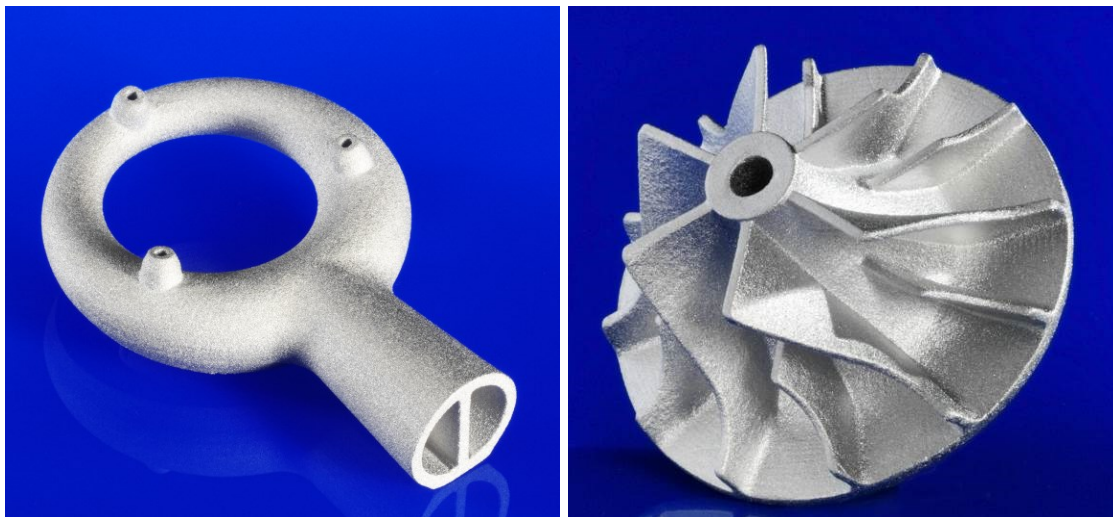
Figure 17: Additive manufacturing use case – Sample products with complex geometry[6]

The training does not focus on specific workpieces and is performed on the job. The training includes the manufacturing of various products with complex geometry (Figure 17). The training task spans multiple sub-tasks from cleaning and filling the machine until the sintering of the workpieces. The sub-tasks performed by the trainee are:

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[6] Image provided by Fraunhofer Institute for Manufacturing Technology and Advanced Materials IFAM

- Putting the personal protective equipment on, consisting of an FFP3 mask, disposable gloves, a lab coat, and an optional whole-body protection suit.
- Fetching the metal powder from the storage area.
- Cleaning of the machine in case the material is changed.
- Inserting the metal powder into the printing machine while under a ventilation exhaust system.
- Starting the machine and software.
- Performing a function test of the machine and setting it into a normal position.
- Configuring printing parameters within the software.
- Loading the workpiece model into the software and performing a scaling, position, and orientation check.
- Starting the printing.
- Monitoring the machine functions during the first 30 layers.
- Continue to monitor the machine functions every 30 minutes to spot faults in the workpiece or if the machine has stopped.
- Extracting the build box containing the workpiece once the printing has finished.
- Placing the build box in an oven for 4 hours at 180°C for curing (to harden the binder).
- Extracting the workpiece with a ventilated extraction station by separating the workpieces from loose powder.
- Cleaning the extracted workpiece (green part) carefully.
- The trainee hands the workpiece over to technical staff for sintering, which completes the task for the trainee.
- Technical staff performs the sintering at >1250°C inside a sintering oven.

The task required multiple tools, machines, and consumables that are summarised in Table 35.

Table 35: Additive manufacturing use case – Tools and consumables

Tools and Machines	Consumables
Printing machine	PPE equipment (FFP3 mask, disposable gloves, a lab coat, and an optional whole-body protection suit)
Ventilation exhaust system	Metal powder
Ventilation extraction station	Binder
Curing oven	
Sintering oven	

The interview started with individual questions that were intended to clarify uncertainties in the task analysis. The following statements were made:

- The training is usually performed on-the-job and not with a specific training task because of the high utilisation of the machine and the significant cleaning effort required to switch the metal powder.
- The training uses the Innovent+® printing system from the manufacturer ExOne (Figure 18).
- Printing tasks on the machine are performed with various metal powders and the corresponding binders.
- The cleaning between tasks differs greatly depending on the metal powders that are used in these tasks. If both tasks use the same metal powder, only a rough cleaning of sensors and movable parts is required. If different metal powders are used, the machine must be thoroughly cleaned to remove all remaining particles. The intensive cleaning takes multiple hours of work.
- The manufacturer also provides an operating software that is used to configure the printing tasks. The most important parameters during the configuration include layer thickness, binder saturation, coating speed, drying time per layer, and powder bed temperature.
- Leftovers of the metal powder are recycled.

Figure 18: The Innovent+® printing system[7]

The task-related applicability factors are analysed in the next subsection following the structure of training risks, training costs, training availability, training transparency, and training adaptability.

5.6.1 Identification of task-related applicability factors regarding simulation-based training

A list of applicability factors was compiled in advance of the interviews by applying the first step of the task analysis to the task model. The resulting list is shown for each category in tables 36 to 40. The significance ratings were filled during step four of the interview. No new applicability factors were identified in steps two and three of the interviews.

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[7] Image provided by ExOne GmbH

The interviewee was asked how the current training could be improved. It was stated that the augmentation of the training with additional information could greatly improve the training. The additional information should convey knowledge about the bonding between metal powder and binder.

The question of how the current training could be improved was repeated, focusing on each category of applicability factors. The following statements were made:

- **Training risks**: Unprotected contact with metal powder and binder should be avoided, and binder vapours could be potentially harmful. Each employee undergoes regular medical examinations to monitor a possible accumulation of heavy metals as a protective measure.
- **Training Costs:** The investment in the printing system is the most relevant cost factor within the training.
- **Training Availability:** The availability could be potentially limited by a shortage of curing and sintering ovens, but this is currently not the case.
- **Training transparency:** Errors can be caused by the software, which is not always clear but also not relevant for training purposes. If human errors are the cause, it is usually comprehensible for the instructor.
- **Adaptability:** The training would benefit from an augmentation of the tasks with a simulation of the bonding between metal powder.

The last step of the interview was to discuss the rating of the identified applicability factors on a numeric rating scale with the possible values of 0 (insignificant), 1 (low significance), and 2 (high significance). The results are described in the following for each category.

5.6.1.1 Training risks

The significance of training risk factors is summarised in Table 36. The following statements support the rating:

- The highest risk within the training environment is caused by the metal powder, which has a particle size below 70 μm. The powder may cause harm if it is inhaled or comes into contact with unprotected skin, which is possible if the trainee does not use the Personal Protective Equipment (PPE) as intended.
- If either the metal powder box or the build box is dropped during the transport, or the ventilation exhaust system is not used as intended, the metal powder may be released into the environment and cause a fire hazard.

- The machine is unlikely to be damaged during cleaning. Operating the machine without setting it into a normal position also does not cause any damage.
- If faults are not spotted during the printing, it causes a loss of time and resources.
- The curing oven's heated surfaces at 180°C are a potential hazard and may cause burns if the trainee comes into contact with them.

Table 36: Additive manufacturing use case – Training risk factors with significance rating

Training risk factors	Significance
Risk of the trainee not using the Personal Protective Equipment (PPE) as intended	2
Risk of dropping the metal powder box	2
Risk of dropping the build box during transport	2
Risk of releasing metal powder outside of the ventilation exhaust system	1
Risk of damaging the machine during cleaning	0
Risk of not setting the machine to normal position	0
Risk of a not properly configured machine	1
Risk of not spotted faults during printing	1
Risk of making contact with heated surfaces of the curing oven	1

5.6.1.2 Training costs

The significance of training cost factors is summarised in Table 37. The following statements support the rating:

- The training task requires multiple tools and machines that are used to form and harden the workpiece. The printing system and the sintering oven are the biggest cost factors.
- The metal powder and binder are the most expensive consumables.
- The training also requires a trainer and occupies the machine not to be used for other jobs during this time.

Table 37: Additive manufacturing use case – Training cost factors with significance rating

Training cost factors	Significance
Cost factor: printing system	1
Cost factor: ventilation exhaust system	0
Cost factor: ventilation extraction station	0
Cost factor: curing oven	0
Cost factor: sintering oven	2
Cost factor: PPE equipment (FFP3 mask, disposable gloves, a lab coat, and a whole-body protection suit)	0
Cost factor: metal powder	1
Cost factor: binder	1
Cost factor: presence of a trainer	2
Cost factor: production downtime	2
Cost factor: indirect manufacturing costs	0

5.6.1.3 Training availability

The training is interrupted multiple times by waiting times. The metal binder jetting takes multiple hours and requires regular monitoring. Additional waiting times occur during the curing and the sintering. The schematic visualisation of training and waiting times is depicted in Figure 19. It is not feasible to skip the real system's waiting times without negatively impacting the result.
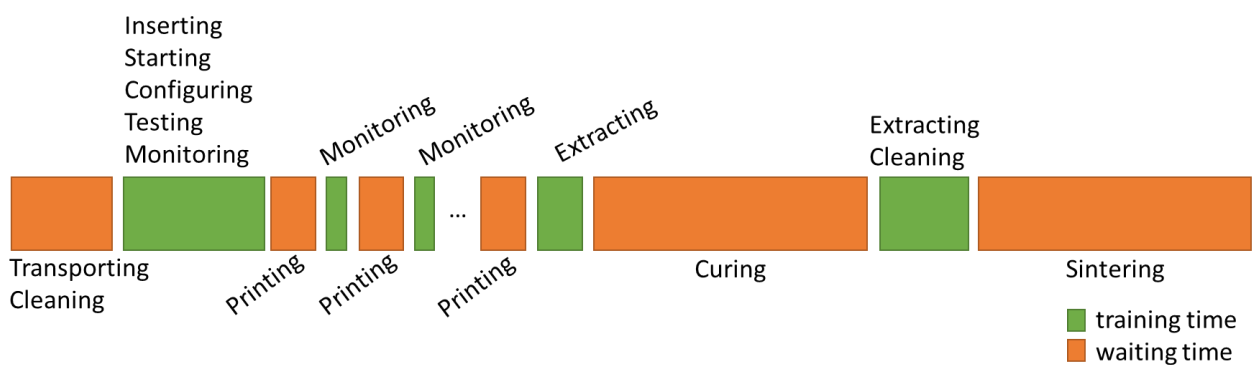
Figure 19: Additive manufacturing use case – Schematic visualisation of training times (green) and waiting times (orange)

The significance of training availability factors is summarised in Table 38. The following statements support the rating:

- Multiple support sub-tasks are required, including the transportation of the metal powder and binder and the cleaning of the printing system. These sub-tasks are not within the training focus. If the executed task's metal powder

differs from the previously used powder, all remaining particles must be removed. This deep cleaning usually involves a partial disassembly of the printing system and takes multiple hours.

- The waiting time during metal binder jetting, curing, and sintering significantly impact the training duration.
- The training requires multiple resources (experts, equipment, binder jetting machine, curing oven, sintering oven, consumables). However, their availability this not a limiting factor in the training.

Table 38: Additive manufacturing use case – Training availability factors with significance rating

Training availability factors	Significance
Support tasks cannot be skipped	2
Repeated waiting times during metal binder jetting	2
Waiting time during curing	2
Waiting time during sintering	2
Availability of technical staff	0
Availability of resources	1

5.6.1.4 Training transparency

The significance of training transparency factors is summarised in Table 39. If the final workpiece properties do not meet the requirements, multiple mistakes could have been made that are not easy to identify. The following statements support the rating:

- If the wrong metal powder or binder was used, the effect might only be recognisable in the final product's diverging material properties. If the wrong binder is used, the printing is more likely to fail and is easy to spot.
- If the printing system was not cleaned properly, the printing either fails, or the final product does not have the intended material properties.
- If not enough metal powder or binder is inserted, the printing system does not notify the trainee. The printing is continued, which leads to a waste of time and resources.
- It is relatively obvious to the user if the machine was not set to normal position or if the workpiece's scaling, positioning, and orientation were not configured properly.
- Layer thickness, binder saturation, coating speed, drying time per layer, and powder bed temperature are parameters that the trainee must configure. A

    mistake in this configuration is not always transparent but can cause the task to fail.

- The curing is required for the binder to harden. Incomplete curing is difficult to spot but may cause damage to the workpiece during further transport or cleaning.
- Damages during the extraction or transport of the workpiece are usually obvious.
- The observation of the training by the trainer is not hindered.
- The causalities of possible errors may be difficult to identify. However, delayed feedback is not considered a critical issue.

Table 39: Additive manufacturing use case – Training transparency factors with significance rating

Training transparency factors	Significance
Non-transparent mistake: The wrong metal powder was used.	2
Non-transparent mistake: The wrong binder was used.	1
Non-transparent mistake: The printing system was not cleaned properly	1
Non-transparent mistake: Not enough metal powder or binder was inserted	2
Non-transparent mistake: The machine was not set to normal position	0
Non-transparent mistake: Scaling, positioning, and orientation was not set properly	0
Non-transparent mistake: Parameters not configured properly in the software	2
Non-transparent mistake: Curing was not performed properly	2
Non-transparent mistake: Workpiece was damaged during extraction or transport	0
Non-transparent mistake: Workpiece was not cleaned properly	0
Training is difficult to observe by the trainer	0
Feedback is delayed	0

5.6.1.5 Training adaptability

The existing safety measures and the required equipment result in limitations to the training design. The significance of training adaptability factors is summarised in Table 40. The following statements support the rating:

- The training requires a metal binder jetting machine, a ventilation exhaust system, a ventilated extraction device, a curing oven, and a sintering oven. These objects cannot be transported to another location without significant effort.
- The training cannot be conducted without personal protective equipment (PPE), including an FFP3 mask, disposable gloves, a lab coat, and an optional whole-body protection suit.
- The task has a significant duration and a high complexity, making learning by a trial-and-error approach impracticable.
- It is not possible to adjust the difficulty or to reduce the complexity without changing the workpiece. However, this is not a critical factor in the current training design.
- The number of trainees per printing system should not be greater than two. It would be beneficial if the training could be conducted in larger groups without reducing the training quality.
- Blended Learning might be beneficial during the COVID-19 pandemic but is not intended in regular training practice.

Table 40: Additive manufacturing use case – Training adaptability factors with significance rating

Training adaptability factors	Significance
The training requires non-portable objects	1
Personal protective equipment (PPE) is required	2
A trial-and-error approach is impracticable	2
Autonomous training is restricted or impractical	2
Difficulty cannot be adjusted	0
Process complexity is high and cannot be reduced for training	0
Additional information cannot be conveyed on site	1
Group size cannot be adjusted	1
Blended Learning cannot be implemented	0

5.6.2 Outline of the HMI design

The first step to defining an HMI design outline is to derive the HMI design requirements from the identified applicability factors (Table 41). Applicability factors that were rated as insignificant by the interviewees (S=0) are removed from the list.

Table 41: Additive manufacturing use case - definition of HMI design requirements

Applicability factor	S	Related training objective	HMI design requirement
Risk of the trainee not using the Personal Protective Equipment (PPE) as intended	2	The trainee can correctly use PPE	The training simulation shall simulate additive manufacturing virtually and include PPE as an option
Risk of dropping the metal powder box	2	No specific training objective	The training simulation shall not require metal powder
Risk of dropping the build box during transport	2	No specific training objective	The training simulation shall not require metal powder
Risk of releasing metal powder outside of the ventilation exhaust system	1	No specific training objective	The training simulation shall not require metal powder
Risk of a not properly configured machine	1	The trainee can configure the machine	The training simulation shall simulate additive manufacturing virtually
Risk of not spotted faults during printing	1	The trainee can identify faulty during printing	The training simulation shall simulate additive manufacturing virtually
Risk of making contact with heated surfaces of the curing oven	1	No specific training objective	The training simulation shall simulate the curing oven virtually
Cost factor: printing system	1	No specific training objective	The training simulation shall simulate a virtual printing system
Cost factor: sintering oven	2	No specific training objective	The training simulation shall simulate a virtual sintering oven
Cost factor: metal powder	1	The trainee can correctly identify and use the metal powder	The training simulation shall simulate metal powder virtually
Cost factor: binder	1	The trainee can correctly identify and use the binder	The training simulation shall simulate the binder virtually
Cost factor: presence of a trainer	2	No specific training objective	The training simulation shall provide automated instruction and feedback to reduce the workload of the trainer

Cost factor: production downtime	2	No specific training objective	The training simulation shall simulate a virtual printing system
Support tasks cannot be skipped	2	The trainee is aware of the support tasks	The training simulation shall include a function to skip support tasks
Repeated waiting times during metal binder jetting	2	No specific training objective	The training simulation shall include a fast-forward function during the metal binder jetting
Waiting time during curing	2	No specific training objective	The training simulation shall include a fast-forward function during the curing
Waiting time during sintering	2	No specific training objective	The training simulation shall include a fast-forward function during the sintering
Availability of resources	1	No specific training objective	The training simulation shall not depend on the availability of machines
Non-transparent mistake: The wrong metal powder was used.	2	The trainee can correctly select and use the metal powder	The training simulation shall simulate metal powder virtually and include a selection
Non-transparent mistake: The wrong binder was used.	1	The trainee can correctly select and use the binder	The training simulation shall simulate the binder virtually and include a selection
Non-transparent mistake: The printing system was not cleaned properly	1	The trainee can clean the printing system and identify when cleaning is required	The training simulation shall simulate contaminations and provide feedback if the printing system was not cleaned properly
Non-transparent mistake: Not enough metal powder or binder was inserted	2	The trainee can insert metal powder and binder and identify a shortage	The training simulation shall simulate the insertion of metal powder and binder and a shortage thereof
Non-transparent mistake: Parameters not configured properly in the software	2	The trainee can configure the printing software	The training simulation shall simulate the configuration options of the printing software
Non-transparent mistake: Curing was not performed properly	2	The trainee can perform the curing of the workpiece	The training simulation shall simulate the curing of the workpiece and provide feedback if it is not performed correctly

The training requires non-portable objects	1	No specific training objective	The training simulator shall be portable
Personal protective equipment (PPE) is required	2	The trainee can correctly use PPE	The training simulation shall simulate additive manufacturing virtually and include PPE as an option
A trial-and-error approach is impracticable	2	No specific training objective	The training simulation shall realistically simulate the consequences of mistakes without risk.
Autonomous training is restricted or impractical	2	No specific training objective	The training simulation shall automatically provide instructions and feedback
Additional information cannot be conveyed on site	1	No specific training objective	The training simulation shall include an option to convey additional information on the manufacturing process
Group size cannot be adjusted	1	No specific training objective	The training simulator shall support external digital media to enable training in larger groups

In the next step, the identified HMI design requirements are consolidated by combining requirements that concern similar issues or objects and removing inconsistencies (Table 42). This step is performed to facilitate the definition of an HMI design outline.

Table 42: Additive manufacturing use case – consolidation of HMI requirements

HMI design requirement	Consolidated HMI design require-ment
The training simulation shall simulate additive manufacturing virtually and include PPE as an option	The training simulation shall simulate a virtual printing system and: • Include a fast-forward function, • Simulate contaminations and cleaning, • Make PPE optional
The training simulation shall simulate additive manufacturing virtually	
The training simulation shall simulate a virtual printing system	
The training simulation shall simulate additive manufacturing virtually	
The training simulation shall simulate a virtual printing system	
The training simulation shall include a fast-forward function during the metal binder jetting	
The training simulation shall simulate contaminations and provide feedback if the printing system was not cleaned properly	
The training simulation shall simulate additive manufacturing virtually and include PPE as an option	
The training simulation shall simulate metal powder virtually	The training simulation shall simulate metal powder virtually and: • Require a selection from multiple powders, • Simulate the consequences of a shortage after inserting insufficient filled metal powder box
The training simulation shall not require metal powder	
The training simulation shall not require metal powder	
The training simulation shall not require metal powder	
The training simulation shall simulate metal powder virtually and include a selection	
The training simulation shall simulate the insertion of metal powder and binder and a shortage thereof	
The training simulation shall simulate the binder virtually	The training simulation shall simulate binder virtually and: • Require a selection from multi-
The training simulation shall simulate the binder virtually and include a selection	

The training simulation shall simulate the insertion of metal powder and binder and a shortage thereof	ple binders, • Simulate the consequences of a binder shortage after inserting not enough binder liquid
The training simulation shall simulate the curing oven virtually	The training simulation shall simulate a virtual curing oven and:
The training simulation shall include a fast-forward function during the curing	• include a fast-forward function for the curing,
The training simulation shall simulate the curing of the workpiece and provide feedback if it is not performed correctly	• simulate the consequences if the curing is not performed correctly
The training simulation shall simulate a virtual sintering oven	The training simulation shall simulate a virtual sintering oven and include a fast-forward function
The training simulation shall include a fast-forward function during the sintering	
The training simulation shall automatically provide instructions and feedback	The training simulation shall automatically provide instructions and feedback
The training simulation shall provide automated instruction and feedback to reduce the workload of the trainer	
The training simulation shall realistically simulate the consequences of mistakes without risk.	The training simulation shall include the configuration options of the original system and simulate the consequences of mistakes without risk
The training simulation shall simulate the configuration options of the printing software	
The training simulation shall include a function to skip support tasks	The training simulation shall include a function to skip support tasks
The training simulation shall not depend on the availability of machines	The training simulation shall not depend on the availability of machines or require non-portable objects
The training simulator shall be portable	
The training simulation shall include an option to convey additional information on the manufacturing process	The training simulator shall support external digital media and be able to display additional content on the manufacturing process
The training simulator shall support external digital media to enable training in larger groups	

The consolidated HMI design requirements (Table 42) confirm the focus on the training of cognitive skills. An exception is the cleaning sub-task. However, instead of replicating a physical cleaning of a model, the simulator may instead focus on the procedural knowledge required to determine if cleaning is required. Because

a specialised haptic interface is not required, a computer-based simulator may be the best choice.

A virtual training environment can be conveyed via Virtual Reality (VR) technology. Without restrictions of the real world, all machines, tools, and consumables of the original task can be simulated without risks, and a fast-forward function can be implemented. VR controllers may be used to manipulate virtual objects and simulate the transportation sub-tasks, including the consequences of a dropped metal powder box.

The hardware of the outlined training simulator consists of a VR system consisting of a VR HMD, VR controllers, base stations, and a computing device. The training simulator would be portable, and the output may be duplicated to external digital media for larger groups.

5.6.3 Analysis of technological risk and assessment of the achievable benefit

The final step of the proposed task analysis methodology is assessing the achievable benefit based on the identified applicability factors, the HMI design outline, and the technological risk.

5.6.3.1 Analysis of technological risk

The intended VR system could be realised with state-of-the-art hardware that inherits no technological risk. A larger challenge lies within the creation of a simulation model with sufficient functional fidelity.

The additive manufacturing process itself has already been simulated using multiple approaches such as a particle-based simulation (Parteli & Pöschel 2016), finite element simulation (Schoinochoritis et al. 2017), microstructure models (Lindgren et al. 2016), and a kinetic Monte Carlo model (Rodgers et al. 2017). The outlined training simulation would require integrating a simulation model for additive manufacturing into a virtual environment that simulates the complete training task.

Because the required VR hardware is available and the additive manufacturing process can be simulated with various approaches, the technological risk of an additive manufacturing training simulator is estimated to be relatively low.

5.6.3.2 Assessment of the achievable benefit

The proposed HMI design outline has a low technological risk, and almost all identified applicability factors result in an achievable benefit (Table 43).

An applicability factor that cannot be fully achieved is caused by the non-transparency of an improperly cleaned printing system. Although the cleaning of a virtual printing system could be simulated, the training simulator cannot provide a high functional fidelity for the cleaning sub-tasks without a specialised haptic interface.

In the studied system, each trainer trains one trainee on the job. Multiple VR systems or a VR system connected to external digital media can enable a trainer to train multiple larger groups. The greatest benefit is gained by the virtualisation of the printing system, the curing and sintering ovens, and consumables. Without the dependency on these resources and hazardous materials, the training can be performed with considerably lower risk and demonstrated in a classroom setting.

Table 43: Additive manufacturing use case – Summary of the achievable benefit

Applicability factor	S	Achievable Benefit
Risk of the trainee not using the Personal Protective Equipment (PPE) as intended	2	Yes
Risk of dropping the metal powder box	2	Yes
Risk of dropping the build box during transport	2	Yes
Risk of releasing metal powder outside of the ventilation exhaust system	1	Yes
Risk of a not properly configured machine	1	Yes
Risk of not spotted faults during printing	1	Yes
Risk of making contact with heated surfaces of the curing oven	1	Yes
Cost factor: printing system	1	Yes
Cost factor: sintering oven	2	Yes
Cost factor: metal powder	1	Yes
Cost factor: binder	1	Yes
Cost factor: presence of a trainer	2	Yes
Cost factor: production downtime	2	Yes
Support tasks cannot be skipped	2	Yes
Repeated waiting times during metal binder jetting	2	Yes
Waiting time during curing	2	Yes
Waiting time during sintering	2	Yes
Availability of resources	1	Yes
Non-transparent mistake: The wrong metal powder was used.	2	Yes
Non-transparent mistake: The wrong binder was used.	1	Yes
Non-transparent mistake: The printing system was not cleaned properly	1	Partly
Non-transparent mistake: Not enough metal powder or binder was inserted	2	Yes
Non-transparent mistake: Parameters not configured properly in the software	2	Yes
Non-transparent mistake: Curing was not performed properly	2	Yes
The training requires non-portable objects	1	Yes
Personal protective equipment (PPE) is required	2	Yes
A trial-and-error approach is impracticable	2	Yes
Autonomous training is restricted or impractical	2	Yes
Additional information cannot be conveyed on site	1	Yes
Group size cannot be adjusted	1	Yes

The purpose of the use cases is to provide a basis for evaluating the research hypotheses, which is performed in the following subsection.

5.7 Discussion of evaluation results

In this subsection, the existing use cases and potential use cases are applied to evaluate the research hypotheses that have been defined in subsection 2.2.

H1: The potential benefit of training simulators varies between manufacturing tasks

Each applicability factor adds a potential benefit to training simulators for manufacturing tasks. Because each of the interviewees provided a unique selection of applicability factors, the potential benefit of training simulators for these manufacturing tasks varies.

Most of the applicability factors from the training risks, costs, availability, and transparency categories were derived directly from the sub-tasks and are therefore individual. The significance of the training availability applicability factors also has been assessed differently by the interviewees. Hypothesis H1 (the potential benefit of training simulators varies between manufacturing tasks) can therefore be confirmed.

H1.1: The potential benefit of training simulators is related to characteristics of the original task that are adverse for training

A potential benefit of simulation-based training can only exist if the conditions for training in the original system are non-ideal, implying that the original training task has inherent characteristics adverse to training. These characteristics have been defined as applicability factors.

The task analysis methodology has been designed to analyse applicability factors (see requirement R2, subsection 4.1). The use cases have shown that the applicability factors are suitable to identify a potential benefit of simulation-based training, thus validating the research hypothesis H1.1.

H2: The achievable benefit of training simulators for manufacturing correlates with the available potential of HMI technologies

The task analysis involved defining an HMI design outline to assess the technological risk and the achievable benefit. The use cases have shown that the achievable

benefit depends on the functional fidelity of the training simulator, which is determined by its HMI design and the potential of the available HMI technologies.

The analysed use cases have shown multiple examples of how the HMI design outline determines the difference between potential and achievable benefit:

- The proposed HMI design outline for the gluing use case requires cleaning the workpieces with a real solvent. An alternative approach with state-of-the-art VR hardware would not yield sufficient functional fidelity regarding the haptic interaction. Because the training simulator includes a real solvent, the trainee must wait until the solvent has evaporated, and the drying time cannot be skipped.
- A very similar challenge has been observed in the additive manufacturing use case. The proposed HMI design is based on a VR training simulation. The functional fidelity of the simulator regarding the cleaning of the printing system sub-task is constrained by the limited haptic interaction with the VR hardware.
- In the welding use case, sensor-based feedback regarding a non-ergonomic posture has been identified as a significant potential benefit of simulation-based training. However, the proposed HMI design outline does not include the required sensors to achieve this benefit, requiring the technical system to capture the trainee's current posture, distinguish a good from a bad posture, and provide feedback.

HMI design outlines have been proven in the use cases to be a fitting tool for a rough assessment of the technological risk and the achievable benefit. The hypothesis H2 (the achievable benefit of training simulators for manufacturing correlates with the available potential of HMI technologies) can be confirmed.

H3: A structured analysis can determine the applicability of simulation-based training for specific manufacturing tasks

The task analysis has led to assessments of the achievable benefit for each use case. These assessments can be used to perform an individual cost-benefit analysis and determine the applicability of simulation-based training.

The task analysis methodology is based on applicability factors sorted into the categories of training risks, costs, availability, transparency, and adaptability (see subsection 4.4.2). The structure has been developed as a framework to support the task analysis and to guide the interviews.

The list of applicability factors has been synthesised by combining related work from other areas with the potential benefit of 204 simulation-based training applications in manufacturing. With a potential benefit due to an adaptation towards

Blended Learning, the use case analysis has identified an additional applicability factor. A Blended Learning approach was motivated by the COVID-19 pandemic and a need for a more adaptive training approach.

The task analysis methodology cannot provide a complete cost-benefit analysis required to determine the applicability of simulation-based training. Nevertheless, it can be used to describe the achievable benefit and the implications of HMI interface technologies. The task analysis methodology can also be applied to various manufacturing tasks and expanded to fit changing environmental effects.

H4: The task analysis methodology can be used to identify factors that cause training simulators to be not applicable.

For the research of this hypothesis, the task analysis methodology has been applied to two potential use cases for which an existing application of simulation-based training has not been identified: gluing and additive manufacturing.

The gluing use case has led to the identification of a technological challenge that hinders the implementation of simulation-based training. The training focus on psychomotor skills requires the training simulator to have a complex haptic interface. The proposed HMI design outline is not ideal because the projected AR approach does not achieve all potential benefits due to its dependence on real liquids and physical objects (see subsection 5.5.3.2). The analysis revealed a potential demand for a haptic and visual interface that simulates virtual liquids with varying viscosity and achieves sufficient functional fidelity for the training task.

The proposed HMI design outline in the additive manufacturing use case features a training simulator that uses VR controllers as a haptic interface. The drawback of this approach is that the haptic interaction does not provide the functional fidelity to train the cleaning sub-task on the virtual printing system. The simulator would require a specialised haptic interface to simulate the haptic interaction during the disassembly of the printing system and the removal of metal powder.

In conclusion, the task analysis methodology can be used to identify challenges regarding the HMI design that impact the achievable benefit and the applicability of training simulators.

5.8   Limitations

The coverage of this research is limited due to the chosen scope that has been defined in subsection 1.3.

With the task analysis methodology, the research focussed on task-related applicability factors. However, stakeholder-related factors may also have an impact on the applicability of simulation-based training. These factors can be attributed to the positive effects of simulation-based training in general and are not depending on the training tasks but are related to stakeholders in the manufacturing systems, such as trainees and trainers. Some of the identified publications describe stakeholder-related factors, which are listed in the annexe in subsection 8.2.

The main objective of this research has been to identify the implications of HMI technologies for the applicability of simulation-based training in manufacturing. While these implications have been identified, the task analysis methodology does not enable a complete determination of the applicability, which would require a cost-benefit analysis. Although HMI technologies also impact the applicability of simulation-based training because they often are a major cost factor in training simulators (Seth et al. 2011), cost factors are not within the scope of this research, as described in subsection 2.2.

During the use case analysis, the interviewees have assessed the significance of each identified applicability factor. Although this assessment reflects the characteristics of the individual manufacturing system, it has been influenced by the interviewee's opinion and has no unique solution. Nevertheless, the interviewees have supported their assessment with statements, and each use case analysis has led to a result that enabled a discussion of the research hypotheses.

The HMI design outline also has no unique solution. Multiple possible approaches have been discussed during the use case analysis, and the HMI design that allows achieving the most benefit has been selected. Although it cannot be guaranteed that another unidentified HMI design does not yield a better result, the HMI design outlines have fulfilled their purpose to allow a discussion of the research hypotheses.

6 Recapitulation

The sixth chapter summarises the presented research and provides an outlook regarding future work that further extends on the topic.

6.1 Conclusion

The objective of this dissertation has been to identify the implications of Human-Machine Interface (HMI) technologies on the applicability of simulation-based training for manufacturing tasks.

A training simulator has been defined within this research as applicable towards a specific task if its implementation is justified because of benefits over conventional training. Therefore, HMI technologies can impact the applicability of simulation-based training by driving the implementation costs and enabling the achievement of benefits over conventional training. Although HMI technologies are considered a major driver of costs in training simulator design (Seth et al. 2011), the costs are a variable and individual figure that provides no basis for transferable findings. Therefore, this research has focused on the implications of HMI technologies on the benefit of simulation-based training for manufacturing tasks.

For this research, the benefits of simulation-based training are further divided into potential benefits and achievable benefits. The potential benefit is defined as the benefit of the ideal training simulation compared to conventional training and is an inherent attribute of a specific task. An achievable benefit is the fraction of a potential benefit that can be achieved in practice.

A task analysis methodology has been designed to assess the potential benefit of simulation-based training for manufacturing tasks and research the impact of HMI technologies on the achievable benefit.

The development of the task analysis methodology has been based on a systematic literature analysis regarding simulation-based training applications in manufacturing. The findings resulted in 204 applications that were aggregated to the group level of DIN 8580:2003. Process groups with more than five publications are in descending order: assembly (53), cutting with geometrically defined edge (45), welding (34), disassembly (27), and coating from liquid state (18).

The first step of the task analysis methodology is the analysis of applicability factors. Applicability factors are related to characteristics of the training task in the original system, which are detrimental to training. Applicability factors result in a potential benefit of simulation-based training compared to training in the original system. A list of applicability factors has been compiled through a combined anal-

ysis of publications from the literature analysis and other areas. These applicability factors have been sorted into five groups: Training risks, training costs, training availability, training transparency, and training adaptability.

The second step of the task analysis is the definition of an HMI outline for each applicability factor. The assessment considers the requirements that sufficient functional, physical, and psychological fidelity must be possible and that the training objectives of the original training task must be accomplishable. The requirements are then consolidated to form an HMI outline.

The third and final step of the task analysis methodology is the assessment of the achievable benefit. The achievable benefit analysis is based on the estimated technical risk of the HMI outline and whether each potential benefit can be achieved with the consolidated HMI outline.

The developed task analysis methodology has been applied to training tasks in four use cases: welding, machining, gluing, and additive manufacturing. The evaluation proved that the potential benefit of training simulators for a certain task could be described with an applicability factor assessment. The evaluation also produced multiple examples of potential benefits that were not achievable due to limitations of the available HMI technologies. These examples showed that the HMI technologies have an implication towards the applicability of simulation-based training in manufacturing due to their influence on the difference between potential and achievable benefits. The examples reveal technological challenges that may indicate a development potential for HMI technologies, adding additional value to the task analysis methodology.

6.2   Outlook and future work

The task analysis methodology is intended as an initial step towards implementing simulation-based training for manufacturing tasks. The evaluation revealed a significant achievable benefit in both potential cases. Especially the relatively high technical risk in the gluing use case could potentially justify a research project towards developing a training simulator for gluing tasks.

Future research may be conducted by applying the task analysis methodology to other training tasks. This work indicates that especially training tasks focusing on psychomotor skills hold a relatively high technical risk and a challenge towards the haptic interface design. Applying the task analysis methodology to other tasks might reveal applicability factors that have not yet been discovered.

The task analysis methodology can identify the achievable benefit of a training simulation for a specific training task. The achievable benefit can be the basis for subsequent cost-benefit analysis. An approach to determine the implementation

costs of simulation-based training is described in the annexe (subchapter 8.5, based on the feasibility study framework for decision systems by Khoong & Ku (1994). However, since cost analysis is not within the scope of this research, future research may expand on this topic.

Most of the analysed publications focus on technological aspects, and only a few stakeholder-related benefits of simulation-based training were identified (see annexe 8.2). Research focusing on occupational science or psychology holds additional factors that could impact a cost-benefit analysis of simulation-based training. These factors may include additional stakeholder-related benefits and the impact of the technology on the socio-technical system and the job specification of training personnel.

7 Literature

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8 Appendix

8.1 Training categories and applicability factors

Table 44 holds applicability factors that have been collected from other areas and sorted into the defined categories. The sources are Farmer et al. (1999), Maran & Glavin (2003), Issenberg et al. (2005), Bradley (2006), The National Research Council (1996), and Hays & Singer (1989), as described in subsection 4.4.1.

Table 44: Training categories and applicability factors from other areas

Category	Applicability factors
Training risks	• Safety, • Training in the real systems is too dangerous.
Training costs	• Replace some of the instructor's functions with a training device, • automating the process of training and instruction and consequently improving efficiency.
Training availability	• there is insufficient time available in the real system, • the circumstances required for training do not occur frequently enough, • This enables more learning experiences per unit of time and the planned distribution of learning experiences.
Training transparency	• Measure of performance and feedback, • Providing feedback, • Defined outcomes, • Providing augmented cueing and feedback, i. e., cues and feedback extrinsic to the (training) task, • Registering and diagnosing trainee performance, e. g., for debriefing or administrative purposes.
Training adaptability	• Instructional flexibility, • Providing a range of difficulties, • Being adaptable, • allowing multiple learning strategies, • Providing a range of clinical scenarios, • Active learning based on individualised needs, • Integrating within curriculum, • Adapting the training task to the performance of the trainee(s); • Providing a range of clinical scenarios,

	• the possibilities for training are restricted by environmental regulations related to noise, pollution, or other causes, • Safety regulations preclude the execution of particular tasks or manoeuvres, • Control of the type and timing of training events presented and, hence, the learning experiences that are offered to the trainee(s), • Allowing repetitive practice, • simulator validity as a realistic recreation of complex clinical situations.

8.2 Stakeholder-related benefits

Some authors of the 204 identified applications of simulation-based training in manufacturing describe stakeholder-related benefits of training simulations:

- *Motivation:* According to multiple publications (Sacks et al. 2013, Ravi 2014, Sun & Tsai 2012), simulation-based training increases the engagement and motivation of the trainees when compared to traditional training. This effect is strongest among younger trainees, related digital media use, and the gamification of learning (Monereo 2004). The National Research Council (1996) depicts improved interactions among peers during simulation-based training sessions.

- *Communication:* An implementation of simulation-based training can also positively impact the communication between stakeholders within the training process. Batista et al. (2009) describe an improved interaction between teacher and trainee. Critique can be supported by sensor data, which improves reception and reduces conflicts between trainer and trainee.

- *Entry barriers:* Some trainees react with fear towards machines or risks present within a manufacturing process. Simulation-based training can benefit these persons, as it reduces the fear and lowers the barrier for a first experience within the manufacturing process (Chang 2010). A simulation can create realistic expectations and enable trainees to learn what to expect in workshop practice during classroom training (Fang et al. 2011).

- *Learning efficiency:* Simulation-based training is believed to have an increased learning effect compared to training in the real system (Sun & Tsai 2012). Through augmentation with additional information or increased training adaptability, simulations can improve the acquisition of process-related knowledge (Fang 2011). The increased learning effect and the ability to skip supportive tasks can result in shorter training times and increase the learning efficiency (Gilles et al. 2006, Crison et al. 2005).

The identified benefits are related to trainers and (potential) trainees. However, training simulations could also be used to support advertisements (cf. Cian et al. 2020). For example, the U.S. Army has used multiple training simulations for advertising purposes (Perez 2012).

8.3   Technology-related costs and limitations

The identified publications listed certain factors that concern the applicability of training simulators related to the applied HMI technologies. These factors mostly concern technological or financial limitations that hinder the applications:

- *Capital costs:* The implementation of simulation-based training may require a significant investment (Sun & Tsai 2012, Ravi 2008). Economic viability is difficult to achieve through high software costs and additional workload (Ravi 2009). Furthermore, it may be necessary to customise a training solution to individual requirements. Customisation of the simulation model results in additional developing costs for training materials and content (Sacks et al. 2013, Ravi 2008, Ravi 2009).
- *Recurrent costs:* Trainers that engage with simulation-based training require skillsets that differ from traditional training. The training simulations can cause an additional workload and demand a qualified technical workforce (Ravi 2008, Ravi 2009).
- *Hardware limitations:* Some authors expressed shortcomings of available hardware that negatively impacts the result. Crison et al. (2004) argued that the functional fidelity of the applied haptic controller was not satisfactory. Gilles et al. (2006) stated that the HMI did not convey the expected resemblance to the real conditions of visuals, sound, noise, vibrations, and smell. In another case, the simulation model had to be simplified to reduce the system load (Li & Winitsky 1999). Sun & Tsai (2012) described drawbacks due to the relative immaturity of the VR technology, which may cause simulator sickness and is not accepted by all users. The HMI design also determines the training adaptability: As workstations are limited, it is difficult to provide individuals in larger groups with opportunities to control the environment (Sacks et al. 2013).
- *Simulation model limitations:* Verifying functional fidelity is difficult due to process complexity (Cockerell et al. 1993). Prediction of defects through simulation software is difficult to predict reliably (Ravi 2009).

8.4   Hazards and operability study methodology for risk analysis in complex systems

Risk analysis is a broad field that is employed in many disciplines and with varying focus. Since the 1970s, this has led to numerous methodologies (Abbasi et al. 1998). Tixier et al. (2002) reviewed 62 risk analysis methodologies for industrial plants. The categorisation lists a group of methodologies that focusses on processes. Among these, the HAZOP (hazards and operability) study method has a strong focus on identifying hazards.

The HAZOP study method was developed in the 1960s and stems from chemical engineering (Crawley & Tyler 2015). It is used to identify potential failure modes that may risk human safety and health, the environment, the facility, or the process (Trammell et al. 2004). Thereby, it can be used to identify process-related hazards that may be reduced or eliminated through the utilisation of simulation-based training.

The results that can be achieved with the HAZOP study method are limited based on the available process knowledge. A holistic analysis of hazards can only be performed if the relevant process parameters are known. On the contrary, the HAZOP study method can be an unnecessary step in case of obvious risks of a manufacturing process. It may also be difficult to assess risks that result from interactions between different entities in a manufacturing system.

The steps of the risk analysis to determine the potential risks of a manufacturing process is based on the HAZOP study method, as defined by Crawley & Tyler (2015):

1. *Define task and design intention:* The first step is to define the task within the manufacturing process that is to be analysed. This definition includes the design intention that determines the expected result of the task. The definition of the expected results serves as a basis to identify possible deviations. A clear definition of the expected results and the system boundaries is a required foundation for structured analysis.

2. *Assess applicability:* It is recommended to assess if the HAZOP study method should be applied for the identified task. This assessment should be based on the process complexity. If the risks related to the focussed task are well-known, it is unnecessary to perform the analysis. In this case, a structured visualisation such as a fault tree analysis might be more appropriate for the task.

3. *Define parameters:* The next step is to define process parameters that the trainee can change or that may change during training. The parameters can

have a quantifiable or binary value. Process-related knowledge is required to identify the parameters that are related to risks.

4. *Generate deviations:* Each defined parameter is combined with guidewords to create a meaningful variation. This method includes combinations of guidewords and parameters that have a physical effect on the system (Crawley & Tyler 2015). The purpose of these guidewords and their combination with parameters is to structure a brainstorming session to achieve comprehensive results. A list of guidewords (Table 45) has been initially proposed by the IEC (2016). Although it stems from the chemical industry, the guidewords are also applicable to manufacturing systems (PQRI 2015).

5. *Identify causes and consequences:* To provide additional context, the causes and the related consequences can be determined for the identified deviations. The consequences should consider immediate or delayed effects and include external entities to the system that may be affected by the tasks (Crawley & Tyler 2015).

6. *Identify safeguards:* The deviations or consequences may be hindered by safeguards. Their availability and reliability should be considered during the analysis.

7. *Risk assessment:* As the last step, the risks can be assessed based on the identified hazards and the available safeguards. The assessment of risks is usually performed with qualitative values regarding their severity and frequency.

The HAZOP study method continues with the definition and assignment of actions, risk communications, and risk reviews (PQRI 2015). For this research, the risk assessment is sufficient to determine the potential benefit of simulation-based training compared to training on-the-job.

Table 45: Exemplary guidewords for the HAZOP study method (Crawley & Tyler 2015, IEC 2016, PQRI 2015)

Guideword	Meaning
No or not	The design intent is not achieved
Other than	Another activity takes place, or unusual activity occurs, or an uncommon condition exists
More	Quantitative increase in a parameter
Less	Quantitative decrease in a parameter
Early/late	The timing is different from the intention
As well as	An additional activity occurs
Before/after	The step (or some part of it) is affected out of sequence
Part of	Only some of the design intention is achieved
Reverse (of intent)	The logical opposite of the design intention occurs

The described approach defines parameters and uses them to structure an analysis of meaningful deviations. Crawley & Tyler (2015) propose an alternative approach that starts with guidewords and uses them as a structure to brainstorm and try each parameter in turn. If the process complexity is high, this can be used as a complementary technique.

8.5 Cost analysis of simulation-based training

An implementation of simulation-based training typically requires a certain investment. Multiple identified publications listed costs as the major downside of manufacturing training simulators (Sun & Tsai 2012, Ravi 2009, Salazar 1994). The authors provide no information on the composition of these costs but generally refer to capital costs required for the procurement and implementation. The Recurring costs of simulation-based training are usually lower than those of training on the job.

The proposed methodology utilises the framework that has been developed by Khoong & Ku (1994). It classifies the costs of simulation-based training into tangible and intangible cost factors and distinguishes between capital costs and recurring costs (Khoong & Ku 1994, p. 104). The categories of cost factors are described in the following subsections.

8.5.1 Tangible cost factors of simulation-based training

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). Training simulators developed for a specific scenario or are bought off the shelf may result in additional costs for customisation (Sacks et al. 2013). The operation of a training simulator requires a skill set that differs from traditional training (Ravi 2008). Trainer and trainee usually must be able to interact with digital media and have basic troubleshooting skills.

It is not always possible or necessary to differentiate the costs related to the implementation or operation of training simulators. If the simulator is bought from another company or cost reporting does not allow for a detailed analysis, this might be the case. However, a detailed list of tangible cost factors can support the analysis and provide a more qualified basis for purchasing.

Khoong & Ku (1994, p. 104) define capital costs as one-time development and installation costs. When applied to the implementation of simulation-based training, these factors may include:

- Hardware costs,
- Software costs,
- Workforce costs for system development,
- System testing costs,
- User training costs,
- Cost of system installation, including the cost of interfacing to existing systems in the organisation,
- Costs associated with the switch from a previous system to the new system, such as the amount of expected remaining returns from the previous system that should now be written off with the removal of the previous system,
- Administrative overhead, including costs of procurement and legal procedures.

The tangible cost factors also include recurring costs related to the operation of a training simulator. The items proposed by Khoong & Ku (1994, p. 104) are:

- Workforce costs for operating the system,
- Hardware maintenance costs,
- Software royalties,
- Rental and lease charges for resources,
- Electrical costs,
- Costs of interactions between the system and external parties include data transfers and CPU time on external systems.

The listed items only represent a selection of tangible cost factors during the implementation and operation of simulation-based training. The impact and composition of these costs depend on the individual business model and training design.

8.5.2   Intangible cost factors

An implementation of simulation-based training can be related to cost factors that are not quantifiable. These intangible cost factors related to risks can cause financial damage for the organisation that employs simulation-based training. For this purpose, Khoong & Ku (1994, p. 104) provide a list of risk factors. The term intangible cost factors are used instead within this research to avoid confusion with the training risks that have been described in section 4.4.4.1 The factors listed by Khoong & Ku (1994, p. 104) are:

- *Power:* Does the hardware provide all necessary capabilities (e.g., in terms of speed' memory' and disk space) in the near to long term? Will the system become obsolete sooner than expected?
- *Reliability:* What is the possibility of system failure? How much damage can a failure cause?
- *Scalability:* Is the system scalable in its problem-solving capabilities? What are the costs of sustaining the utility of the system when problem complexities scale up?
- *Extensibility:* Related to scalability. If future requirements necessitate modifications and extensions to the system, how difficult would that be? What and when is the likelihood of a total system revamp?
- *Organisational risk:* The extent to which the organisation can carry out the changes required by the project, i.e., the user requirements.
- *Information system infrastructure risk:* The degree to which the proposed project fits into the overall information systems direction of the organisation.
- *Technological uncertainties:* Technological uncertainties are a clear risk factor when a substantial investment needs to be made, and useful products are needed. However, if the project is intended mainly to serve research goals, then technological uncertainties may be accepted characteristics of the project and thus not explicitly treated as risks.
- Risks associated with the *competence of resources* involved in the project development phase, such as the domain experts, knowledge engineers, and programmers.
- Risks associated with the *users' resistance* to the system and their competence in operating the system.
- Risks associated with the *warranty period* for hardware and software maintenance, and the strength of technical support from vendors.

8.6 Program code for the training task in Computer Numerical Control (CNC) machining

The analysed task involves the CNC machining of the training workpiece "Lachplatte". The workpiece, which resembles a smiley, has a challenging geometry and has been specifically designed for training.

The CNC program includes multiple steps:

- Milling a rectangular pocket (114 x 74 x 1mm),
- Milling a rectangular pocket (35 x 30 x 3mm),
- Milling two circular pockets (Ø 25 x 6mm),
- Milling a circular pocket (Ø 30 x 6mm),
- Milling a cavity (r=42mm x 15mm, angle=70°),
- Milling two cavities (30 x 10 x 3mm),
- Milling a cavity (40 x 10 x 6mm),
- Milling a cavity (r=42mm x 8mm, angle=70°),
- Milling three circular pockets (Ø 8mm).

The correct program code for the task is:

```
0 BEGIN PGM Lachplatte MM
1 BLK FORM 0.1 Z X+0 Y+0 Z-20
2 BLK FORM 0.2 X+120 Y+80 Z+0
3 TOOL CALL "VHM-12" Z S10000 F8000
4 M3 M25
5 * - TASCHE <114*74*1mm>
6 CYCL DEF 251 RECHTECKTASCHE Q215=+0
7 L X+60 Y+40 Z-1 FMAX M99
8 * - TASCHE<35*30*3mm>
9 TOOL CALL "VHM-8" Z S12000 F8000
10 M3 M25
11 CYCL DEF 251 RECHTECKTASCHE Q215=+0
12 L X+94 Y+54 Z-1 FMAX M99
13 CYCL DEF 251 RECHTECKTASCHE Q215=+0
14 L X+26 Y+54 Z-1 FMAX M99
15 * - KREISTASCHE <25mm>
16 CYCL DEF 252 KREISTASCHE Q215=+0
17 L X+26 Y+54 Z-3 FMAX M99
18 L X+94 Y+54 Z-3 FMAX M99
19 * - KREISTASCHE<30mm>
20 CYCL DEF 252 KREISTASCHE Q215=+0
21 L X+60 Y+40 Z-1 FMAX M99
22 * - RUND NUT <15mm>
23 CYCL DEF 254 RUNDE NUT Q215=+0
24 CYCL CALL
25 * - NUTFRAESEN
26 CYCL DEF 253 NUTENFRAESEN Q215=+0
27 L X+12 Y+14 Z-1 FMAX M99
28 CYCL DEF 253 NUTENFRAESEN Q215=+0
29 L X+108 Y+14 Z-1 FMAX M99
30 CYCL DEF 253 NUTENFRAESEN Q215=+0
31 L X+60 Y+65 Z-1 FMAX M99
32 TOOL CALL "VHM-6" Z S12000 F6000
```

```
33 M3 M25
34 * - RUND NUT <8mm>
35 CYCL DEF 254 RUNDE NUT Q215=+0
36 CYCL CALL
37 * - KREISTASCHE<8mm>
38 CYCL DEF 252 KREISTASCHE Q215=+0
39 L X+34 Y+54 Z-3 FMAX M99
40 L X+86 Y+54 Z-3 FMAX M99
41 CYCL DEF 252 KREISTASCHE Q215=+0
42 L X+60 Y+40 Z-6 FMAX M99
43 L X-500 Y-1 Z-1 FMAX M91 M30
44 END PGM Lachplatte MM
```