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Technology Adoption Of Collaborative Robots For Welding in Small And Medium-sized Enterprises: A Case Study Analysis

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Abstract

Welding tasks in small and medium-sized enterprises (SMEs) are exemplary for high mix and low volume manufacturing. Today, 96 % of newly installed workplaces in SMEs are set up without a robot, although collaborative robot solutions for small lot sizes are emerging. In a study across the institutional ecosystem, technology providers, and technology adopters of the regional state Baden-Württemberg in Germany, SME technology adoption with respect to the use of collaborative robots was surveyed in form of expert interviews with feedback by direct users. The study helps SMEs to understand the necessary requirements and prerequisites for the design of collaborative work systems. As a result, the main barriers and potentials of the use of collaborative robots in welding in SMEs are presented, including ergonomic benefits to workers, the importance of skilled tradesmen in robot programming, and the lack of general robot knowledge across SMEs. Furthermore, the detailed analysis of two case studies gives insights into individual implementation processes at pioneering SMEs in this technological application field.

Keywords

Industrie 4.0; Human-Robot Interaction; Collaborative Robots; Technology Adoption; Small and Medium-sized Enterprises.

1. Introduction

For over ten years, Industrie 4.0 has held various promises for technological advances with regard to productivity, cost-efficiency, quality and flexibility improvements [1,2]. We define Industrie 4.0 as the existence of networked factory systems that use “intelligence” from sensors and algorithmic decision-making to collaborate with other machines and humans within the factory, rather than operating independently [3]. Larger manufacturing companies have implemented multiple use cases based on Industrie 4.0 technologies, while significant effects on productivity outcomes could not always be observed [4,5]. Although they represent a valuable fraction of industrial economies, small and medium-sized enterprises (SMEs) are especially lagging behind in terms of Industrie 4.0 technology adoption [6]. Large manufacturers are equipped with a multitude of industrial robots, and installations have grown steadily over the past years as robots have become more capable of both intelligence and networking across other factory systems [7]. SMEs have not yet reached the same level of automation due to limitations in economies of scale and investment budgets.

SMEs are characteristically high mix and low volume manufacturing, which provides viable opportunities for the use of Industrie 4.0 technologies for increased flexibility [8], such as smarter and easier-to-program

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robots that can support human-robot collaborations [3]. This study aims to explore Industrie 4.0 technology adoption with respect to the use of collaborative robots in welding processes at SMEs. The study is designed across the institutional ecosystem, technology providers, and technology adopters of the regional state Baden-Württemberg in Germany.

This paper presents the findings from the study and is structured as follows. Chapter 2 explains the relevant backgrounds for collaborative robot welding in SMEs, including this study's definition of SMEs, the basics of human-robot collaboration and the manufacturing ecosystem of collaborative robot welding. In chapter 3, the study design and research methodology are presented. Chapter 4 encompasses the overall results of the study with technology adoption barriers and benefits, as well as two case studies with detailed information on the technology adoption at two representative SMEs. The limitations of the study are discussed in chapter 5, followed by the conclusions in chapter 6.

2. Background: the use of collaborative robots in welding processes at SMEs

SMEs represent 99 % of all businesses in the EU as well as in Germany [9,10]. SMEs are usually characterized by the headcount of employees, sometimes in combination with financial limits. According to the definition of the European Commission, SMEs are defined by a staff headcount of up to 250 employees and either a turnover of €50 million or below or a balance sheet total of €43 million or below [9]. In addition to SMEs, the widely used but not clearly defined German term *Mittelstand* exists, which describes highly focused, very efficient and often family-owned enterprises of up to 500 employees [11,12]. For this study, the definition limit for an SME was set to up to 500 employees.

As one of many technological advances of Industrie 4.0, the use of collaborative robots in the form of human-robot collaboration (HRC) or human-robot interaction (HRI) has become a broad spectrum for research activities [13–16,3]. Human-robot collaboration has the potential to safely increase productivity of human labour and improve the ergonomics of manual tasks, by optimizing for the inclusion of a human participant in the decision-making loop as a member of a human-robot team [17]. A collaborative robot is a robot that is capable of collaborative operation, defined as an operation where purposely designed robots work in direct cooperation with a human within a defined workspace [18]. Thus, a collaborative operation is always defined by a combination of workspace and task specifics, resulting in four different interaction levels according to Behrens (2019): (1) shared workspace without shared task; (2) shared workspace and shared task without physical interaction; (3) Shared workspace and shared task that is ''handed-over'' from human to robot; and (4) shared workspace and shared task with physical interaction [19,20]. Users increasingly expect cobots to be easier to program than industrial or non-collaborative robots, often by the same shop-floor workers who share workspace with the cobots rather than dedicated robot programmers.

The range of applications for use of collaborative robots includes assembly operations, transportation of goods, material handling and commissioning, machine feeding, service robotics, and the automation of unergonomic tasks, e.g. in welding. Welding is a manufacturing process to join materials, e.g. metals, by using high heat to melt different parts together and allowing them to cool, causing fusion [21]. Welding can be carried out with different filler materials and energy sources. In combination with a welding nozzle on a collaborative robot arm, different gas welding types are available [21].

This paper is concerned with an analysis of the manufacturing ecosystem and value chain of collaborative robots for welding, which is displayed in Figure 1. The value chain consists of technology providers and technology adopters as well as the end customers. The central group of technology adopters in this study is only represented by the sub-group of SMEs of up to 500 employees. In general, all types of metalworking manufacturing companies qualify as technology adopters and there are various examples for applications in larger manufacturing enterprises. The supplier side is represented by multiple stages of technology providers. The collaborative robots are produced by the original robot manufacturers, and then either sold via regionally distributed resellers and integrators, or via a joint reseller/integrator organization. The end customers are not central in this study and have only been included as an external group with certain needs and requirements towards the technology adopting SMEs. The ecosystem of collaborative robot welding includes third-party institutions, associations and other funding bodies providing valuable assistance for SMEs and the other value chain entities. As new solutions such as easy programming becoming available, start-ups and other innovative service providers gain importance in the manufacturing ecosystem for collaborative robot welding.

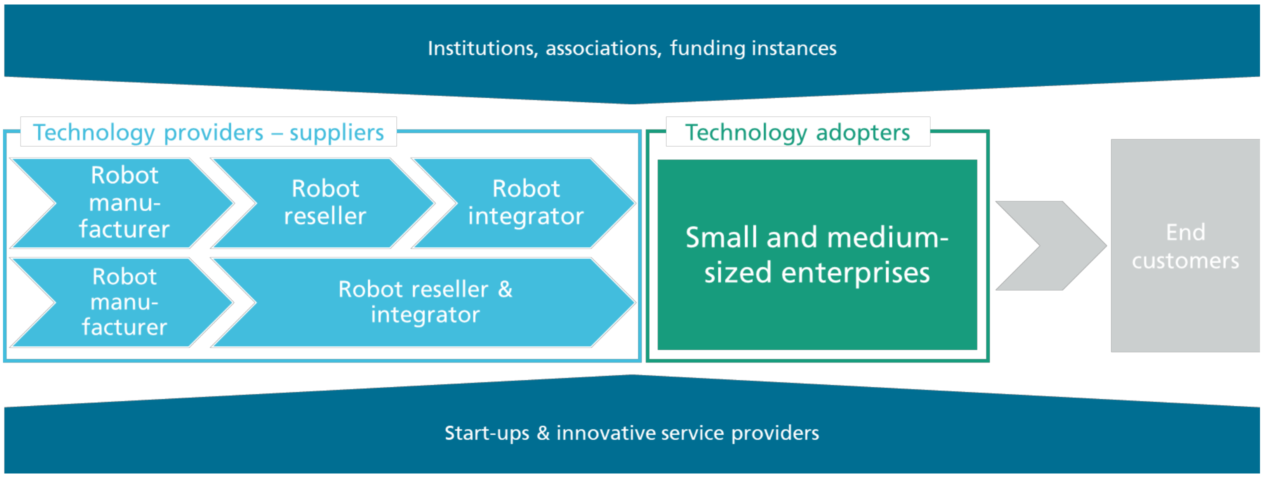

Figure 1: Manufacturing ecosystem for collaborative robot welding

3. Study design and research methodology

In the tradition of firm-level corporate interviews and factory tours across sociology and human factors research [22,23], this study consists of a field study with interviews of participants in the collaborative robot welding ecosystem of the German regional state Baden-Württemberg, from November 2021 – January 2022. The aim of the study is to analyse the Industrie 4.0 technology adoption of SMEs as well as the institutional ecosystem. According to the manufacturing ecosystem presented in Figure 1, the study covers four levels: (1) institutional ecosystem; (2) technology providers; (3) technology adopters; (4) workplace and workers. As mentioned beforehand, the study is focused on SMEs as technology adopters. The workplace level is included in the study in order to not only analyse the managerial decision making by SMEs, but also the potential shop floor changes through the introduction of new technologies and their implications for new skills and competence profiles.

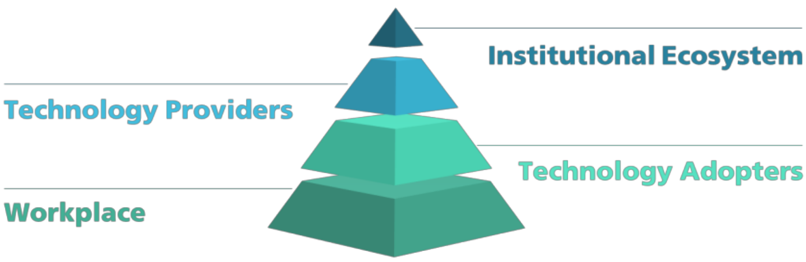

Figure 2: Study levels

The study design as well as the execution of interviews were affected by the global coronavirus pandemic. Interview questionnaires were designed to be used for both in-person and remote interviews. Strict General Data Protection Regulation (GDPR) measures were applied in order to guarantee the anonymous and only study-related use of company data during and after the interviews. E.g. the interviewees were always free to quit the interview or not to answer certain questions, and the raw data was held on secured servers reserved for this study only.

The selection of participants for the study was made upon certain criteria to reach representative participants from each of the four study levels. Public and private ecosystem institutions were required to provide active support for SMEs to assess and acquire new Industrie 4.0 technologies. Criteria for technology providers were the provision of collaborative robots in an original manufacturer, reseller, or integrator role with multiple products sold to SMEs. Criteria for SMEs to be assessed as technology adopters were the workforce limit of up to 500 employees, the implementation of a cobot solution and the access to workplace insights. Because of the scarcity in SMEs with cobots for welding automation, the selection of participants was not made randomly, but through mainly publicly available information on pioneering SMEs with early installations. The analysis of the interviews from this field study is mainly based on qualitative data to explore the Industrie 4.0 technology adoption of the sample group. The analysis process is based on video and audio recordings, anonymised transcription of the recorded interviews, and attribution of codes for statements. A common transcription software was used for the transcription and coding activities. The clustering of codes allowed for detailed analysis of the interviews. The qualitative interview data serves to summarize technology adoption barriers and benefits for the sample group of interviewed participants.

4. Study results: Industrie 4.0 technology adoption by SMEs in Baden-Württemberg

During the field study from November 2021 – January 2022, 16 interviews were carried out with companies and institutions from Baden-Württemberg. The field of participants consists of 7 public ecosystem institutions, 1 private ecosystem start-up, 4 technology providers (who have collectively provided dozens of collaborative robots to SMEs), and 4 technology-adopting SMEs (representing a total of 862 workers who have been exposed to cobots, although only a handful of workers regularly interact with the robots). Each group was interviewed with an adapted semi-standardized questionnaire, which asked how companies decided to buy a robot, how they integrated the robot, how they chose and educated people to operate the robot, whether operation has differed from expectations, and how the robot itself might be improved. The interviews were recorded, transcribed and analyzed. All technology providers and adopters voluntarily provided access to their factories and workplaces. In this chapter, the results will be presented in an overall summary of technology adoption barriers and benefits deduced from all 16 interviews. Sections 4.1 and 4.2 provide detailed insights into the technology adoption at SMEs through two case studies from representative companies, in which many of the barriers and benefits listed below can be identified.

In general, the reported barriers for cobot welding adoption are relatively low– in stark contrast to the difficulties experienced by SMEs adopting industrial robots [6,8]. All participants of the ecosystem and especially the SMEs as users of the technology were satisfied or even surprised by the successful implementation process. Open-mindedness was mentioned the most as a crucial success factor or barrier, when missing. Table 1 lists further technology adoption barriers, especially with regard to the current limitations of the relatively new technology.

Table 1: Summary of technology adoption barriers from the interviews

Technology adoption barriers for welding cobots
1. Mindset: Management and workers cannot be closed-minded about new technology
2. Lack of cobot versatility: Humans can better adjust to unexpected events and perform complex/critical tasks
3. Lot sizes: Cobot automation of jobs is rarely beneficial for very small (<5) and large lot sizes (>100)
4. Physical interference: Cobot can only weld in certain positions without bumping into itself or other limitations
5. Welding jigs: Cobots require new jigs to hold parts in place during robotic welding, while humans can use hands
6. Monotonous leftover jobs: After partial automation, cobots may create boring and monotonous leftover tasks

The interviews shed light on various possible benefits of the Industry 4.0 technology adoption for SMEs. The introduction of cobot welding has several positive effects on the work system, e.g. improvements of human factors and ergonomics for workers [14,16]. The work organization allows the welding experts to be autonomous in terms of their decision of which work piece to weld manually or with cobot assistance. The ease of use even causes excitement for the job, and was mentioned by two firms as a selling point for attracting welding apprentices to adopting workplaces. Most of the process preconditions are fulfilled by the cobot, while output in terms of high and steady welding quality as well as reduced rework can be optimized. From a managerial standpoint, the relatively low investment cost seems to be over-compensated by savings for health insurance costs, reduced wages for contract welders, waste reduction, and flexibility gains in shift planning. See Table 2 for the list of technology adoption benefits from the interviews.

Table 2: Summary of technology adoption benefits from the interviews

Technology adoption benefits for welding cobots
1. Human factors: Less toxic fumes breathed in by welders
2. Human factors: Reduced stress for eyes, particularly for older workers
3. Human factors: Reduced physical strain with regard to uncomfortable posture, particularly for older workers
4. Task: Welding is a very suitable process for cobot automation due to tooling and relatively low feeding speed
5. Quality: Cobots provide consistently high-quality welding results over a whole shift or longer
6. Rework: Cobot welding can reduce the overhead on rework processing due to the homogeneity of welds
7. Ease of use: Cobot programming is perceived as very easy to use by the welding experts
8. Investment costs: Relatively low investment costs (ca. 50.000 € – 100.000 €) versus industrial robots
9. Operating costs: Welding cobots can be cheaper than workers for repetitive, non-variable tasks
10. Worker shortages: Automation of a fraction of welding jobs can help to cope with welding expert shortages
11. Flexibility: Cobot use can be scaled up or down instead of hiring contractor workers
12. Added shifts: Cobot can work through night shifts, holidays, and when humans are unwilling to work
13. Worker autonomy: Welders can choose on their own which jobs to automate and which to do manually
14. High-tech signalling: Adopting firms can use cobots to attract new workers and advertise to end customers

Considering the task profile of human, collaborative or automated welding, different variables have to be taken into account when planning for the right individual workplace setup. In combination with other variables such as the geometry and length of welding parts and seams, the interviewees named the lot size of planned jobs as an important variable for the use of collaborative robots for welding. Even when jobs are technically feasible for welding with a collaborative robot, the process of programming the cobot for a small batch size takes too long to justify automation. In SMEs, this planning task is usually transferred to the welding expert with cobot programming skills, who decides which jobs to automate. From the interviews, these experts seemed to appreciate the additional workforce provided by the cobot. With growing, but rather low reported lot sizes, the programming efforts scale with the lot size. Since SMEs typically have high variety in their products and jobs, the lot size should be considered as a key variable in planning of cobot welding capacities. For higher lot sizes, cobot welding faces competition with existing industrial robot solutions, which tend to outperform them at scale even though the initial programming takes longer. However, other variables apply as well and need to be considered holistically.

4.1 Case study 1: Medium-sized enterprise with movable welding cobot

The first case study is based on the interview with the head of production of an SME from Baden-Württemberg with 220 employees and annual revenues of about €23 million. The SME produces make-to-order goods with smaller lot sizes. The SME has global customers, four international factory locations, and delivers in the premium quality segment for special applications. The SME covers the full value-creation chain from electromechanical engineering and constructing, manufacturing, assembling, mounting, and servicing for the produced goods. With regard to the institutional ecosystem, the SME is member of the Chamber of Commerce and Industry (*Industrie- und Handelskammer, IHK*) and the German Welding Society (*Deutscher Verband für Schweißen und verwandte Verfahren e.V., DVS*). The SME regularly hosts three apprentices per year in its own facilities and is actively involved in the apprenticeship curriculum in collaboration with IHK and DVS. The SME also collaborates with research institutions for specific engineering-related projects and opens up its factory as a best practice for visits by other German manufacturing companies.

As one of the first users of this technology, the SME set up a workplace consisting of a *Universal Robot* collaborative robot arm equipped with a welding tool and nozzle by an integrator. The workplace serves as an addition to other manual welding stations. In the initial setup from 2018, the cobot was attached to the welding table and able to be moved to various positions– which turned out to be too rigid (Barriers #2 and 5). In order to build two separate workplaces next to each other, a five meter long linear axis was installed above the table with a hanging cobot solution in 2019. This new and current setup allows for the next job to be prepared by a human co-worker while another welding job is running. Usually, the preparation covers the removal of finished goods, the optional change of welding jigs, and the positioning of new welding pieces. Figure 3 and 4 show manual welding and the current cobot welding workplaces.

The cobot welding solution was first identified as an innovation at a metalworking trade fair in 2017. With a suitable job of 100 identical parts to be delivered in 2018 (Barrier #3), both middle management and the owner were convinced that the relatively low investment costs would quickly pay off by freeing up more time for valuable human welders (Benefit #9) and improving workplace satisfaction by reducing welding fumes (Benefit #1). Except for welding time calculations, no other investment or cost-related calculations were made: the cobot's welding speed was comparable to human welders (Benefit #4). Due to the steel types welded at this SME, it was crucial that the cobot welding solution acquired was capable of switching between metal inert/active gas (MIG/MAG) and tungsten inert gas (TIG) welding, which was satisfied by a market ready and integrated solution. The trust as well as the open-mindedness by the owner/CEO is typical for an SME and was important for the fast acquisition process (Barrier #1). The welding manager estimated that 95 % of the firm's welding jobs could theoretically be done by the cobot, yet the cobot is only responsible for about 3 % of jobs due to the burden of programming time for smaller batches.

Figure 3 and 4: Workplaces for manual welding (left) and cobot welding (right) at the SME from case study 1

The SME identified further use cases for the application of a second cobot workplace, which is already planned as a next acquisition. The identified case would use another Universal Robots cobot to handle materials in an integrated IT system with an existing laser cutting machine, and could be used to add a night shift in addition to the current work organization (Benefit #12). The company is also trying to advance with the current welding cobot solution to weld thinner metal sheets as well as to add sensors to the welding tool for higher adaptability and quality (Benefit #5).

4.2 Case study 2: Medium-sized enterprise with stationary welding cobot

The second case study is based on an interview with three representatives of an SME from Baden-Württemberg with 160 employees and annual revenues of about €26 million. The SME produces individually engineered machinery for a special branch application. The SME exports 80 % of its goods to global customers and offers a product range from small special machinery to small businesses, as well as premium and huge-dimension special machinery to industrial corporate firms. The SME covers the full value-creation chain from electromechanical engineering and constructing, manufacturing, assembling, mounting, and servicing for the produced goods. Over 70 current employees, i.e. nearly 50 % of the workforce, completed work-study apprenticeships in this company, and the SME hosts multiple apprentices per year in its own facilities. With regard to the institutional ecosystem, the SME as an early pioneer user collaborates with technology providers and research institutions in order to identify new improvement measures for the cobot welding workplace. Since 2007, the SME has built up and established its own lean production system, which is not typical for an SME, including a Kaizen system for continuous improvement processes, and various Lean principles and methods such as a milk run based on a Kanban system.

As a pioneering SME, this company acquired a first version of an integrated cobot solution provider in 2017 before its official market entry. The cobot is placed in an upright position on a typical welding table and can be flexibly moved (Barrier #4). As required by the SME from case study 1, the firm needed a solution to switch between the welding types MIG/MAG and TIG. With improvements during the last years, the analysed setup can be used for welding stainless steel plates of 1 mm or thicker. The cobot welding results were reported to be of high overall quality, leading to drastic reductions in rework after welding (Benefits #5 and 6). Figure 5 and 6 show the cobot welding setup with an exemplary, relatively complex work piece.

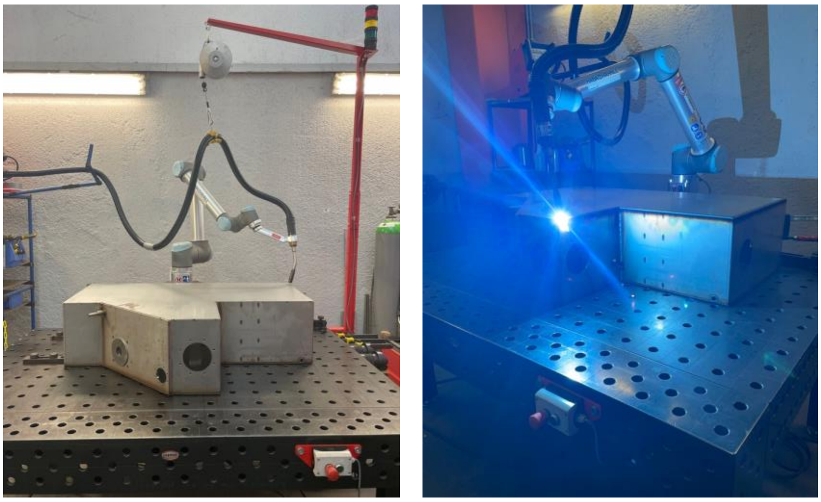

Figure 5 and 6: Workplace for collaborative robot welding at the SME from case study 2

The selection of programmers for the cobot was dependent on existing proficiency as a welding expert as well as open-mindedness (Barrier #1). At this SME, three welding experts were qualified for this role. One of them is under 22 years old, while the oldest is over 60 years old and appreciates the reduced eye strain from programming the robot instead of welding himself (Benefit #2). The training provided by the integrator took less than one day, followed up by 1-2 weeks of workers figuring out the programming on their own.

The direct users were surprised by the ease of use and improved ergonomics, and found joy in this new task (Benefits #3 and 7). The introduction of this technology was accompanied by the works council and did not lead to changes in wages paid, but to up-skilling and increased involvement of welders (Benefit #13). The SME built up expertise in their own construction of jigs and racks for welding automation (Barrier #5). In an exemplary joint effort by welding experts and the Lean production team, a high-volume job of 300-400 pieces per year was set up for cobot welding, using a rack for five pieces per automated welding program.

With help from shop floor welders, production managers have identified further work pieces to be welded by means of the cobot. Furthermore, the SME engages with research institutions to integrate sensor-based features for automated weld seam following, which could enable further applications and the need for standardisation of fabricated parts (Barrier #2). The management did not calculate the overall economic effects, but is convinced that the solution has led to several improvements for both workforce and company. The ease of use of cobot programming as well as the open-mindedness by the workers were stressed multiple times by the interviewees.

5. Limitations of the study

Although this study presents new insights, limitations are inherent in any study and should be transparently addressed. Due to the need to interview SMEs with the cobot technology in use, participants were not randomly selected. Another sample group could have resulted in different and further findings. The sample group of 16 participants including only 4 SMEs does not allow for broadly-applicable conclusions. As laid out in the research methodology, it was not planned to derive quantitative data from the interviews, but to perform a qualitative analysis on the ecosystem. The results from chapter 4 are promising for this approach. The authors look forward to continuing with interviews on this topic in order to gather further insights from the manufacturing ecosystem in an international context, especially focusing on the contribution of a publicly available qualitative and quantitative data set (see outlook in chapter 6). The interviews were carried out by four researchers from two research institutions from different continents and from three different professions. Despite the diverse backgrounds, researcher bias can be assumed. A predefined, semi-standardized questionnaire with a fixed set of questions was used to standardize and objectify the interviews. As another limitation, the interviews as well as the analytical work were carried out in German and English, which led to minor difficulties in the general understanding of translated technical terminology as well as colloquial expressions. The overall analysis results should not be affected by this.

6. Conclusions

This paper shows the results of a study with different participants of the collaborative robot welding ecosystem in Baden-Württemberg, Germany with a focus on SME technology adoption. In 16 interviews, several technology adoption benefits were identified, including worker safety, worker autonomy, quality and performance improvements, and organizational flexibility. Although technology adoption barriers exist, the reported limitations are mainly based on technological limitations of cobots, which can be assumed to be advancing with future developments, and the often-stressed managerial mindset of open-mindedness. The interview results highlight the feasibility of cobot welding solutions even for SMEs as a technology adoption group. Two case studies give detailed insights into the barriers and benefits experienced by early adopting SMEs, who proved to be successful pioneers of cobot welding in the analysed region. With first hand impressions of the workplace level, the perception of this new technology by SME workers can be described as very positive, with welding professionals easily becoming cobot programmers based on the latest market-ready solutions.

The paper contributes to both academia and industrial practice. In contrast to other studies in which Industrie 4.0 technologies are too expensive and/or underdeveloped for use in manufacturing firms and especially SMEs, this study presents a solid picture of contemporary Industrie 4.0 technology adoption across a small subset of early-adopter SMEs [8]. The findings are based on interviews across the manufacturing ecosystem in a single regional state. Further industrial policy findings will be published in an according outlet. For industrial practice, the interview results and case studies serve as blueprints for other SMEs thinking of the adoption of similar cobot solutions. The interviewed companies were assisted with further assistance for own reflection with regard to improvement potentials. This research is part of an international comparative study between the industry-heavy regional states of Ohio, United States of America and Baden-Württemberg, Germany, which aims to better understand the workforce implications of robot adoption, and to support both SMEs and their workers in technological advancement. Future work will entail further interviews with robot-adopting SMEs and institutions, as well as additional analysis to build up a thorough data set for applied research purposes.

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Biographies

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