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Industry 4.0 and the SME Challenge: A Mixed-Methods Study on IIoT Adoption in Mechanical Engineering Enterprises

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Abstract

The Fourth Industrial Revolution has transformed production processes, primarily through the integration of the Industrial Internet of Things (IIoT), enabling real-time data exchange across the value chain. While large corporations often lead this transformation, small and medium-sized enterprises (SMEs), especially in the mechanical engineering sector, face challenges in adopting IIoT due to limited resources and compatibility issues. This empirical study investigates the current state of IIoT adoption within SMEs in Germany in this sector, employing a mixed-methods approach that combines a systematic literature review with quantitative and qualitative data from surveys and expert interviews. Our research focuses on five core areas: implementation levels, driving forces, digital infrastructure readiness, potential benefits and challenges, and recommended measures. The findings reveal low IIoT adoption rates among SMEs, driven by internal motivators and hindered by factors such as insufficient digital infrastructure, lack of standardized interfaces, and complex bureaucratic barriers. The study highlights the potential of IIoT to enhance transparency and efficiency but underscores the need for targeted support to overcome adoption barriers. Recommendations include standardizing IIoT frameworks, improving access to funding, and fostering innovation. This study provides a nuanced understanding of the unique challenges SMEs face in implementing IIoT and offers actionable insights for stakeholders aiming to facilitate IIoT integration in this sector.

Keywords
Industrial Internet of Things (IIOT), Industry 4.0, Mechanical Engineering, SMEs, Digital Transformation

1. Introduction

The use of cyber-physical systems (CPS) is continuously increasing the interconnection, autonomy and performance of (production) processes in companies as part of the growing complexity and with respect to the Fourth Industrial Revolution. The Industrial Internet of Things (IIoT) enables real-time data exchange of these CPS and guarantees comprehensive transparency and continuously newly generated knowledge along the entire value chain as key factors (Bauernhansl 2014). However, the literature and real-life experience shows that the integration of IIoT into companies and their processes can be challenging, especially for small and medium-sized enterprises (SMEs), which often have difficulties with implementation in various fields e.g. due to limited resources.

1.1 Objectives

This empirical research study aims to assess the extent to which IIoT is currently adopted and used within the SME mechanical engineering sector in Germany. To achieve this objective, both primary and secondary research methods are employed. The secondary research, conducted as a systematic literature review, serves to analyze the topic and thereby facilitate the development of the study's guiding questions. These questions are subsequently addressed in primary research, which uses a mixed-method approach to conduct independent empirical investigations. Through this approach, insights from quantitative and qualitative research will be integrated, yielding comprehensive findings on the current state of IIoT adoption within the SME mechanical engineering sector. In addition, this research seeks to identify the main challenges and propose potential solutions. Drawing on the insights gained from the mixed-method approach, the study's conclusion will ideally address the following guiding research questions:

1. **Implementation Level**: What is the current level of IIoT implementation?
2. **Driving Forces**: Which stakeholders and forces are driving the topic in the companies?
3. **Digital Infrastructure**: To what extent is the digital infrastructure prepared for IIoT implementation?
4. **Potential & Challenges**: How can the potential of IIoT be maximized within this sector?
5. **Measures**: What specific actions are necessary to promote the adoption of IIoT?

2. Literature Review

Generally, the term Industry 4.0 describes the idea of an intelligent, hierarchical and inter-connected production system (Serpanos and Wolf 2018). The aim is to increase the efficiency, productivity, safety and transparency of industrial processes (Boyes et al. 2018). CPS and the IIoT are the basis for all this. CPS are objects that contain embedded systems that consist mostly of sensors, actuators and a certain amount of computational intelligence. The IIoT enables CPS-capable objects to communicate with each other via an intranet and/or the internet and exchange data (Bauerhansel 2014).

Already more than five years ago, Sethi and Sarangi (2017) analyzed IIoT architectures and proposed a foundational three-layer framework for IIoT (application layer, network layer and perception layer). However, due to the lack of comprehensive standards, such as a universally applicable IIoT reference architecture model, integrating IIoT into companies' digital infrastructures remains challenging, complex, and time-consuming (Domínguez-Bolaño et al. 2022). Compatibility and interoperability are also critical issues within IIoT (Hazra et al. 2021). Here, compatibility refers to the seamless exchange of data between machines or systems, whereas interoperability entails an open-standard communication link for data exchange between machines and/or servers on a heterogeneous shop floor.

As preliminary research, we analyzed 24 studies after an intense selection process, identifying nine as particularly suited to our research objectives based on their structure and thematic focus on relevant fields. The topics were organized into predefined categories, aligning with an action-oriented research approach, and therefore grouped into the above already mentioned five key fields. Our approach, methodology and main findings are summarized in Figure 1.

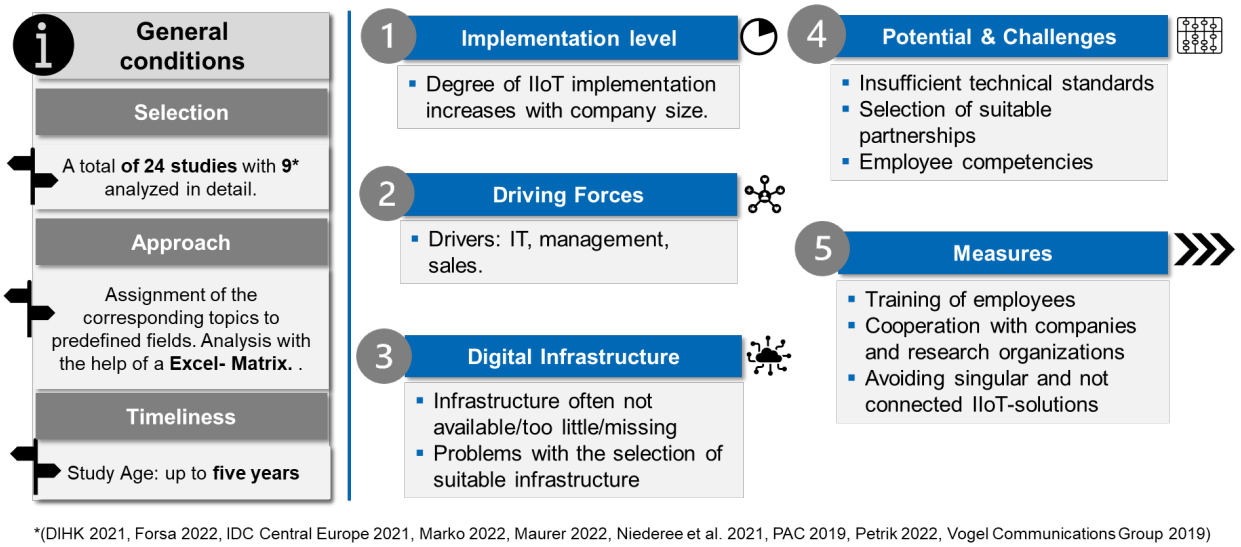

Figure 1. Summary of the specific literature and study analysis

The reviewed studies reveal certain characteristics:

- **Mixed sample construction**: Most samples in the studies consist of a mix of SMEs and large enterprises.
- **Diverse industry sectors**: In studies that specifically examine SMEs, samples often include a variety of industry sectors.
- **Lack of differentiated perspectives**: There is a lack of nuanced analysis regarding the roles and perspectives of IIoT stakeholders.

These limitations formed the basis for our further research efforts as our approach seeks to address these open issues. By carefully selecting methods, procedures, and considering the background and roles of survey participants, our aim is to address these three points comprehensively.

3. Methods

The research design of this paper consists of three stages, based on empirical research where systematic analyses of experiences yield new insights (Bortz and Döring 2006). The methodology follows the principle of triangulation within a mixed-methods approach. Here, the research focus is examined from at least two perspectives, which are subsequently synthesized to provide an integrated understanding. By incorporating differentiated perspectives, the approach ideally enhances the depth of insights gained (Flick 2011). The mixed-methods approach, as a form of methodological synergy, combines inductive and deductive processes to evaluate the research subject, thereby enabling novel and more comprehensive perspectives.

Quantitative and qualitative data collection differ. Quantitative methods address the width of the research object, while qualitative methods explore it in depth (Brosius et al. 2022). The objectivity of quantitative data collection is supplemented by the contextual richness of qualitative research, whereas the generalizability and quantified assessments provided by quantitative research help to offset the specific, subjective insights characteristic of qualitative approaches, culminating in an integrated outcome (Maier et al. 2018).

In this study, quantitative and qualitative data collection was conducted via surveys. These are the most widely used data collection methods in empirical social research. Surveys are estimated to yield up to 90% of empirical data within this field (Bortz and Döring 2006). Figure 2 provides a schematic overview of our entire methodological process.

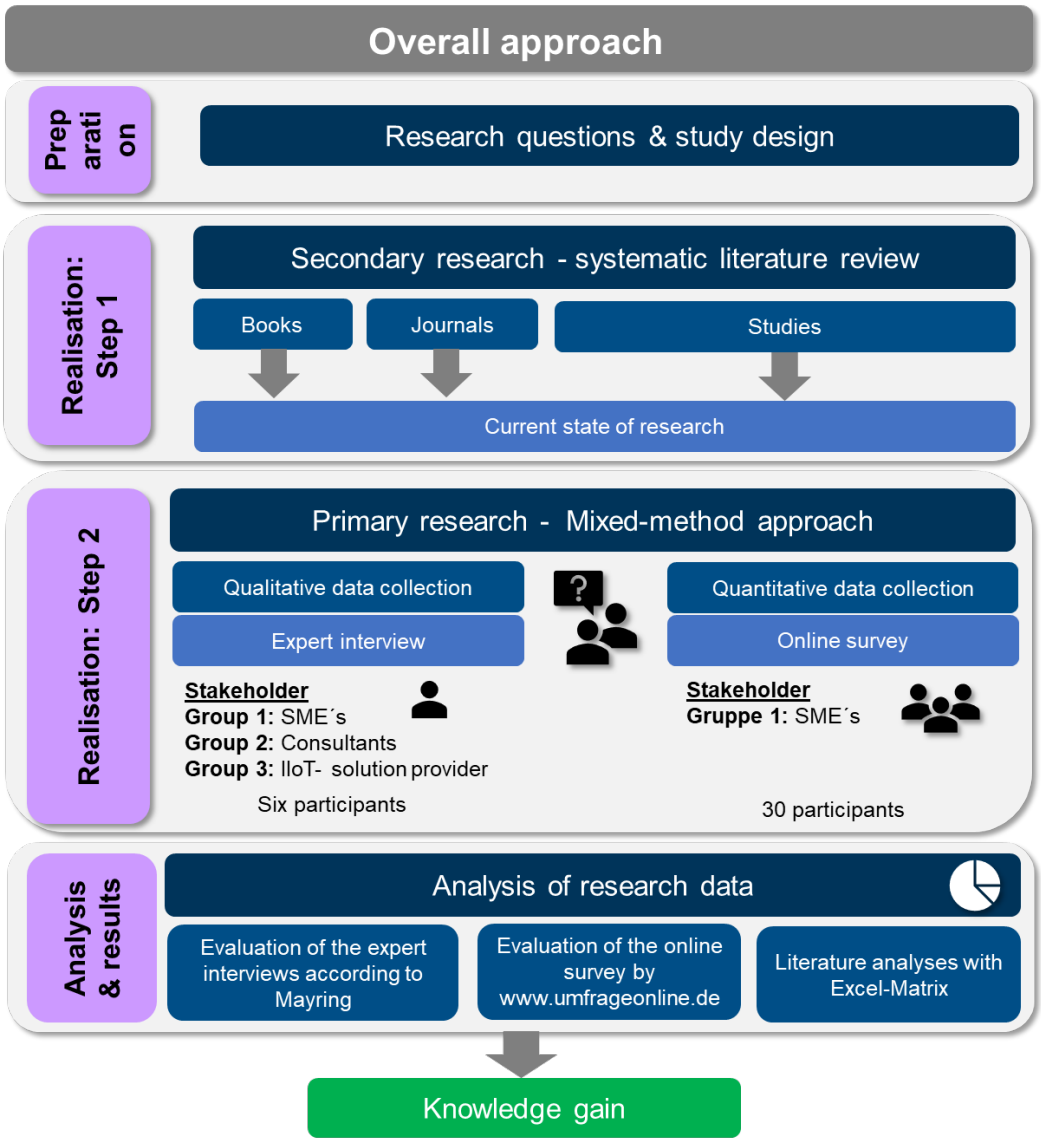

Figure 2. Overview of overall mixed-method approach, principally based on Mayring (2001)

4. Data Collection

4.1 Quantitative approach

Objectivity, reliability, and validity, the three key quality criteria in quantitative research within communication sciences, were considered (Brosius et al. 2022). An online survey with only closed questions was selected as the data collection tool due to its simplicity, efficiency, and the anonymity it provides. The survey consisted of 21 questions, with an average completion time of 14.53 minutes by the respondents. The questionnaire was structured according to the five guiding research questions presented already in Chapter 1.1. Based on this, specific questions were developed and organized as follows:

- Research question 1 includes sub questions 1 to 4 and corresponds to survey questions 1 to 9.
- Research question 2 includes sub questions 5 to 7 and corresponds to survey questions 10 to 12.
- Research question 3 includes sub question 8, corresponding to survey question 13.
- Research question 4 includes sub question 9, corresponding to survey questions 14 to 20.
- Research question 5 includes sub question 10, corresponding to survey question 21.

The sample consisted of 30 participants recruited through networks to ensure data quality and a high response rate. Data collection was conducted via www.umfrageonline.de with data analysis and extraction performed using MS Excel.

4.2 Qualitative approach

The expert interview method, widely established in empirical social research, was chosen due to its reliance on the specialized knowledge of participants concerning the research focus (Liebold and Trinczek 2009). The entire process conducted is illustrated in Figure 3.

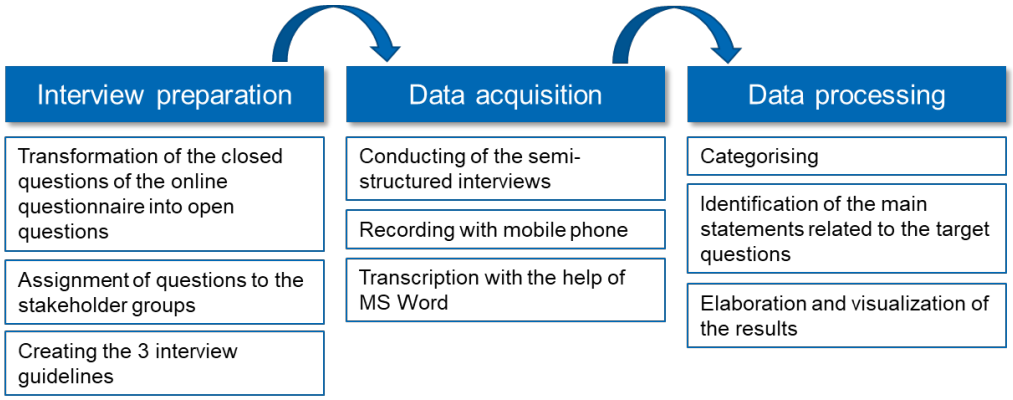

Figure 3. Research process in the field of qualitative data collection

A semi-structured expert interview was conducted in this study, based on the closed questions from the quantitative survey, which were adapted into an open format for the interviews. Following the interviews, data analysis was carried out using Mayring's qualitative content analysis (Mayring 1991 and 2001). In total, six experts were interviewed, representing three key stakeholder groups: SMEs in the mechanical engineering sector (Group 1), industry consultants (Group 2), and IIoT solution providers (Group 3).

4.3 Supplementary comments

Recruiting participants for studies is an ongoing challenge. Attempts to recruit actively through so-called "survey communities," commonly used in empirical social research, were unsuccessful. Participation in other studies to increase response rates in our study was deemed too time consuming. According to the corresponding survey community website's information, no responses were obtained from this recruitment method, indicating an inefficient cost-benefit balance. Survey communities tend to be more suitable for empirical scientific studies with broadly defined target groups. Furthermore, due to the passive recruitment approach and anonymity in the quantitative analysis, it cannot be guaranteed that the sample consists exclusively of SMEs in the mechanical engineering sector. However, we endeavoured to clearly define the target group in advance.

5. Results and Discussion

5.1 Results of the quantitative analysis

The results were extracted on the basis of the above-described approach and the analyses were carried out. Depending on the type of question, the results were visualized in different ways, but mostly with the help of bar charts (splitted up if necessary). For each of the five core questions, Figure 4 shows the results for five survey question as an example. The most important answers or the most frequently given answers were graphically emphasised with a red box.

The figure provides insights into the state of IIoT adoption and its key influencing factors. The level of IIoT implementation is low across most companies, particularly those with fewer employees. Driving forces include IT as a major supporter, followed by management sales. Challenges in digital infrastructure, such as compatibility and standardization, remain significant barriers. Cost reduction is identified as the greatest potential benefit of IIoT, alongside process flexibility and strategic business development. To better utilize IIoT, companies require measures like increased benefit argumentation, standardization of technical interfaces, and external support for innovation and education.

Figure 4. Exemplary survey results of the quantitative analysis, presented in an overall figure for a comprehensive and focused overview. The figure displays the most common responses to one key question in each of the five predefined categories, with key answers highlighted.

5.2 Results of the qualitative analysis

Figure 5 shows an overview of the results of the expert interviews. These were summarised and extracted from the interviews. Based on the responses of the participants, three sub-categories were introduced in the area of challenges. These are shopfloor, organisation and IIOT platforms. The measures were also divided into politics and internal company measures.

The results show that the current implementation level remains low across organizations, with management identified as critical driving force supporting IIoT initiatives. However, challenges persist within the digital infrastructure, particularly due to a lack of standardization and compatibility among IIoT platforms, which hinders seamless integration. IIoT offers significant potential, such as cost reduction with respect to operational efficiency, but faces challenges at multiple levels. On the shopfloor, integration issues are prominent, while organizational hurdles include skill gaps, resistance to change, and insufficient collaboration. To address these challenges, various measures can be proposed. Politically, promoting the relevance of IIoT in technical education and introducing simplified and favorable funding models are crucial steps. At the company level, actions such as investing in young talent, fostering innovation circles, and encouraging cooperation between research institutes and businesses are essential to drive progress.

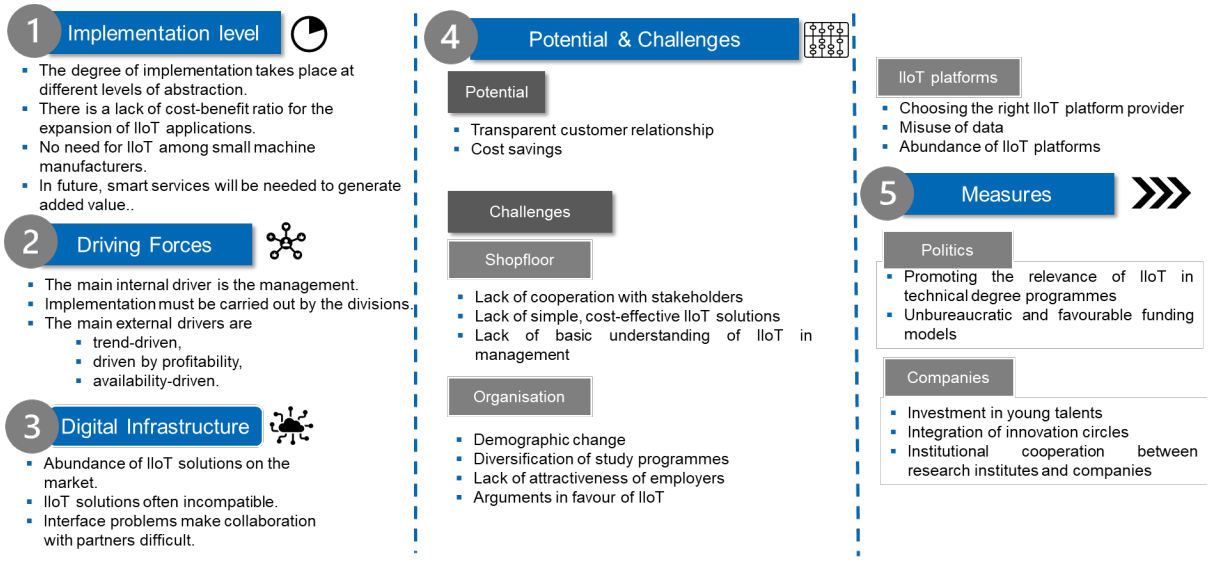

Figure 5. Key findings of the expert interviews in the five predefined categories according to the research questions

The overall findings from the quantitative survey are summarised together with the results from the qualitative data collection in the conclusion section in accordance with the procedure shown in Figure 2.

6. Conclusion

This paper highlights the current state and challenges of implementing Industrial Internet of Things (IIoT) solutions in SME´s in Germany. Despite its potential, the implementation level remains very low due to limited investment in IIoT-related research and development, driven by an imbalanced cost-benefit ratio. Internally, top management, IT, and sales teams act as key supporters, while external drivers are shaped by market trends, profitability, and availability. However, a significant obstacle lies in the digital infrastructure, where the abundance of diverse IIoT solutions leads to compatibility and integration challenges. IIoT offers promising opportunities, such as cost reduction and enhanced transparency in customer relationships, but it also faces various challenges. These include a lack of collaboration on the shopfloor, organizational hurdles like demographic changes and knowledge gaps, and difficulties in selecting suitable IIoT platform providers. To address these issues, several measures are recommended, including political support through simplified funding models, organizational initiatives like fostering innovation circles and training employees, and technological advancements focusing on the standardization of interfaces. In conclusion, unlocking the potential of IIoT requires coordinated efforts across political, organizational, and technological domains to overcome existing barriers and drive adoption.

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