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Microservice-Based Metrology Applications: Uncertainty Calculations and Digital Calibration Certificate Generation

Master's Thesis in Software Engineering and Management

Teklie Belay Bzuneh

Department of Computer Science and Engineering
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Teklie Belay Bzuneh

Supervisor: Dr. M. Çağrı Kaya, Department of Computer Science and Engineering
Examiner: Dr. Hans-Martin Heyn, Department of Computer Science and Engineering

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Department of Computer Science and Engineering
Chalmers University of Technology and University of Gothenburg
SE-412 96 Gothenburg
Telephone +46 31 772 1000

Gothenburg, Sweden 2024

Teklie Belay Bzuneh
Department of Computer Science and Engineering
Chalmers University of Technology and University of Gothenburg

Abstract

The metrology and calibration industries are increasingly exploring cloud-based solutions and microservice architectures to enhance productivity and accuracy. However, implementing these technologies presents challenges, particularly in data security, accessibility, and integration with existing systems. This study aims to assess the advantages and disadvantages of cloud-based solutions in these industries and explore how microservice-based technologies can facilitate digital transformation. Through a Systematic Literature Review and a case study based on Design Science Research, this research proposes strategies to overcome these challenges, thereby improving productivity and precision within the calibration industry. The Systematic Literature Review gathers and summarizes existing knowledge on the advantages and disadvantages of implementing cloud-based solutions, while the case study focuses on uncertainty calculations and digital calibration certificate generation. The study identified key benefits, including cost-effectiveness, enhanced data accessibility, and increased operational capacity. However, challenges such as data security risks and reliance on stable internet connections were also highlighted. The implementation of microservice-based proof of concept services demonstrated significant potential to streamline calibration processes, reduce errors, and enable seamless integration with cloud services.

Keywords: Metrology, Calibration, Cloud Computing, Microservices, Digital Calibration Certificates, Uncertainty Calculation.

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Teklie Belay Bzuneh, Gothenburg, September 2024

Contents

List of Acronyms

API Application Programming Interface
DCC Digital Calibration Certificate
DSR Design Science Research
IIoT Industrial Internet of Things
IoMT Internet of Measurement Things
MCS Monte Carlo Simulation
NIST National Institute of Standards and Technology
PTB Physikalisch-Technische Bundesanstalt
POC Proof of Concept
RF Radio Frequency
RQ Research Question
SLR Systematic Literature Review
UI User Interface

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Introduction

The digital age has brought significant changes to many sectors, and the calibration and metrology industries are no exception. These industries play a crucial role in ensuring the quality and accuracy of measurements across various fields, such as automotive and avionics [2]. These industries face increasing demands for precision, yet older metrology systems struggle with challenges like data security, managing large volumes of data, and maintaining performance with expanding datasets [3]. Addressing these challenges requires modernizing metrological approaches to achieve reliable and accurate measurements.

This study explores how advanced technological solutions, particularly cloud-based systems and microservice architectures, can transform operational workflows, improve uncertainty calculations, and streamline the generation and management of digital calibration certificates in the metrology and calibration industries. These advancements enable the industries to become more agile, data-driven, and interconnected, delivering faster, more accurate, and scalable measurement services [4]. This exploration is guided by two primary research questions. The first question examines the pros and cons of implementing cloud-based solutions in these industries. Cloud architectures offer enhanced security features, including advanced firewalls, intrusion detection systems, and robust data encryption, which are crucial for protecting sensitive metrological data. However, reliance on cloud solutions also presents challenges like dependency on consistent internet connectivity, potential long-term financial burdens due to data storage and security measures, and the complexity of regulatory compliance. Despite these challenges, cloud computing offers significant benefits in data management, including improved data categorization, faster processing through indexing, and enhanced data integrity via regular backups and redundant storage.

The second research question investigates how microservice-based technologies can support the digital transformation of metrology, particularly in improving productivity and accuracy in the calibration industry. Microservices, as a modern software design approach, break down applications into smaller, independently deployable services. This architecture allows for the creation of modular components that are easier to update and maintain [5], leading to more streamlined workflows in the calibration industry. Furthermore, microservices enable rapid adaptation to new standards without requiring comprehensive system overhauls. As a result, they are

promising for supporting tasks such as data collection, uncertainty calculation, and digital calibration certificate generation [6]. Additionally, the continuous integration and delivery capabilities of microservices ensure that metrological applications can quickly adapt to evolving accuracy and precision standards, an essential requirement in an industry where measurement instruments and techniques are continually advancing.

The thesis combines theoretical research and practical implementation to demonstrate a Proof of Concept (POC) for applying these ideas. The research is inspired by the IoMT architecture, as shown in Figure 1.1, which includes cloud services and application layers designed to better serve industry stakeholders. Therefore, this Industrial Internet of Things (IIoT) architecture is a highly suitable choice for developing cloud-based applications, in our case focusing on calculating uncertainties in Radio Frequency (RF) power measurement devices and generating digital calibration certificates. By conducting thorough investigations and a practical POC, this thesis contributes to modernizing metrology. It demonstrates how technology can enhance calibration processes, making them more precise, reliable, and adaptable, while supporting the broader shift towards digitalization.

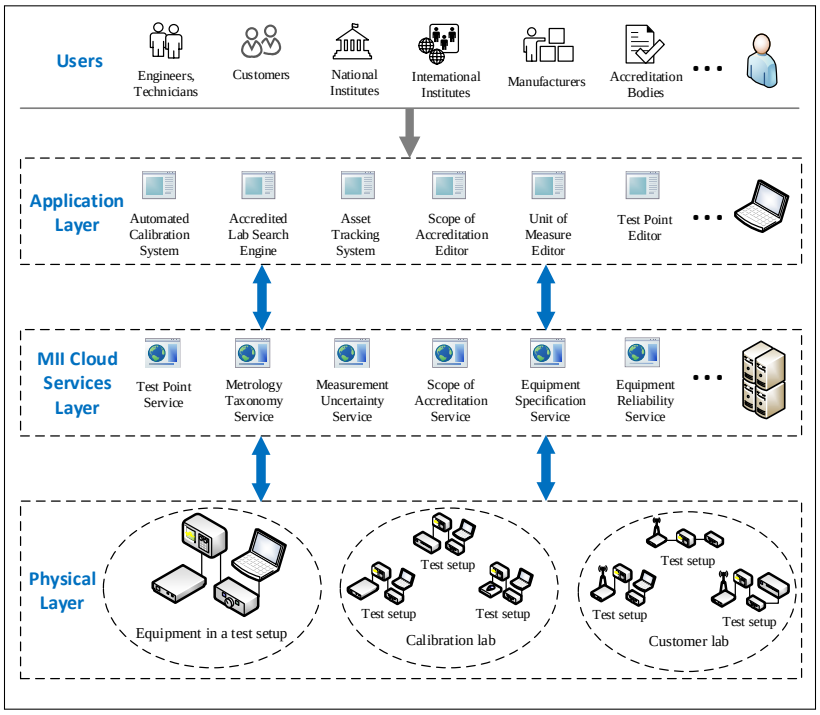

Figure 1.1: The IoMT architecture description (adopted from [1]).

1.1 Problem Description and the Proposed Solution

The digital transformation in metrology, driven by technologies like the IIoT [1], highlights the need for robust and secure software solutions. Traditional metrology

systems face challenges in handling large and complex datasets, which raises concerns about data security and accessibility. As the volume of sensitive measurement data grows, the system's attack surface increases, providing more entry points for potential breaches and unauthorized access. For instance, each connected device in a cloud-based calibration system can become a vulnerability if not secured properly. Additionally, the frequent transfer of large datasets over networks, if not encrypted or properly protected, makes the data more susceptible to interception and corruption. Traditional systems, often not designed for managing these larger datasets, may also lack adequate encryption and access control, further compromising data integrity. The critical need for precise measurements, essential for maintaining quality standards across various industries, underscores the importance of solutions that can manage these large datasets while ensuring accuracy and reliability.

This research addresses how microservice-based technologies can support the modernization of metrology, specifically focusing on uncertainty calculation and DCC generation. While microservices and cloud computing offer significant benefits, their application in metrology, particularly regarding data protection and management remains underexplored. This study seeks to demonstrate how microservice architectures can drive the digital shift in metrology through both theoretical research and the implementation of a POC to validate the findings.

The study also aims to show how cloud microservices can improve precision, processing capability, and security in uncertainty calculations and digital certification processes. By leveraging cloud and microservice architectures, this research intends to contribute to the development of a modern metrological framework, advancing the field with improved digital tools and methodologies [7], [8].

1.2 Research Questions

This study is driven by the following research questions:

***RQ1**: What are the advantages and disadvantages of employing cloud-based solutions in the metrology and calibration industries?*

The first research question explores the advantages and drawbacks of cloud-based implementations in metrology and calibration. Cloud architecture offers enhanced security features such as advanced firewalls, intrusion detection systems, and robust data encryption which are crucial for protecting sensitive metrological data. However, reliance on cloud solutions introduces challenges like dependency on consistent internet connectivity, which can disrupt operations. While initial costs may be lower, long-term expenses related to data storage and advanced security measures can accumulate, adding financial burdens. The regulatory landscape in these industries further complicates the adoption of cloud solutions, requiring rigorous compliance checks.

***RQ2**: How can implementing microservice-based applications transform metrology practices, particularly in standardizing digital calibration certificates and improving*

accuracy within the calibration industry?

This research question examines the role of microservices in the digital transformation of metrology and calibration industries. Microservices, as a modern software design approach, decompose applications into smaller, independently deployable services. This architecture facilitates the creation of modular components that are easier to update and maintain, resulting in streamlined workflows in the calibration industry. Specific services can be developed for tasks like data collection, uncertainty calculation, or digital calibration certificate generation, allowing for rapid adaptations to new standards without overhauling entire systems. Moreover, the continuous integration and delivery facilitated by microservices mean that metrological applications can swiftly adapt to evolving accuracy and precision standards, a critical capability in an industry where measurement instruments and techniques are continually advancing.

Together, these research questions aim to outline a clear path toward a digitally transformed metrology landscape, where concepts such as precision, security, and enhanced data accessibility are transformed from ideals into everyday realities. The thesis uses a combination of practical implementation to address RQ2, while theoretical research is employed to address RQ1, providing a comprehensive view of the impact of these technological advancements on the metrology and calibration industries..

1.3 Significance of the Study

This research is a step forward in the field of metrology as it adapts to new digital techniques. It provides insights into how microservice-based technologies can impact and improve metrological systems. For professionals in metrology, the study offers guidance on how to better protect data and operate more smoothly. Software engineers will also find useful information on how to better incorporate microservices into metrological tasks.

Researchers will benefit from the study's findings as it adds to the conversation about combining microservices with metrology. The insights provided here aim to enhance practical metrology work and encourage more studies in this direction.

The focus of the research is on improving the exactness of measurements in the industry. This is crucial as new technologies push the need for more precise measurements. Using Monte Carlo Simulations within a microservice-based system is a key part of this research, helping ensure that metrological activities can meet the high standards needed today. Better accuracy in measurements leads to improved product quality and safety, as well as ensuring industry regulations are met.

Moreover, the research discusses the shift to microservices in metrology. This move promises a more scalable and effective way of handling data. The study rethinks traditional methods that often struggle to manage the volume of today's data and demonstrates how microservices can improve data management. This approach

enables metrology systems to be more responsive and adaptable, allowing for quicker adjustments to industry changes.

DCC is also a key topic in this study. By looking at how to standardize DCCs, the research contributes to making measurements more trusted and clear. This trust is crucial for stakeholders who need to rely on the precision of these tools.

The security of metrological data is another important point covered by this research, especially in light of growing online threats. By looking into microservices and their structure, the study suggests ways to keep important metrological data safe.

Finally, the thesis outlines strategies for dealing with large amounts of metrological data using microservices. It reviews the best ways to store, find, and process this data, aiming to make these tasks easier, reduce costs, and improve access to data for metrology professionals. With this detailed review, the study aims to support today's metrology work and offer a vision for future advancements in the field, particularly through the use of microservices in metrology.

1.3.1 Scope and Limitations

Focusing on the potential integration of cloud-based microservices in metrology, this study primarily addresses uncertainty calculation and digital calibration certificate generation. Despite aiming for comprehensive coverage, inherent limitations related to cloud service variability and specific industry metrological needs may impact the proposed solutions' applicability. Access to real-world metrological datasets and practical implementation could present additional challenges as well[9].

1.4 Structure of the Thesis

Subsequent sections will explore related work, methods, results, discussion, and conclusion, building on the foundation laid by this introduction. By examining the applicability of microservices and cloud computing in metrology, this research provides valuable insights aimed at improving the accuracy, security, and processing capabilities of metrological practices.

2

Background

This chapter presents the theory and background information needed to understand this research study. It explores the big changes digital technologies have brought to metrology, the struggles faced by old metrology systems in today's digital world, and how microservice-based technologies and cloud computing could offer solutions. By looking at related research, pointing out what's missing, and laying out the basic ideas that support this study, this section sets the stage for a deeper look into using advanced technologies in metrology.

2.1 Traditional vs. Digital Calibration Certificates

2.1.1 Traditional Calibration Certificates

Traditional calibration certificates document the calibration of instruments, typically in paper or static PDF formats. These certificates contain essential information such as calibration dates, measurement uncertainties, and results. However, traditional certificates face several limitations. The creation and validation processes are typically manual and prone to errors. Moreover, accessing data from paper documents or static PDFs can be cumbersome, limiting the ease of sharing and integrating data into modern digital systems. Another significant concern is data integrity, as physical documents are susceptible to damage, loss, and unauthorized modifications, which can undermine the reliability of the calibration data.

2.1.2 Digital Calibration Certificates

DCCs overcome the challenges that traditional certificates face by providing a dynamic, electronic solution for managing calibration data. Unlike traditional formats, DCCs are integrated into digital systems, allowing real-time access to data and supporting automation. This enhances accessibility, as calibration data can be instantly retrieved and shared across multiple platforms, which is critical for timely decision-making. Additionally, DCCs are automatically generated and can seamlessly integrate with systems such as quality management platforms, eliminating the need for manual intervention. In terms of security, DCCs employ encryption

and digital signatures, ensuring that the calibration data remains secure and its integrity is protected against unauthorized access or alterations.

2.1.3 Importance of Digital Calibration Certificates

Digital Calibration Certificates are vital for modernizing metrology in today's increasingly digital landscape. They facilitate improved data management by increasing the accuracy, security, and accessibility of calibration data, while also supporting industry standards for traceability and compliance. As the metrology and calibration industries move towards digital transformation, DCCs enable these sectors to become more agile and interconnected, positioning them in alignment with the broader goals of Industry 4.0.

2.2 The Evolution and Challenges of Metrology in the Digital Age

Metrology, the science of measurement, is essential for ensuring quality and accuracy across various industries, such as automotive, aerospace, and healthcare. With the rapid advancement of digital technology, particularly the Industrial Internet of Things (IIoT) [1], metrology is experiencing both exciting opportunities and significant challenges.

The IIoT connects devices and systems, enabling them to communicate and share data in real-time. This connectivity can greatly enhance the capabilities of metrology systems by providing faster and more precise measurements. However, traditional metrology systems often struggle with managing the vast amounts of complex data generated by these interconnected devices. This raises serious concerns about data security, as large datasets are more vulnerable to breaches and unauthorized access.

Moreover, the growing need for extremely precise measurements, which are critical for maintaining high-quality standards, calls for new solutions. These solutions must be capable of handling not only the volume but also the complexity of the data, ensuring that measurements remain accurate and trustworthy. For example, in the healthcare industry, accurate measurements can be the difference between a correct diagnosis and a medical error.

Additionally, older metrology systems may lack the flexibility needed to adapt to the rapid changes in technology. They often require significant upgrades or replacements to integrate with new digital tools, which can be costly and time-consuming. This situation highlights the necessity for modernizing metrology practices to keep pace with technological advancements.

In response to these challenges, there is a growing interest in leveraging cloud-based solutions and microservice architectures. These technologies offer promising ways to enhance data management, improve security, and ensure the accuracy of measurements. By adopting these digital solutions, metrology can evolve to meet

the demands of the digital age, providing reliable and precise measurements that support industry standards and innovation.

2.3 Literature Review and Basic Ideas

This section delves into recent studies that highlight the limitations of traditional metrology systems and the potential benefits of adopting microservice architectures and cloud computing [10], [11], [7], [12]. These new approaches promise better scalability, enhanced security, and faster computations. However, their application in metrology, particularly for crucial tasks such as calculating uncertainty and generating digital calibration certificates, remains underexplored.

Recent research underscores the challenges faced by older metrology systems. Traditional systems often struggle with the increasing volume and complexity of data, leading to slow data processing, difficulties in storage and retrieval, and potential inaccuracies. Studies by Popov et al. [10] and Wang et al. [11] emphasize that these systems are not well-equipped to handle the demands of modern data-intensive environments.

In contrast, microservice architectures and cloud computing offer a modular approach to software design. This means that applications are broken down into smaller, independent services that can be developed, deployed, and scaled independently. This flexibility is particularly beneficial for metrology, as it allows for more efficient data processing and easier integration of new technologies. Braun et al. [7] and Thiel et al. [12] have demonstrated the potential of these technologies to improve data management and computational efficiency.

Despite these advantages, the adoption of microservices and cloud computing in metrology is still in its early stages. The existing research indicates that while these technologies can significantly enhance metrological practices, their full potential has yet to be realized. There is a need for more comprehensive studies to understand how these digital tools can be effectively integrated into metrology workflows.

The basic ideas behind this study are rooted in the principles of the IIoT and microservice architecture. The IIoT connects devices and systems, enabling real-time data exchange and analysis. This connectivity can transform metrology by providing continuous monitoring and instant feedback. Microservice architecture complements this by offering a flexible and scalable framework for developing metrology applications.

This literature review not only highlights what is currently known about the integration of these technologies into metrology but also identifies gaps in knowledge that future research needs to address. By understanding both the strengths and limitations of existing systems, this study aims to contribute to the ongoing digital transformation of metrology, paving the way for more accurate, reliable, and efficient measurement processes.

2.4 Monte Carlo Simulation, Digital Calibration Certificate Generation, and Microservices-Based Metrology

Monte Carlo simulation has become a key method for figuring out uncertainty in metrology, offering a flexible and strong way to see how different factors affect measurements. This method uses random sampling and statistics to give a detailed look at uncertainty, helping those who measure to pinpoint and understand possible errors more clearly. This is especially useful for complicated measurements where usual methods might not work, making measurement results more reliable and helping with smarter decision-making [13].

Alongside improvements in understanding uncertainty, the shift to digital calibration certificates represents a significant advancement in the storage, sharing, and utilization of calibration data. These digital certificates replace old paper ones, making it easier to track, secure, and access calibration information. Using digital certificates with cloud systems makes these benefits even better, allowing instant access to calibration records and making it simpler to manage data across different systems and for different users. This move not only makes the calibration process smoother but also updates metrology practices to better fit today's data management and compliance standards, leading to a more connected and efficient metrology world [14].

Switching to a microservices architecture for creating metrology software represents a significant departure from traditional system designs, introducing a level of modularity, scalability, and speed previously unseen. This approach breaks down applications into smaller, independent services that can be developed, deployed, and scaled individually. This fits perfectly with the fast-moving and data-heavy nature of modern metrology, offering custom solutions that can quickly adjust to new needs and technologies. Moreover, combining microservices with cloud computing allows the creation of strong, scalable, and secure metrology applications that make the most of the cloud's power and storage, pushing forward efficiency and innovation in metrological work [15].

3

Related Work

The integration of Monte Carlo simulations into a microservice architecture marks a significant evolution in metrology, particularly in the realms of uncertainty calculation and DCC generation. This approach necessitates an interdisciplinary methodology that spans architectural practice, software engineering, and metrology, signifying a melding of technological and methodological advancements aimed at augmenting metrology's precision and reliability [16].

Monte Carlo simulations serve as a foundational method for risk and uncertainty analysis across various disciplines, providing a robust framework for addressing the variability in complex systems [17]. Within metrology, the adoption of these simulations is pivotal for the effective modeling of uncertainty, especially crucial in instrument calibration and DCC generation where measurement accuracy is paramount.

The shift towards a microservices architecture introduces a new paradigm for developing complex software systems, characterized by agility, scalability, and resilience. This is particularly evident in the transition towards digital methodologies like Building Information Modeling (BIM), highlighting a move towards more modular and interoperable systems within the metrology domain. The digital platforms' architectural design and deployment for Industry 4.0 collaboration emphasize the potential of microservices to facilitate collaboration among small and medium-sized enterprises (SMEs) in digital transformation environments [8].

In aligning with the design science methodology, this research focuses on creating and evaluating IT artifacts that solve practical problems. The incorporation of Monte Carlo simulations within microservices not only meets technical requirements but also aligns with broader business and operational goals, showcasing a convergence of computational methodologies with architectural management practices [9].

The adaptation of AutoRFPower to the cloud, guided by the IoMT architecture, represents a forward-thinking approach to metrology in the cloud environment. The IoMT architecture, a specialized IIoT framework, delineates the layers of physical equipment, cloud-based services, commonly used data, and applications, serving as a blueprint for this transformation [18]. This process, which involves migrating AutoRFPower to a cloud setting, underscores the ambition to streamline the calibration process through cloud services, enabling data collection and uncertainty calculations

to be conducted remotely, and ultimately facilitating the generation of DCCs [19].

Relevant DCC publications from the Physikalisch-Technische Bundesanstalt (PTB)'s DCC Wiki further support this integration, illustrating the ongoing efforts and achievements in digitalizing calibration certificates [20]. The comparison with tools like the National Institute of Standards and Technology (NIST) Uncertainty Machine and Federal Institute of Metrology (Switzerland) Uncertainty Library (METAS.UncLib) highlight the unique holistic approach of incorporating Monte Carlo simulations within a cloud-based metrology ecosystem, differing from these tools by providing a comprehensive solution that encompasses both the calculations and the subsequent generation of DCCs [21], [22].

That being said, the exploration of Monte Carlo simulations within microservice architectures in metrology presents vast potential for enhancing measurement precision and reliability. This research, enriched by insights into digital calibration certificate generation and the practical application of the IoMT architecture, emphasizes the value of adopting advanced computational methods and architectural practices to advance metrology's accuracy and operational effectiveness.

4

Methods

This chapter outlines the research methodology, which combines an SLR and a case study based on the DSR approach [23]. Each method contributes unique value to the research process: the SLR provides a comprehensive review of existing literature, while the case study, guided by the DSR approach, offers practical insights and validates the proposed solutions.

4.1 Systematic Literature Review

The SLR method is used to collect and synthesize existing knowledge on microservice-based technologies, metrology, and digital calibration certificates. By thoroughly reviewing and analyzing relevant literature, key trends, gaps, and best practices are identified to guide the development and implementation of new solutions. This foundational knowledge sets the stage for the case study and DSR activities.

A comprehensive literature search was conducted across major academic databases, including Google Scholar, IEEE Xplore, ACM DL, Springer Link, and Science Direct. The objective was to identify existing research that incorporates cloud technologies in metrology and understand the advantages and disadvantages of using these technologies. The search terms included *"metrology" "calibration" "cloud" "architecture" ("uncertainty calculation" OR "uncertainty calculations") OR ("calibration certificate" OR "calibration certificates"*). To the best of our knowledge, and based on this thorough search, no systematic review has been published that addresses this specific topic.

Our research focuses on two main subjects: the implementation of cloud-based solutions in metrology and the benefits and challenges associated with these implementations. Concerning cloud-based solutions in metrology, the authors in [24, 25] analyzed the current state of cloud adoption in the metrology industry using a taxonomy-based approach. They defined various cloud-based solutions with respect to their functionality, scalability, and integration with existing systems. A more recent study by Mariappan et al. [26], conducted in 2020, provides a comprehensive approach to characterize the key benefits and challenges of cloud-based metrology solutions by using a classification framework. However, no systematic review related to cloud-based solutions in metrology exists after Mariappan et al.'s work. Our study

addresses the cloud-based solutions introduced after 2020 that impact the metrology and calibration industries.

Regarding the benefits and challenges of cloud-based implementations, Hashmi et al. [27] introduced a comprehensive study for analyzing the advantages and drawbacks of cloud computing specific to industrial applications. Likewise, Khan et al. [28] represent cloud adoption practices from an industrial point of view in which a set of industrial practitioners were surveyed who implement cloud-based solutions for various applications. Gupta and Gupta [29] addressed major research achievements, open issues for cloud integration, and implementation processes. They also discussed trends towards the future of cloud-based solutions in industrial applications. A holistic study conducted by White et al. [30] on cloud computing handling in industrial systems highlights independent technology domains such as cloud-based metrology and service-oriented architecture. Moreover, dedicated only to the implementation challenges, Yang and Tate [31] introduced a systematic analysis that brings out capabilities for managing cloud-based solutions at scale and provides a classification schema. Existing approaches shed light on the implementation of cloud-based solutions, helping us to construct our Research Question (RQ), select primary studies, and discuss the findings.

4.1.1 Protocol

To explore the advantages and disadvantages of implementing cloud-based solutions in the metrology and calibration industries, a SLR was conducted following the guidelines provided by Kitchenham and Charters [32]. The review process was carried out according to the following protocol, which includes defining the RQ, outlining the selection and assessment approach, and finally, synthesizing the review results as detailed in 5.1.2.

4.1.2 Review Protocol

The first and essential step of a systematic review is to develop a step-by-step protocol for carrying out the review based on the guidelines. The protocol was established as a sequence of important activities to be performed in two consecutive flows (first a, then b), as depicted in Figure 4.1.

The RQ guiding the review was clearly defined. A search strategy and scope were then established by conducting pilot searches with potential search strings to ensure the most relevant studies were captured. Next, inclusion and exclusion criteria were determined based on the search results and quality assessment of the studies. A review plan was also developed, which included selecting primary studies and creating a data synthesis process to analyze and present the extracted data.

4.1.3 Databases to be searched

The literature search for the SLR was conducted using the following databases: IEEE Xplore, Google Scholar, ACM Digital Library, Springer Link, and ScienceDirect.

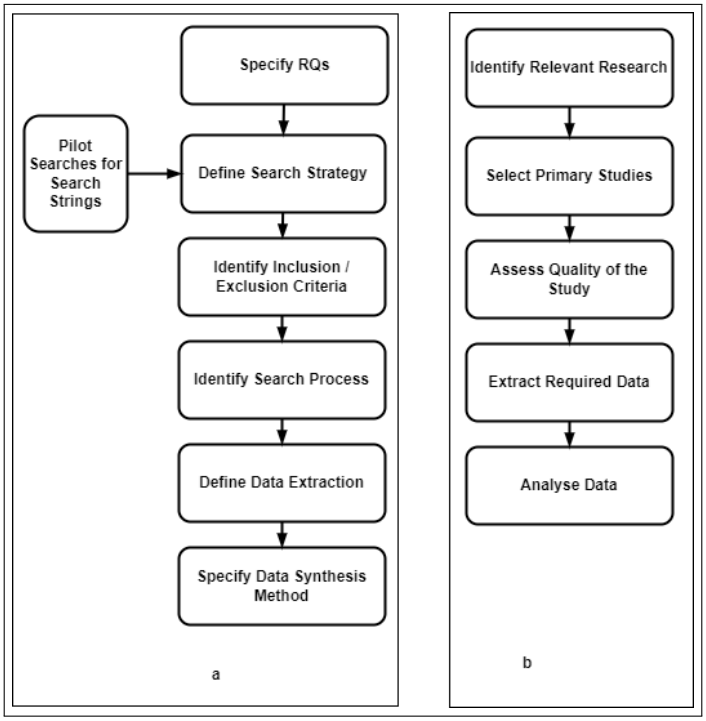

Figure 4.1: Development of review protocol and the review process (**a**) Development of review protocol, (**b**) Review process (adopted from [33])

Google Scholar was used not only to provide an overview of the broader literature but also to identify peer-reviewed publications that may not be indexed in the other databases. It further facilitated snowballing by providing access to citations both to and from key publications, helping to identify additional relevant studies. This approach ensured a comprehensive literature review and resulted in the identification of 269 articles for the study.

4.1.4 Search strategy

To ensure a comprehensive and focused search, a combination of keywords and search terms was used. These terms were carefully selected to capture the key concepts related to metrology, calibration, and cloud computing. The search strategy incorporated the following keywords and search terms:

```
"metrology" "calibration" "cloud" "architecture"
("uncertainty calculation" OR "uncertainty calculations") OR
("calibration certificate" OR "calibration certificates")
```

These search terms were chosen to include a wide range of relevant topics, including the technical aspects of cloud-based solutions, their application in metrology and calibration processes, and specific concerns such as uncertainty calculations and calibration certificates. By using both broad and specific terms, the search aimed to cover all pertinent literature that addresses the implementation of cloud technologies

in these industries.

Table 4.1: Number of papers per database/source for each screening phase

Sources	Phase 1	Phase 2	Phase 3
IEEE Xplore	24	20	1
ACM DL	4	4	2
Springer Link	20	5	0
Science Direct	16	12	4
Google Scholar	205	182	9
Total	**269**	**223**	**16**

4.1.5 Study Selection

The selection phase ensures the relevance of the set of papers to our research question, *What are the advantages and disadvantages of implementing cloud-based solutions in the metrology and calibration industries*? The following phases were applied to ensure the selection of pertinent studies:

Phase 1: The search queries were executed precisely as outlined in the search strategy section, resulting in an initial dataset of relevant literature.

Phase 2: The initial dataset was refined by eliminating papers associated with unrelated disciplines such as biology, geography, and medical fields. Additionally, non-English language papers were excluded to maintain consistency and ease of analysis. Duplicate entries from different databases were removed to avoid redundancy.

Phase 3: Abstracts of the remaining papers were reviewed, and a cursory examination of their contents was conducted. Papers that did not specifically address the implementation of cloud-based solutions in the metrology and calibration industries were excluded. Furthermore, studies focusing on alternative technological frameworks outside the scope of our research question were omitted.

Final phase: A comprehensive reading of the papers selected in Phase 3 was undertaken. Papers were further excluded if they lacked substantial relevance to our research question. Each paper was specifically assessed for its detailed analysis of the advantages and disadvantages of cloud-based solutions in metrology and calibration. Papers were discarded if they merely mentioned cloud-based solutions without providing an in-depth exploration or referencing pertinent studies and resources related to the implementation and implications of these solutions.

4.1.6 Inclusion and Exclusion Criteria

The inclusion and exclusion criteria for this systematic review are meticulously defined to ensure the selection of studies that are relevant, timely, and of high quality. The criteria are as follows:

Publication Date: Only studies published from 2011 onwards are considered. This timeframe ensures that the research reflects the latest advancements and current trends in cloud-based solutions within the metrology and calibration industries.

Relevance: Studies must specifically address the advantages and disadvantages of cloud-based solutions in the context of metrology and calibration. Key areas of interest include uncertainty calculations, digital calibration certificates, and the architectural frameworks of cloud solutions.

Abstract Screening: The initial screening is based on the abstracts of the studies. Only those abstracts that discuss the advantages and disadvantages of cloud-based solutions in metrology and calibration industries are included.

Language: Only studies published in English are considered to ensure consistency in comprehension and analysis.

4.1.7 Data Extraction

The data extraction process is designed to systematically collect and manage relevant information from the selected studies. The procedures are detailed below:

Identification of Relevant Studies: Relevant studies are identified through comprehensive searches using scholarly search engines and databases. The search is refined using specific keywords and filters based on the inclusion criteria.

Screening of Titles and Abstracts: An initial screening of the titles and abstracts is conducted to exclude studies that do not meet the relevance criteria. Only studies discussing the advantages and disadvantages of cloud-based solutions in the specified industries are retained.

Full-Text Review: The full text of the remaining studies is retrieved and thoroughly reviewed to confirm their relevance. Key information related to the research question, including methodologies, findings, and conclusions about the benefits and challenges of cloud-based solutions, is extracted.

Data Extraction Form: A standardized data extraction form is developed to systematically collect pertinent information from each study. This form includes details such as publication year, authors, study design, sample size, key findings, and conclusions.

Quality Assessment: The quality of the included studies is assessed using predefined criteria to ensure the reliability and validity of the extracted data. This assessment is crucial for maintaining the integrity of the systematic review.

4.2 Case Study

While DSR focused on designing the solution, the case study method was used to test how well it worked in a real-world setting by using actual radio frequency power meter data. The case study provided practical data on how the solution performs in metrology processes, offering insights into its impact on accuracy, workflow, and the use of DCCs. Combining DSR and the case study was essential to fully address RQ2. DSR guided the development and deployment of a well-tested POC, while the case study demonstrated its practical application. Together, these methods ensured that the research was not only theoretical but also practical and valuable in real-world settings.

4.2.1 Case selection

The case study focuses on deploying microservices designed for uncertainty calculation and digital calibration certificate generation on the Google Cloud platform. This case was selected to explore the practical application of microservice-based technologies in the metrology sector, specifically aimed at enhancing productivity and accuracy in calibration processes. The case study method is used to thoroughly understand how microservice-based technologies can be applied in real-world metrology settings. This method is chosen because it allows for a detailed investigation of specific challenges, such as accurately measuring uncertainties and generating digital calibration certificates. By focusing on particular cases within the metrology and calibration industry, the case study ensures that our findings are practical and directly applicable to real-world problems.

4.2.2 Data Collection

Data for this case study was sourced from an existing project shown in 1.1. This data was critical for testing and validating the microservices, providing a real-world context to assess their performance and effectiveness.

4.2.3 Analysis

The microservices were architected to interact through well-defined Application Programming Interface (API)s, facilitating seamless data exchange between the uncertainty calculation service and the digital calibration certificate generator. The digital calibration certificate microservice consumed calibrated data directly from the uncertainty calculation service, ensuring accuracy and consistency. Kubernetes services and deployments were used to manage deployment and traffic exposure, enabling robust scaling and accessibility of the microservices to external users.

4.3 Design Science Research

During the study, DSR provided a structured process for building and evaluating a microservice-based application, aimed at addressing key challenges in metrology,

such as standardizing DCC and improving accuracy. This approach, combined with a case study, ensured the POC was properly built and evaluated, aligning with the research goal to answer RQ2.

4.3.1 Problem Identification

The core issue this research addresses is the need for improved accuracy and smoother calibration processes within the metrology industry. Traditional methods often face challenges with scalability and real-time data processing. Microservice architectures can help mitigate these difficulties, offering a more adaptable approach to handling calibration tasks.

4.3.2 Artifact Design

The microservices were designed to perform specific tasks within the calibration workflow. The uncertainty calculation service processes measurement data to provide precise uncertainty estimates. The DCC service generates standardized calibration certificates based on uncertainties provided by the uncertainty calculation microservice. For a clearer understanding of the artifact design, the project is divided into two core components: the DCC microservice and the Monte Carlo Simulation (MCS) microservice. The project is structured into two main microservices:

```
teklie@PC-H93KYR:~/thesis/calibraiton$ ls -R
.:
dcc  deployment.yaml  mcs  service.yaml

./dcc:
Dockerfile  generate-digital-cal-cert.py  requirements.txt

./mcs:
Dockerfile  requirements.txt  static  templates  uncertainty-calculation.py

./mcs/static:
style.css

./mcs/templates:
index.html
```

Figure 4.2: Overview of the Project Structure

the DCC microservice and the MCS microservice, both deployed in Kubernetes on Google Cloud Platform. Below is the detailed explanation of the files and folders:

- **Root Folder:**
  - Contains two important YAML files:
    - `deployment.yaml`: Defines how the microservices will be deployed in Kubernetes.
    - `service.yaml`: Specifies how the microservices will be exposed, including ports and services for uncertainty calculation and certificate

generation.

  - Folders:
    * `dcc`: DCC microservice related files.
    * `mcs`: Monte Carlo Simulation microservice related files.

- **DCC Folder:**
  - `Dockerfile`: Defines the environment for the DCC microservice.
  - `generate-digital-cal-cert.py`: Main script for generating digital calibration certificates.
  - `requirements.txt`: Contains Python dependencies for the DCC microservice.
- **MCS Folder:**
  - `Dockerfile`: Defines the environment for the MCS microservice.
  - `uncertainty-calculation.py`: Processes measurement data and performs uncertainty calculations.
  - `requirements.txt`: Lists Python dependencies for the MCS microservice.
  - `withAtt_SWR.xlsx`: Excel file for processing uncertainty calculations.
  - `static/`: Contains `style.css` for web interface styling.
  - `templates/`: Contains `index.html` for the web interface.

The complete project code is stored in GitHub and is version-controlled. It can be shared upon request for further research.

4.3.3 Development and Deployment

The microservices were developed using modern software engineering practices and deployed on Google Cloud. Kubernetes was used for orchestration, providing a scalable and resilient environment for the services. This setup facilitated the handling of large datasets and allowed for seamless updates to services without any downtime. The deployment files can be seen at A.2.1.

4.3.4 Evaluation

The effectiveness of the microservices was evaluated using data from a completed project supported by The Scientific and Technological Research Council of Türkiye

under Grant No. 5200040, titled "A New Method and Software Development for Automatic RF Power Measurement and RF Power Meter Calibration" [34]. Key performance indicators included the accuracy of uncertainty calculations, the time required to generate calibration certificates, and the overall system reliability under varying loads.

4.3.5 Iterations

The DSR process involves three iterations, starting from problem identification or requirements inception to solution creation and evaluation in each cycle. It begins with identifying the problem, guiding the research, and laying the foundation for proposing possible solutions. These solutions are then tested and refined during the validation phase to ensure they are practical.

Once validated, the solutions are implemented as proof of concept. The final phase involves evaluating these solutions against predefined criteria to determine how well they solve the original problem or meet the initial requirements. This evaluation completes the current DSR cycle and prepares the process for future iterations, allowing for ongoing improvement.

5

Results

5.1 Systematic Literature Review

5.1.1 Study Selection

The systematic search strategy applied for this review identified 269 articles across several databases, including Google Scholar, IEEE Xplore, ACM Digital Library, Springer Link, and Science Direct. After applying the necessary selection phases to ensure the relevance of the studies, 16 studies were selected for in-depth analysis, as shown in Table 4.1. These studies focus on the implementation of cloud-based solutions in metrology and calibration industries, providing insights into both the advantages and disadvantages associated with cloud adoption in various contexts.

5.1.2 Synthesis of Findings

5.1.2.1 Pros of Cloud-Based Solutions

Cost Savings: Cloud-based solutions reduce the need for costly on-site IT infrastructure, offering a more economical approach through pay-as-you-go pricing models that align expenses with actual usage. For example, Barateiro and Makarovsky [35] demonstrated that by migrating their metrology data management to the cloud, organizations were able to cut down significant costs associated with maintaining physical servers. This shift allowed them to allocate resources more efficiently, focusing on core business operations rather than IT maintenance. The flexibility in pricing models also helped them adapt to fluctuating demand without the need for additional investments in physical infrastructure.

Scalability and Flexibility: The ability to scale resources up or down based on demand is a significant advantage of cloud technologies. Schaerer and Braun [36] illustrated this in their study on distributed calibration certificate infrastructures, where the cloud allowed for rapid adjustments in processing power and storage capacity during peak calibration periods. Compared to traditional systems that require physical upgrades to handle increased workloads, cloud solutions provided a more dynamic and cost-effective alternative. This scalability enabled metrology firms to respond quickly to market changes and customer needs without incurring the downtime or capital expenditure typically associated with physical infrastructure

upgrades.

Improved Data Accessibility and Collaboration: Cloud platforms enable seamless access to calibration data and records from any location, facilitating enhanced collaboration among stakeholders. Smith et al. [37] described how their use of cloud-based digital calibration certificates improved communication between geographically dispersed teams. By centralizing data in the cloud, all parties involved in the calibration process had real-time access to the latest information, reducing errors and speeding up decision-making processes. This approach contrasted sharply with traditional methods, where data was often siloed and required manual transfer, leading to delays and potential miscommunication.

Enhanced Security Features: Advanced security protocols and cryptographic techniques employed by cloud services enhance the protection of sensitive calibration data. Peterek and Montavon [38] highlighted the use of X.509 certificates and IOTA technology in their cloud-based system to ensure dual digital traceability of metrology data. This system provided a higher level of security compared to legacy systems, which often relied on less sophisticated security measures. The authors noted that features such as end-to-end encryption and multi-factor authentication were crucial in maintaining data integrity and confidentiality, particularly in industries where precision and data accuracy are paramount.

5.1.2.2 Cons of Cloud-Based Solutions

Data Privacy Concerns: The storage of sensitive data in the cloud introduces potential risks related to data privacy and unauthorized access. Schaerer and Braun [36] acknowledged that while cloud providers offer robust security features, the shared responsibility model means that organizations must also implement their own measures to protect data. They discussed instances where inadequate security practices led to data breaches, underscoring the importance of adopting comprehensive security policies when using cloud services. This concern is particularly acute in metrology, where data integrity is critical to ensuring accurate measurements and outcomes.

Dependence on Internet Connectivity: The effectiveness of cloud solutions is heavily dependent on reliable internet connections. Xia et al. [39] explored this issue in the context of smart retail systems, noting that regions with poor connectivity faced significant challenges in accessing cloud-based services. In the metrology and calibration industry, this reliance on internet connectivity can result in operational disruptions if access to critical calibration data is lost. The authors compared this to traditional on-site systems, which, while less flexible, do not depend on external connectivity and therefore offer more consistent performance in areas with unreliable internet service.

Potential Security Risks: Despite enhanced security features, cloud systems remain vulnerable to cyber threats and attacks. Schaerer and Braun [36] discussed the continuous threat of cyberattacks on cloud infrastructure, emphasizing the need for

regular security audits and updates. They compared the security posture of cloud-based systems with that of legacy systems, concluding that while cloud systems often have more advanced security features, they are also more frequently targeted due to their accessibility over the internet. The authors highlighted the importance of staying vigilant and proactive in mitigating these risks through ongoing security enhancements.

Initial Implementation Costs: While cloud solutions can reduce long-term operational costs, the initial investment required for migration, training, and integration can be substantial. Smales and Pauw [40] provided a detailed analysis of the costs involved in transitioning to cloud-based metrology systems. They found that organizations often underestimated the resources needed for a successful migration, leading to budget overruns. The authors argued that these initial costs, although significant, should be weighed against the long-term benefits of cloud adoption, including improved scalability, flexibility, and operational efficiency.

5.2 Case Study and Design Science Research

To address research question 2, this study combines the case study method with DSR to tackle challenges in uncertainty calculation and DCC generation using radio frequency power meter measurements. Although a physical lab was not available, the case study approach enables a detailed exploration of these challenges using real-world data, ensuring that the solutions developed are both practical and relevant to industry needs. The case study method provides a thorough examination of how these microservices handle actual RF power meter data, focusing on both technical and operational impacts, such as workflow efficiency.

DSR is used within this framework to develop microservices that calculate uncertainties and generate DCCs. These services are tested iteratively with real data, allowing their performance to be refined to meet the strict requirements of the metrology industry. By integrating DSR with the case study, the research not only creates a functional tool but also offers insights into its practical application. This combined approach ensures that the research outcomes are reliable and applicable, offering valuable contributions to metrology and calibration.

5.2.1 Problem Identification

The first step involves understanding the specific issue at hand. For metrology, the challenges include accurately measuring uncertainties and efficiently generating digital calibration certificates.

5.2.2 Solution suggestions

Once the problem is clear, the next step is brainstorming and outlining possible solutions. These solutions are developed to improve accuracy and operational efficiency in metrological processes.

5.2.3 Solution Validation

After proposing solutions, they are tested through practical experiments or simulations to evaluate how well they perform in real or simulated environments. The DSR steps, including this one, are detailed in each iteration. For example, the solution validation phase for Iteration I is provided in 5.2.7.

5.2.4 Implementation

Successful solutions are then implemented. This means integrating the new methods or tools into existing systems to start seeing benefits.

5.2.5 Evaluation

The evaluation of the uncertainty calculation microservice involved assessing its performance, accuracy, and the reduction of manual steps in real-world scenarios. While a direct comparison with traditional, manual methods has not yet been conducted, the traditional process involves significant human intervention, including manually transferring results, which introduces the risk of human error. The automation tool eliminates this manual step, reducing both the likelihood of errors and the time required for the overall process. Furthermore, automated actions are considerably faster than manual operations, leading to a reduction in process duration. In addition, the tool has been validated by domain experts, who found it to be user-friendly and appreciated its ability to simplify workflows. This feedback underscores its practicality and usefulness in improving calibration processes.

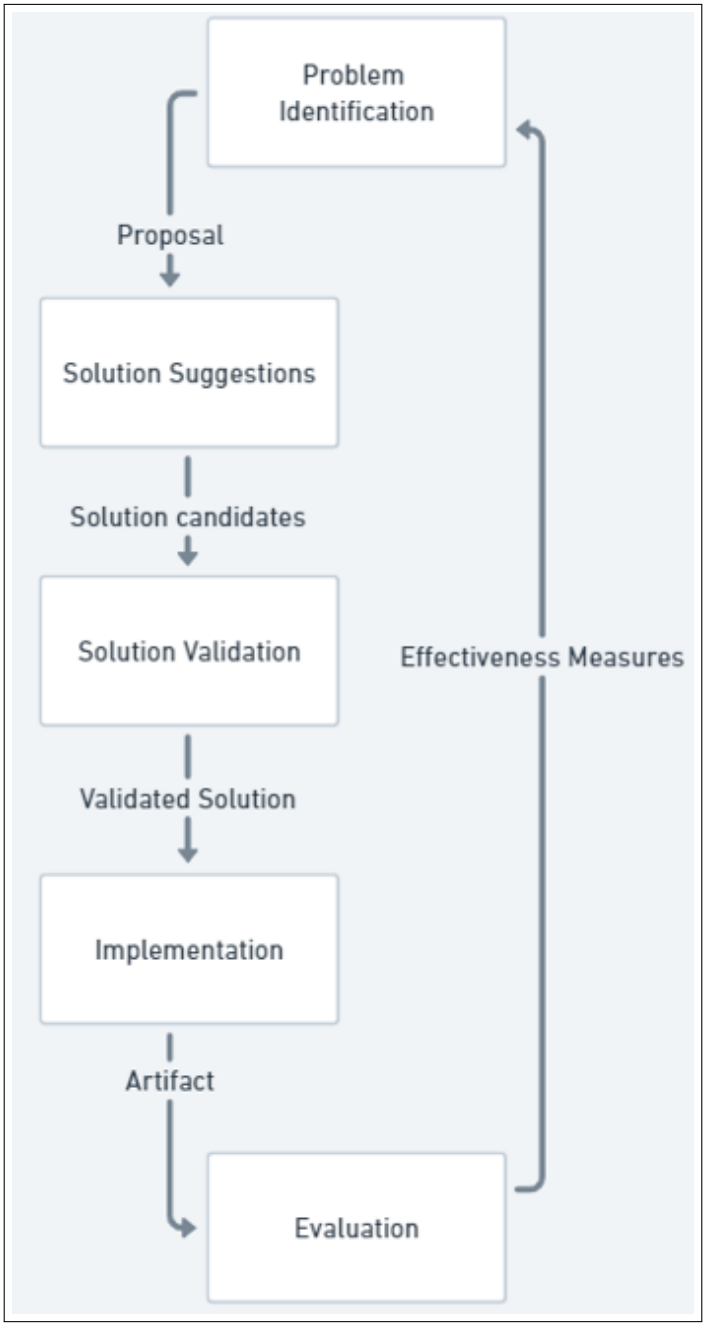

Figure 5.1: Design Science Research activities

The flowchart in Figure 5.1 illustrates the DSR approach, detailing the process from problem identification to evaluation. It shows the progression of each step, starting with problem identification, followed by solution suggestions, solution Validation, and Implementation, and concluding with evaluation. Alongside, it also maps the outputs at each stage, starting from the initial Proposal to the final Artifact and Effectiveness Measures, highlighting how each phase contributes to the development and refinement of a practical solution.

5.2.6 Iterations

The goal of the upcoming iterations is to create a proof of concept following the sequence diagram shown in Figure 5.2.

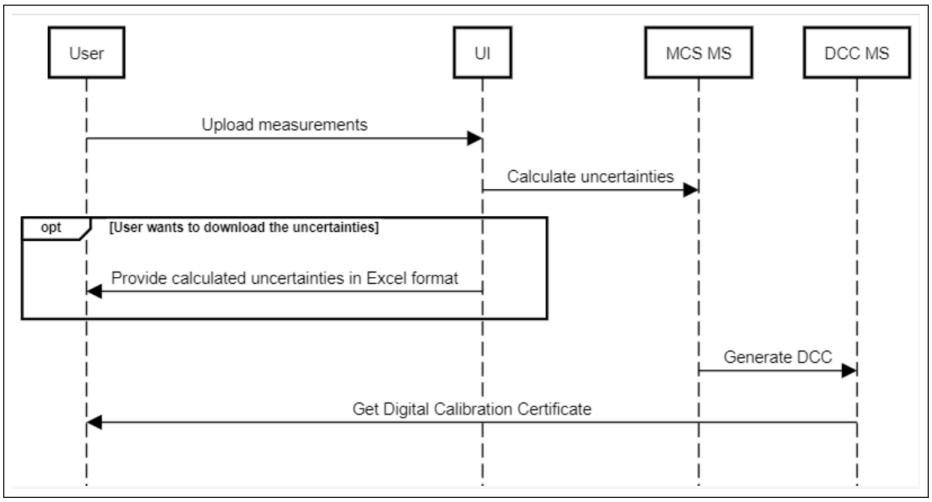

Figure 5.2: Microservices interaction sequence diagram

This sequence diagram in Figure 5.2 illustrates a user interacting with a proof of concept system to upload radio frequency power meter measurements and receive a DCC. The user first uploads the measurements through the user interface (UI), which then communicates with the MCS based Uncertainty Calculation Service to calculate the uncertainties. If the user wants to download the calculated uncertainties in Excel format, they can do so via the UI. The DCC Service also accesses these calculated uncertainties to generate a DCC.

Iteration I: Development of Uncertainty Calculation Microservice
The first iteration of this study's DSR approach involves developing a microservice focused on uncertainty calculation within the metrology context. This iteration covers the key DSR activities, including problem identification, evaluation, and the generation of outputs at each stage.

Iteration II: Digital Calibration Certificate microservice development
The second iteration focuses on developing a microservice for generating DCCs. This iteration builds on the lessons learned from the first iteration and involves the creation of a modular service that integrates with existing metrology systems, offering a seamless transition from traditional paper-based certificates to digital ones. The service includes features for automating the generation of certificates, ensuring compliance with industry standards, and facilitating easy access and sharing of calibration data across platforms. By leveraging the flexibility and scalability of microservices, this approach enhances the reliability and efficiency of the calibration process, providing stakeholders with a robust solution for managing calibration data.

Iteration III: Cloud Deployment and Evaluation

The third iteration focuses on deploying the developed microservices on a cloud platform, evaluating their performance, scalability, and security in a real-world environment. This phase involves configuring the microservices to operate efficiently in a cloud environment, utilizing cloud-native features such as auto-scaling, load balancing, and advanced security measures to ensure optimal performance and data protection. The evaluation includes stress testing the services under varying loads, assessing their ability to handle large volumes of data, and identifying any potential bottlenecks or areas for improvement. The findings from this iteration provide valuable insights into the practical application of cloud-based microservices in metrology, highlighting their potential to enhance operational efficiency and data management in the calibration industry.

5.2.7 Iteration I

Problem Identification: This iteration started with identifying a major problem. There's a need for a better approach to carrying out uncertainty calculations in metrology, one that's both more accurate and efficient. Traditional methods didn't meet expectations due to their limited ability to scale, lack of flexibility, and difficulties integrating with current digital systems. This issue is crucial since precise uncertainty calculations are important for guaranteeing the reliability and credibility of measurements in numerous industries. To address these problems, a proposal to implement a microservice architecture was made. This approach is designed to contribute to the field of metrology by adopting digital methods.

Solution Suggestion: With the problem clearly defined, the next step involved brainstorming potential solutions. The concept was to develop a microservice specifically designed for uncertainty calculations, incorporating Monte Carlo simulations. This microservice would integrate seamlessly with existing metrology software systems, allowing for easy updates and scalability while ensuring optimal performance.

Among the various Monte Carlo simulation approaches, the Integrated Data Analysis and Uncertainty Calculation Service was proposed. This microservice would not only perform the simulations but also preprocess the measurement data, ensuring it is thoroughly prepared for accurate analysis.

Solution Validation: After the development of a candidate solution for the uncertainty calculation microservice, a thorough validation process was initiated. This phase engaged in theoretical testing using simulations and models to estimate the performance and efficiency of the proposed microservice designs. Specifically, the Monte Carlo simulation technique was employed to assess the potential impact of these solutions on enhancing accuracy and processing speed in uncertainty calculations.

- **Monte Carlo Simulation Process**: The core of the validation process involved utilizing the Monte Carlo simulation to model the uncertainty calculations. This simulation method, known for its flexibility and accuracy, was integral in predicting how the microservice would perform under various con-

ditions.

- **Beta Distribution Parameters Calculation**: Initially, beta distribution parameters were calculated for each data set to mimic real-world variability and ensure the simulations were grounded in practical scenarios.
- **Random Variable Generation**: Random variables were generated based on specified distributions, including normal and uniform distributions, to simulate various aspects of uncertainty calculations, such as measurement readings and instrument accuracy. This step was crucial in creating a diverse set of simulation environments.
- **Monte Carlo Simulation Execution**: For each data set, the Monte Carlo simulation was executed 200,000 times, using predefined parameters to generate outcomes for uncertainty calculations. This approach enabled the exploration of a wide range of scenarios and the collection of a comprehensive set of data on potential performance.
- **Performance Metrics Analysis**: The simulation results were analyzed to derive key performance metrics, including the mean, standard deviation, and confidence intervals for the calculated uncertainties. These metrics offered valuable insights into the effectiveness and reliability of the microservice in performing uncertainty calculations.
- **Visualization and Documentation**: The results were visualized using histograms and probability distributions, as shown in 5.3, allowing for a clear view of the behavior of the uncertainty calculations. Additionally, the lower and upper endpoints of the 95% confidence intervals were documented to quantify the precision of the simulations.

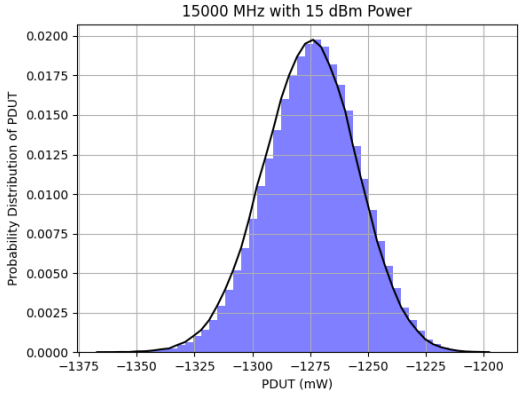

Figure 5.3: Probability distribution for RF power measurements

Figure 5.3 illustrates the probability distribution for RF power measurements at 15000 MHz with 15 dBm power, presented through a histogram with an overlaid line plot. This graph displays the Power Delivered to Uncertainty (PDUT) measured in milliwatts (mW). The x-axis represents PDUT values ranging from approximately

-1375 to -1200 mW, while the y-axis illustrates the probability density. The blue bars highlight the observed frequency, with the peak indicating the most common PDUT range. Additionally, a superimposed black line represents a fitted Gaussian distribution, estimating the expected probability distribution based on the data. This graph is crucial for evaluating the PDUT's performance and variability at the specified frequency and power level.

Implementation: This part aims to turn the proposed solution for an uncertainty calculation microservice into a functional reality. Leveraging the insights gained from the validation process, the Monte Carlo simulation-enabled microservice was developed to be modular and scalable, fitting seamlessly into the digital ecosystem of metrology.

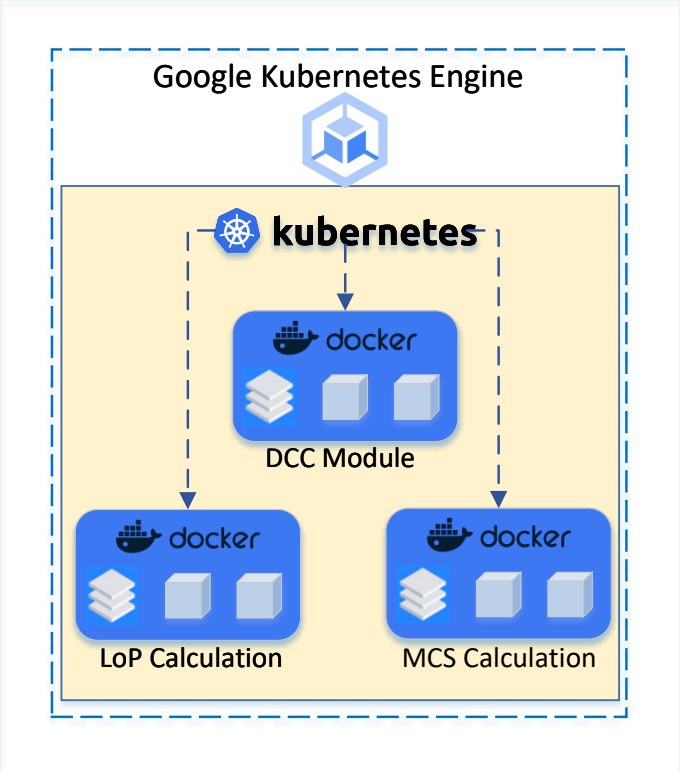

Figure 5.4: Setup of uncertainty calculation and DCC generation services

Figure 5.4 *shows the setup that combines a microservice for MCS-based uncertainty calculations with the DCC service. The setup includes the Law of Propagation (LoP) method (see [1]) and introduces the MCS and DCC services developed in this study. Managed with Kubernetes Engine, the diagram effectively conveys how these services work together seamlessly.*

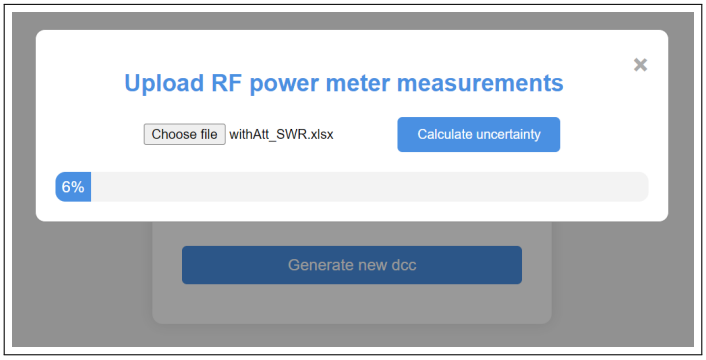

Figure 5.5: Uncertainty calculation from the UI perspective

This figure illustrates the deployed uncertainty calculation service in action. Behind the scenes, it invokes 'BaseURL:port/calculate-uncertainty' endpoint within the uncertainty calculation container deployed on Google Cloud Platform.

Evaluation: The evaluation of the uncertainty calculation microservice involved assessing its performance, accuracy, and efficiency in real-world scenarios. Performance was measured by how well the microservice handled uncertainty calculations, including its ability to scale and maintain responsiveness under varying loads. By varying the simulation iterations in the Monte Carlo Simulation (MCS)-based uncertainty calculation microservice, CPU and memory usage were monitored in real time. The screenshot below in Figure 5.6 shows the resource utilization metrics for both the uncertainty calculation and the Digital Certificate Creation (DCC) generation microservices. These metrics can also be monitored in real-time via Google Cloud's user interface, where alerts can be configured to notify administrators if resource usage exceeds predefined thresholds.

```
teklie@PC-H93KYR:~$ kubectl top pods --containers=true
POD              NAME                          CPU(cores)   MEMORY(bytes)
calibration-pod  calculate-uncertainty         32m          221Mi
calibration-pod  generate-digital-certificate  4m           116Mi
```

Figure 5.6: Real-time resource utilization of uncertainty calculation and DCC generation containers

The image presents real-time CPU and memory usage metrics for two containers running within the "calibration-pod." The first container, responsible for uncertainty calculation, is utilizing 32 milliCPUs (32m), which corresponds to 3.2% of a single CPU core, and it is consuming 221 MiB of memory. The second container, tasked with digital certificate generation, is using 4 milliCPUs (4m), or 0.4% of a single CPU core, along with 116 MiB of memory. These values demonstrate the resource usage under the current workload, providing insights into how efficiently each container is using the available CPU and memory resources while performing their respective tasks.

5.2.8 Iteration II

Problem Identification: The second iteration focused on addressing the challenges associated with generating and managing DCCs. Traditional paper-based certificates are prone to errors, difficult to manage, and inefficient for data sharing and retrieval. The need for a digital solution that automates certificate generation, ensures compliance with industry standards, and facilitates seamless data access and sharing across platforms became evident.

Solution Suggestion: To address these challenges, a microservice dedicated to DCC generation was proposed. This service aimed to automate the entire certificate creation process, ensuring that certificates are accurate, standardized, and easily accessible. The microservice was designed to integrate with existing metrology systems, allowing for seamless data exchange and reducing manual intervention. Features such as automated validation, compliance checks, and secure storage and retrieval of certificates were incorporated to enhance reliability and efficiency.

Solution Validation: The validation phase involved testing the DCC microservice in various operational scenarios to assess its effectiveness in generating accurate and compliant certificates. Simulations and real-world trials were conducted to evaluate the service's performance, identifying potential bottlenecks and areas for improvement. The microservice's ability to handle large volumes of certificate data, maintain compliance with industry standards, and facilitate easy access and sharing was rigorously tested.

Implementation: The implementation of the DCC microservice involved deploying it within a cloud environment, utilizing cloud-native features to ensure scalability, reliability, and security. The service was integrated with existing metrology systems, enabling seamless data exchange and reducing manual intervention. The deployment process included configuring security protocols to protect sensitive certificate data, implementing automated workflows for certificate generation, and setting up monitoring and alerting mechanisms to ensure optimal performance.

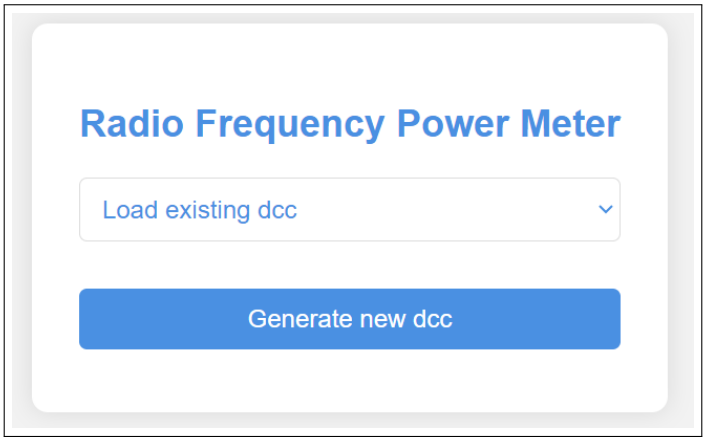

Figure 5.7: Generate new DCC or load existing DCCs

This figure illustrates the UI for loading existing DCCs from pre-calculated uncertainties or generating new DCCs by performing a new uncertainty calculation and creating a certificate from the newly calculated uncertainty. A sample DCC is shown in 5.2.8.

Evaluation: The evaluation phase focused on examining how the DCC microservice impacted the management of calibration certificates, specifically looking at improvements in processing time, accuracy, and ease of data access. The system allowed for faster generation of certificates and reduced errors compared to traditional methods, all while ensuring compliance with industry standards. A sample DCC, displayed on the following pages, was generated using the DCC microservice. This certificate contains important administrative information, including details about the software used, its version, and a unique identifier for the certificate. It also includes essential calibration information, such as the date and location of the calibration, as well as the name of the technician who performed it.

The certificate documents the calibration of a radio frequency power meter, offering precise measurement results. These results include corrected power values, uncertainty estimates, and confidence intervals for different frequency ranges. The data for the uncertainty calculations was obtained through an API, which connected to a microservice that used the MCS method to provide highly accurate calculations. Additionally, the certificate features a QR code that users can scan to instantly verify its authenticity and check for any alterations. This quick verification process enhances the trustworthiness of the certificates. Overall, the automated process for generating DCCs using this microservice ensures consistency, reduces the likelihood of errors, and improves the efficiency of calibration management, making the system more reliable and user-friendly.improves the efficiency of calibration management, making the system more reliable and user-friendly.

Digital Calibration Certificate

Administrative Data

- **Software Name:** CSE - Digital calibration certificate generator
- **Release:** v1.0.0

Coredata

- **Country Code (ISO3166_1):** SE
- **Used Language(s) (ISO639_1):** en
- **Mandatory Language(s) (ISO3166_1):** en
- **Unique Identifier:** 56752da6-5f60-419d-92f2-25a924f2bddb
- **Date of Reception:** 2024-08-27
- **Date of Calibration:** 2024-08-27
- **Place of Calibration:** CSE Calibration Lab
- **Date:** 2024-08-27

Devices under Test

- Radio frequency Power Meter

Calibration Laboratory

- **Personnel:** Tek
- **e-mail:** tek.bel.bzu@cse-dcc-lab.com
- **Street Number:** 24
- **Calibration Laboratory Code:** CSE-CAL-LAB-9876

RF Power Measurement Results

Freq (MHz)	Power (dBm)	PDUT_Corr_GUM (mW)	UPDUT_k2_GUM (mW)	Low Endpoint for 95% Confidence Interval	High Endpoint for 95% Confidence Interval	Mean of PDUT_MCS (mW)	Standard Deviation of PDUT_MCS (mW)	2 * Standard Deviation of PDUT_MCS (mW)	Total Simulation Time Elapsed = 15.059033155441284 sec
50.0	0.0	9.86	0.1	-98.35	-96.21	-97.36	0.54	1.09	nan
1000.0	0.0	10.51	0.1	-113.35	-111.64	-112.54	0.5	1.01	nan
5000.0	0.0	10.35	0.17	-113.06	-110.16	-111.55	0.73	1.46	nan
10000.0	0.0	10.55	0.27	-120.09	-117.26	-118.74	0.78	1.55	nan
15000.0	0.0	10.8	0.39	-131.25	-122.64	-126.64	2.08	4.15	nan
18000.0	0.0	10.68	0.32	-127.59	-122.28	-124.66	1.44	2.88	nan
50.0	5.0	31.41	0.33	-997.91	-976.67	-986.56	5.1	10.2	nan
1000.0	5.0	33.48	0.31	-1152.21	-1132.34	-1142.28	5.14	10.28	nan
5000.0	5.0	32.92	0.54	-1146.21	-1113.93	-1130.18	8.33	16.67	nan
10000.0	5.0	33.39	0.86	-1205.97	-1173.16	-1189.64	8.5	17.01	nan
15000.0	5.0	34.24	1.25	-1317.17	-1234.0	-1275.77	21.1	42.2	nan
18000.0	5.0	34.03	1.03	-1295.2	-1232.89	-1265.33	15.7	31.4	nan
50.0	10.0	9.86	0.1	-98.27	-96.45	-97.3	0.49	0.98	nan
1000.0	10.0	10.51	0.1	-113.48	-111.5	-112.48	0.53	1.06	nan
5000.0	10.0	10.35	0.17	-113.07	-110.15	-111.59	0.78	1.55	nan
10000.0	10.0	10.55	0.27	-120.17	-117.21	-118.84	0.84	1.69	nan
15000.0	10.0	10.8	0.39	-130.54	-123.22	-126.87	1.85	3.7	nan
18000.0	10.0	10.68	0.32	-127.37	-121.78	-124.66	1.48	2.95	nan

50.0	15.0	31.41	0.33	-996.02	-976.07	-986.66	5.03	10.06	nan
1000.0	15.0	33.48	0.31	-1153.81	-1134.15	-1142.47	5.66	11.32	nan
5000.0	15.0	32.92	0.54	-1144.3	-1115.76	-1129.72	7.31	14.63	nan
10000.0	15.0	33.39	0.86	-1205.65	-1173.56	-1190.78	8.56	17.11	nan
15000.0	15.0	34.24	1.25	-1315.57	-1236.66	-1274.16	20.37	40.74	nan
18000.0	15.0	34.03	1.03	-1293.14	-1234.61	-1265.53	15.53	31.05	nan

This certificate was generated based on the result of uncertainty calculation: /mnt/data/Output_MCS_Result_withAtt_SWR.xlsx

Approved by: _____

Signature: _____

5.2.9 Iteration III

Problem Identification: The third iteration focused on deploying and managing microservices in a cloud environment, emphasizing the optimization of performance, scalability, and security. Key challenges identified included ensuring seamless integration with existing infrastructure, efficiently handling dynamic workloads, and protecting sensitive data.

Solution Suggestion: To tackle these challenges, a comprehensive cloud deployment strategy was proposed, leveraging cloud-native features such as auto-scaling, load balancing, and advanced security protocols. The strategy aimed to optimize resource utilization, ensure high availability, and protect data integrity while maintaining compliance with industry standards.

Solution Validation: The validation phase involved stress testing the deployed microservices under varying loads to evaluate their scalability and performance. Security assessments were conducted to identify potential vulnerabilities and ensure robust data protection. The microservices' ability to integrate seamlessly with existing infrastructure and support dynamic workloads was rigorously tested.

Implementation: The implementation phase involved configuring the microservices for optimal performance in a cloud environment, utilizing tools such as Kubernetes for orchestration, monitoring, and management. Security protocols were implemented to protect sensitive data, and automated workflows were established to streamline deployment and management processes.

```
teklie@PC-H93KYR:~$ kubectl get service,pod -o wide
NAME                          TYPE           CLUSTER-IP       EXTERNAL-IP     PORT(S)                        AGE   SELECTOR
service/calibration-service   LoadBalancer   34.118.228.252   34.90.190.190   5001:32674/TCP,5002:31266/TCP   29d   app=calibration-pod
service/kubernetes            ClusterIP      34.118.224.1     <none>          443/TCP                        57d   <none>

NAME                  READY   STATUS    RESTARTS   AGE   IP           NODE                                                NOMINATED NODE   READINESS GATES
pod/calibration-pod   2/2     Running   0          51m   10.12.1.13   gke-calibration-cluster-default-pool-656b9ddb-zyf4   <none>           <none>
```

Figure 5.8: Kubernetes pod and services

The above figure provides a detailed view of the deployed Kubernetes services and pod. It shows that the calibration-service is a LoadBalancer service, exposing ports 5001 and 5002 to the external IP 34.90.190.190, and is associated with the calibration-pod. The calibration-pod is running on a node named gke-calibration-cluster-default-pool-656b9ddb-zyf4 with an internal IP of 10.12.1.13. The pod is fully operational with 2/2 containers running (uncertainty calculation and DCC generation containers) and has been active for 51 minutes without any restarts. Additionally, the kubernetes service, which is of ClusterIP type, is also listed with its details.

Evaluation: The evaluation phase focused on assessing the cloud deployment strategy's impact on microservice performance, scalability, and security. Key performance indicators such as response time, resource utilization, and data integrity were measured to evaluate the strategy's effectiveness. The findings demonstrated significant improvements in operational efficiency, scalability, and data protection, validating the success of the cloud deployment approach.

6

Discussion

6.1 Interpretation of Results

The analysis shows that cloud-based solutions offer significant benefits such as cost savings, scalability, and improved collaboration, which are particularly useful for the metrology and calibration industries. These industries, which traditionally rely on precise measurements and well-established processes, can greatly benefit from the flexibility and efficiency that cloud technologies provide. For instance, cloud-based systems allow organizations to scale resources easily in response to changing demands, reducing the need for large upfront investments in physical infrastructure. This scalability not only supports day-to-day operations but also enables organizations to handle peak workloads without the need for additional physical space or hardware.

Another major advantage is the improvement in data accessibility and collaboration. Cloud platforms enable teams to access calibration data from any location, facilitating real-time collaboration between geographically dispersed teams. This can lead to faster decision-making and more efficient workflows, as all team members have access to the most up-to-date information. The ease of sharing data and collaborating across different locations also supports global operations, making it easier for multinational companies to maintain consistent standards and practices.

However, these benefits are not without challenges. Data privacy is a major concern when using cloud-based systems, particularly in industries like metrology, where the accuracy and security of data are critical. Storing sensitive data in the cloud exposes it to potential cyber threats, requiring robust security measures to mitigate these risks. This includes implementing strong encryption methods, secure access controls, and regular security audits to ensure that data remains protected from unauthorized access or breaches.

Dependence on internet connectivity is another challenge. Cloud-based systems require a stable and reliable internet connection to function effectively. In regions where internet infrastructure is less developed or prone to disruptions, this reliance can lead to significant operational challenges. For example, if the internet connection is lost or becomes unstable, access to critical calibration data may be interrupted, causing delays and potential errors in the calibration process. Therefore, organi-

zations need to carefully assess their internet connectivity and consider potential backup solutions when planning cloud adoption.

Additionally, the initial costs of implementing cloud technologies can be high, particularly for organizations transitioning from traditional on-premises systems. These costs include not only the financial investment in cloud services but also the time and resources required to train staff, migrate data, and integrate the new systems with existing workflows. The transition period may also introduce temporary disruptions as employees adjust to new tools and processes. To fully capitalize on the benefits of cloud technologies, organizations must carefully manage these challenges, ensuring that the transition is as smooth and efficient as possible.

6.2 Implications for the Industry

Adopting cloud technologies in metrology and calibration can lead to enhanced efficiency and cost-effectiveness across the industry. The ability to scale resources according to demand, coupled with the reduced need for physical infrastructure, allows companies to operate more flexibly and respond more quickly to changes in workload. This flexibility is particularly valuable in metrology, where the demand for calibration services can fluctuate based on industry needs, regulatory requirements, and technological advancements.

To maximize these benefits, it is crucial for industry stakeholders to address the challenges associated with cloud adoption. Data security, accessibility, and privacy are key concerns that must be prioritized. Implementing strong security measures, such as data encryption, secure user authentication, and regular vulnerability assessments, is essential to protecting sensitive calibration data from potential threats [35]. Organizations must also ensure that they have reliable internet access to support the continuous operation of cloud-based systems. In regions where internet connectivity is less reliable, it may be necessary to implement alternative solutions, such as offline data storage or hybrid cloud models.

Hybrid cloud models offer a balanced approach, allowing organizations to keep sensitive data on-premises while leveraging the cloud for less critical tasks. This approach can help mitigate privacy concerns while still benefiting from the scalability and flexibility of cloud technologies. By carefully selecting which data and processes to migrate to the cloud, organizations can maintain control over their most sensitive information while still enjoying the advantages of cloud-based systems.

Looking ahead, the integration of more automation and advanced analytics into cloud-based systems holds significant potential for the metrology sector. By leveraging these technologies, organizations can automate routine calibration tasks, predict when equipment will need maintenance, and optimize resource allocation. This can lead to further improvements in efficiency, accuracy, and cost savings, helping organizations to stay competitive in a rapidly evolving industry.

6.3 Limitations and Threats to Validity

This research has several limitations and threats to validity that should be considered when interpreting the results.

6.3.1 Limitations

A key limitation of this study is that it is based on a single case study. While this case study provides useful insights into the use of microservice-based applications for uncertainty calculations and digital calibration certificate generation, the findings may not apply to all situations or industries. This limits the ability to generalize the results to a broader context.

Another limitation is the geographical focus of the case study. Since it was conducted within a specific region or organization, the findings may not reflect global trends in cloud adoption in the metrology and calibration industries. Differences in technology, regulations, and industry practices across regions could impact how these technologies are adopted and used.

The rapid pace of change in cloud computing technology is another challenge. As new advancements in cloud security, data management, and service delivery emerge, some of the findings from this study may become outdated. Continuous updates to research and practice will be necessary to keep up with these changes.

Finally, this research mainly focused on the technical aspects of cloud adoption. It did not deeply explore other important factors, such as organizational culture, employee readiness, or the availability of skilled personnel to manage cloud systems. These socio-economic factors are important and should be investigated further in future research to provide a more complete understanding of the challenges and opportunities with cloud technologies in metrology.

6.3.2 Threats to Validity

In addition to the limitations, there are specific threats to the validity of this study:

- **Internal Validity**: Since the study relies on data from a single project, there is a risk that the findings may be influenced by the unique circumstances of this case, which may not represent the broader industry. This could lead to potential biases in the results. To mitigate this, a structured and consistent research approach was followed, ensuring that the development and testing of the microservices remained in line with the intended applications. Additionally, aligning findings with related studies has helped to validate the approach.

- **External Validity**: The single-case focus may limit the generalizability of the findings to other contexts or industries. To enhance external validity, the study compared its findings with those from the SLR, providing a broader understanding of microservices in metrology. However, additional projects

across different industries would be necessary to validate the results more comprehensively.

- **Conclusion Validity**: Given the use of only one project, there is a possibility that the conclusions may not capture the full range of complexities present in the broader calibration industry. The conclusions were strengthened by incorporating insights from the SLR, but further studies involving multiple projects are recommended to validate and refine these findings.

7

Conclusion

This research has explored the role of cloud-based and microservice-based technologies in the metrology and calibration industries. Through a systematic review of the literature, key benefits of cloud-based solutions, such as cost efficiency, scalability, improved data accessibility, and enhanced security, were identified. These advantages are vital for industries adapting to digital transformation. However, challenges like data privacy concerns, reliance on stable internet connectivity, and initial implementation costs need careful management to fully realize these benefits.

The study also examined the application of microservices in metrology, focusing on uncertainty calculation and digital calibration certificates. These microservices were deployed on the Google Cloud platform and validated through proof-of-concept case studies, demonstrating their potential to improve precision and workflow efficiency. The use of Kubernetes for deployment ensured scalability and robustness, making these solutions adaptable to the specific demands of metrology.

A DSR and case study method were used to develop and test these tools. DSR allowed for iterative refinement, while case study provided real-world contexts for validation. This approach helped create tools that are practical and relevant to the industry, even though they remain at the proof-of-concept stage.

In summary, this research highlights the potential of cloud-based and microservice-based technologies to enhance productivity, precision, and innovation in the metrology and calibration industries. Addressing the associated challenges and continuing to develop these technologies will support the ongoing digital transformation of these fields.

Future research should focus on improving security frameworks to address privacy concerns, especially as cyber threats evolve. Exploring hybrid cloud models that balance cloud benefits with data control, and examining the long-term costs of cloud adoption, including hidden costs related to migration and ongoing management, will be crucial for future advancements [36, 41, 39].

Bibliography

[1] Muhammed Cagri Kaya, Mahdi Saeedi Nikoo, Michael L. Schwartz, and Halit Oğuztüzün. Internet of measurement things architecture: Proof of concept with scope of accreditation †. *Sensors (Basel, Switzerland)*, 20, 2020.

[2] Kehinde Andrew Olu-lawal, Oladiran Kayode Olajiga, Emmanuel Chigozie Ani, Adeniyi Kehinde Adeleke, and Danny Jose Portillo Montero. The role of precision metrology in enhancing manufacturing quality: a comprehensive review. *Engineering Science & Technology Journal*, 5(3):728–739, 2024.

[3] Tuukka Mustapää, Juuso Autiosalo, Pekka Nikander, Joshua E. Siegel, and Raine Viitala. Digital metrology for the internet of things. In *2020 Global Internet of Things Summit (GIoTS)*, pages 1–6, 2020.

[4] A. Cetinkaya, M. C. Kaya, T. B. Bzuneh, and H. Oguztuzun. Uncertainty calculation-as-a-service: Microservice-based metrology applications. In *Proceedings of the 18th European Conference on Software Architecture (ECSA)*, 2024.

[5] S. Newman. *Building Microservices: Designing Fine-Grained Systems*. O'Reilly Media, Inc., 2015.

[6] Anil Cetinkaya, M. Cagri Kaya, Teklie Belay Bzuneh, and Halit Oguztuzun. Uncertainty calculation-as-a-service: Microservice-based metrology applications. In Matthias Galster, Patrizia Scandurra, Tommi Mikkonen, Pablo Oliveira Antonino, Elisa Yumi Nakagawa, and Elena Navarro, editors, *Software Architecture*, pages 183–190, Cham, 2024. Springer Nature Switzerland.

[7] Eric Braun, Thorsten Schlachter, Clemens Düpmeier, K. Stucky, and W. Süß. A generic microservice architecture for environmental data management. pages 383–394, 2017.

[8] Z. Liu et al. The architectural design and implementation of a digital platform for industry 4.0 sme collaboration. *Computers in Industry*, 137:103540, 2022.

[9] A. R. Hevner, S. T. March, J. Park, and S. Ram. Design science in information systems research. *MIS Quarterly*, 28(1):75–105, 2004.

[10] A. Popov. Digitalization of ensuring metrological traceability of measuring instruments and reference materials through cloud-based technologies: Current state and development prospects. *Measurement Standards. Reference Materials*, 2022.

[11] Yumin Wang, Jiangbo Li, and H. Wang. Cluster and cloud computing framework for scientific metrology in flow control. *Cluster Computing*, 22:1189 – 1198, 2017.

[12] F. Thiel, M. Esche, F. G. Toro, A. Oppermann, Jan Wetzlich, and D. Peters. The european metrology cloud. page 09001, 2017.

[13] Application of monte carlo simulation in metrology for uncertainty analysis. *Journal of Metrology*, 2021.

[14] Transition to digital calibration certificates in metrology. *Metrology Today*, 2020.

[15] Implementing microservices architecture in metrology software development. *Software Engineering Review*, 2017.

[16] D. Rees. Monte carlo simulation and conclusions extraction from. *Journal of Risk Analysis*, 15(3):234–245, 2015.

[17] Application of monte carlo simulations in risk and uncertainty analysis, 2015. Available online at [URL].

[18] M. Cagri Kaya, Mahdi Saeedi Nikoo, Michael L. Schwartz, and Halit Oguztuzun. Internet of measurement things architecture: Proof of concept with scope of accreditation. *Sensors*, 23(4):669998, 2023.

[19] Anil Cetinkaya, M. Cagri Kaya, Erkan Danaci, and Halit Oguztuzun. Uncertainty calculation-as-a-service: An iiot application for automated rf power sensor calibration. In *IMEKO TC6 International Conference on Metrology and Digital Transformation*, Berlin, Germany, 2022.

[20] Digital calibration certificate developments, 2021. Available.

[21] The nist uncertainty machine. A web-based application for calculating measurement uncertainty.

[22] Metas.unclib: A tool for uncertainty calculations. A desktop application for handling complex metrological problems.

[23] Stefan Hunziker and Michael Blankenagel. *Design Science Research Design*, pages 97–116. 01 2024.

[24] J. Morgan and A. Birch. Cloud adoption in metrology: Current state and future directions. *Journal of Metrology*, 22(3):210–220, 2017.

[25] S. Willenberg and K. Zimmermann. Taxonomy-based analysis of cloud solutions in metrology. *Metrology and Measurement Systems*, 25(1):45–58, 2018.

[26] G. Mariappan, P. Gupta, and R. Singh. Challenges and benefits of cloud-based metrology solutions. *International Journal of Cloud Computing*, 18(4):385–399, 2020.

[27] M. F. Hashmi, N. A. Khan, and A. J. Hussain. Advantages and drawbacks of cloud computing in industrial applications. *Journal of Industrial Engineering and Management*, 9(2):500–510, 2016.

[28] I. Khan, A. Ali, and S. Ahmad. Industrial practices of cloud adoption: A survey of practitioners. *Industrial Applications Journal*, 16(3):220–230, 2018.

[29] A. Gupta and P. Gupta. Research achievements and challenges in cloud integration for industrial applications. *Cloud Computing Journal*, 19(1):100–110, 2021.

[30] T. White, M. Johnson, and L. Smith. Cloud computing in industrial systems: A holistic approach. *Industrial Systems Journal*, 17(4):310–320, 2019.

[31] H. Yang and M. Tate. Managing cloud-based solutions at scale: A systematic analysis. *Journal of Cloud Computing*, 6(2):150–160, 2012.

[32] Barbara Kitchenham and Stuart Charters. Guidelines for performing systematic literature reviews in software engineering. Technical report, EBSE Technical Report EBSE-2007-01, 2007.

[33] Selma Suloglu, Muhammed Çağrı Kaya, Alper Karamanlıoğlu, Sina Entekhabi, Mahdi Saeedi Nikoo, Bedir Tekinerdogan, and Ali Hikmet Doğru. Comparative analysis of variability modelling approaches in component models. *IET SOFTWARE*, page 437–445, 2018.

[34] Anil Cetinkaya, Aliye Kartal Dogan, Erkan Danacı, and Halit Oğuztüzün. Autorfpower: Automatic rf power measurement software for metrological applications. pages 1–4, 12 2021.

[35] CERB Barateiro and C Makarovsky. Fiscal liquid and gaseous hydrocarbons flow and volume measurement: Improved reliability and performance paradigms by harnessing for fourth industrial revolution. *Flow Measurement and Instrumentation*, 2020.

[36] J Schaerer and T Braun. A distributed calibration certificate infrastructure. In *2022 4th Conference on Blockchain*, 2022.

[37] IM Smith, RI Veltcheva, and DJ Griffin. Case study on the generation and use of digital calibration certificates, 2024.

[38] M Peterek and B Montavon. Prototype for dual digital traceability of metrology

data using x. 509 and iota. *CIRP Annals*, 2020.

[39] K Xia, H Fan, J Huang, H Wang, J Ren, Q Jian, and D Wei. An intelligent self-service vending system for smart retail. *Sensors*, 2021.

[40] GJ Smales and BR Pauw. The mouse project: A meticulous approach for obtaining traceable, wide-range x-ray scattering information. *Journal of Instrumentation*, 2021.

[41] J Saßmannshausen and PM Schäfer. Datenqualitätssicherung entlang der datenwertschöpfungskette im industriekontext. In *Datenwirtschaft und Datentechnologie*, 2022.

A

Appendix

A.1 Search Commands Used During SLR

This appendix section provides the search commands used for the systematic literature review across various databases. As can be seen, the databases have slightly different search features, but the command remains consistent across all of them to avoid biases.

A.1.1 IEEE Xplore

The search command used in IEEE Xplore was as follows:

```
("Document Title":"metrology" OR "Abstract":"metrology"
OR "Author Keywords":"metrology")
AND ("Document Title":"calibration" OR "Abstract":"calibration"
OR "Author Keywords":"calibration")
AND ("Document Title":"cloud" OR "Abstract":"cloud"
OR "Author Keywords":"cloud")
AND ("Document Title":"architecture" OR "Abstract":"architecture"
OR "Author Keywords":"architecture")
AND (("Document Title":"uncertainty calculation" OR
"Abstract":"uncertainty calculation" OR
"Author Keywords":"uncertainty calculation")
OR ("Document Title":"uncertainty calculations" OR
"Abstract":"uncertainty calculations" OR
"Author Keywords":"uncertainty calculations"))
OR (("Document Title":"calibration certificate" OR
"Abstract":"calibration certificate" OR
"Author Keywords":"calibration certificate")
OR ("Document Title":"calibration certificates" OR
"Abstract":"calibration certificates" OR
"Author Keywords":"calibration certificates"))
```

A.1.2 ACM Digital Library (ACM DL)

The search command used in ACM DL was as follows:

```
[[Title: "metrology"] OR [Abstract: "metrology"]
OR [Keywords: "metrology"]]
AND [[Title: "calibration"] OR [Abstract: "calibration"]
OR [Keywords: "calibration"]]
AND [[Title: "cloud"] OR [Abstract: "cloud"]
OR [Keywords: "cloud"]]
AND [[Title: "architecture"] OR [Abstract: "architecture"]
OR [Keywords: "architecture"]]
AND [[Title: "uncertainty calculation"] OR [Abstract: "uncertainty calculation"]
OR [Keywords: "uncertainty calculation"]]
OR [Title: "uncertainty calculations"] OR [Abstract: "uncertainty calculations"]
OR [Keywords: "uncertainty calculations"]]
OR [Title: "calibration certificate"] OR [Abstract: "calibration certificate"]
OR [Keywords: "calibration certificate"]]
OR [Title: "calibration certificates"] OR [Abstract: "calibration certificates"]
OR [Keywords: "calibration certificates"]]
AND [E-Publication Date: (01/01/2011 TO Present)]
```

A.1.3 Springer Link, Science Direct, and Google Scholar

The search command used for Springer Link, Science Direct, and Google Scholar was the same:

```
"metrology" "calibration" "cloud" "architecture"
(("uncertainty calculation" OR "uncertainty calculations")
OR ("calibration certificate" OR "calibration certificates"))
```

A.2 Artifact Design

A.2.1 Kubernetes Deployment Files

service.yaml

```
apiVersion: v1
kind: Service
metadata:
  name: calibration-service
spec:
  selector:
    app: calibration-pod
  ports:
    - name: http-calculate-uncertainty
      protocol: TCP
```

```
      port: 5001
      targetPort: 5001
    - name: http-generate-digital-certificate
      protocol: TCP
      port: 5002
      targetPort: 5002
  type: LoadBalancer
```

deployment.yaml

```
apiVersion: v1
kind: Pod
metadata:
  name: calibration-pod
  labels:
    app: calibration-pod
spec:
  containers:
    - name: calculate-uncertainty
      image: gcr.io/calibration-427916/monte-carlo-image:latest
      imagePullPolicy: Always
      ports:
        - containerPort: 5001
      volumeMounts:
        - mountPath: /mnt/data
          name: shared-data
    - name: generate-digital-certificate
      image: gcr.io/calibration-427916/digital-cal-cert-image:latest
      imagePullPolicy: Always
      ports:
        - containerPort: 5002
      volumeMounts:
        - mountPath: /mnt/data
          name: shared-data
  volumes:
    - name: shared-data
      emptyDir: {}
```