Universität Regensburg
Fakultät für Wirtschaftswissenschaften
Professur für IoT-basierte Informationssysteme

Methods and Models for Industrial Internet of Things-based Business Process Improvement

Dissertation

zur Erlangung des Grades eines Doktors der Wirtschaftswissenschaft (Dr. rer. pol.)
eingereicht an der Fakultät für Wirtschaftswissenschaften der Universität Regensburg

vorgelegt von
Christoph Stoiber, M.Sc.

Berichterstatter:
Prof. Dr. Stefan Schönig
Prof. Dr. Günther Pernul

Eingereicht am: 28.04.2023

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To my parents Marianne and Otmar,
And my Franziska

Abstract

Over the last three decades, the Internet of Things (IoT) has gained significant importance and has been implemented in many private, public, and business contexts. Leveraging and combining the IoT's capabilities enables far-reaching transformations and disruptive innovations that are increasingly recognized, especially by industrial organizations. In this regard, the Industrial IoT (IIoT) paradigm has emerged, describing the use of IIoT technology in the industrial domain.

One key use of the IIoT is the incremental or radical improvement of business processes. This goal-oriented change of business processes with IIoT technology to accomplish organizational goals more effectively is called IIoT-based Business Process Improvement (BPI). Many use cases demonstrate the benefits of IIoT-based BPI for all types of industrial organizations. However, the interconnection between IIoT and BPI lacks theoretical knowledge and applicable artifacts that support practitioners. Moreover, a significant number of related projects fail or do not achieve the anticipated benefits. This issue has drawn attention in recent scholarly literature, which calls for further research.

The dissertation at hand approaches this research gap by extending and advancing existing knowledge and providing valuable contributions to managerial practice. Three critical challenges for conducting IIoT-based BPI projects are addressed in particular: First, the essential characteristics of IIoT-based BPI applications are explored. This enables their classification and a foundational comprehension of the research field. Second, the required capabilities to leverage IIoT for BPI are identified. On this basis, industrial organizations can assess their maturity and readiness for implementing corresponding applications. Third, the identification, specification, and selection of appropriate applications are addressed. These activities enable the successful practical execution of IIoT projects with BPI potential.

Acknowledgement

This dissertation has been conducted at the Professorship for IoT-based Information Systems at the University of Regensburg. It started in December 2019 as an external doctorate project and was completed in April 2023. Composed of different research papers and projects, it is the result of countless hours of work, discussion, and exchange of ideas. During these years, I was privileged to meet inspiring, supportive, and warm-hearted people. This page is dedicated to them.

First and foremost, I would like to thank my supervisor Prof. Dr. Stefan Schönig, for his unwavering support and for making this doctorate possible. Besides the professional guidance and mentoring, he strongly supported me during the uncertain times of the pandemic and never stopped to believe in me and our research. I could not have imagined a more friendly and trusting relationship with my doctoral advisor. In addition, I would like to thank my secondary supervisor Prof. Dr. Günther Pernul, who gave me purposeful and valuable feedback on my research endeavor.

Second, I would like to thank all my colleagues at the Professorship for IoT-based Information Systems for the research support, team spirit, and leisure activities. Markus for being my counterpart during countless discussions on IoT, BPM, research methodologies, and the meaning of life. I will also miss his company at research conferences, although I can do without sharing beds in the future. Toni, Leo, and Christoph for the fruitful research seminars and the new ideas that came from them. Furthermore, for introducing me to the nightlife of Regensburg. Petra, for the kind support during organizational topics. You all made me feel like an integral part of the professorship even though I was an external doctoral candidate.

Third, I am thankful for all other faculty colleagues' professional and personal support. This includes Marcus, with whom I had both relaxing days by the pool and profound conversations at the ECIS conference in Romania. Another huge thank you goes to Ludwig, my first contact at the University of Regensburg, who advised me on many organizational questions. Therefore, I am all the more pleased that we have also worked together successfully in research.

Finally, but no less important, I would like to thank my parents, Marianne and Otmar, my beloved Franziska, my brother Andreas, and my whole family for their support, encouragement, and understanding. On many occasions, they had to take a back seat to my research work. This dissertation is dedicated to them because they keep me on track when the path is uncertain.

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Part I

Overview of the Thesis

1 Introduction

The Internet of Things (IoT) enables manifold disruptive applications and has the capability to bridge the gap between the physical and digital worlds. Smartwatches, smart thermostats, or connected cars are just a few examples of possible IoT manifestations, which are gradually becoming integral to everyday life. Depending on the specific use case, a distinction can be made between different application areas of IoT technology. Besides, e.g., Smart Home, Smart Grid, or Smart City, especially its use in the industrial domain is of high interest. In this regard, a paradigm denoted as the Industrial IoT (IIoT) has evolved that leverages the IoT, albeit transcending the concept of the thing toward industrial applications [110]. Hence, the IIoT distinguishes itself from the IoT by the aims and purposes to which the used technologies are put [17].

In general, the IoT can be defined as a network that connects uniquely identifiable *things* to the Internet. These things can be any tangible physical objects and animate or inanimate entities. Through the exploitation of unique identification and sensing, information about the thing can be collected, and the state can be changed anytime, anywhere, by anything [74]. Therefore, the main idea is the pervasive presence of things that can interact and cooperate [8]. Correspondingly, the term *internet* refers to the ability of the things to build a network of interconnected devices using several specific network technologies [8]. On this basis, the IIoT can be defined as a system of networked smart objects within the industrial environment that enables various data-based services to optimize the overall business value [17].

By using IIoT technology in industrial organizations, data can be collected, processed, and used for services of all kinds. This real-time transformation of analog information into digital data enables new business models and revolutionizes existing ones [83]. The increased connectivity creates a complex network of people, data, and processes while information is turned into actions, creating new capabilities and unparalleled economic opportunities [1]. Especially for the improvement of business processes, generating and using comprehensive data and connecting process entities can be advantageous.

The practice of improving business processes, denoted as Business Process Improvement (BPI), is part of the Business Process Management (BPM) lifecycle, displayed in Figure 1. Of all activities encompassed by the BPM lifecycle, the improvement of business processes is considered the most value-adding one [115, 30, 126]. Thanks to its features, IIoT technology can now be a highly valuable technological lever for this essential activity [36]. The use of IIoT can lead to increased productivity and reduced costs [27], wherefore it fits well as a technology for BPI and process redesign [36]. Consequently, a plethora of different applications is present in any kind of industrial organization. In this respect, the term *IIoT-based BPI application* refers to integrating IIoT technology into a distinct business process to incrementally or radically improve it according to business goals. A basic example is to equip tools used in a business process with sensors to collect location data. This would allow the deletion of a *search tool* task within the process and increase its performance.

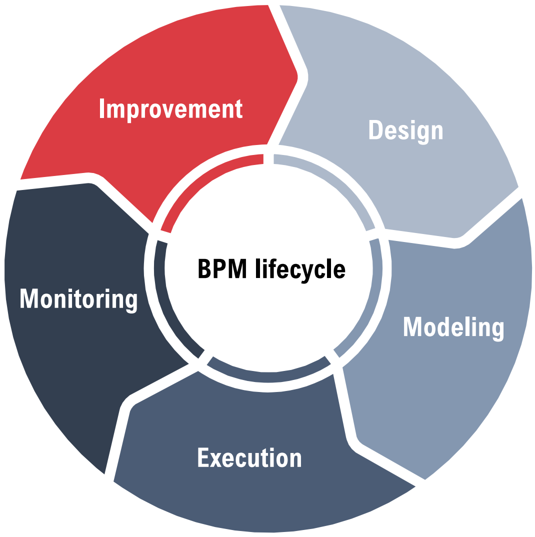


Figure 1: BPM lifecycle

Although the IIoT offers numerous benefits, many organizations encounter difficulties leveraging it for BPI. For this reason, the interaction of IIoT with business processes has been identified as one of the least understood phenomena in the BPM discipline [14]. A current study discovered that IIoT impacts business processes in an unusual way and, therefore, demands a revised adoption approach [125]. Accordingly, organizations need a novel and effective technology management to exploit the IIoT for improving process performance [26]. This is necessary as smart devices, i.e., IIoT, within business processes boost complexity to a new level [14]. The increasing complexity motivates reflecting and updating strategies and best practices for redesigning business processes [14]. Data and findings from practice strengthen this suggestion. A global survey of over 500 business executives revealed that 90% of organizations remain in the proof of concept or early-stage planning phases for IIoT projects [16]. These facts indicate the existence of fundamental hurdles for successfully realizing corresponding projects. Three significant challenges can be identified when analyzing the status quo in practice and research.

First, there is a lack of comprehension of all essential characteristics and facets of the connection between IIoT and business processes. Organizations do often not have IIoT expertise [125] or neglect the process perspective of respective projects [38]. Second, effective adoption of IIoT technology requires a substantial investment of time and money in technology, generation of commitment, communication, and training [6]. Organizations must develop the skills and capabilities required to thrive and compete in the IIoT era [10]. In this respect, they need support in identifying and developing these capabilities. Third, the "Act of Improvement" for IIoT-based BPI, i.e., how existing business processes are transformed to the improved target state by integrating IIoT, can often not be defined precisely. An unclear "Act of Improvement" reduces the plannability and the chance of a successfully performed project [37, 32]. Organizations must understand how, where, and why to use IIoT technology within business processes [125].

This dissertation addresses the identified challenges by advancing and extending existing research. This is necessary, as established BPI methods, e.g., SixSigma, NESTT, 7FE, or Process Model Canvas, support organizations in improving their business processes but do not consider IIoT a BPI driver. Accordingly, the BPM lifecycle requires additional artifacts that connect its *improvement* activity with the IIoT paradigm. To address this gap, the research endeavor is structured along the three presented challenges for organizations regarding IIoT-based BPI, as shown in Figure 2:

- **Challenge 1: Comprehension and classification** describes the fundamental activity to understand all essential characteristics of IIoT-based BPI. Organizations must be able to classify respective applications and identify similarities, differences, and relations within them.
- **Challenge 2: Assessment of maturity and readiness** addresses the identification of relevant capabilities for conducting IIoT-based BPI projects. On this basis, organizations can assess their related maturity and readiness. However, a singular assessment is insufficient for dynamic and fast-changing organizational environments. A continuous approach is required to guarantee an updated view.
- **Challenge 3: Identification, specification, and selection** describes activities to discover and implement applications that fit the organization's business goals. This includes goal-oriented decision support for selecting the most beneficial applications.

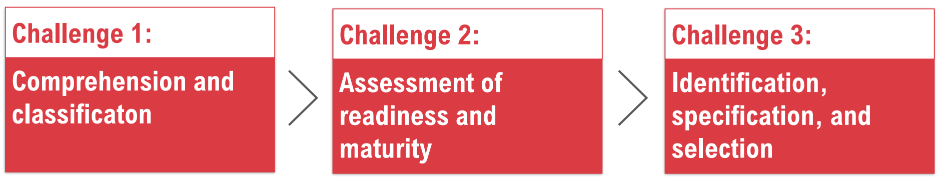


Figure 2: Challenges for IIoT-based BPI

This dissertation further discusses and approaches these three challenges by presenting five individual research papers. However, since this dissertation connects the two research fields of IIoT and BPI, some preliminary remarks must be made.

As there is no universally accepted definition of the IIoT as a subset of the IoT, many researchers and practitioners still use the term IoT in the industrial environment. For an enhanced reading flow, the term *IIoT* is stringently used in the dissertation. This is also the case when referring to sources that use the term IoT, but the addressed findings also apply, or specifically apply, to the industrial environment. Thus, the underlying statements are not rendered incorrectly but according to the context.

Furthermore, many different terminologies and sometimes inconsistent definitions have appeared in the literature associated with improving business processes [2]. Examples are Business Process Improvement (BPI) [47], Business Process Redesign [23], Business Process Reengineering (BPR) [45], Core Process Redesign [56], or Continuous Improvement Process [51]. For most of these terminologies, there are no universally accepted definitions, which leads to confusion regarding the interpretation and scope [89]. The main reason is that the different terms do not adequately reflect the differences in their contents [66]. However, a distinction can be made in the literature between transactional and transformational business process improvement methods [30]. While the former aims to change business processes incrementally, the latter points to radical breakthroughs. In this dissertation, both transactional and transformational improvements are considered under the term BPI, as they follow the same idea of improving processes [126]. In that sense, the main goal of BPI is to enhance the effectiveness and efficiency of business processes [47] by changing their state so that the degree of accomplishing organizational goals is increased [33].

Finally, the introduced term *organizations* refers not only to industrial companies, businesses, and enterprises but also to subordinate departments. This generalization is relevant, as the management of IIoT-based BPI applications is not always done on a high business level, and the presented findings and artifacts might only be used by a specific part of the company.

2 Related Research

This section gives a concise overview of the connection between the IIoT and BPM lifecycle activities and presents the highlights researchers have set. Furthermore, it summarizes research and practical reports regarding the use of IIoT technology to improve business processes. Accordingly, it outlines research of the *improvement* activity of the BPM lifecycle and its linkages to the IIoT paradigm.

Predominantly, IIoT and BPM have been regarded as separate topics in research and practice [53]. However, some works that specifically address the combination of IIoT technology and BPM activities have been emerging. Hence, BPM research increasingly recognizes the challenges and opportunities of integrating IIoT and vice versa. A recent structured literature review (SLR) of Vukšić et al. [121] highlighted the topic's relevance by analyzing the temporal distribution of published articles. While research has been relatively scarce from 2010 to 2015, a noticeable growth can be seen since 2016. Consequently, the topic is still in an early scientific research stage but can be considered a growing trend [112].

Existing research papers comprise more general articles on the intersection of IIoT and BPM but also specific solutions to open questions. For example, Mandal et al. [67] presented a range of IIoT scenarios and described how BPM concepts might be advantageous for realizing them. Thus, they created a fundamental connection between the IIoT and BPM paradigms. One of the most recognized general overviews has been proposed by Janiesch et al. [53]. Their manifesto describes to what extent IIoT and BPM can be combined and which challenges must be tackled. This paper has already been used as a basis for multiple other research endeavors.

Beyond that, more concrete research covers all associated activities of the BPM lifecycle and proposes solutions. These research papers address, e.g., modeling IIoT-enhanced business processes [113]. In this respect, many researchers focused on extensions or substitutions to, e.g., the Business Process Modeling and Notation (BPMN) for modeling IIoT requirements and their characteristics [15, 73, 11]. Regarding the implementation, various architectures and approaches have been presented. For example, Schönig et al. [97] described the benefits and necessary adaptions for integrating IIoT and BPM systems and developed an integrated communication architecture. Several other authors proposed orchestration architectures to bridge the abstraction gap between IIoT data and business activities [70, 55, 106]. Having implemented the process, research has also addressed the execution of business processes that include IIoT technology. This involves how to monitor the process execution and how to collect and analyze relevant data [19].

Research and practical reports on redesigning and improving business processes using IIoT have as well resulted in several noteworthy publications. The foundation was laid in the early 1990s when disruptive information technology had been acknowledged as an essential enabler for the radical improvement of business processes. A large body of literature saw in novel technologies possibilities to achieve performance breakthroughs in quality, speed, and cost [45, 89, 43]. After inventing and shaping the IIoT, many organizations have recognized it as such a novel technology. Thus, various use cases are present in all kinds of industry sectors. Examples are applications in the logistics of retailers [25], the pharmaceutical industry [76], or the food industry [61]. Furthermore, IIoT can be used to improve warehousing processes fundamentally [63]. Other use cases describe applications that increase process performance in automotive production [124] or production industry [98]. Also, for, e.g., German [36], and Chinese ports [105], or the steel industry [71], IIoT holds precious benefits. The high number of use cases shows that organizations have already acknowledged the potential benefits of IIoT technology for improving their business processes.

Besides practical reports, some articles provide a more general overview of the capabilities of IIoT for redesigning and improving business processes. A publication by Haller et al. [44] describes major application areas where IIoT can generate business value. Also, Chui et al. [20] specifically highlighted the importance of IIoT for improving business processes while defining six emerging applications. Yang et al. [123] stated that IIoT could be used to redesign production processes and, thus, achieve higher efficiency. A study by Sestino et al. [100] shows how IIoT can be used for BPI and illustrates several central topics in current literature. Moreover, Arnold et al. [7] presented the impact of IIoT technology on business models and business processes in different manufacturing industries. More recent research by Drechsler et al. [29] describes how the emergence of IIoT technologies follows a cascading growth pattern. The result is a continuous discovery of new application options. Furthermore, Ahmad and Van Looy highlighted the IIoT's potential for business processes [4].

In addition to the constructive findings, research has also identified significant challenges, many of which are presented in Section 1. Based on this, several researchers encourage relevant and well-motivated research on the interconnection of IIoT and BPM [4]. The dissertation at hand addresses the formulated challenges and research gaps, proposes useful design artifacts contributing to the dedicated stream of literature, and goes beyond practical use cases and general theoretical articles.

3 Research Questions

The research included in this dissertation was motivated by the challenges organizations encounter when leveraging IIoT technology for BPI. Practical studies and reports underscore the research topic's relevance and suggest the existence of fundamental hurdles [16, 103]. From a scholarly perspective, the motivation originates from literature that encourages a revised adoption approach for IIoT [125] and a reflection of existing BPI methods [14]. On this basis, the main Research Question (RQ) of the dissertation is formulated:

> **Main RQ:** How can organizations effectively improve their business processes by integrating IIoT technology?

To detail this main RQ, it is segmented into three research areas, each with a subordinate RQ. These research areas address the main challenges of IIoT-based BPI that were described in Section 1. This encompasses: (1) The comprehension and classification of IIoT-based BPI, (2) the assessment of readiness and maturity, and (3) the identification, specification, and selection of appropriate applications. By elaborating all research areas from a theoretical and practical viewpoint, knowledge transfer to practice can be achieved. The three research areas are described in the following.

Research Area 1: Comprehension and classification

The first research area of this dissertation considers the challenge of fully comprehending IIoT-based BPI. This requires a fundamental understanding of the facets and aspects that make up IIoT applications within processes. In this regard, both characteristics of IIoT technology and business processes are essential. Comprehending the phenomenon in its entirety allows projects to be successfully planned and conducted.

Contributing to the theoretical nature of IIoT, several white papers, case studies, and extensive definitions have been proposed [110]. These provide in-depth descriptions of the IIoT's characteristics [17] or technical details of their composition [102]. However, most IIoT research lacks the necessary connections to BPI and does not include details of business processes. The same applies to the research area of BPI, which lacks aspects of IIoT technology. Due to this, many organizations do not have adequate knowledge of IIoT technology [125] or neglect the importance of the processes perspective [38] when conducting related projects.

These facts necessitate the development of a design artifact that enables the systematic and structured comprehension of IIoT-based BPI and its essential characteristics. One type of design artifact that provides theoretical insights into inner correlations, characteristics, and relations of phenomena is a classification. Classifications constitute the arrangement of a set of entities into distinct groups, dimensions, and characteristics [9]. Therefore, classifications can be used by both researchers and practitioners to understand, analyze, and structure the knowledge within a distinct field [85]. While there are already classifications for IIoT- [96] or BPM-related topics [119], their combination still needs to be addressed, leading to the first RQ:

> **RQ1:** How can organizations comprehend and classify IIoT-based BPI in terms of their essential characteristics?

The first RQ establishes a baseline against which IIoT-based BPI can be further explored. The creation of a classification allows two things. First, it enables researchers to describe, understand, and analyze IIoT-based BPI and create a starting point for further research [85]. Second, it supports organizations with the cognitive process of comprehending and classifying respective applications [110].

Research Area 2: Assessment of readiness and maturity

The digital transformation and included technologies, e.g., IIoT, become so disruptive that they might fundamentally change the resources and capabilities that organizations and people need to manage business processes [14]. Organizations require a substantial investment of time and money in technology, commitment generation, communication, and training [6]. Accordingly, organizations must develop the skills and capabilities required for managing IIoT technology [10]. The second research area focuses on these required capabilities and seeks to provide means for their identification and assessment.

Maturity models have proven to be a valuable tool for identifying the strengths and weaknesses of organizations by reference to an underlying phenomenon [58]. Regarding IIoT-based BPI, they can depict the relevant capabilities and allow for an assessment of maturity and readiness. However, a singular maturity assessment is insufficient to keep an updated overview of an organization's capabilities. Organizations are liable to change due to the complex and ever-changing technological, organizational, and economic environments in which they are embedded [80]. This means that capabilities are dynamic and can transform or deteriorate, implying evolutionary progress [72]. Furthermore, novel technologies, such as IIoT, are changing and constantly evolving while demanding different types of capabilities for their proper management. Therefore, a continuous maturity assessment is required.

To the best of the author's knowledge, no maturity model has addressed the capabilities that are required to leverage IIoT for BPI. Moreover, no maturity assessment method supports a continuous maturity model application, bringing up the second RQ:

> **RQ2:** How can organizations continuously assess their readiness and maturity regarding the implementation of IIoT-based BPI applications?

The objective of RQ2 is to provide artifacts that enable a continuous maturity assessment regarding IIoT-based BPI. This helps organizations to identify relevant capabilities, have an updated view of their maturity and readiness, and develop action plans for capability creation or improvement.

Research Area 3: Identification, specification, and selection

After comprehending the characteristics of IIoT-based BPI and assessing maturity and readiness, organizations can begin to conduct corresponding projects. This conduction includes the identification of potential applications and their explicit specification. If multiple applications are possible, the most beneficial one must be selected. However, it is often unclear how to identify possible IIoT solutions to business process problems and how to specify them. A major reason is the lack of adoptable blueprints or explanatory templates for IIoT-based BPI applications. Accordingly, an update of best practices is required [14]. On this basis, the third RQ is formulated:

> **RQ3:** How can organizations systematically identify, specify, and select appropriate IIoT-based BPI applications?

The third RQ seeks to provide design artifacts illuminating the "Act of Improvement" for IIoT-based BPI. Hence, organizations should be supported in developing and specifying application ideas. This must be done based on the underlying business process details and the features of IIoT technology. If there are several potential applications, managers must also be supported in the goal-oriented selection.

The three presented RQs, embedded in individual research areas, approach the main RQ from different perspectives. They are addressed with five research papers provided in Chapter II and summarized in Section 5. To ensure rigor, the paper creation followed a distinct research methodology described in the following section.

4 Research Methodology

The dissertation was conducted at the Professorship for IoT-based Information Systems and is embedded in the Information Systems (IS) discipline. In German-speaking countries, this research discipline is referred to as *Wirtschaftsinformatik* [18]. This section provides an overview of the IS research discipline and the research methodology used in the dissertation.

The IS discipline is positioned at the interconnection and confluence of people, technology, and organizations [49]. Its objective is to acquire an understanding that enables the development and implementation of technology-based solutions to unsolved business problems. Inherently, IS research follows two paradigms: Behavioral Science and Design Science. Behavioral Science Research has its roots in natural sciences and focuses on observing characteristics [127]. Thus, it aims to develop theories that explain or predict human and organizational behavior [49]. On the other hand, Design Science Research (DSR) has its roots in engineering and the creation of artifacts [101]. It seeks to extend the boundaries of human and organizational capabilities by creating novel IS artifacts [49]. In this regard, IS artifacts can be defined as constructs, models, methods, or instantiations. Constructs illustrate concepts and vocabulary of a domain, while models introduce relationships between constructs, and instantiations depict situated implementations of models. Furthermore, methods can be comprehended as a set of activities or processes directed towards a predefined goal [69].

Since the formulated RQs aim to create novel artifacts, DSR was taken as the basis of the dissertation. Through the design of artifacts and their demonstration and evaluation, IIoT-based BPI research can theoretically progress. Furthermore, practically applicable artifacts can be used by organizations to solve existing problems and challenges. To translate DSR into fundamental principles, the dissertation is based on the guidelines for DSR by Hevner et al. [49]. These guidelines are briefly discussed in the following.

Guideline 1: Design as an artifact

The main goal of DSR is the creation of purposeful and viable artifacts that address existing problems and challenges of organizations. These artifacts can be divided into constructs, models, methods, or instantiations. More specifically, the outcome can be models, metamodels, algorithms, abstractions, taxonomies, representations, or many other manifestations of the main categories. In this dissertation, artifacts are designed for each formulated RQ.

Guideline 2: Problem relevance

A second guideline that must be considered is the design of technology-based solutions to important, relevant, and unsolved business problems. Relevance, in this regard, emerges from the problems faced and the opportunities afforded by the interaction of people, organizations, and information technology. The connection between IIoT and BPM research areas is relatively new and considered a relevant phenomenon in IS research [53].

In addition, the combination of IIoT and BPI is a topic that has received little attention to date and offers excellent potential for innovative solutions.

Guideline 3: Design evaluation

A core requirement of DSR is the rigorous demonstration of the artifacts' utility, quality, and efficacy. This must be done by applying evaluation methods that fit the requirements of the business environment. Proper evaluation provides evidence that the DSR artifact achieves its purpose. Without evaluation, the research outcome is an unsubstantiated design theory or hypothesis that the artifact solves an underlying problem [118].

The designed artifacts are evaluated within the dissertation using established and appropriate methods. This includes formative evaluations that support the design process and summative evaluations that provide a basis for creating shared meanings about the evaluand in the face of different contexts [118].

Guideline 4: Research contributions

DSR must provide clear contributions in the form of the artifact itself, extensions to the design construction knowledge, or the design evaluation knowledge. Several novel artifacts are designed and presented in this dissertation as distinct contributions. These include theoretical and practical contributions in the research field of IIoT-based BPI.

Guideline 5: Research rigor

The fifth guideline addresses how DSR is conducted. Both the construction and evaluation of the design artifact require the application of well-defined rules and rigorous methods. All papers within the dissertation follow appropriate techniques to construct the artifacts and appropriate means to evaluate them. In addition, the individual research projects build on existing knowledge and extend and advance it.

Guideline 6: Design as a search process

Another critical aspect of DSR is that it should be conducted iteratively. In this respect, design is applied as a search process to discover practical solutions to existing problems. This necessitates an iterative cycle, where generated design alternatives are tested against basic requirements. Researchers must utilize available means to reach the desired results with reasonable effort and available resources. In addition, the underlying problem's environmental factors must be considered [101]. The papers within the dissertation were developed iteratively, including several different design methods. The generate-test-cycle was considered by including formative evaluations and testing artifacts early during the design phase. Established methods, e.g., Delphi studies, semi-structured interviews, surveys, or case studies, were used in this regard.

Guideline 7: Communication of research

The last guideline requires conducted research to be presented to an appropriate audience. This includes the communication of the research findings to both technology- and management-oriented groups. Technology-oriented audiences enable the artifact to be implemented and used within organizations. For this reason, the presentation should highlight the design process details and the main benefits of the constructed artifact.

On the other hand, management-oriented audiences should be presented with ideas and concepts on how the artifact can be used in an organizational setting. The papers included in this dissertation were published in journals, and conference proceedings of the BPM, IIoT, and general IS communities.

The guidelines for rigorous DSR by Hevner et al. [49] formed the foundation of the research endeavor. They provided fundamental requirements for creating viable artifacts in the IS research domain. To allow additional structure within the research process, the paper development followed the methodology and process model proposed by Peffers et al. [90]. Figure 3 illustrates the process model and all included activities.

A research methodology combines the process, methods, and tools used to conduct research in the research domain [87]. Peffers et al. [90] based their methodology on the guidelines of Hevner et al. [49] and translated them into an applicable process model. The process model includes six activities and four possible research entry points. Each of the first four activities can be a potential entry point for artifact creation. This could be a problem-centered initiation based on the identification of a problem. Furthermore, an objective-centered solution may start research endeavors. Alternatively, the design and development or client and context-centered initiation provide possible entry points. In the following, the six activities are briefly outlined, and the representation of each activity within the dissertation is described.

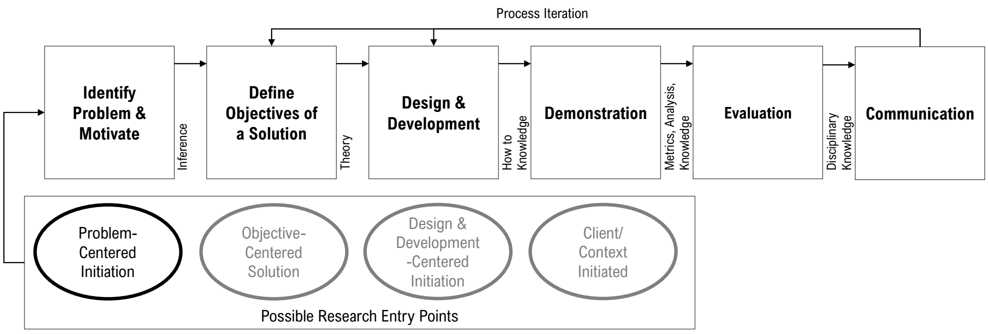


Figure 3: Process model according to Peffers et al. [90]

Activity 1: Problem identification and motivation

In the first activity, the central research problem is specified, and the value of a solution is justified. This motivates the researcher and the audience to accept the delivered results. In the dissertation at hand, all research papers address and answer the formulated RQs of the three research areas. Hence, every paper includes a comprehensive individual motivation for the tackled RQ. The dissertation's main RQ is motivated by the lack of research regarding IIoT-based BPI and its extensive potential benefits.

Activity 2: Definition of objectives of a solution

The second activity addresses the definition of possible objectives of solutions. These quantitative or qualitative objectives must be derived and inferred from the problem definition. They either describe how solutions improve the as-is state or how a novel artifact can contribute to the solution. The individual papers include distinct objectives that, when combined, aim at supporting the use of IIoT technology to improve an organization's business processes. This comprises artifacts for the comprehension and classification, maturity assessment, and identification, specification, and selection of IIoT-based BPI applications.

Activity 3: Design and development

The artifact is created in the design and development activity, which also includes determining the artifact's desired functionality and architecture. The papers presented in this dissertation include established design and development methods, which are explicitly explained.

Activity 4: Demonstration

Within the demonstration activity, the artifact must be used to solve at least one instance of the underlying problem. This could involve, e.g., experiments, simulations, or case studies. A suitable demonstration type was chosen for each developed artifact.

Activity 5: Evaluation

As already formulated in the guidelines of Hevner et al. [49], proper evaluation is crucial for rigorous DSR. The objective achievement can be assessed by observing and measuring how well the artifact solves the problem. For the created artifacts, comprehensive evaluations were conducted. This comprises both formative and summative evaluation episodes. Applied methods range from semi-structured interviews and surveys to Delphi and case studies. In that sense, it was possible to address the so-called "design theory indeterminacy", i.e., the criticism of DSR for generating mostly theoretical artifacts that remain without practical application [65].

Activity 6: Communication

According to Peffers et al. [90], the last activity addresses the communication of the conducted research. Thus, the importance of the underlying problem, the artifact's utility, design rigor, and effectiveness must be described. It is essential to present the results to the appropriate audiences of the research discipline. The included papers were published in prestigious venues of the BPM, IIoT, and general IS community.

Due to the given methodological guidance of Peffers et al. [90], each RQ could be rigorously addressed. The collected research papers in Chapter II present the individual contents of each DSR activity in further detail. The subsequent section provides a summary of the main research findings and created design artifacts.

5 Results

5.1 Overview of research papers

Section 3 presented the main RQ and its particularization in three associated RQs, embedded into distinct research areas. These research areas form the basis and structure of the dissertation, whereby five research papers answer the respective RQs. In addition, six complementary papers are included and briefly presented that provide further insights into the research topic. All papers were developed according to the guidelines and research methodology presented in Section 4.

During the compilation of the dissertation, all core and complementary research papers were peer-reviewed or are under peer review. To ensure a communication of the research results to appropriate audiences, the papers were submitted to renowned journals and scientific conferences of the BPM, IIoT, and IS communities. This allowed for critical feedback during the reviews and led to productive discussions. The feedback further improved the papers and positively impacted the results. Since the research results are intended for transfer into organizations, practice-oriented journals and conferences were also selected. The main findings and a summary of all papers are presented in the following subsections. The full papers in their published or submitted versions are included in Chapter II of this dissertation.

Figure 4 gives a graphical overview of all research areas and the categorization of the five core papers within them. Each research paper is assigned to a distinct RQ and given an identifier P1-P5. This identifier numbering is based on a logical sequence, not a chronological one. Table 1 lists all papers with their given identifier, full citation, submission status, and a type classifier. The submission status defines whether the paper is under review or published when finalizing this dissertation. The type classifier specifies whether the research paper has been submitted for publication in a scientific journal (J), a conference proceeding (C), or a book chapter (B).

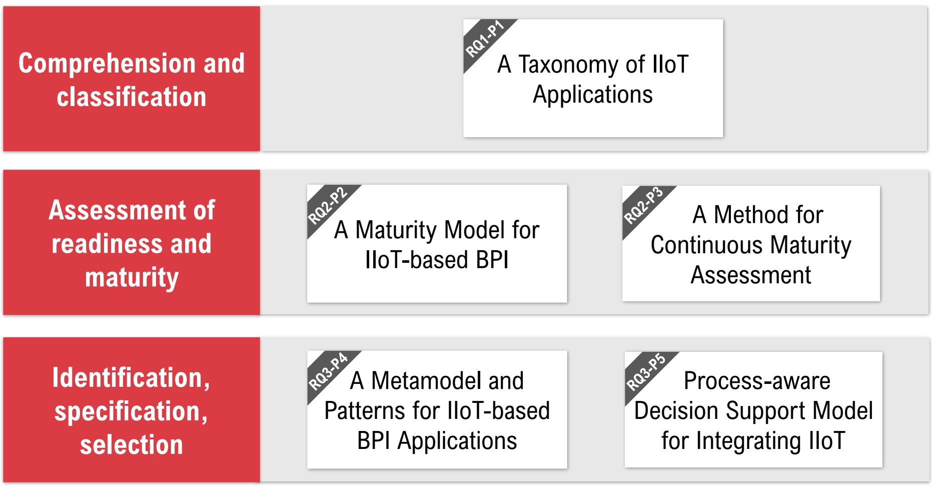


Figure 4: Overview of research areas and corresponding research papers

No.	Publication	Status	Type
P1	Stoiber, C. and Schönig, S., 2022. Improving Business Process with the Internet of Things – A Taxonomy of IIoT Applications. In: *Proceedings of the 30th European Conference on Information Systems, ECIS*.	published	C
P2	Stoiber, C. and Schönig, S., 2022. Digital Transformation and Improvement of Business Processes with Internet of Things: A Maturity Model for Assessing Readiness. In: *Proceedings of the 55th Hawaii International Conference on System Sciences, HICSS*, pp. 4879-4888.	published	C
P3	Stoiber, C., Stöter, M., Englbrecht, L., Schönig, S. and Häckel, B., 2023. Keeping Your Maturity Assessment Alive. *Business & Information Systems Engineering* (2023).	published	J
P4	Stoiber, C. and Schönig, S., 2023. Conceptualizing Industrial IoT-based Business Process Improvements – A Metamodel and Patterns. *Springer Nature Computer Science* (2023).	under review	J
P5	Stoiber, C. and Schönig, S., 2021. Process-aware Decision Support Model for Integrating Internet of Things Applications using AHP. In: *Proceedings of the 23rd International Conference on Enterprise Information Systems, ICEIS*, pp. 869-876.	published	C

Table 1: Research papers included in the dissertation

The first paper **P1** of this dissertation belongs to the first formulated research area and presents a taxonomy of IIoT-based BPI applications. This design artifact illustrates all essential dimensions and characteristics of the phenomenon and enables an in-depth comprehension. In addition, the taxonomy can be used to classify and deconstruct existing or potential future applications.

Once organizations have gained a fundamental comprehension of IIoT-based BPI, they can assess their maturity and readiness to conduct related projects. The results of a maturity assessment can also be used to develop action plans to create or improve necessary capabilities. Papers **P2** and **P3** address this topic and provide means to answer the associated RQ. First, a maturity model is presented in paper **P2** that organizations can use to assess their maturity and readiness. However, a singular and non-perpetual maturity assessment contradicts the dynamic nature of organizations and the changes within internal capabilities. Therefore, paper **P3** provides a maturity assessment method to continuously apply any given maturity model.

Having assessed an organization's maturity and readiness, the actual execution of specific IIoT-based BPI applications can be performed. In this research area, papers **P4** and **P5** provide valuable and useful design artifacts. First, paper **P4** enables the identification and specification of applications by providing generic yet descriptive patterns. These patterns are based on a created metamodel and can be seen as generic blueprints or templates for IIoT-based BPI applications. Organizations can map their internal processes with these patterns, identify solutions to business process problems, and specify applications. Finally, in the case of multiple alternatives, a goal-oriented decision support model is provided in paper **P5**.

The following subsections summarize all research papers according to a consistent structure. The summary begins by explaining the motivation for the design artifact's creation, followed by a description of the methods used to design and develop it. Then, the artifact itself, as well as the core contributions and implications, are described. Finally, the evaluation episodes and results are presented.

5.2 Comprehension and classification

The first step towards adopting a novel technology, method, or organizational routine is an in-depth comprehension of all relevant facets, aspects, and characteristics. Projects without a solid knowledge base are unlikely to yield the desired results and may ultimately fail. Therefore, a design artifact that supports comprehending IIoT-based BPI is necessary, especially for organizations that have not yet conducted several related projects. In this respect, classifications have proven to be appropriate tools and are used for numerous research topics in the IS discipline.

Classifications are design artifacts that deliver theoretical insights into a phenomenon's inner correlations, characteristics, and relations. Their key advantages are, amongst others, the capability for description, reduction of complexity, identification of similarities and differences, and an illustration of relationships [9]. Classifications have become popular within the IS discipline, as they serve as a foundation for sense-making [40] and theory building [28], especially for fast-changing socio-technical topics [59]. They support researchers and practitioners with the cognitive process to comprehend and classify an underlying phenomenon [85]. Accordingly, a multitude of different classifications have been developed, often as a starting point for further research and early after the respective phenomenon has been invented.

P1: Improving Business Processes with the Internet of Things - A Taxonomy of IIoT Applications

The first paper P1 addresses the formulated RQ1 and, therefore, the challenge to fully comprehend and classify IIoT-based BPI. To this end, a taxonomy is proposed that encompasses all relevant dimensions and characteristics of the interconnection of IIoT and BPI. The lack of descriptive knowledge suggests the need for such a design artifact. A taxonomy is a classification approach based on empirical data [9], which can help researchers and practitioners simplify their understanding of IIoT-based BPI. Moreover, it might avoid being overwhelmed by the complexity of the topic [24].

The taxonomy design followed the Extended Taxonomy Design Process (ETDP) by Kundisch et al. [59] that provides methodological guidance for designing taxonomies in the IS discipline. The ETDP is based on Nickerson et al.'s [85] established taxonomy development method and extends it with additional evaluation activities. It includes 18 steps organized along the six DSR activities presented in Section 4. Therefore, it augments rigorous taxonomy building and evaluation [59].

The taxonomy design was motivated within the first five ETDP steps, and the underlying phenomenon was specified. Moreover, objective and subjective conditions that stop the iterative development procedure were defined. Concerning the objective ending conditions, the final taxonomy must have at least one application classified under every characteristic, have unique dimensions and characteristics, and no need for further changes. As subjective ending conditions, the authors must have agreed that the taxonomy is concise, robust, comprehensive, extendible, and explanatory. To finish the development procedure and receive the final taxonomy, all subjective and objective ending conditions must be achieved.

Having initialized the ETDP, the iterative design and development steps were performed. Two conceptual-to-empirical and two empirical-to-conceptual iterations were conducted to consider inductive and deductive design approaches. After these four iterations, the objective and subjective ending conditions were met. Within the first deductive iteration, the authors defined a set of taxonomy dimensions and characteristics based on their knowledge of IIoT and BPI. In the second inductive iteration, 81 IIoT applications from the literature were analyzed using open, axial, and selective coding techniques according to Corbin and Strauss [22]. This enabled the identification of additional essential dimensions and characteristics of IIoT applications with BPI prospects. In the third deductive iteration, a Delphi study was conducted to refine the previous results. The study included six practitioners from market-leading organizations and six researchers with experience in IIoT and BPM. Finally, the fourth inductive iteration was based on twelve real-life applications from a chemical industry organization. However, no additional dimensions or characteristics could be found within an in-depth analysis. Consequently, the development procedure ended with the fourth iteration.

Figure 5 shows the final taxonomy of IIoT-based BPI applications. It is illustrated according to the established hierarchical tree technique that facilitates the presentation of semantic information [54]. The taxonomy comprises six dimensions, seven subdimensions, and 40 characteristics and is in line with typical size recommendations [85].

The first dimension *Key Capability* includes characteristics that describe the most relevant capabilities of the IIoT. Fundamental knowledge of these capabilities is crucial for organizations as they can be exploited to improve business processes. While often the combination of several capabilities leads to beneficial IIoT-based BPI applications, in many cases, specific key capabilities can be defined that are particularly important.

The second dimension *Value Proposition* outlines how the IIoT's key capabilities are leveraged for value generation. They explain what benefit can be expected by integrating IIoT technology into business processes and give an understanding of the impact on the business process. In this respect, the value propositions are the main drivers for adopting, accepting, and using IIoT applications.

The third dimension *Business Process Type* describes the business area in which the

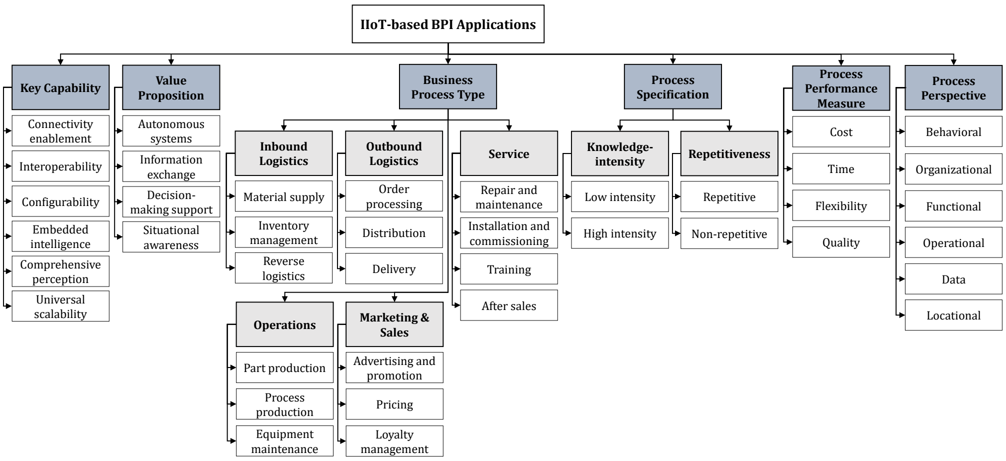


Figure 5: Taxonomy of IIoT-based BPI applications based on paper P1

IIoT technology is embedded. This information allows for understanding the IIoT's main application area. The established concept of the value chain by Porter [92] is used to distinguish between these areas, which enables classifying applications in the five primary value chain activities represented as subdimensions. These value chain activities include generic business process types as characteristics.

The fourth dimension *Process Specification* comprises two subdimensions that describe the knowledge-intensity and repetitiveness of the underlying business process. These characteristics are essential information for integrating IIoT technology, as they significantly influence the application's complexity and may limit the achievable BPI benefit. Business processes with a low knowledge-intensity can be easier changed and redesigned with the IIoT than those with a high knowledge-intensity. Also, repetitive business processes that always follow the same process flow can be easier improved than non-repetitive ones.

The last two dimensions refer to the actual impact of the IIoT-based BPI application and which process perspectives are influenced most. The dimension *Process Performance Measure (PPM)* refers to the BPI indicators stated by Dumas et al. [30] and describes the type of improvement. Finally, the dimension *Process Perspective* includes characteristics defined by Jablonski and Bussler [52]. Each business process includes, e.g., organizational, functional, or operational aspects. Thus, a business process can be seen from different perspectives, whereby each of them can be influenced by IIoT technology.

The final taxonomy was summatively evaluated within two individual episodes. In the first episode, the taxonomy's robustness and reliability were evaluated. *Robustness* refers to the taxonomy's ability to handle invalid inputs or stressful environmental conditions, e.g., low levels of information [93]. On the other hand, *reliability* constitutes the proportion of joint judgment in which there is an agreement when multiple people classify the same applications [79]. First, two researchers were asked to classify 30 IIoT-based BPI applications described in the literature and ten use cases from a market-leading organization. Accordingly, a set of 40 applications formed the basis of the evaluation episode. The dimension-specific hit ratios of the individual researchers were compared to analyze the inter-judge agreements and, therefore, the taxonomy's reliability. Second, the object-specific hit ratios were compared between the literature applications with a low level of information and the real-life applications with a high level. The minor differences between all results showed the taxonomy's high reliability and robustness for varying expert views and levels of information.

In the second evaluation episode, an expert panel of 16 practitioners participated in a survey. They were asked three questions to which they could indicate their agreement or disagreement on a Likert scale [62]. The questions were formulated to point to the degree of the taxonomy's *completeness*. The results showed that the taxonomy included all relevant dimensions and characteristics to illustrate IIoT-based BPI applications. Hence, the taxonomy was considered complete. Due to the positive evaluation results, the taxonomy constitutes a practical artifact for comprehending and classifying IIoT-based BPI and can be effectively used by researchers and practitioners.

The classification results of the first evaluation episode also provided valuable insights into the distribution of characteristics within existing applications. The most relevant findings are now briefly presented while stating the relative distribution of the characteristics in brackets. The most represented key capabilities in the set of 40 applications are *comprehensive perception* (43%) and *embedded intelligence* (28%). These capabilities are, in most cases, used for applications that provide *information exchange* (50%) or *situational awareness* (45%). The most relevant application areas are *operations* (53%) and *logistics* (22.5%) processes. While no clear trend was identified for the knowledge-intensity, primarily *non-repetitive* (70%) business processes are improved by IIoT. The majority of the BPI goals is an improved *quality* (53%) that is generated by impacting, in many cases, the *functional* (48%) and *data* (33%) perspectives of the processes. These results also highlighted areas where IIoT had not been frequently used for improving business processes. In this regard, applications in *service* (5%) or *marketing & sales* (5%) are scarce. These analysis results can be used for future application developments, e.g., by IIoT solution providers.

Contribution of P1:

Paper P1 presents a taxonomy of IIoT-based BPI applications that considers both IIoT- and business process-related dimensions and characteristics. The taxonomy forms the basis for comprehending the research topic and contributes to its theoretical and practical knowledge. From a theoretical perspective, it is the first classification tool to focus on IIoT as an enabler for BPI. This introduces a novel catalytic idea and helps researchers identify the research topic's essential characteristics. From a practical perspective, it supports managers with the cognitive process of classifying, deconstructing, and comprehending IIoT-based BPI applications.

5.3 Assessment of readiness and maturity

The previous subsection presented a taxonomy that facilitates the comprehension and classification of IIoT-based BPI applications in terms of their essential characteristics. Having set the necessary knowledge foundation, organizations must assess their readiness and maturity before conducting related applications. This is particularly relevant for novel and complex technologies, such as the IIoT, which require a specific set of capabilities for a successful implementation.

Different technologies or methods require different types of organizational capabilities, which must be developed through targeted action plans if they are not already present. However, creating such action plans is complex without an up-to-date overview of the capabilities' status quo. Also, organizations and their capabilities, as well as underlying technologies, are changing, which requires a continuous assessment of maturity and readiness. Two research papers address these challenges and the formulated RQ2 of the research area. First, paper P2 proposes a maturity model that can be used to assess the maturity and readiness regarding IIoT-based BPI. Second, paper P3 presents a maturity assessment method for continuously applying any given maturity model.

P2: Digital Transformation and Improvement of Business Processes with Internet of Things: A Maturity Model for Assessing Readiness

To date, no maturity model has been tailored to IIoT-based BPI and its unique characteristics. However, this is necessary as many related projects fail due to lacking the required capabilities. Consequently, organizations must develop the skills and capabilities required to thrive and compete in the IoT era [10]. Paper P2 presents a maturity model that allows organizations to assess their readiness and maturity. It addresses and answers RQ2 by providing an overview of relevant organizational capabilities.

For the model design, the structured procedure of Becker et al. [12] was applied that follows the guidelines for DSR by Hevner et al. [49]. Paper P2 presents the first four phases that address the design and development of a theoretically sound maturity model. The first phase describes the motivation for developing a new maturity model. Subsequently, the underlying research topic's existing maturity models were compared. Since no maturity model directly addressed the interconnection of IIoT and BPI, models of both individual topics were analyzed. The results provided an overview of existing knowledge and relevant capabilities in both subareas. In the third phase, the development strategy was determined, i.e., whether an existing model should be refined or a new model developed. Eventually, in the fourth phase, the maturity model was developed iteratively.

The first maturity model draft was developed based on findings from an extensive SLR. A set of 80 identified papers related to IIoT and BPI maturity models was analyzed in detail to derive relevant capabilities. A total of 100 capabilities were found that could be structured along 25 capability dimensions and four capability levels. The first draft was refined by conducting a four-round Delphi study with 15 experts from industry and academia. In this respect, additional capabilities were formulated, and irrelevant ones were deleted. To achieve group consensus within each iteration, a decision tree was used that indicated if adaptions to the model were required. The result of the model constituted the final maturity model draft.

The developed maturity model comprises five maturity levels analog to the established Capability Maturity Model Integration (CMMI) [21]. These maturity levels indicate an organization's fitness to use IIoT technology for BPI. The first level *Initial* refers to a very low level of maturity, indicating that knowledge of IIoT technology and BPI methods is scarce within the organization. The second level *Managed* represents a more advanced yet still rudimentary state. Basic awareness is present while the first IIoT technologies are already implemented into some business processes. This situation is different in the third level *Defined*. Here, IIoT technology is already used to support process execution and realize beneficial BPI. In the fourth level *Quantitatively Managed*, there is strategic planning regarding the implementation of IIoT-based BPI. Ultimately, the fifth and highest level *Optimized* indicates the existence of multiple applications within all kinds of business processes. The whole organization established procedures and methods to achieve even advanced applications.

While maturity levels give an absolute description of an organization's fitness, the actual readiness of an organization depends on its concrete plans for adopting IIoT technology. Implementing complex IIoT applications might not be feasible for maturity levels one and two, which is why individual consideration is always necessary.

To illustrate and organize the capabilities, a so-called capability matrix was developed. This matrix comprises 21 capability dimensions clustered in seven focus areas on the first axis. The other axis shows four capability levels that include a distinct organizational capability for each dimension. The result is a matrix with 84 organizational capabilities structured along 21 dimensions and four capability levels. Increasing capability level represents increased maturity of an organization regarding the corresponding capability dimension. Table 2 shows all capability dimensions of the final maturity model on the left side. The right side of the table will be explained later in this subsection.

For enhanced comprehension, seven focus areas have been created, each including a set of thematically similar capability dimensions. The first focus area *Strategy and Leadership* includes capability dimensions concerning the organization's strategy and the management's commitment towards IIoT-based BPI. Effective adoption is challenging without appropriate vision and decision-making commitment. The second focus area *Culture, Ethic, and Behaviour* corresponds to the organization's attitude and mindset of the employees. Employees must be willing and open to IIoT technology to use it effectively in a business context. Strongly connected to this area is the third focus area *People, Skills, and Competences*. It incorporates dimensions focusing on the knowledge of IIoT and BPM distributed among employees, departments, and teams. More technical is the fourth focus area *Infrastructure and Data* addressing the organization's technical setup, including networking or data processing capabilities. Pointing at the organization's capabilities regarding BPM, the fifth area *Business Process Management* includes capability dimensions for properly managing business processes. The sixth focus area *IoT*

Capability Dimension	Required Capability Levels for Maturity Level				
	1	**2**	**3**	**4**	**5**
IoT vision	1	2	2	3	4
Decision making	1	2	3	3	4
Technology affinity	1	2	3	3	4
Continuous improvement culture	1	2	3	4	4
Interdisciplinary, interdepartmental collaboration	1	1	2	3	4
Knowledge management	1	1	2	3	4
IoT competences along employees	1	2	3	4	4
Dedicated teams for IoT	1	2	3	4	4
Dedicated teams for BPM	1	1	2	3	4
Enterprise software systems	1	2	3	3	4
Networking	1	2	3	3	4
Data processing	1	2	3	4	4
Data analytics and interpretation	1	2	3	4	4
Alignment and methods	1	2	3	3	4
Process performance controlling	1	2	3	3	4
Process documentation	1	2	3	4	4
IoT architecture	1	1	2	3	4
IoT technology	1	2	2	3	4
System integration	1	2	2	3	4
Behavioral and organizational impact	1	2	3	3	4
Functional and operational impact	1	2	3	3	4

Table 2: Final translation metric based on paper P2

Application Maturity directly refers to capabilities for developing an IIoT architecture and integrating and maintaining IIoT technology. Finally, the seventh focus area *IoT Integration into Business Processes* comprises dimensions and capabilities for properly integrating IIoT technology into business processes. This describes if an organization has the capabilities to effectively combine the paradigms of IIoT and BPI.

For most maturity models, the formulated capability levels would be equal to maturity levels. In this regard, an organization must fulfill all capabilities included in, e.g., capability level three, to reach maturity level three. However, for this maturity model, a different approach is selected. By decoupling the capability levels from the maturity levels, weighting and emphasis on specific capability dimensions are enabled. A so-called translation metric connects the maturity levels with the capability matrix. Figure 6 shows the functionality of the translation metric for the exemplary maturity level *Defined*. In this example, an organization would have to achieve capability level two for the capability dimension *IoT vision* and capability level three for the capability dimensions *Technology affinity* and *Data processing*. The other 18 dimensions are reduced and not displayed.

A final translation metric was developed within the already mentioned Delphi study. In two iterations, the expert panel indicated which capabilities are relevant to reach a specific maturity level. This allowed to map a weighting and emphasize within the 84 capabilities and their dimensions. The right side of Table 2 shows the results for the final

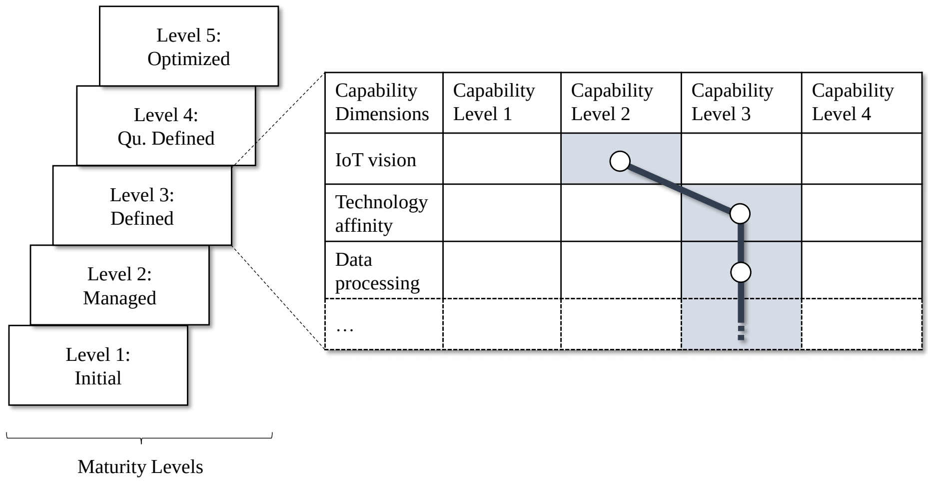


Figure 6: Functionality of the translation metric based on paper P2

translation metric. It illustrates which capability levels for each capability dimension are necessary to achieve a certain maturity level. Therefore, it illustrates the expert panel's emphasis on individual capabilities.

Contribution of P2:
Paper P2 presents a maturity model for IIoT-based BPI. It enables the assessment of maturity and readiness to effectively use IIoT technology for improving business processes. The maturity model is the first to connect both research topics and includes all necessary organizational capabilities. In addition, it is the first model to use a translation metric that facilitates weighting and emphasis on specific capabilities. Organizations can use the proposed maturity model to assess their maturity regarding the seven formulated focus areas. Furthermore, a targeted creation of action plans to develop or improve capabilities can be achieved.

P3: Keeping your Maturity Assessment alive - A Method for the Continuous Tracking and Assessment of Organizational Capabilities and Maturity

Paper P3 is connected to paper P2 and proposes a maturity assessment method that supports organizations to continuously apply the presented maturity model for IIoT-based BPI. Likewise, the maturity assessment method can be used for any other maturity model due to its generality. Developing a new maturity assessment method was necessary because no existing method provided suitable methodological guidance. During the investigation of existing maturity methods, two general problems were identified.

First, there is a discrepancy between *generality* and *comprehensiveness* within existing methods. Many maturity assessment methods provide comprehensive guidance and are tailored to a specific type of maturity model. However, this makes them incongruous with the developed maturity model of paper P2 or any other model. On the other hand, more generic methods are not comprehensive and lack essential activities of the so-called application cycle of maturity models, as defined by Mettler [72].

Second, existing methods do not sufficiently consider a continuous assessment of maturity. Yet, this is critical, as capabilities are liable to change [64], and organizations should have an updated view of their maturity. Therefore, a comprehensive and generic maturity assessment method that takes into account principles for continuity is necessary.

The Continuous Maturity Assessment Method (CMAM) was developed to address the formulated research gap. Due to its generality and comprehensiveness, it can be used to continuously apply the developed maturity method of paper P2 and any other existing maturity model. Therefore, it answers the second aspect of RQ2. Its development followed the DSR methodology of Peffers et al. [90], presented in Section 4. This also included an extensive evaluation according to the framework of Venable et al. [118]. Four central design objectives were formulated to allow for a rigorous development procedure: The method should be generally applicable, comprehensive, easy to use, and reflect principles of continuity. In the first development phase, empirical data on existing maturity assessment methods was collected within an SLR. Analyzing the results with open and axial coding techniques [22] and inductive reasoning [48] enabled the identification of common principles and best practices of proper maturity assessment methods. These best practices should be preserved in the new artifact.

Subsequently, a first formative evaluation episode was performed to include external knowledge in the design procedure. An expert panel of seven researchers and practitioners was surveyed through semi-structured interviews. They needed to formulate activities and principles that would help to achieve the design objectives. The results from the first development phase and the formative evaluation were utilized in the second development phase to design the CMAM. Applying the method of abductive reasoning [91] enabled the selection of the most potent activities and principles from the first development phase and the formative evaluation. Thereafter, the expert panel refined the CMAM draft iteratively in a second formative evaluation episode. After 21 semi-structured interviews, all experts agreed that the CMAM attained the design objectives. Consequently, the development procedure ended.

The final CMAM is displayed in Figure 7. It reflects best practices of established maturity assessments and principles for generality, comprehensiveness, and continuity. Therefore, it extends and advances existing knowledge on the application cycle of maturity models and contributes to general IS research. Within five phases and respective activities, organizations are guided during the continuous assessment of their capabilities. The essential contents of all phases are described in the following.

In the first phase *Maturity Model Preparation*, the organization selects a suitable maturity model and defines the assessment goals and potential roadmaps. In addition, commitment among stakeholders for the CMAM is demanded and generated. After that, a so-called assessment specification metamodel is instantiated in the second phase *Assessment Specification Instantiation*. This specification defines the core parameters and information about the assessment procedure. A more detailed description of this phase is

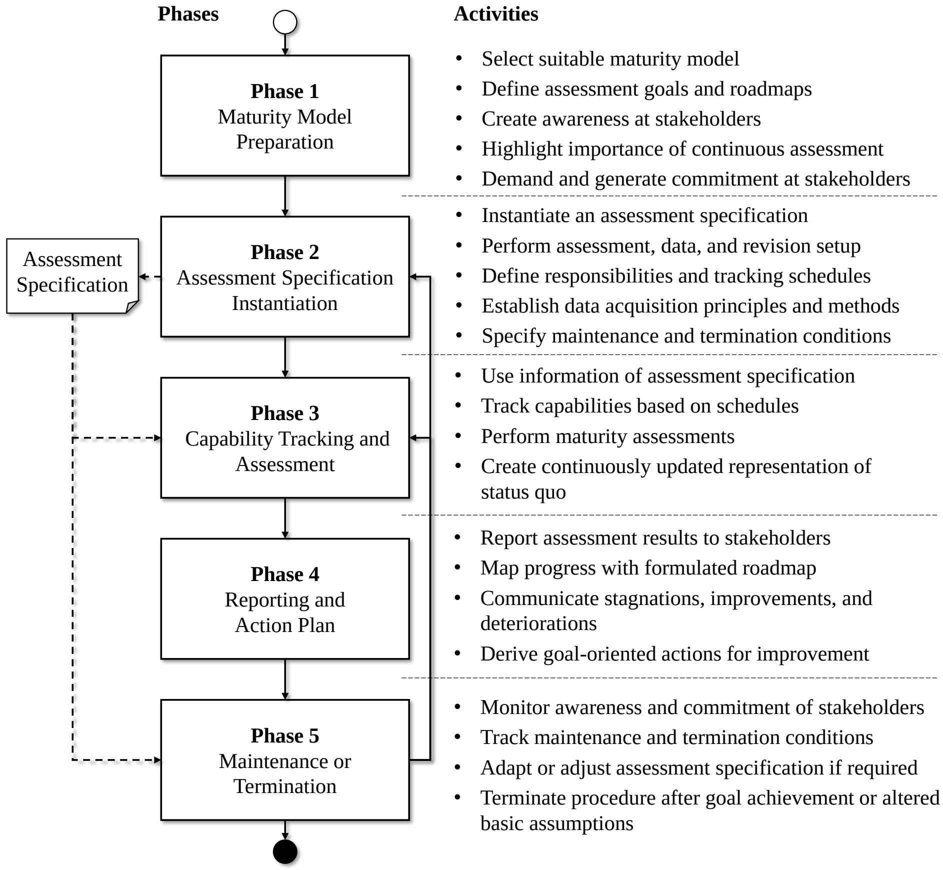


Figure 7: Continuous Maturity Assessment Method (CMAM) based on paper P3

provided later in the subsection. In the third phase *Capability Tracking and Assessment*, the instantiated assessment specification is used to collect capability data and perform the actual maturity assessment. Thus, a continuous representation of organizational capabilities is performed. Subsequently, the assessment results are reported to stakeholders in the fourth phase *Reporting and Action Plan*. This allows for the derivation of goal-oriented action plans. Finally, in the fifth phase *Maintenance or Termination*, the necessity for any changes within the continuous procedure is checked. If adaptions are needed, the second phase is repeated. The procedure is terminated if the maturity assessment is no longer necessary in the underlying area.

Figure 8 illustrates the assessment specification metamodel. It constitutes a key artifact within the CMAM and is instantiated in its second phase. The metamodel is presented as a Process Data Diagram, a modeling technique that includes standards of the Unified Modeling Language (UML) [114]. The process view on the left is a UML activity diagram, and the view on the right is a UML class diagram. Accordingly, the user performs the activity diagram to specify the classes and attributes. The classes represent decision parameters that are relevant for the subsequent CMAM phases. Being a standard UML artifact, it can be understood by most process managers in organizations. In addition, it is also possible to implement it as a software tool.

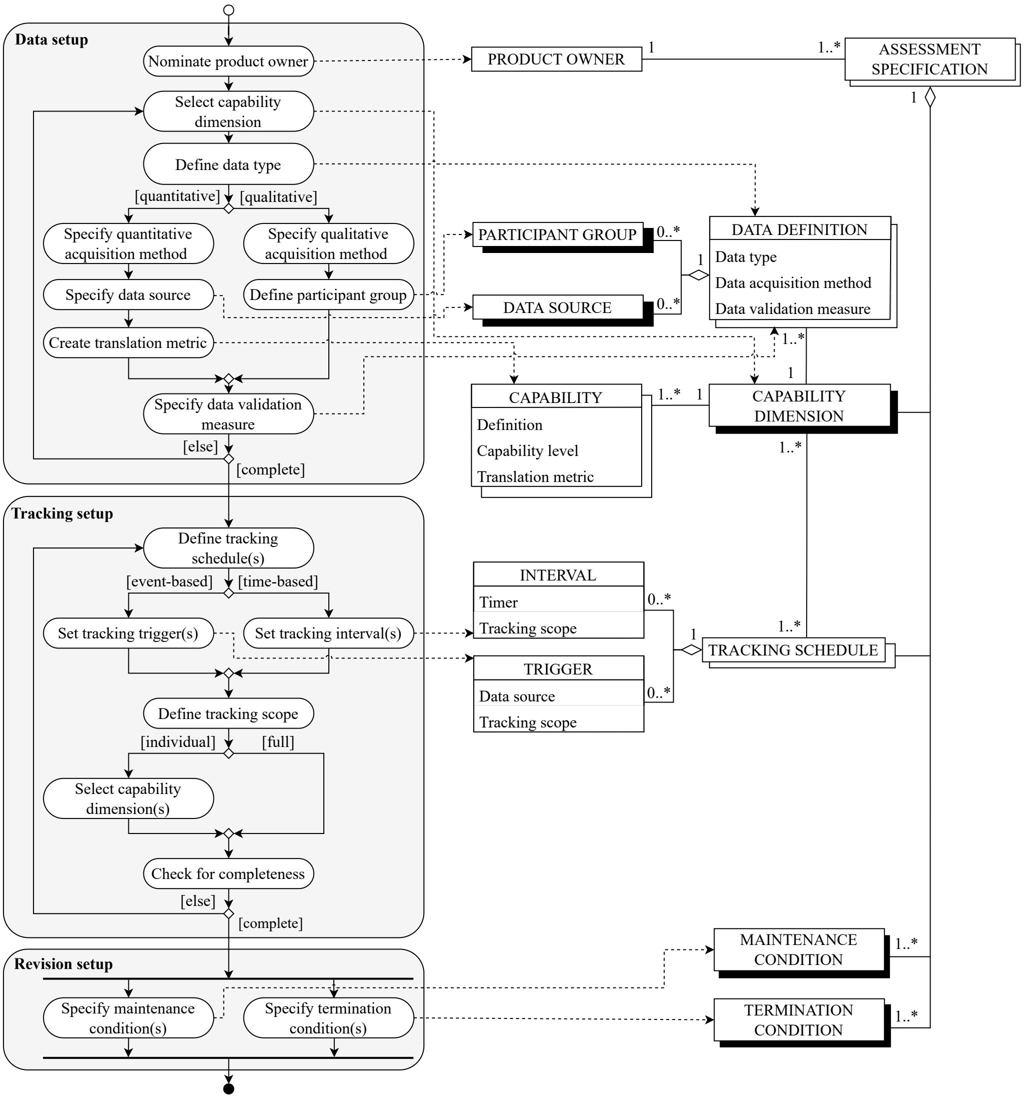


Figure 8: Assessment specification metamodel based on paper P3

Within the assessment specification metamodel, the user performs activities of three types. During the *Data setup*, all data-related decision parameters are defined. First, a product owner is nominated that manages the whole CMAM. Then, for each capability dimension, the underlying data is defined. This includes defining whether quantitative or qualitative data is used and how the capability data can be acquired. In the case of quantitative data, a translation metric must be created that maps the data with primarily qualitative capability definitions. During the *Tracking setup*, it is decided on which temporal or causal basis the capabilities are tracked. Capabilities can be tracked according to fixed schedules or triggers that make tracking necessary. Triggers could be changes within the organizational structure or the introduction of novel systems. These schedules can be set globally or for specific capability dimensions. Finally, the *Revision setup* lays the foundation for maintenance and termination criteria. Hence, parameters must be defined that lead to a revision of the specification or termination of the whole CMAM.

The final CMAM was evaluated in two summative evaluation episodes. First, an

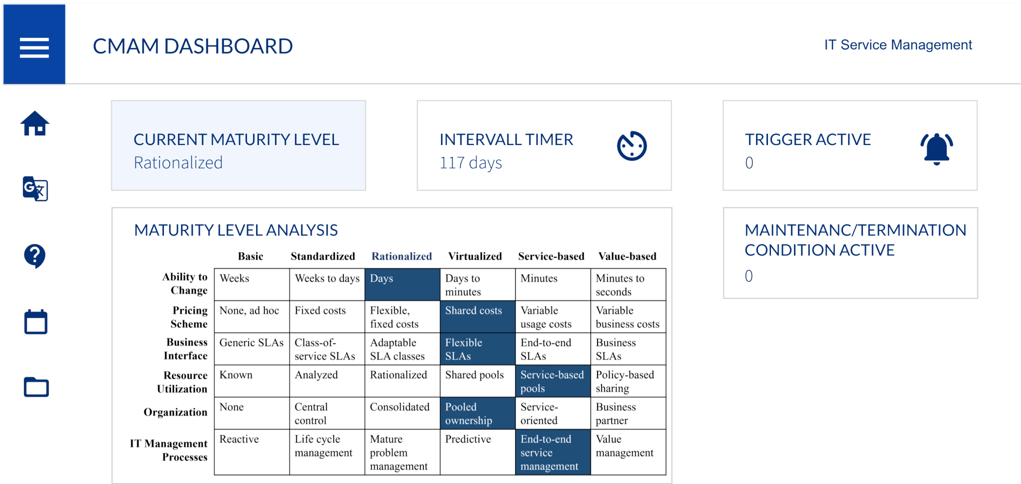


Figure 9: Developed CMAM dashboard based on paper P3

extensive survey was conducted with maturity model experts from six organizations. This included a questionnaire based on a Likert scale [62] and semi-structured interviews. The results showed that the CMAM is operationally feasible and generic enough to be used for various maturity models at any organization. Second, the CMAM was introduced at a market-leading organization. It has been implemented as an organizational routine to continuously apply a model for IT infrastructure maturity. To illustrate the assessment specification and show relevant information, e.g., schedules or capability data sources, a software tool was developed. The dashboard of the software tool is depicted in Figure 9. After six months of use, feedback on the CMAM was collected by the organization and the CMAM's main stakeholders. Due to the positive experiences with the method, it was evaluated as highly effective and applicable.

Contribution of P3:
Paper P3 proposes the CMAM, a comprehensive, generic, and continuous maturity assessment method. It supports organizations during all phases of the maturity model application and ensures an updated representation of organizational capabilities. As capabilities are liable to change, the CMAM is a precious tool that can be implemented as an organizational routine. Due to its generic yet comprehensive design, it can be used to continuously apply the maturity model presented in paper P2 or any other maturity model. This allows the derivation of targeted action plans to develop or improve relevant capabilities.

5.4 Identification, specification, and selection

The dissertation's first two research areas focused on comprehending and classifying IIoT-based BPI, and assessing organizations' maturity and readiness. These two steps are essential prerequisites and must be performed before the actual projects are conducted. This conduction encompasses identifying, specifying, and selecting appropriate applications, as represented in RQ3. Paper P4 tackles this challenge by discussing how organizations can effectively identify and specify IIoT-based BPI applications based on existing business process problems and BPI goals. In addition, paper P5 proposes a decision-support model that assists organizations in selecting appropriate applications aligned with their business objectives.

P4: Conceptualizing Industrial IoT-based Business Process Improvements - A Metamodel and Patterns

Paper P4 proposes a metamodel and a first set of patterns for IIoT-based BPI applications. The design of such design artifacts is required, as there are no concrete blueprints or templates that practitioners can use to develop process-oriented IIoT applications. The metamodel and patterns are designed to precise the so-called "Act of Improvement" [37, 32], meaning they support the transformation of the business process from the as-is to the to-be state. As the created patterns are concise and rather generic, they can be applied to various scenarios while, at the same time, they include enough information to effectively guide practitioners.

The concept of *patterns* was initially coined by Alexander [5] and has been used for many research topics in the IS discipline. Patterns describe a recurring problem or challenge in the real world and the basic features of the solution to this problem. Accordingly, patterns of IIoT-based BPI can support organizations in identifying problems within their business processes and finding suitable IIoT solutions. From a formal perspective, patterns constitute models derived from an origin metamodel.

The metamodel development followed the already described DSR methodology of Peffers et al. [90]. To build on established knowledge, the design is based on the existing metamodel for BPI patterns by Falk et al. [32]. This metamodel already comprises valuable aspects of BPI applications and can be extended concerning IIoT technology. The development procedure consisted of two iterations.

The first design iteration used the baseline metamodel of Falk et al. [32] and extended it with information gathered from an SLR. In this respect, publications that describe IIoT applications were analyzed to extract indispensable elements. This was done using open and axial coding techniques as part of Grounded theory [22]. By applying inductive reasoning [48], the most relevant elements for the metamodel were selected.

The initial metamodel underwent refinement during the second design iteration by conducting a Delphi study. A panel of nine experts from academia and industry refined the metamodel by including or excluding classes and attributes. After four rounds, group consent was found, and no more adaptions were requested. The final metamodel of IIoT-based BPI is presented in Figure 10. As for the baseline metamodel of Falk et al. [32], a UML class diagram was used for modeling because it provides sufficient semantic expressiveness. Classes represent elements of IIoT-based BPI applications, and attributes further describe the properties of these classes. Undirected binary associations and their multiplicity illustrate relationships between the classes.

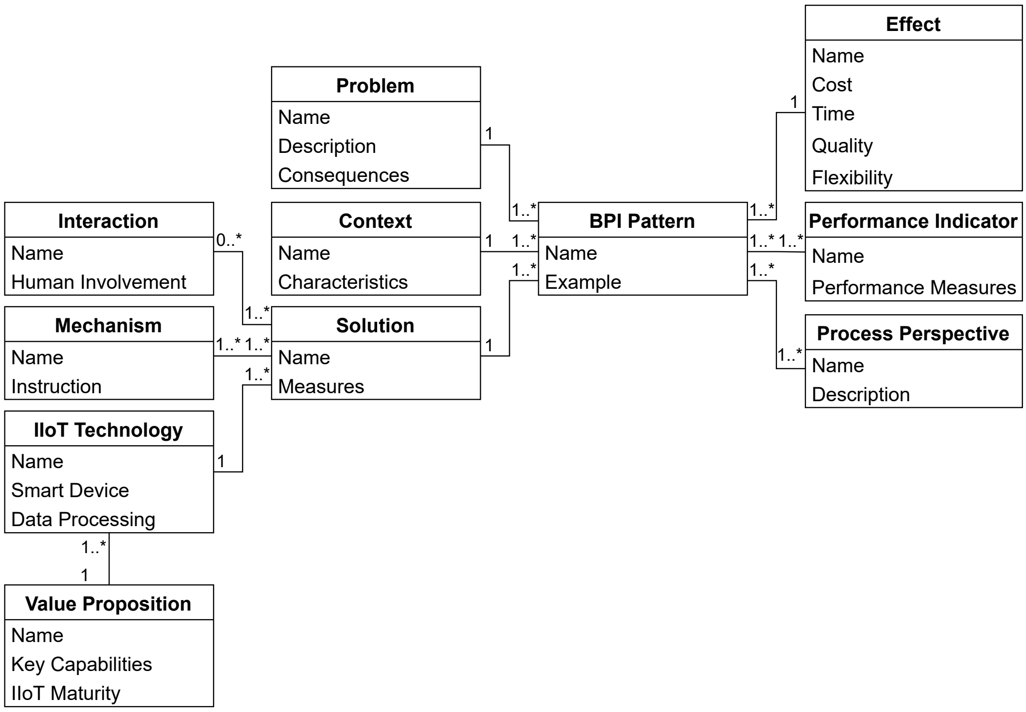


Figure 10: Metamodel of IIoT-based BPI based on paper P4

The final metamodel consists of eleven classes and 28 attributes. The central class of the metamodel is *BPI Pattern*. As with all other classes, it is instantiated by a unique name that summarizes the primary purpose of the pattern. In addition, it is characterized by an example that explains a potential instance. The second class *Problem* describes the underlying problem and its consequences for the organization. The *Context* class gives additional details on the circumstances for the pattern to be applicable. The class *Solution* is connected to three other classes and generically defines the required measures to solve the problem. The classes *Interaction*, *Mechanism*, and *IIoT Technology* further specify the technical solution. They indicate the degree of human involvement in the solution, provide precise instructions for practitioners, and describe the included IIoT technology. To specify the IIoT technology, the class *Value Proposition* depicts which key capabilities are exploited and how complex the technical implementation of the application is. Finally, to explain the impact of the application on the business process, the three classes *Effect*, *Performance Indicator*, and *Process Perspective* are introduced. The generic effect of the solution can be measured using the already-mentioned PPMs. A more particular way is using distinct performance indicators that detail the PPMs based on the process type. Finally, it is helpful to illustrate which perspectives and aspects of the process are affected by the application. Jablonski and Bussler [52] have stated six process perspectives that can be used in this regard.

An expert survey was conducted to evaluate the metamodel's *completeness* and *conciseness*. The metamodel must be complete in the sense of containing all aspects that are relevant to identify and specify an IIoT-based BPI application. Thus, organizations must be able to map the derived patterns with actual business processes. However, the metamodel must also be concise, meaning it must be generic enough to be applicable to any organization and business process. This means it must not be too specific or contain unnecessary information. The expert panel received a list of six statements for which they needed to indicate their agreement or disagreement on a Likert scale [62]. The positive study results proved that the metamodel is complete and concise enough for the derivation of meaningful patterns.

Having developed a useful metamodel, a first set of patterns was created with a panel of seven experts from three organizations. The panel was asked to select and analyze a number of IIoT applications within their specific departments. In total, 34 IIoT applications with BPI propositions were identified that served as a basis for the pattern creation. These applications included several different IIoT technologies and business processes along the primary value chain activities. In a joint workshop, all applications were discussed in detail to abstract them and create generic patterns that illustrate and describe their core information. As a result of multiple workshops, five patterns could be derived that cover all 34 underlying IIoT applications.

The first pattern *Process Guidance* describes IIoT applications that provide user guidance through business processes. This pattern is illustrated in Figure 11. Especially for process participants that are new to the process or for complex business processes, this pattern can be precious. IIoT technology can collect process-related and situational data and provide useful information about the current process tasks. This can be done using audiovisual devices, e.g., lightbars or wearables. The effect on the process can be an improved processing time or a lower error rate and fewer repetition loops. This pattern mainly affects the operational and data perspective of the process as it uses process and situational data to ensure a correct task execution.

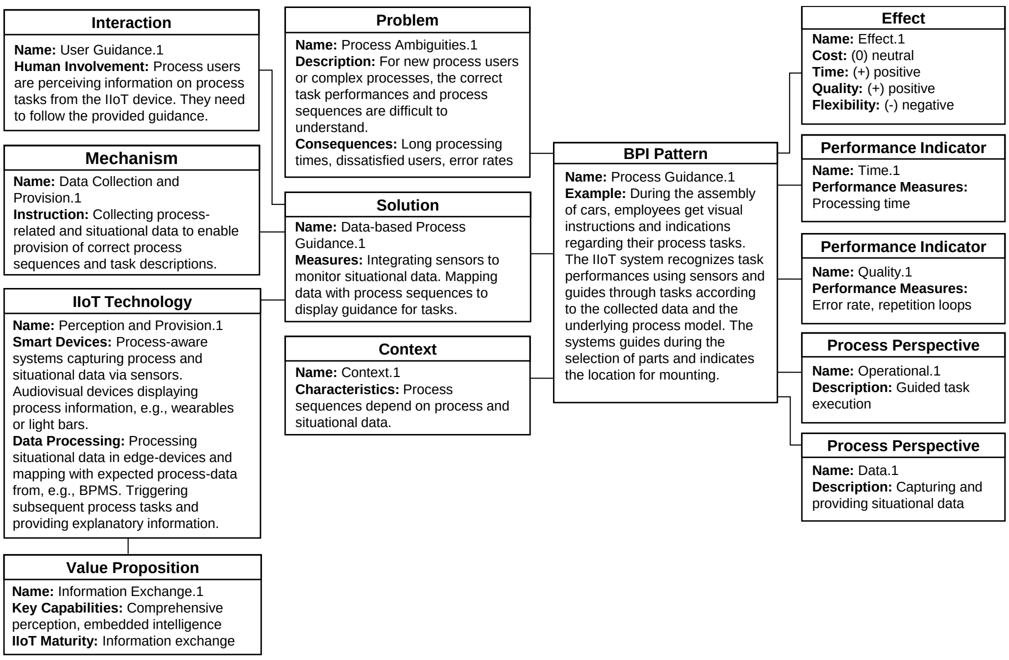


Figure 11: Pattern *Process Guidance* based on paper P4

The second pattern *Deviation Detection* allows the identification and indication of wrongly executed process tasks. IIoT technology compares the actual process data with expected process data and displays deviations. The third pattern *Authentication and Authorization* describes applications that enable the authentication of process participants. This facilitates an authorization mechanism for specific process tasks. In the fourth pattern *Task Distribution*, IIoT technology can support the systematic distribution of process tasks to employees. This can be based on their current location, fatigue, skills, or competencies. Consequently, the most fitting employee can be selected. The fifth pattern *Activity Automation* illustrates applications that replace manual tasks within processes using appropriate sensors and actuators. With the combination of multiple IIoT capabilities, specific tasks can be executed without human involvement.

Contribution of P4:
In summary, paper P4 proposes a metamodel of IIoT-based BPI and a first set of patterns. These design artifacts contribute to the descriptive knowledge of the phenomenon and facilitate sense-making, theory-led design, and practical execution of IIoT projects. The metamodel includes all indispensable elements and relations of IIoT-based BPI applications and can be used to derive patterns representing blueprints. As these patterns illustrate a description of the process problems, the impact on performance indicators and process perspectives, and a generic description of potential solutions, an effective identification and specification of applications are possible.

P5: Process-aware Decision Support Model for integrating Internet of Things Applications using AHP

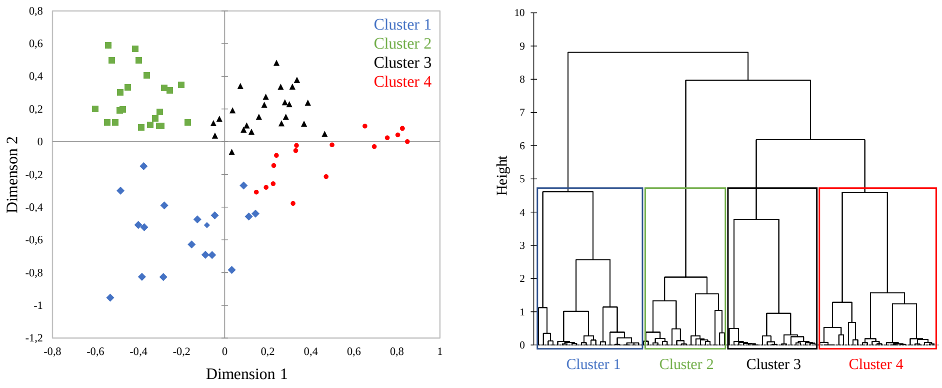
In paper P4, a metamodel and a first set of patterns are proposed that can be used to identify and specify IIoT-based BPI applications. However, organizations are often limited in resources and capacities, making it difficult to realize all application alternatives. Thus, practitioners require support during the goal-oriented selection. To the best of the authors' knowledge, no decision methods or models consider the underlying business process and aspects of IIoT technology. To fill this research gap, paper P5 presents a decision support model for the integration of IIoT technology into business processes.

For the development of the decision-support model, the structured Analytical Hierarchy Process (AHP) technique was utilized. The AHP is a theoretical modeling technique that enables and facilitates complex decision-making [95]. A goal-oriented selection of potential alternatives is possible by constructing a multi-layer decision tree according to the underlying topic. It consists of at least three layers, with the primary objective of the decision on top, relevant criteria that affect the decision in the middle, and the possible alternatives at the bottom. Including even more middle layers that further specify the decision criteria is possible. The top layer element is connected with all elements of the middle layer. In reverse, all elements of the second layer are connected with the elements of the bottom layer. Hence, all decision criteria can influence the main objective, and all decision alternatives can contribute to all decision criteria. The most promising alternatives can be selected by pairwise comparisons of the decision criteria and the possible alternatives.

The AHP for IIoT-based BPI consists of three layers: The top layer represents the overall objective of the decision-making. In this case, the objective is to improve the underlying business process. The second layer comprises decision criteria influencing the degree of objective achievement. These criteria specify the overall objective and depict potential manifestations of BPI. For this AHP, the already described PPMs of time, cost, flexibility, and quality were used. The bottom layer includes potential alternatives that can be selected. These can be already specified IIoT applications or rather generic patterns, as described in paper P4. Accordingly, the actual design of the bottom layer depends on the particular use case of an organization. For the presented paper, exemplary IIoT application clusters were created as alternatives.

To create these IIoT application clusters, an extensive SLR was conducted, whereby 81 publications that include application descriptions were identified following the structured procedure of vom Brocke et al. [120]. After that, a two-step analysis framework was applied. First, publications were categorized in a concept matrix according to Webster and Watson [122], resulting in an overview of each publication's main statements and contents. Subsequently, a cluster analysis was performed by applying a Multiple Correspondence Analysis (MCA) [39] and a Hierarchical Clustering on Principal Components (HCPC) [77]. The MCA was used as preprocessing to transform the categorical binary variables from the concept matrix into continuous ones, which were then used in the HCPC to find distinct clusters in the data set.

Figure 12 (a) shows the analysis results plotted in a two-dimensional space. The smaller the distance between two data points, respectively publications, the higher the similarity. Another form to visualize the results is a dendrogram, shown in Figure 12 (b). Here, the different distributions of each cluster are indicated in the form of precisely two branches per level. The higher the tree, the higher the variance between the included publications.



(a) MCA factor map (b) Dendrogram

Figure 12: Data analysis based on paper P5

Following this framework, four distinct IIoT application clusters were identified. The first one *Improved Information Exchange (IE)* includes applications that collect information about the process flow and environment. The second cluster *Tracking and Tracing (TT)* provides tracking and monitoring solutions by mainly using simple activity-aware devices, such as RFID tags. The third cluster *Faster Reaction to External Influences (RI)* describes applications that enable the identification and analysis of environmental factors and allow for a targeted and rapid response. The fourth and final cluster *Flexible Automated Systems (FS)* contains more complex IIoT applications. These applications combine sensing and actuating capabilities, forming completely autonomous systems within business processes.

These four clusters were used as the bottom layer of the AHP. The final AHP for IIoT-based BPI is illustrated in Figure 13. It comprises BPI as the overall objective, the PPMs as the decision criteria, and the created IIoT application cluster as alternatives. As already mentioned, instead of application clusters, the patterns described in paper P4 or more concrete applications could be used as alternatives.

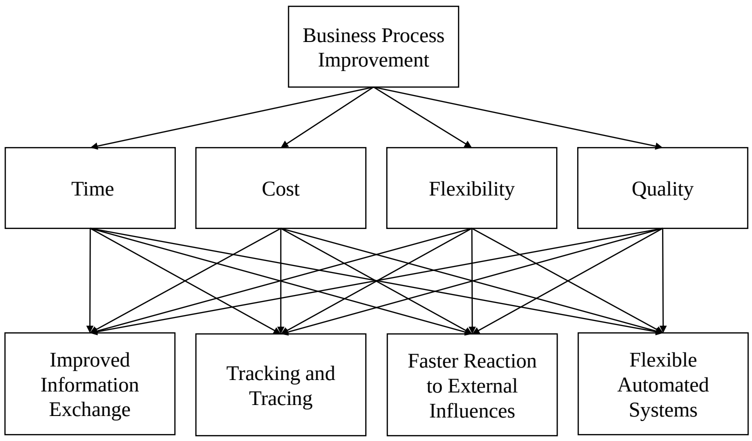


Figure 13: AHP model based on paper P5

To evaluate the usefulness of the AHP and to demonstrate its application, it was introduced to a market-leading organization. An expert panel of 15 employees and a business process from the production area formed the basis for the evaluation. The organization had identified performance problems for the business process and aimed to improve it by integrating IIoT technology. Also, the organization had not yet specified concrete applications, so the presented application clusters served as alternatives.

First, the AHP setup and all layers were presented to the experts in detail. Subsequently, a survey was conducted with the expert panel to collect data for the AHP calculation. The decision criteria had to be evaluated in pairs to determine the relative importance between them and their relative weight to the main objective. Analog, the alternatives had to be evaluated in pairs to determine the relative importance between them and their relative weight to the decision criteria. Based on the expert data, the weight scores W_C, W_L, and W_G were calculated. The score W_C represents the relative importance of each decision criterion concerning the main objective of BPI. W_L describes the relative importance of each alternative, i.e., application cluster, to achieve the decision criteria. Furthermore, the score W_G describes the relative importance of each alternative for achieving the main objective.

		Local Weights W_L			
Criteria	Criteria Weight W_C	IE	TT	RI	FS
Time	0.53	0.18	0.33	0.06	0.43
Cost	0.12	0.18	0.34	0.32	0.16
Flexibility	0.26	0.24	0.24	0.13	0.40
Quality	0.09	0.14	0.26	0.14	0.47
Global Weight W_G		0.19	0.30	0.11	0.39
Priority		3	2	4	1

Table 3: AHP results of case study based on paper P5

This calculation provided an overview of the priorities of the decision criteria and the possible alternatives. Figure 3 gives a concise overview of all AHP results of the case study. The PPM *time* was selected as the most relevant criterion to improve the business process as it received a W_C value of 0.53. The highest ranked application cluster for improving the business process was *Flexible Autonomous Systems* with a W_G value of 0.39. Accordingly, this alternative was assigned the highest priority. Based on these results, the organization analyzed potential applications within this cluster in detail.

Contribution of P5:
Paper P5 introduces a decision-support model enabling a goal-oriented selection of IIoT-based BPI applications. By using the AHP modeling technique, a multi-layer decision tree is presented. This AHP includes BPI as the main objective, PPMs as the criteria for measuring objective achievement, and potential alternatives that impact the criteria. The work contributes to research by highlighting the relevant influencing factors for selecting appropriate IIoT applications. It also contributes to practice, as it can be used for complex decision-making, including varying expert opinions.

5.5 Summary of the contributions and implications

This subsection briefly highlights the dissertation's core contributions and expected implications without repeating and summarizing all individual findings. In this context, *contributions* constitute the new knowledge that has been created, and *implications* describe the effect and impact of this knowledge on research and practice.

In general, this dissertation contributes to the *improvement* phase of the BPM lifecycle and seeks to provide methods and models for theory and practice. Concerning theory, the dissertation aims to extend and advance existing knowledge on IIoT-based BPI and stimulate future research. Regarding practice, it provides practical support and guidance within the key challenges for improving business processes with the IIoT.

Theoretical contributions and implications

Despite the IIoT's popularity in organizations and its recognition as a significant lever for economic success, its impact on business processes has only been insufficiently addressed. As presented in Section 2, research has come up with limited descriptive knowledge and lacks fundamental design artifacts that can be used as a basis for further research. The dissertation tackles this research gap by providing methods and models that extend and advance existing research on IIoT, BPI, and their interconnection. Therefore, it contributes to both topics and research fields. It introduces a novel catalytic idea within BPM research by including IIoT technology as a powerful technology for improving business processes. Its methods and models can be seen as an enrichment of the *improvement* phase of the BPM lifecycle. For this reason, it joins the existing research topics of connecting IIoT and BPM activities. Likewise, it broadens the predominant technical focus of IIoT research [88] by including a business process perspective. In this regard, it adds artifacts to the existing knowledge base for applying IIoT in a business context.

The theoretical contributions of the dissertation should create a common basis for the interconnection of IIoT and BPI and stimulate researchers to conduct further research on the topic. The included research papers can be used as starting point as they provide theoretical insights and fundamental descriptive knowledge. This should also highlight the importance of BPI within the BPM lifecycle, as in this activity, only limited research distinctly considers IIoT.

Practical contributions and implications

The dissertation also provides valuable contributions to managerial practice that address existing challenges and problems. The prevalent lack of methods and models regarding IIoT-based BPI necessitated the development of applicable design artifacts. This need has also been highlighted by current studies that illustrate prevalent hurdles and research that requests further exploration of the topic. Allocating the research endeavor along the three research areas enabled a practice-oriented artifact creation. This supports organizations in performing a straightforward project conduction. The challenges organizations face were addressed by providing means for comprehending, assessing readiness, and identifying, selecting, and specifying applications.

The impact on organizations has already been demonstrated during the evaluation episodes of each research paper. Managers and practitioners can sequentially use the methods and models to conduct IIoT projects with BPI prospects. Guidance and support are provided during all key phases. Furthermore, the artifacts can be embedded into already implemented organizational routines. As many organizations have already established practices for each BPM lifecycle phase, the proposed design artifacts can also be used as additional tools.

5.6 Complementary publications

The main and three detailed RQs were addressed and answered by the publications P1-P5. These core publications are included in the results part of the dissertation and provide useful findings about IIoT-based BPI. However, the research topic was also considered from different perspectives and points of view. This led to further ideas and results which do not directly address the three derived RQs. In total, six complementary publications were developed. These publications are not included in the dissertation but significantly impacted the core publications. Furthermore, one of them formed the baseline for an extended journal article. Therefore, the complementary publications A1-A6 are briefly presented in this subsection. Table 4 gives an overview of the complementary publications, including an identifier, the full citation, its publication status, and the publication type.

No.	Publication	Status	Type
A1	Stoiber, C. and Schönig, S., 2021. Event-Driven Business Process Management Enhancing IoT – A Systematic Literature Review and Development of Research Agendas. In: *Ahlemann, F., Schütte, R., Stieglitz, S. (eds) Innovation Through Information Systems. WI 2021. Lecture Notes in Information Systems and Organisation, vol 48*. Springer, Cham.	published	C
A2	Stoiber C., 2021. Exploiting Internet of Things for Business Process Improvement. In: *Proceedings of the 11th International Workshop on Enterprise Modeling and Information Systems Architectures, EMISA*.	published	C
A3	Stoiber, C., and Schönig, S., 2022. Patterns for IoT-based Business Process Improvements - Developing a Metamodel. In: *Proceedings of the 24th International Conference on Enterprise Information Systems, ICEIS*, pp. 655-666.	published	C
A4	Schönig, S., Hornsteiner, M., and Stoiber, C., 2022. Towards Process-Oriented IIoT Security Management: Perspectives and Challenges. In: *Augusto, A., Gill, A., Bork, D., Nurcan, S., Reinhartz-Berger, I., Schmidt, R. (eds) Enterprise, Business-Process and Information Systems Modeling. BPMDS 2022. Lecture Notes in Business Information Processing, vol 450*. Springer, Cham.	published	C
A5	Hornsteiner, M., Stoiber, C., and Schönig, S., 2022. Towards Security- and IIoT-Aware BPMN: A Systematic Literature Review. In: *Proceedings of the 19th International Conference on Smart Business Technologies, ICSBT*, pp. 45-56.	published	C
A6	Stoiber, C. and Schönig, S., 2023. The Smart Vending Cabinet: Leveraging the Industrial Internet of Things for Business Process Improvement. In: *vom Brocke, J., Mendling, J., Rosemann, M. (eds), Business Process Management Cases Vol. 3*. Springer, Berlin, Heidelberg.	under review	B

Table 4: Overview of complementary research papers

The complementary paper **A1** examines the paradigm of Event-Driven Business Process Management. It highlights the challenges organizations face when using high-frequency IIoT data in business processes and analyses the status quo in research. By conducting an SLR and clustering the identified publications, a comprehensive overview of technical aspects of IIoT data within business processes is provided. Furthermore, a research agenda is presented that can be used as guidance for further research on the interconnection of IIoT and BPM. This paper was presented at the *16th International Conference on Business Information Systems (WI) 2021* [109].

The second additional paper **A2** is a Ph.D. Research Proposal and based on the dissertation's exposé. It illustrates the overall research endeavor, including the addressed RQs and the planned publications. It was presented at the *11th International Workshop on Enterprise Modeling and Information Systems Architectures (EMISA) 2021* [108]. The successful presentation of the research topic and dissertation plan to one of the field's most relevant research communities confirmed their relevance. The feedback received at the conference could be used in many places in the dissertation.

Paper **A3** proposes a metamodel and patterns for IIoT-based BPI applications. It was accepted and presented at the *24th International Conference on Enterprise Information Systems (ICEIS) 2022* [111]. Based on the consistently positive reviews and affirmative feedback from the conference committee, the paper received the Best Paper Award. Furthermore, the authors were invited by the *SN Computer Science Journal* to publish an extended version of the paper within their topical issue *Advances on Enterprise Information Systems*. The extended version is included in the dissertation as paper P4.

The fourth complementary paper **A4** addresses the topic of security within the IIoT and illuminates the research area from another perspective. Integrating IIoT technology into business processes constitutes the convergence of industrial operational technology (OT) and information technology (IT). This enables beneficial possibilities for BPI but also has drawbacks regarding increased cyber-attack vulnerability. The solution to security risks includes integrating a Security Operations Center (SOC). A SOC provides awareness of security risks through detecting, containment, and remediation of threats. To enable effective IIoT security management within these SOCs, the BPM discipline provides several techniques and methods for systematically modeling and system-supported execution and analysis of processes. By mapping the VDI/VDE standard paper *IT-security for industrial automation* [117] with the BPM lifecycle, potential guidance is outlined. The paper was presented at the *23rd International Conference on Business Process Modeling, Development, and Support (BPMDS) 2022* [99], which was held in conjunction with the *34th International Conference on Advanced Information Systems Engineering (CAISE) 2022*.

The fifth additional paper **A5** also addresses the security challenges of processes that include IIoT technology. When integrating IIoT technology into business processes and redesigning the process, following the *security by design* concept is crucial. This means that processes must be modeled IIoT- and security-aware. Using the established BPMN, it is important to include security principles and measures early in the design phase. The publication analyses and presents the current state of research in IIoT- and security-aware BPMN extensions. Moreover, it compares the requirements from practice and research based on the EU security standard IEC62443. These two reviews of existing research and formulated requirements enabled the derivation of prevalent gaps and a research agenda. The paper was presented at the *9th International Conference on Smart Business Technologies (ICSBT) 2022* [50].

The sixth and final complementary paper **A6** presents an actual industry use case for an IIoT-based BPI application. The developed *Smart Vending Cabinet* is an application that radically improved a central distribution process of a market-leading organization in the Scandinavian region. To execute the project, the organization successfully used the methods and models presented in papers P1, P2, P4, and P5. Accordingly, the paper constitutes an evaluation case of the artifacts included in this dissertation. It addresses the frequent criticism of DSR for generating mostly theoretical artifacts that remain without practical application. Hence, it was possible to overcome the so-called "design theory indeterminacy" [65]. The paper was presented at the *20th Business Process Management Conference (BPM) 2023*. An extended version is under review for publication as a chapter of the book *Business Process Management Cases Vol. 3*.

5.7 Future Work

The presented methods and models significantly contribute to theory and practice, creating new perspectives and providing a useful set of tools. However, due to its novelty, the research field leaves ample opportunities for future work, while the dissertation can have a stimulating effect and provide potential starting points. The following paragraphs present a synopsis of possible future research topics.

Development of an IIoT-based BPI pattern catalog

The first potential future research topic ties directly to paper P4, in which five concrete patterns for IIoT-based BPI applications are presented. However, the five patterns represent merely a starting point for the creation of a comprehensive pattern catalog. Establishing such a pattern catalog would be highly valuable as it would increase the probability of practitioners discovering connection points within their business processes. To derive additional patterns, a significant number of literature and real-life applications must be found within an SLR and extensively analyzed.

Automated identification of IIoT-based BPI opportunities

The act of identifying BPI potentials within organizations is, in most cases, a manual task that heavily depends on the knowledge of domain experts [78]. Identifying redesign and improvement potentials requires manual activities such as traditional creativity techniques that are time-consuming, expensive, and labor-intensive [42, 116, 13]. Patterns, such as those presented in paper P4, must be mapped with business processes while existing methods only enable limited manual support [81, 68]. This usually includes conducting workshops with process stakeholders to analyze challenges and opportunities within underlying processes [126]. Developing methods and tools that enable a certain degree of automation in identifying and specifying BPI ideas is a relevant topic [34]. Consequently, redesign and improvement automation is an important future research direction. Recently, it has been considered one of the nine biggest existing BPM problems by eminent researchers of the BPM community [13].

In the last few years, first ideas and approaches to automating or semi-automating pattern suggestions for improving business processes have been presented [35, 82, 107]. Niedermann [86], for example, developed the deep Business Optimization Platform (dBOP) that enables a semi-automated detection and application of BPI patterns from a comprehensive catalog. Another example is the assisted business process redesign ($_{A}$BPR) that guides users in improving business processes based on redesign patterns [34]. However, these methods are often inflexible due to hard-coded assumptions [31] and, thus, cannot include the patterns of IIoT-based BPI. Therefore, a novel solution must incorporate the previously suggested pattern catalog and map them with any industrial business process. To do so, the generic problem definitions of the patterns must be automatically identified within business processes.

Another possibility to discover IIoT-based BPI potentials is the use of modern information technology without an explicit mapping with patterns. In this respect, it might be beneficial to leverage the computational creativity of artificial intelligence. A first approach has been proposed by van Dun et al. [115], who developed the ProcessGAN. This system supports organizations in the identification and specification of new BPI ideas. Other technologies for the identification of BPI ideas could be Evolutionary Algorithms (EAs) [3] or Natural Language Processing (NLP) [78]. However, as these existing approaches do not particularly consider IIoT technology a key driver for BPI, additional research is necessary.

IIoT-based BPI for small and medium-sized enterprises

The artifacts presented in this dissertation were designed for organizations of all sizes. This includes large corporations as well as small and medium-sized enterprises (SMEs). However, using taxonomies, maturity models, or patterns entails a certain degree of effort and requires experience with managerial design artifacts. This experience is often not readily available at many SMEs. Also, SMEs are often highly affected by the so-called technological turbulence, i.e., the rate of technological advancement within an industry [104]. Novel technologies, such as IIoT, significantly impact the relationship between strategic orientation and firm performance [94]. Therefore, SMEs might need special attention and different approaches for IIoT-based BPI artifacts. Nevertheless, SMEs can benefit from using IIoT technology for BPI for several reasons.

First, investments in BPI are a crucial area for SMEs to stay competitive [57]. SMEs are more willing to process innovation than larger enterprises [60] and have a more flexible business environment [84]. This makes redesigning processes and performing incremental or radical BPI projects more manageable.

Second, the IIoT is a crucial technology for SMEs. A recent survey on SMEs showed that 90% of the participants recognized IIoT as a key for industrial performance [75]. Among the variety of different Industry 4.0 technologies, IIoT is preferred by SMEs due to their relatively low costs [46]. However, IIoT technology is still a novelty for many SMEs, and the support of external consultants or academic researchers is required [75].

In summary, IIoT technology is expected to provide more opportunities to SMEs rather than being a burden [94]. Nonetheless, additional research is required to support SMEs in its adoption. To mitigate the lack of expertise among SMEs, simplifying related tools, methods, and models would be a critical success factor [75]. Consequently, future research should engage in practices with attention to how novel technologies such as IIoT can effectively be applied in SMEs [41]. This could imply adapting the artifacts within this dissertation or developing entirely new artifacts tailored to SMEs' specific needs.

6 Conclusion

This dissertation presents methods and models for IIoT-based BPI that contribute to both theory and practice. Research on this topic is relevant and timely because there is a prevalent lack of descriptive knowledge about the interconnection between IIoT and BPI. Furthermore, a considerable number of organizations encounter significant challenges in effectively leveraging IIoT technology for the improvement of their business processes. Based on this motivation, a main RQ was formulated and further detailed by deriving three particularized RQs. These RQs are embedded into three distinct research areas that form the basis of this dissertation.

To approach each research area, design artifacts were created following the guidelines of Hevner et al. [49], as well as the DSR methodology of Peffers et al. [90]. The design artifacts are based on inductive and deductive development procedures and were communicated to the relevant communities of IIoT, BPM, and IS research. A transfer to organizations was facilitated by selecting practice-oriented outlets for the papers.

The first research area discusses the need for organizations to fundamentally comprehend IIoT-based BPI. This also includes understanding how respective applications can be classified regarding their essential characteristics. While the IIoT and BPI are established paradigms in research, their interconnection is instead a novelty and lacks explanatory design artifacts. In that sense, RQ1 aims to establish a design artifact that facilitates the comprehension and classification of IIoT-based BPI. To answer this RQ, a taxonomy encompassing all essential dimensions and characteristics of the phenomenon is proposed. It enables a targeted analysis of potential manifestations and enhances its descriptive, theoretical understanding.

After comprehending the fundamental characteristics of IIoT-based BPI, organizations can review if they are ready to conduct related projects. Thus, the second research area focuses on required capabilities and, on this basis, assessing maturity and readiness.

However, a singular assessment contradicts the ever-changing character of capabilities within dynamic industrial environments, wherefore a continuous approach is required. The answer to RQ2 is twofold. First, a maturity model to assess the readiness and maturity regarding IIoT-based BPI is proposed, which allows for an in-depth analysis of relevant capabilities. Second, a method for the continuous application of maturity models is provided that can be implemented as an organizational routine. Both artifacts can help to measure whether an organization is ready to leverage IIoT for BPI or if crucial capabilities must be improved or developed first.

Having set a knowledge basis and assessed required organizational capabilities, actual projects can be executed. This execution involves identifying, specifying, and selecting applications. The formulated RQ3 is addressed by proposing patterns of IIoT-based BPI and a decision-support model. The patterns are derived from existing literature and actual applications and constitute blueprints of generic IIoT applications within business processes. They are illustrated based on a created metamodel and describe problems of business processes and how IIoT technology can resolve them. Therefore, practitioners can map them with their underlying processes and identify how IIoT technology can be harnessed. Having identified and specified a set of different applications, a decision-support model is presented that helps to select the most appropriate alternative.

In summary, this dissertation proposes contributions to IIoT and BPM research. It enriches the *improvement* phase of the BPM lifecycle by providing design artifacts that consider IIoT an enabler for BPI. Furthermore, it adds a business process perspective to the predominantly technical research on IIoT. Organizations can use the methods and models as standalone approaches or embedded into comprehensive organizational BPI routines. For future research, the presented findings can be a strong foundation and incentive for further exploring the connection between IIoT and BPM.

Part II

Research Papers

1 P1: Improving Business Process with the Internet of Things – A Taxonomy of IIoT Applications

Current status:	Published
Conference:	30th European Conference on Information Systems, ECIS, Timișoara, June 18-24, 2022
Date of acceptance:	19 April 2022
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Improving Business Processes with the Internet of Things - A Taxonomy of IIoT Applications

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IMPROVING BUSINESS PROCESSES WITH THE INTERNET OF THINGS - A TAXONOMY OF IIOT APPLICATIONS

Research Paper

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Abstract

The Industrial Internet of Things (IIoT) paradigm constitutes the connection of uniquely identifiable things to the internet in an industrial context. It provides disruptive capabilities and value propositions, especially for the management and improvement of business processes. To exploit these, many companies have already implemented manifold IIoT applications along their value chain activities aiming at beneficial Business Process Improvements (BPI). However, research on IIoT-based BPI is low on theoretical insights. To add to the descriptive knowledge of the IIoT, a structured synoptic view and classification scheme are required. The work at hand addresses this need by providing a taxonomy of IIoT-based BPI applications. Based on the combination of an inductive and deductive research methodology, the created taxonomy consists of six dimensions, seven subdimensions, and 40 characteristics. The taxonomy is evaluated on a sample of 30 IIoT applications from the literature and 10 real-life applications from a market-leading company.

Keywords: Industrial Internet of Things, Business Process Improvement, Business Process Management, Taxonomy

1 Introduction

In the last three decades Internet of Things (IoT) applications have spread massively in all areas of private and professional life, summing up to at least 43 billion IoT devices by 2023 (Dahlqvis et al., 2019). The connection of uniquely identifiable things to the internet by equipping all kinds of objects with sensors and actuators provides disruptive innovations for the private, public, and industrial sectors (Atzori et al., 2010). The IoT, therefore, bridges the gap between the physical and the digital world enabling the integration of objects into the networked society. Furthermore, a paradigm denoted as the Industrial Internet of Things (IIoT) has evolved that leverages the IoT, albeit transcending the concept of the *thing* toward industrial applications. In contrast to the IoT comprising various applications, e.g., smart home or smart city, the IIoT constitutes an explicit use of IoT technologies within industrial organizations and applications. Increasing connectivity between virtually every animate and inanimate entity within industrial processes creates a complex network of communication and interaction (Langley et al., 2021). In this context, the IIoT comprises people, data, processes, and things while information is turned into actions, creating new capabilities, richer experiences, and unparalleled economic opportunities (Azam et al., 2016). Thus, IIoT applications are projected to provide extensive benefits based on their technological capabilities and the underlying business process details (Langley et al., 2021), while the primary value drivers include both cost-cutting and revenue-raising impacts (Demirkan et al., 2015). Organizations that adapt their extant business models and business processes to these new technological possibilities have considerable opportunities to innovate and are potentially highly competitive. Hence, it is important to understand, how beneficial Business Process Improvements (BPI) can be achieved. This is important from a theoretical and a practical point of view as the combination of both fields IIoT and BPI is only sparsely addressed in current research (Stoiber and Schönig, 2021). No existing models sufficiently describe the dimensions and characteristics of IIoT applications with the goal of beneficial BPIs. This lack of knowledge constitutes a barrier for properly understanding the convergence of IIoT and BPI and advancing it for the beneficial transfer to practical use. Against this backdrop, we close the existing research gap by formulating and eventually addressing the following research question (RQ):

RQ: *How can IIoT applications aiming at Business Process Improvements be classified in terms of their essential characteristics?*

We present a conceptual taxonomy of IIoT-based BPI applications to address this research question. In this regard, we define the term "IIoT-based BPI application" as the purposeful use of IIoT technology within an industrial process to improve the same concerning predefined objectives. This includes a wide range of applications, e.g., tracking and tracing of process entities using simple RFID tags, or complex automation of formerly manual process activities using combinations of sensors and actuators. The taxonomy has been developed according to the systematic method of Kundisch et al. (2021) that reasonably extends the proven procedure of Nickerson et al. (2013) by adding supplementary steps. As this method follows principles of the Design Science Research (DSR) methodology (Hevner et al., 2004), the final taxonomy has been rigorously designed as a DSR artifact. For the taxonomy, we mainly focused on value-adding processes and activities within industrial organizations which are crucial for creating competitive advantage. For these primary value chain activities, the IIoT has the greatest leverage to generate value (Sisinni et al., 2018). To evaluate the usefulness of the taxonomy, we performed a classification of 30 literature and 10 real-life applications, and an expert survey.

The contribution of the taxonomy consists of two parts. First, it connects the research fields of IIoT and BPM and, therefore, extends and advances existing knowledge on both topics. The taxonomy constitutes the first structured and systematic classification tool of IIoT-based BPI and gives an overview of relevant elements and possible manifestations of IIoT-based BPI applications. Thus, it enables researchers to describe, understand, and analyze the phenomenon and create a starting point for further research (Nickerson et al., 2013). Second, it supports practitioners with the cognitive process of classifying already existing and possible future IIoT-based BPI applications. This leads to an improved analysis of the IIoT's potential. Decision-makers are able to perform an in-depth analysis of applications and get an impression of relevant elements and influencing factors to effectively select and implement IIoT-based BPI applications.

The remainder of this article is structured as follows. In section 2 we illustrate the theoretical background of the IIoT and its value propositions for business processes. Moreover, already existing taxonomies regarding IoT, IIoT, and Business Process Management (BPM) are presented to illustrate past and current research. In section 3, the applied research methodology of Kundisch et al. (2013) is described, while its application is illustrated in section 4. Subsequent, in section 5 the final taxonomy of IIoT-based BPI applications is presented in detail. We conclude with a general discussion of the final taxonomy, its limitations, and potential future research in section 6.

2 Theoretical Background and Related Work

2.1 IIoT meets Business Process Improvement

There are dozens of different approaches for defining the term IoT, its components, features and capabilities, and the *thing* itself. The Institute of Electrical and Electronics Engineers (IEEE) tried to combine several different descriptions toward a universal definition. According to the IEEE, the IoT is a network that connects uniquely identifiable things to the internet. Through the exploitation of unique identification and sensing, information about the thing can be collected and the state can be changed from anywhere, anytime, by anything (Minerva et al., 2015). Therefore, the term *things* corresponds to the idea of creating a ubiquitous presence of objects equipped with sensors, actuators, or tags. On the other side, the term *internet* refers to the ability of these things to build a network of interconnected objects based on several specific network technologies. These two perspectives can be complemented by a semantic view, which represents the ability of IoT to uniquely identify things and store, process, and exchange data (Atzori et al., 2010). While the IoT has the potential to create or transform products, services, and business models, its capabilities have also a disruptive impact on business processes (Leminen et al., 2018). In line with the growing share of industrial IoT applications, a more specified paradigm has been developed, called the Industrial IoT (IIoT). In contrast to the generic definition of IoT, the IIoT constitutes the use of certain IoT technologies, e.g., certain kinds of smart objects within cyber-physical systems, in an industrial setting, to promote goals distinctive to industry. The IIoT, therefore, differentiates itself from the IoT by the purposes to which the technologies are put (Boyes et al., 2018). Current research and already implemented applications clearly show that IIoT reveals many extensive possibilities for improving business processes. This is highly relevant as many companies follow a process-oriented view of their organization and all including operations (Porter, 1985). In this context, especially redesigning and improving business processes is a highly relevant topic in both research and the business environment and is considered one of "the most important and common titles in both literature and applications" (Coskun et al., 2008). BPI, in this context, is part of the Business Process Management (BPM) discipline, which is responsible for identifying, discovering, analyzing, redesigning and improving, implementing, and monitoring business processes (Dumas et al. 2018).

2.2 Taxonomies in IoT and BPM Research

Contributing to the theoretical and practical insights of IoT and IIoT, several white papers, case studies, technical articles, and classifications have been proposed. Here, especially classifications provide theoretical insights on inner correlations, characteristics, and relations of the phenomena. A classification, reduced to its mere definition, enables the arrangement of a set of entities into distinct groups, dimensions, and characteristics (Bailey, 1994). Therefore, classifications enable researchers and practitioners to understand, analyze, and structure the knowledge within a distinct field (Nickerson et al., 2013). Classifications come in different forms, e.g., frameworks, typologies, ontologies, or taxonomies, which are often used interchangeably. Among them, taxonomies, defined as an empirically or conceptually derived system of groupings of objects, have proved to be particularly useful within information system (IS) research (Glass and Vessey, 1995), given the speed of sociotechnical progress that requires continuous efforts of understanding. Regarding IoT and IIoT, researchers have already created a multitude of taxonomies that address different facets of both phenomena.

As IoT and IIoT technology enables novel business models, a classification scheme to further analyze its potential is of high importance. Woroch and Strobel (2021) and Hodapp et al. (2019) addressed this topic by creating a taxonomy of IoT-enabled business models. Regarding the technical specifications of the IoT system, several taxonomies focused on characteristics on a device level, e.g., Dorsemaine et al. (2015). This includes characteristics of the types of used sensors, e.g., motion, position, pressure, communication protocols, functional attributes, or software resources. While this does not provide any information about the actual role of the IoT device, an IoT stack-centric taxonomy allows further classification dimensions (Püschel et al., 2016). By classifying an IoT or IIoT application according to established layer architectures and IoT stacks that also include the application and service layer, the role of the application can be defined. Also, a taxonomy on the socio-material perspective of the IoT has been developed that focuses on business-to-thing interactions (Oberländer et al., 2018). However, this does not allow to draw any conclusion about the business objectives that are associated with the IoT application. In this respect, Yaqoob et al. (2017) have developed an IoT architecture taxonomy that combines a mixture of business architecture and technical characteristics, also including business objectives and enabling technologies of IoT. However, lacking a specific view on IIoT applications, it has limited value for classifying these kinds of applications. Against this, Schneider (2017) developed a taxonomy of IIoT which focuses on industrial applications. But only consisting of six characteristics, it does not provide a useful tool for a detailed classification. Finally, Boyes et al. (2018) merged all the stated taxonomies with their different viewpoints to develop an analysis framework for IIoT that enumerates and characterizes IIoT devices. Certainly, without providing any characteristics that allow the classification considering business processes, it does not serve to address the formulated research question. While some taxonomies address BPM cases (vom Brocke and Mendling, 2017), business processes (Regev et al., 2006), and options for BPI (Falk et al., 2013), they collectively lack connections to the IIoT paradigm. Having analyzed existing research, we target to fill the identified research gap and address the formulated research question.

3 Research Method

To develop the taxonomy of IIoT-based BPI applications, we applied the extended taxonomy design process (ETDP) by Kundisch et al. (2021). This design process is based on the proven method for taxonomy design in IS research by Nickerson et al. (2013) which has been applied by approximately two-thirds of all IS taxonomies since 2013 (Kundisch et al. 2021). Despite being the de facto standard for the design of IS taxonomies, it lacks transparency for reporting relevant design decisions and guidance regarding taxonomy evaluation. Providing additional design and evaluation steps, the ETDP tackles these issues and constitutes an improved procedure. The ETDP comprises 18 steps and is organized along with the six DSR methodology activities stated by Peffers et al. (2007). In steps 1 to 3, the observed phenomenon (Step 1), the target user groups(s) (Step 2), and the intended purpose(s) (Step 3) of the taxonomy are specified. Further, in step 4, the meta-characteristics are formulated, which define the angle a taxonomy takes on the phenomenon under consideration. As the ETDP is iterative, ending conditions and evaluation goals must be determined in step 5, before the actual artifact creation. These conditions can be both subjective and objective and have a significant influence on the created taxonomy. The actual iterative development procedure starts by choosing the development approach in step 6. Researchers must select either an inductive/empirical-to-conceptual or a deductive/conceptual-to-empirical approach. The selection of the initial approach depends on the availability of data and the researchers' knowledge of the relevant domain (Nickerson et al., 2013). In choosing an empirical-to-conceptual approach, real-life objects are identified first (Step 7e), and dimensions and characteristics are identified (Step 8e) and grouped (Step 9e) subsequently. Selecting the conceptual-to-empirical approach, the taxonomy's dimensions and characteristics are conceptualized first (Step 7c), and real-life objects are mapped to the dimensions and characteristics second (Step 8c). Hereafter, the current taxonomy draft is created or revised (Step 10) and mapped with the formulated objective (Step 11 and 12) and subjective (Step 13 and 14) ending conditions. If all ending conditions have been met, the next step can be reached, else wise, a new iteration starts. Having met all ending conditions, steps 15 and 16 support assessing the conditions of the taxonomy evaluation. This implies adequately configuring an evaluation (Step 15) and performing it (Step 16). In step 17, an *ex-post* evaluation in light of the evaluation goals must be performed to decide, if the taxonomy requires further adaption. If the taxonomy proves to be useful within the evaluation, it must be reported in a manner that fits the purpose and target user groups (Szopinski et al., 2020) (Step 18). To support the taxonomy creation, Kundisch et al. proposed 26 operational taxonomy design recommendations, that we also considered.

In section 4, the application of the outlined ETDP is described to develop the taxonomy of IIoT-based BPI applications. This comprises the problem identification and objective definition (Steps 1 to 5), the actual design, development, and demonstration (Steps 6 to 10), and the evaluation (Steps 11 to 17). The communication and presentation (Step 18) of the final taxonomy are performed in section 5.

4 Taxonomy Design Approach

4.1 Problem Identification and Objective Definition

The theoretical background of IIoT and BPM, respectively BPI, have been discussed in sections 1 and 2. At the same time, we outlined the need for a taxonomy of IIoT-based BPI applications, as no existing taxonomy enables a sufficient conceptualization of this phenomenon. We designed the taxonomy for researchers in the fields of IIoT, BPM, and IS in general. In addition, industrial experts related to IIoT technology and BPM, as well as managerial decision-makers may benefit from our contribution. The purpose of the taxonomy is to identify and structure the characteristics of IIoT-based BPI applications and their relationships. This may enable researchers to further study this field and practitioners to gain insights into potential applications. We define IIoT applications as enablers to improve business processes by either tackling existing challenges or enabling opportunities. Therefore, the development procedure is based on the meta characteristics:

Characteristics of IIoT applications embedded in business processes aiming at beneficial Business Process Improvements.

As objective conditions, we selected the following: *i)* at least one object is classified under every characteristic of every dimension *ii)* every dimension is unique and not repeated, *iii)* every characteristic is unique within its dimension, and *iv)* no new dimensions or characteristics were added in the last iteration (Nickerson et al., 2013). In addition, as subjective ending conditions, the authors must agree that the taxonomy is concise, robust, comprehensive, extendible, and explanatory. These conditions constitute criteria for the *ex-ante* evaluation. Further, a rigorous taxonomy design requires conformity with formulated goals after the *ex-post* evaluation. These goals are, that the taxonomy must enable users to *i)* describe, *ii)* classify, and *iii)* analyze the phenomenon of IIoT-based BPI applications.

4.2 Design, Development, and Demonstration

After initializing the design procedure, we performed four iterations including two inductive and two deductive approaches. Figure 1 illustrates these iterations by stating the selected approaches, the used information sources and methods to perform a conceptualization, and the identified dimensions. After four iterations, no additional knowledge could be generated wherefore the procedure ended.

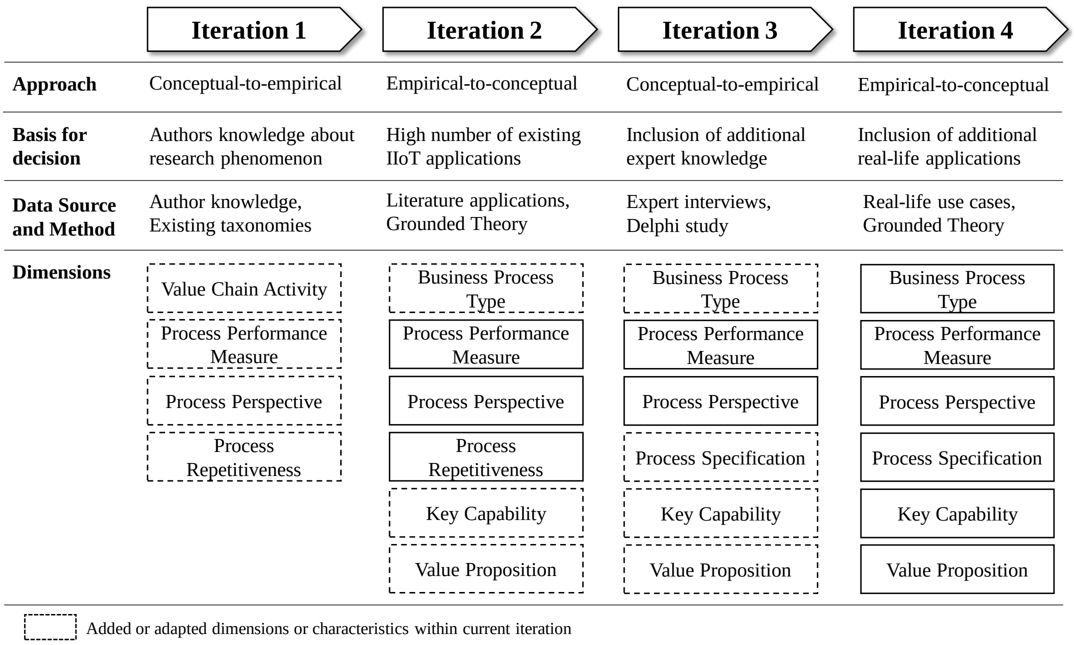

Figure 1. Design iterations.

Iteration 1. We have selected the conceptual-to-empirical approach for the first iteration, as the authors' knowledge holds relevant insights about the phenomenon under consideration. To integrate an even broader knowledge base, we also accounted for and referred to existing IoT, IIoT, and BPM taxonomies. Analyzing IIoT applications at the highest level, we conclude that it is possible to classify them according to their application area within the industrial value chain. We defined the first dimension as *value chain activity* and the primary activities as characteristics (Porter, 1985). Further, specific Process Performance Measures (PPMs) are used to quantify the degree of BPI, which can take different forms. We added *process performance measure* as a dimension including the characteristics defined by Dumas et al. (2018). As different IIoT applications do not uniformly address all facets of business processes, it is essential to define, which perspectives of the process are influenced most. We, therefore, added the dimension *process perspective*, proposed by Jablonski et al. (1996) and Schönig et al. (2014) including the stated characteristics. Finally, we formulated *process repetitiveness* as a binary dimension to specifiy the underlying process type. For IIoT applications, it is highly relevant, if the process and all included data sets and activities are repetitive, or if the IIoT system needs to adapt to varying environments (Benešová et al., 2019). We have identified several literature IIoT applications that can be mapped to the created dimensions and characteristics. The taxonomy T_1 consisted of four dimensions and 17 characteristics. Since this has been the first iteration, the procedure continued.

Iteration 2. For the second iteration, we have selected the empirical-to-conceptual approach as a significant number of objects are available to represent the phenomenon under consideration. To identify a subset of objects, we performed a Systematic Literature Review (SLR) on IIoT applications within business processes. The SLR followed the established procedure proposed by vom Brocke et al. (2009). To improve the structure of the literature search, it has been conducted according to the PRISMA statement (Liberati et al, 2009). At first, the search string *("IIoT" OR "IoT" OR "CPS") AND ("BPI" OR "Process Improvement" OR "Process Optimi?ation" OR "Application")*, as well as the written-out forms have been formulated. We queried the most relevant databases of the underlying research fields, including ACM Digital Library (81 hits), AISeL (132 hits), IEEE Xplore (334 hits), ScienceDirect (238 hits), Scopus (133 hits), and Springer Link (353 hits). To reduce the number of records, three eligibility criteria have been formulated that define, if an article is appropriate for the anticipated purpose. We defined the eligibility criteria as *i)* topicality, *ii)* relevance, and *iii)* credibility. The criteria are translated by only considering peer-reviewed articles with a publication date after 2014 and at least 50 citations. After excluding 546 duplicates and 539 records according to the formulated criteria, we analyzed 186 full-text publications. Eventually, we excluded another 80 publications due to lacking IIoT implementations or BPI references. Moreover, we excluded 25 further publications because of redundancies. This means, that an IIoT application described in a publication is very similar to at least another one and does not provide additional information. The remaining 81 eligible publications have been investigated using the grounded theory. The grounded theory is a qualitative research method that seeks to develop a theory that is grounded in data systematically gathered and analyzed (Urquhart et al., 2010). Especially in IS research, it has proved to be extremely useful in developing context-based descriptions and explanations of information systems phenomena (Myers, 1997). Strauss and Corbin (1997) proposed the coding stages of open coding, axial coding, and selective coding to conceptualize an existing IS phenomenon. This method enabled the derivation of additional dimensions and characteristics and supported the adaption of taxonomy T_1. First, we could identify the dimension *key capability* by performing all coding stages. This describes the capabilities that are most relevant to achieve the respective value propositions and PPMs. Furthermore, an even more specific classification scheme for the application area could be defined. We renamed the dimension *value chain activity* to *business process type* and arranged the newly introduced characteristics along with the primary value chain activities. This implies the insertion of subdimensions as second-level groupings. Further, the coding showed that the actual *value contribution* of the IIoT application can be determined. The adapted taxonomy T_2 included six dimensions, six subdimensions, and 33 characteristics. As we have added further dimensions and characteristics in this iteration, the procedure continued with taxonomy T_2.

Iteration 3. We have selected the conceptual-to-empirical approach for the third iteration, as we intended to include further expert knowledge in the taxonomy creation procedure. We performed expert surveys with six practitioners from market-leading companies and six researchers with experience in IIoT and BPM. All experts received taxonomy T_2 and were asked to adapt or extend it. This interviewing procedure followed the method of Delphi studies, which supports soliciting information about a specific topic by completing several surveys (Loo, 2002). After a four-round Delphi study, we added seven additional characteristics for the dimensions *business process type*, *key capability*, and *value proposition*. In addition, we created the dimension *process specification* and demoted the dimension *process repetitiveness* to a subdimension. Eventually, we added the binary subdimension *knowledge intensity*. As stated by Davenport (2015), Gronau et al. (2005), and others, the amount of knowledge required for the performance of processes highly influences the deployment of technology and its automation. We identified several IIoT applications that could be classified under the formulated dimensions and characteristics. The adapted taxonomy T_3 included six dimensions, seven subdimensions, and 40 characteristics. As we have added further dimensions and characteristics in this iteration, at least one ending condition is not met. The procedure continued with taxonomy T_3.

Iteration 4. For the fourth iteration, the empirical-to-conceptual approach has been selected, as it may lead to new insights considering the adoptions performed in iteration 3. To find a new sample of objects, we selected 12 applications from Linde plc, a market-leading industrial company, and analyzed them using the grounded theory. As a result, no additional dimensions or characteristics could be identified. We checked the objective ending conditions and concluded that at least one object was classified under each dimension and characteristic. Further, every dimension and characteristic is unique and not repeated, and no additional dimensions or characteristics have been added. Checking the subjective ending conditions, both authors individually assessed the taxonomy as concise, robust, comprehensive, extendible, and explanatory. The procedure ended with iteration 4 and the unmodified taxonomy T_3.

4.3 Evaluation

As the *ex-ante* evaluation of checking the objective and subjective conditions has been solely performed by the authors, an adequate *ex-post* evaluation is required. In light of the intended taxonomy purpose, we defined three evaluation criteria that needed to be met to achieve the evaluation goals. For each of the criteria, we selected an evaluation method and an evaluation measure, as summarized in table 1. To follow the stream of existing research, we selected the most frequently used methods and criteria of prior taxonomy evaluations, as analyzed by Kundisch et al. (2021).

Evaluation criteria	Method	Measure
Reliability	Illustrative scenario	Dimension-specific hit ratios
Robustness	Illustrative scenario	Object-specific hit ratios
Completeness	Expert survey	Questionnaire results

Table 1. Evaluation approach.

Since the taxonomy should be used by researchers and practitioners to classify different kinds of possible IIoT applications within several industry branches, it must be robust. Robustness describes the artifact's ability to handle varying, and possibly low levels of information (Prat et al., 2015). Further, as it should enable different kinds of people to achieve similar or identical results for classifying the same objects, it must be reliable. Reliability constitutes the proportion of joint judgment in which there is an agreement (Nahm et al., 2002). Finally, the taxonomy should contain all necessary dimensions and characteristics to classify all objects of the phenomenon under consideration, represented by the criterion completeness.

To assess the **robustness** and **reliability** of the taxonomy, we used a sample of 30 illustrative scenarios from the literature and 10 real-life IIoT applications from Linde plc, a global market-leading company. To identify a new subset of literature objects without re-using those from the development steps, we performed a SRL analogously as in subsection 4.2, but changed the eligibility criteria. We now also considered publications with less than 50 citations, published not earlier than 2014, and excluded the already analyzed ones. If a publication mentioned more than one use case, we highlighted the one that needed investigation. For the final selection, we considered applications that cover at best all of the taxonomy's dimensions, subdimensions and characteristics. For the 10 real-life applications, we considered IIoT applications that cover a wide range of different technologies, business processes, and value chain activities. An expert panel of two researchers with knowledge in IIoT technology classified the sample using taxonomy T_3. The researchers have profound expertise in the underlying research field and had six weeks to classify the sample of objects. To select appropriate experts, we investigated researchers who have published at least two articles in the AIS „Basket of Eight" journals on the fields of IIoT and BPM. Furthermore, we specifically searched for researchers who have been involved in the development of taxonomies for IoT or BPM-related topics. From the identified group of researchers, we selected those two who are currently researching IoT and IIoT and therefore have up-to-date knowledge. For analyzing purposes we used the concept of hit ratios, representing inter-judge agreements within the expert panel (Nahm et al., 2002). This approach has proven to be appropriate for similar taxonomy evaluations as it renders the consensus within multiple classification results of the same application (Püschel et al., 2016). Agreement among the experts is counted as 1 and disagreement as 0 for all dimensions. Partially agreements of non-exclusive characteristics are coded on a scale from 0 to 1. To measure the robustness of the taxonomy, we compared the object-specific hit ratios of all IIoT applications from the literature with those from the real-life applications. As the literature applications only contain low to medium levels of information and the real-life applications have been discussed with the expert panel in detail, this comparison appropriately evaluates the robustness according to our definition. Eventually, the reliability is measured by assessing the dimension-based hit ratios (Moore and Benbasat, 1991) for measuring agreement among experts. Analyzing the results of the classifications, we also examined the exclusivity of characteristics and their scale. Table 2 shows the results of the classifications' dimension-specific results, whereas table 4 in the appendix includes all classified objects and hit ratios.

	Dimension Properties		
Dimensions	**Scale**	**Exclusivity**	**Hit Ratio**
Key Capability	Nominal	Non-exclusive	75%
Value Proposition	Ordinal	Non-exclusive	83%
Business Process Type	Nominal	Non-exclusive	85%
Process Specification	Nominal	Mutually exclusive	91%
Process Performance Measure	Nominal	Non-exclusive	81%
Process Perspective	Nominal	Non-exclusive	77%

Table 2. Dimension properties and dimension-specific evaluation results.

While all dimensions are nominally scaled, *value proposition* comprises characteristics with a specific type of order. Analyzing the classification results, we also conclude that most of the dimensions are non-exclusive, while only the characteristics of *process specification* are mutually exclusive. As already shown by Püschel et al. (2016), mutual exclusiveness within IoT-related taxonomies is hard to achieve due to the complexity and extent of applications. Yet, this does not pose a problem for its utility. The results for the dimension-specific hit ratios range between 75% and 91%, revealing an adequate consensus along with all experts. This showed us, that taxonomy T_3 complies with the criterion of reliability. However, while for the dimensions *business process type* and *process specification*, with ratios of 85% and 91%, high conformity have been reached, especially the dimensions *key capability* and *process perspective*, with ratios of 75% and 77%, seem to be not unambiguous. Analyzing the object-specific hit ratios, we achieved an overall hit ratio of 81% for literature-based applications and 85% for real-life applications. This small difference shows, that reasonable classification is possible in each case. Therefore, we conclude, that the taxonomy is also robust and can handle low levels of information in a manner that comes close to applications with higher levels of information.

To assess the taxonomy's **completeness**, we performed an expert survey. The expert panel consisted of 16 practitioners from five industrial companies that have working experience from four to 22 years. The industrial companies ranging from medium-sized to large multi-national corporations located in Germany, Sweden, the Netherlands, and the USA. At first, the expert panel had received the taxonomy including a comprehensive introduction and explanation of all dimensions and characteristics. Then, each expert classified a set of five to eight IIoT applications of their company using the given taxonomy.

Finally, after three weeks, the experts received a questionnaire where they needed to indicate if *i)* the taxonomy included all relevant dimensions and characteristics to classify the objects, *ii)* the definition of the taxonomy characteristics allowed a direct mapping with object characteristics, and *iii)* the dimensions and characteristics were detailed enough to allow differentiation between similar objects.

Statement	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
The taxonomy includes all relevant dimensions and characteristics to classify the objects.	88%	12%	0%	0%	0%
The dimensions and characteristics are detailed enough to allow differentiation between similar objects.	81%	13%	6%	0%	0%
The definition of the taxonomy's characteristics allows direct mapping of all object characteristics.	75%	17%	8%	0%	0%

Table 3. Survey results.

Finally, we aggregated and assessed the expert survey results to evaluate the taxonomy's completeness. All experts agreed or strongly agreed with the statement, that the taxonomy included all relevant dimensions and characteristics to classify the objects. Further, 94% of the experts confirmed that the dimensions and characteristics are detailed enough to allow differentiation between similar objects, while 92% confirmed that the definition of the taxonomy's characteristics allowed a reasonable mapping with object characteristics. These results showed us, that the current taxonomy draft is complete.

Since the evaluation criteria have been met, we conclude that the current taxonomy draft T_3 reached the formulated evaluation goals. The hit ratios and the survey results proved that the taxonomy enabled the researchers and practitioners to *i)* describe, *ii)* classify, and *iii)* analyze the phenomenon of IIoT-based BPI applications. The objects' characteristics could be mapped with the taxonomy's dimensions and characteristics, while also a differentiation between similar objects was possible.

5 A Taxonomy of IIoT-based BPI Applications

To effectively communicate and illustrate the taxonomy, we have chosen the hierarchical tree technique as it has been adopted by a multitude of prior taxonomy designers. Also, it allows a clearer illustration and distinction of the taxonomy's elements compared with mathematical notations or tables. Figure 2 shows the final taxonomy of IIoT-based BPI applications. Consisting of six dimensions, seven subdimensions, and 40 characteristics, its size is in line with the recommendations of existing research without being too oversized or too marginal for complex classifications (Nickerson et al., 2013).

The IIoT comprises novel and disruptive capabilities that distinguish it from other technologies (Atzori et al., 2010). To enable beneficial BPIs, these capabilities must be used profitably and systematically. While the combination of these capabilities is often relevant for IIoT-based BPI, in most cases individual key capabilities can be identified that are exploited in particular. Thus, it is necessary to identify these key capabilities and focus on them while developing the application. Adding the dimension *key capability*, we state six characteristics that paraphrase the capabilities of IIoT. *Universal scalability* is the ability of the IIoT to adapt to changes in the environment and therefore enable the extension or adaption of existing information systems within processes (Gupta et al., 2017). Further, a *comprehensive perception* of the environment through sensors enables manifold monitoring and tracking applications (Tao et al., 2014). As IIoT applications often have the resources for edge computing directly on the shop floor, this *embedded intelligence* bridges the gap between the physical and digital worlds (Dai et al., 2019). Due to the different layers of an IIoT system, it is highly *configurable*, making the whole IIoT application flexible and customizable based on concrete business requirements. Another capability that originates from the layer architecture is the *interoperability* of the IIoT between systems and interfaces, which utilize different communication standards (Desai et al., 2015). Finally, as the IIoT is based on the connection of things via the internet, it can enable *connectivity* for any entity.

By exploiting the capabilities of the IIoT, potential *value propositions* can be defined which are the main drivers for the adoption, acceptance, and use of IIoT applications. *Situational awareness* describes the localization and condition assessment of objects at any time, e.g. by using RFID (Tai Angus Lai et al., 2018). One step further, IIoT systems can also be a tool for *decision-making support*. Here, extensive statistical models and big data analytics can reveal patterns that can simplify complex decisions making. *Information exchange* in IIoT can take place between things, things, and people, and between people. This enables the connection of different systems to perform complex tasks. Thus, IoT systems can actively control the course of processes and enable collaboration between actors (Schönig et al., 2018). Moreover, *autonomous systems* can analyze unpredictable situations and make automated decisions. Therefore, these IIoT systems can function independently of environmental conditions and human input.

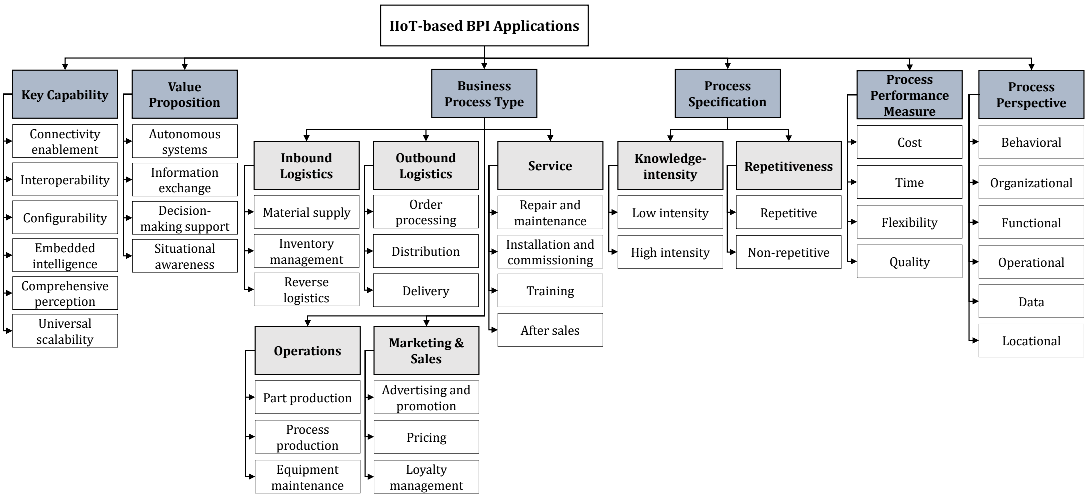

Figure 2. Taxonomy of IIoT-based BPI applications.

The nature of the IIoT application largely depends on the area of application and therefore the *business process type* in which it is embedded. The most common and widely used methodology to distinguish the activities of a company is the concept of value chains by Porter (1985). This helps to classify the IIoT applications based on the primary value chain activities, mapped as sub-dimensions. *Inbound logistics* comprises processes associated with *supplying raw materials*, *managing the inventories*, as well as *reverse logistics* of final products. Downstream, *operations* processes are responsible for transforming the raw materials into final products via *product* or *process production* and *maintaining* the used equipment. Subsequent, *outbound logistics* comprises the *processing of orders*, their *distribution*, and *delivery* to customers. Activities that provide the means to purchase the product are categorized as *marketing and sales*, including *advertising and promotion*, *pricing*, and *loyalty management*. Finally, *service* processes are associated with providing service to enhance or maintain the product's value (Barnes, 2000). This can be categorized as *repair and maintenance*, *installation and commissioning*, *training*, and *after sales*. For each of the stated subdimensions and characteristics, or process types, the implemented IIoT applications differ significantly. This is the case due to different objectives, process actors, and interfaces to internal or external information systems and stakeholders.

In addition to the exploited IoT capabilities and the business process type, to appropriately classify an IIoT-based BPI application, the underlying *process specification* needs to be analyzed as it has a major influence on the actual IIoT application and the achievable BPI. Especially the *knowledge-intensity* and *repetitiveness* of processes increase the requirements for IIoT applications and may limit the actual BPI, as they represent the degree of variety and complexity. Processes with a high knowledge-intensity often require human judgment (vom Brock et al., 2016) and can only be partially automated due to unpredictable decisions or tasks (Gronau et al., 2005). In addition, traditional methods for process measurement and BPI seem to be inappropriate due to their unstructured and often collaborative nature (Benešová et al., 2019). This also applies to non-repetitive processes as they require more detailed planning and hamper the use of novel technologies (Thiemich and Puhlmann, 2013).

Apart from classifying an IIoT application in terms of IIoT-related or process-related characteristics, it is necessary to determine the expression of actual BPIs. One possibility of quantifying this is to define various key performance indicators (KPIs), in the context of BPM also called *PPMs*. PPMs can take different forms depending on the type of process and the desired output, but most of the literature defines PPM in terms of *time*, *cost*, *quality*, and *flexibility (*Dumas et al., 2018). The characteristic *time* may have different forms, e.g., the cycle time, processing time, or waiting time. The *costs* associated with processes consist of various components, such as wage costs, IT costs, or service costs. A definition of the PPM *quality* is more complex and could constitute, e.g., the performance of workflows or processes without deviations in an anticipated way. Lastly, the characteristic *flexibility*, i.e. the responsiveness of the process to changes in the environmental conditions, must also be made measurable.

Finally, an IoT application, and particularly the resulting BPI, can influence one or multiple specific perspectives of a business process. Therefore, the dimension *process perspective* outlines, which constituents of the process are influenced most by the BPI. In that regard Jablonski and Bussler (1996) and Schönig et al. (2014) have formulated six process perspectives. The *behavioral perspective* mainly comprises elements of the right process workflow or sequence, legal regulations such as reporting obligations, and internal requirements. The *organizational perspective* focuses on the personnel that is involved in the process execution and monitoring. Its main components are responsible process owners, admins, and process users. In addition, the underlying system is part of this perspective and represents for example the IT environment. The *functional perspective* includes the concrete process steps, activities, and events. Most of the processes, especially in the manufacturing industry, comprise several facilities, machines, tools, software applications, or items that can be described as the *operational* perspective. The *data perspective* involves all data and documents that are necessary for process execution. Finally, the *locational* perspective is also relevant, as assigning tasks to participants and the progression of a process may then depend on specific locations. With complex processes including human workers and machines, the locational attributes are highly relevant and can be influenced and exploited by IIoT systems.

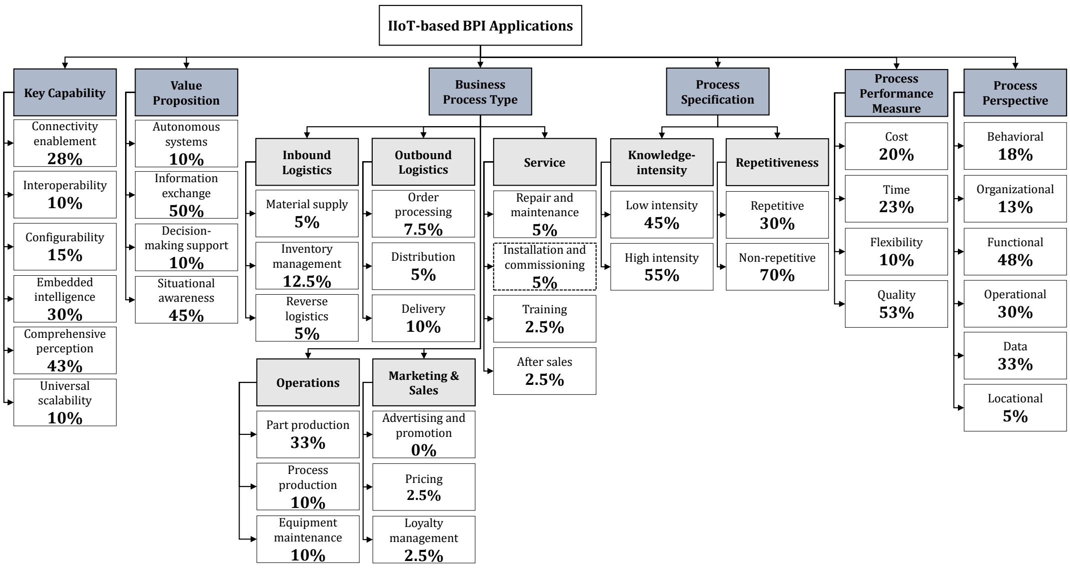

Figure 3. *Classification results.*

To provide even deeper insights into the characteristics of IIoT-based BPI applications, we calculated the ratios of all classifications performed in subsection 4.3. Figure 3 illustrates the characteristics' absolute ratios for the 40 classified literature and real-life applications. The sum of all characteristics might exceed 100% for non-exclusive dimensions. The results for key capability show that most of the applications exploit the capabilities comprehensive perception and embedded intelligence. This highlights the importance of sensors, actuators, and distributed computing paradigms associated with the IoT, e.g., edge computing. Analyzing the value proposition ratios, we conclude that basic awareness of the environment and process parameters as well as exchanging information is most relevant. With only 10%, *autonomous systems* are not represented often, although the automation of whole processes has the most significant leverage for BPI. This reveals the need for further research to enable this value proposition. The distribution of applications shows, that a focus lies on operations and logistics processes with a ratio of 53%. We could identify a lack of use cases in marketing and sales which, however, could be the source for major BPIs. For the mutually-exclusive subdimensions of *process specification*, no clear trend could be derived. More than half (53%) of all applications focused on improving the process quality. This is reasonable, as most simple monitoring and tracking use cases do not have a direct link to the cost, time, or flexibility measures. These applications increase the overview and transparency, and thus the quality of the processes. Finally, almost half of the applications (48%) influenced the functional *process perspective* representing the actual process tasks and activities.

6 Conclusion and Future Research

Though its importance and relevance, a systematic classification of IIoT applications aiming at BPI has not been addressed so far. Yet, classifications are highly relevant as they provide a structure and an organization to the knowledge of an existing field of research (Glass and Vessey, 1995). We, therefore, developed a taxonomy of IIoT-based BPI applications following the development procedure of Nickerson (2013) and its extension by Kundisch et al. (2021). Combining inductive and deductive methods, the resulting taxonomy consists of six dimensions, seven subdimensions, and 40 characteristics. From a research perspective, it adds to the descriptive knowledge of the IIoT and provides a starting point for further research. From a managerial or practical point, the taxonomy supports a classification of all kinds of IIoT applications within business processes. The resulting information can be used to compare existing applications with those of competitors or to ensure that dimensions relevant to IIoT applications can be considered entirely for future projects. From the perspective of an IIoT solutions provider, the taxonomy helps identify relevant components of IIoT applications and potentials for developing novel technologies. Although being developed according to DSR principles, including an extensive evaluation, the final taxonomy is not without limitations. First, the selection of an approach for each development iteration, the ending conditions, and the included literature during the SLR highly influenced the taxonomy creation. Different approaches and literature may have led to different taxonomies. However, this is not a fundamental issue, as DSR allows varying artifacts for varying preconditions (Hevner et al., 2004). Another limitation is the non-exclusiveness of some characteristics and, therefore, minor redundancies. Though, this does not contradict or violate the general utility and applicability of the taxonomy. For each specific combination of characteristics, an own characteristic might be introduced, resulting in a mutually exclusive but inflated set of characteristics (Püschel et al. 2016). Moreover, the taxonomy's dimensions are not perfectly orthogonal, i.e., the characteristics of each dimension cannot be arbitrarily combined with characteristics of any other dimension (Püschel et al. 2016). This implies, that some combinations of characteristics are rather unlikely to happen. That is especially the case, as particular value propositions require the exploitation of specific key capabilities. In section 5, we stated the classification results for a sample of 40 IIoT applications. As this sample has been selected mainly for evaluation purposes, it might be too small to represent the broad range of applications. To ensure representativity, a larger sample of IIoT applications could be classified. Future research should re-evaluate and apply the taxonomy for further validation.

Appendix

Literature Object (Reference)	Key Capability	Value Proposition	Business Process Type	Process Specification	PPM	Process Perspective	Hit Ratio (Object)
Ayvaz and Alpay (2021)	0.67	0.00	1.00	1.00	0.67	0.50	**0.67**
Bag and Wood (2019)	0.50	1.00	1.00	1.00	0.50	1	**0.83**
Civerchia et al. (2017)	0.00	1.00	1.00	1.00	1.00	0.75	**0.79**
Compare et al. (2020)	0.75	1.00	1.00	1.00	1.00	0.75	**0.92**
Dhungana et al. (2021)	0.86	1.00	1.00	1.00	0.67	0.40	**0.82**
Garrido-Hidalgo et al. (2019)	1.00	0.00	1.00	0.50	1.00	0.75	**0.71**
Gnoni et al. (2020)	0.76	1.00	1.00	0.50	0.67	1.00	**0.82**
Guerra-Zubiaga et al. (2021)	1.00	1.00	1.00	1.00	0.75	1.00	**0.96**
Guo (2021)	1.00	1.00	1.00	1.00	0.50	1.00	**0.92**
Hofmann and Rüsch (2017)	0.67	1.00	1.00	1.00	1.00	0.50	**0.86**
Jose (2018)	0.75	1.00	1.00	1.00	1.00	1.00	**0.96**
Kessler et al. (2019)	1.00	1.00	1.00	1.00	1.00	0.67	**0.95**
Kumar et al. (2018)	0.75	0.00	1.00	1.00	1.00	0.50	**0.71**
Lee et al. (2017)	0.50	1.00	1.00	1.00	0.75	1.00	**0.88**
Leng et al. (2021)	1.00	1.00	0.00	0.50	1.00	0.67	**0.70**
Liu et al. (2018)	0.67	0.00	1.00	1.00	0.75	0.75	**0.70**
Liu et al. (2019)	0.50	1.00	0.00	1.00	0.00	1.00	**0.58**
Mohsin and Yellampalli (2017)	0.00	1.00	1.00	1.00	1.00	0.40	**0.73**
Moradi (2021)	1.00	1.00	0.00	1.00	1.00	0.33	**0.72**
Nyato et al. (2016)	0.67	1.00	1.00	1.00	1.00	1.00	**0.95**
Ploder et al. (2021)	0.80	0.00	1.00	1.00	0.33	1.00	**0.69**
Rasmussen and Beliatis (2019)	0.86	1.00	1.00	0.50	0.67	0.50	**0.75**
Reljić et al. (2021)	1.00	1.00	1.00	1.00	1.00	1.00	**1.00**
Sasiain et al. (2020)	1.00	1.00	1.00	0.50	0.50	1.00	**0.83**
Schneider et al. (2019)	0.75	0.00	1.00	1.00	1.00	0.00	**0.63**
Schönig et al. (2018)	0.80	1.00	0.00	1.00	0.50	1.00	**0.72**
Taylor et al. (2018)	0.75	1.00	1.00	1.00	1.00	1.00	**0.96**
Ursu et al. (2020)	0.80	1.00	1.00	1.00	0.50	1.00	**0.88**
Yerra and Pilla (2017)	0.75	1.00	1.00	1.00	1.00	0.00	**0.79**
Zhu (2021)	0.86	1.00	0.00	1.00	1.00	1.00	**0.81**
Real-life Object from the Linde plc							
Authorization Check	0.75	1.00	1.00	1.00	0.75	1.00	**0.92**
Deviation Detection	1.00	1.00	0.00	1.00	1.00	1.00	**0.83**
Location-based Safety Check	0.67	1.00	1.00	1.00	0.33	0.50	**0.75**
Manufacturing Process Guidance	0.67	1.00	1.00	0.50	1.00	1.00	**0.86**
Predictive Maintenance	0.50	1.00	1.00	1.00	1.00	0.50	**0.83**
Pressure Monitoring	1.00	1.00	1.00	0.50	0.75	0.75	**0.83**
Process Data Visualization	0.67	0.00	1.00	1.00	1.00	1.00	**0.78**
Remote Maintenance Support	0.67	1.00	1.00	1.00	1.00	1.00	**0.96**
Visual Customer Guidance	0.75	1.00	1.00	1.00	0.75	0.50	**0.83**
Warehouse Tracking	0.67	1.00	1.00	1.00	1.00	1.00	**0.95**
Hit Ratio (Dimension)	**0.75**	**0.83**	**0.85**	**0.91**	**0.81**	**0.77**	

Table 4. Hit ratios of classification results.

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2 P2: Digital Transformation and Improvement of Business Processes with Internet of Things: A Maturity Model for Assessing Readiness

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Digital Transformation and Improvement of Business Processes with Internet of Things: A Maturity Model for Assessing Readiness

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Abstract

Companies of all industrial sectors are increasingly integrating Internet of Things (IoT) technology into their processes to realize a data-driven transformation of their businesses. The generation and use of comprehensive process data in real-time and the connection of process entities enables an improvement and beneficial redesign of business processes of all kinds. However, a goal-oriented exploitation of IoT technology for digital transformation and Business Process Improvements (BPI) is challenging due to the complexity of integrating IoT into existing processes. Companies require appropriate guidance to evaluate and scope their initiatives regarding IoT-based BPI. We therefore propose a holistic IoT-based BPI Maturity Model that assists organizations to determine their current state and get assistance to optimize or develop specific capabilities. This paper provides an overview about the structured development process of the maturity model comprising an extensive literature review and a six-round Delphi study.

1. Introduction

The Internet of Things (IoT) constitutes a technological revolution that has a disruptive impact on a wide range of social, technological, and economic areas. For industrial companies, IoT can be seen as both a digital innovation opportunity as well as a digital transformation opportunity [1]. In this context, digital transformation is characterized by enabling connectivity, collecting data, and therefore using digital technology to redefine a value proposition and to change the identity of the organization [2]. As IoT offers the capabilities to enhance connectivity and collect data, it is a main technology to enable digital transformation [3]. One major lever to transform the organization is IoT-based Business Process Improvement (BPI) which changes the way, companies are doing their businesses [4]. However, a structured and goal-oriented integration of IoT technology to achieve BPI constitutes a major challenge for companies. Most companies already have mature and complex process landscapes, IT system architectures, organizational structures, and corporate cultures that often prevent an easy implementation of disruptive technologies, such as IoT [5]. In addition, organizations are often unable to determine the status quo of their fitness regarding IoT-based BPI [6] and therefore are incapable in developing a substantive action plan for performing IoT projects [7]. Furthermore, the design of strategic roadmaps to enhance the competitive position requires a continuous analysis of the status quo [8]. Maturity Models (MM) have proven to be a useful management tool to guide organizations in the identification, prioritization, and development of relevant capabilities [9]. Especially in the area of Industry 4.0 and IoT, MMs have been recognized as a topic of great interest with increasing numbers of approaches from academia and industry [10]. However, with a share of only 6%, a very limited number of IoT-related MM publications also incorporates the topic of business processes into their model design [11]. Moreover, the aspect of designing a MM to evaluate the capabilities to effectively exploit IoT for digital transformation and BPI has not been considered at all. The paper at hand therefore aims at filling this research gap by addressing the following research questions:

- **RQ1:** How can industrial organizations assess their readiness to effectively exploit IoT technologies for the digital transformation and improvement of their business processes?
- **RQ 2:** How can industrial organizations prioritize actions to develop and improve capabilities relevant for the digital transformation and improvement of their processes by exploiting IoT technologies?

To address these research questions, we developed a prescriptive MM for assessing readiness to effectively exploit IoT technology for BPI, in the further course the "IoT-based BPI MM". The IoT-based BPI MM includes 21 capability dimensions representing action fields for organizations. For each of these capability dimensions, we formulated individual capabilities arranged in four capability levels. Furthermore, we formulated five maturity levels that represent the overall assessment of the organization regarding their fitness to effectively exploit IoT for BPI. In our approach, each maturity level

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is aligned to a set of capability levels that need to be achieved. A translation metric indicates, which capability levels are relevant to accomplish a specific maturity level. To obtain a rigorous and evaluated MM, it has been developed according to the proved design framework of Becker et al. [8].

The remainder of this article is structured as follows. Section 2 presents the theoretical background of the research area including related work. In section 3, the underlying research methodology and the deployed development process are described in detail. The development of the initial MM is outlined in section 4, while the refinement including an extensive Delphi study is presented in section 5. A summary of the main contributions, existing limitations, and future research topics are depicted in section 6.

2. Theoretical Background

2.1. Internet of Things meets Business Process Improvement

The term IoT can be outlined as a network that connects uniquely identifiable things to the internet. Through the exploitation of unique identification and sensing, information about the thing can be collected and the state can be changed from anywhere, anytime, by anything [12]. Hereof the term *thing* describes the creation of a ubiquitous presence of objects of all kinds, equipped with sensors and actuators. Further, the term *internet* refers to the ability of the things to build a network of interconnected objects based on designated network technologies. Beyond, the IoT paradigm incorporates a *semantic* view that refers to the ability of uniquely identifying things and storing, processing, and exchanging data [13]. The transformation of analog information into digital data, which can be processed worldwide in real-time, can have major impacts on business models and processes [14]. This impact is highly relevant for enterprises following a business-oriented view of their organization and all including operations. By implementing IoT technology, enterprises can digitally transform and therefore improve their business processes. This is highly relevant, as redesigning and therefore improving business processes has been one of the most relevant topics in both research and business environment and is considered as one of "*the most important and common titles in both literature and applications*" [15]. To effectively integrate IoT applications into business processes and therefore realize beneficial BPI, specific capabilities are required within adopting organizations.

2.2. Capabilities and Maturity Models

According to Barney's [16] resourced-based view, organizations can be comprehended as configurations of different resources. Therefore, competitive advantage and long-term performance enhancement is accomplished by providing valuable, unique, inimitable, and non-substitute resources that consist of assets and capabilities [17, 18]. While assets can be seen as resource endowments the organization has accumulated, capabilities enable these assets to be deployed advantageously [19]. Capabilities cannot be given a monetary value and are so deeply embedded in the organizational routines and practices that they cannot be traded or imitated [20]. In this paper, capabilities will be defined as complex bundles of skills, accumulated knowledge, and systems exercised through organizational processes, that enable firms to coordinate activities and make use of their assets [20]. They enable the organization to perform certain activities to achieve a particular outcome [21]. It is therefore highly relevant for organizations to have an objective view on capabilities and to assess their current state. In that respect MMs have extensively been used to *i)* assess the capabilities of an organization with regards to a certain discipline, *ii)* provide a base for benchmarking with competitors, and *iii)* guide an organization into acquiring the needed capabilities to improve that discipline [22]. Depending on which of the goals to focus on, there are three types of models that have been widely utilized as a management tool. Descriptive MMs assessing the status quo, comparative MMs providing benchmarking, and prescriptive MMs enabling the development of roadmaps for improving the maturity level [9]. MMs are often represented as matrices with distinct maturity levels on the one axis and capability dimensions on the other one [23].

One of the first MMs was the Capability Maturity Model (CMM) that has been designed for assessing the maturity of software development processes [24]. It has been adopted for many other disciplines leading to a widespread of distinct MMs suffering from overlaps, contradictions, and lack of standardization. To create a standardized framework model that can be used by organizations regarding enterprise-wide process improvement, the Capability Maturity Model Integration (CMMI) project was initiated [25]. Based on the CMMI, many further MMs have been developed for a variety of different research areas.

2.3. Related Work

To the best of the authors' knowledge, there has not been any MM research that focuses on the organizations' capability maturity for effectively exploiting IoT for goal-oriented BPI. However, several MMs have been developed to assist organizations in understanding their maturity level regarding IoT, Industry 4.0, or BPM topics.

For example, Jæger and Halse [26] proposed an IoT maturity scorecard that can assist companies in the manufacturing industry in adopting IoT technologies. Similarly, Tan et al. [27] developed a MM with a special focus on the manufacturing shop-floor environment. Further, Serral et al. [22] concentrated on the retail industry and provided a MM to assess the as-is situation and give advice on future actions for a successful IoT adoption. Other MMs even applied a broader technological view and incorporated other technologies regarding Industry 4.0 [28]. Klötzer and Pflaum [29] developed a MM concerning the digital transformation of companies within the manufacturing industry's supply chain. Moreover, some publications do not specially focus on industrial branches but on the maturity of organizational disciplines regarding IoT or Industry 4.0, such as the IT system landscape [30]. Regarding BPM and BPI, the topic's second focus, there has already been prior MM research. Rosemann and De Bruin developed a BPM MM which facilitates the assessment of basic BPM capabilities [31]. Furthermore, Tarhan et al. provided a wide overview of existing MMs that are addressing general BPM capabilities [32]. In addition, Koetter et al. developed a MM for business process optimization [33].

With considering capabilities for effectively exploiting IoT for digital transformation of business processes and goal-oriented BPI, the work at hand addresses a new scope.

3. Methodology and Development Process

Most of the MM that have been investigated within this research project have been developed according to the frameworks of either De Bruin et al. [21] or Becker et al. [8]. As De Bruin et al. [21] provided a general framework for MM development, it can be adapted for any MM instance. However, we have chosen the structured procedure of Becker et al. [8] as it provides a more detailed procedure allowing the development of a theoretically sound and rigorously tested MM. The development process consists of eight phases based on design science research principles by Hevner et al. [34]. These eight phases can be arranged in two sections, namely the *Design and Development* section, and the *Transfer and Evaluation* section [18]. The work at hand will focus on the first section, while the second section will be provided in future research by means of an extensive industrial use case. Figure 1 shows the development process including the comprised phases.

Phase 1, *Problem definition*, describes the motivation for developing the MM including existing conditions for its application and the intended benefits. Also, the identification of the problem relevance is clarified in this phase. Within this work, these topics are addressed in section 1, where the motivation and relevance of IoT-based BPI are outlined. Organizations require assistance for assessing their capabilities and guidance for deriving roadmaps to build up or improve capabilities. The formulated RQs summarize the objectives of the model development.

The second **Phase 2**, *Comparison of existing MMs*, substantiates the need for the development of a new MM and therefore reveals an existing research gap. This is described in subsection 2.3.

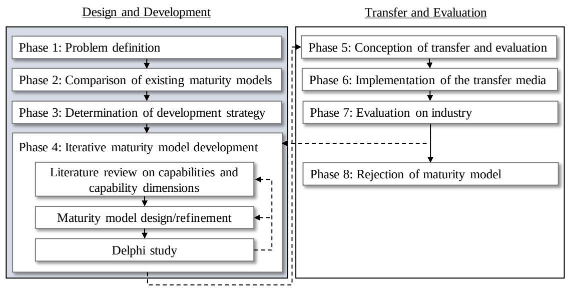

Figure 1. Development Process

Phase 3, *Determination of the development strategy*, defines the basic approach for developing the MM. According to Becker et al. [8], there are four strategies, namely *i)* design of a new model, *ii)* enhancement of an existing model, *iii)* combination of models to form a new one, and *iv)* the transfer of existing models to new application domains. For the work at hand, the strategy of designing a new model has been chosen, as there are no existing MMs that are sufficiently addressing the formulated RQs. Also, this gives the opportunity to flexibly design the MM according to the requirements of the topic. However, also insights and components of already existing models have been used and enhanced.

The fourth **Phase 4**, *Iterative MM development*, depicts the actual model creation steps that lead to the final MM. For the IoT-based BPI MM, this is performed in a multi-methodological approach consisting of two steps. First, an initial MM is created based on the findings of an extensive literature review on existing MMs of both research disciplines IoT and BPM. Subsequently, the initial model is refined by conducting a Delphi study with experts from industry and academia. Both development steps will be presented in sections 4 and 5.

As mentioned, **Phases 5 to 8**, which constitute the *Transfer and Evaluation* of the MM, will not be addressed within this work. These phases will be conducted in future research.

4. Initial Maturity Model Development

4.1. Maturity Model Design

In most cases, MMs are designed as matrices that include capability dimensions on the one axis and maturity levels on the other axis. Within these MMs, to accomplish a specific maturity level, it is necessary to achieve all capabilities that are stated for the respective maturity level. For the MM at hand, however, we use a staged MM design approach. This means that we first arrange the capabilities of all dimensions along four capability levels in the so-called capability matrix. Increasing capability level refers to increasing complexity and relevance of the capability dimension. To accomplish a certain maturity level, an organization must achieve particular capability levels for each capability dimension. This staged MM approach enables a weighting and emphasis of importance for individual capability dimensions. To illustrate which capability levels are required for each maturity level a translation metric is used.

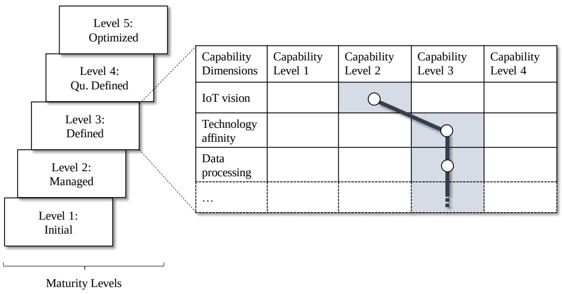

Figure 2. Translation Metric Example

Figure 2 shows the relation between maturity levels on the left, and the capability matrix on the right-hand side. To accomplish, e.g., maturity level 3, an organization must achieve capability level 3 for the capability dimensions *technology affinity*, and *data processing*, while capability level 2 is sufficient for dimensions *IoT vision*. Each capability level then contains individual capabilities for each dimension. We defined five maturity levels *Initial*, *Managed*, *Defined*, *Quantitatively Managed*, and *Optimized* referring to the levels of the CMMI [25]:

- **Maturity Level 1: Initial**
  IoT technology and BPM is hardly existent within the organization. Integration of IoT technology into business processes is not performed.
- **Maturity Level 2: Managed**
  Awareness for the benefits of IoT technology is present. Basic IoT technology is integrated into actively structured and managed processes.
- **Maturity Level 3: Defined**
  Multiple IoT applications are present, and BPM is actively performed. IoT technology is used to support process execution and realize basic BPIs.
- **Maturity Level 4: Quantitatively Managed**
  Strategic planning of IoT projects and well-established integration of IoT technology into business processes. IoT applications enable beneficial BPI.
- **Maturity Level 5: Optimized**
  IoT technology is used to improve and redesign business processes of all kinds. Structured and strategic organization-wide procedures to achieve advanced IoT-based BPI.

4.2. Literature Review

For the creation of an initial IoT-based BPI MM, it is necessary to identify potential capability dimensions and individual capabilities that are appropriate to represent all aspects that organizations need to assess. Therefore, an extensive literature review on existing MMs of both research areas IoT and BPM has been conducted. In addition, publications that illustrate IoT and BPM respectively BPI capabilities have been investigated. As the exploitation of IoT for BPI requires capabilities regarding the management of IoT technology and the organization's BPM, this will give an outlook on all relevant aspects. The literature review has been performed according to the structured procedure proposed by vom Brocke et al. [35].

At first the search strings *("IoT" OR "CPS" OR "BPI" OR "BPM") AND ("maturity model" OR "capability maturity model")* and *("IoT" OR "CPS" OR "BPI" OR "BPM") AND ("capabilit*")* as well as the written-out forms have been formulated. The abbreviation CPS (Cyber-Physical Systems) is also incorporated, as it is often used as a synonym for IoT. To consider preferably all relevant journals and conference proceedings of the research area, ACM Direct Library, AISeL, IEEE Xplore, ScienceDirect, Scopus, and Springer Link have been queried.

For the title, abstract, and keyword queries with the first search string, 16 papers related to IoT MMs and 18 papers related to BPI or BPM MMs have been found after removing duplicates. While analyzing the publications, 272 capabilities have been identified that were coded and clustered in 26 capability dimensions. A query with the second search string added 19 papers regarding IoT capabilities and 27 papers regarding BPI or BPM capabilities. Another 89 further capabilities could be worked out and were clustered in 11 supplementary capability dimensions. In total, 361 capabilities were derived from the literature review, clustered in 37 capability dimensions. After discarding redundancies and summarizing similar ones, 25 capability dimensions were finally derived that comprise 100 capabilities in four different capability levels. The formulated capability dimensions are now briefly outlined in the following subsection.

4.3. Capability Dimensions of the Initial MM

The organization's strategy and the management's commitment towards IoT technology are important factors for an effective selection and execution of IoT projects. Structured decision making is a key factor to evaluate project options and to decide on the most beneficial ones. Also, the organization's openness for changing existing processes is highly relevant. Therefore, the capability dimensions *IoT vision & roadmap*, *structured decision making* [36], *management support*, and *willingness to adapt business processes* are considered for the initial MM [6].

The prevailing organizational culture and ethics are enormously relevant when it comes to introducing new technologies such as IoT [18]. Especially the organization's attitude towards change of any kind is a crucial factor as IoT projects might suffer from negative reservations. Furthermore, the existence of methods and capabilities regarding business improvement plays a major role. As most IoT projects are carried out by interdisciplinary teams consisting of different groups of experts, a collaboration must be performed. These topics comprise the capability dimensions *degree of technology affinity*, the existence of a *continuous improvement culture* [6], as well as an *interdisciplinary and interdepartmental collaboration* [37].

The complexity, maturity, and value propositions of IoT applications highly depend on the skills and competences of the responsible personnel. If knowledge about IoT technology is not present within an organization, only basic technologies with limited benefits can be implemented. Also, the transformation and improvement of existing business processes requires skilled experts. These skills and the accumulated knowledge must be managed, maintained, and distributed within the organization. Therefore, the capability dimensions *knowledge management*, *IoT competences along employees*, *dedicated teams for IoT*, and *dedicated teams for BPM* are introduced [22].

Further, the technical infrastructure represents an important area that includes several capabilities regarding the organizations' ability to transmit and process data. The capability dimensions *networking technologies* and *enterprise software systems* depict a highly relevant aspect regarding the integration of IoT technology into business processes [38].

IoT devices are generating massive amounts of event data that can be used within business processes. To do so, a mature data management is required comprising *data analytics & interpretation*, *data integration* and *privacy* capability dimensions [39].

As the redesign, transformation, and improvement of business processes are topics of BPM research, the organization's *alignment towards business process orientation* as well as the implemented *methods of managing business processes* is highly important [40]. Further, the definition and *usage of metrics to track process performance* and the existence of *proper process documentation* are necessary to realize effective BPI [38]. These capability dimensions are crucial to outline specific BPM-related capabilities.

Another focus area for capability dimensions is the characterization of present IoT applications itself. It describes the maturity of the implemented IoT applications and the technological characteristics. First, the adopted *IoT architecture* is highly relevant as it describes the capabilities of the IoT application to create value and improve businesses [39]. Moreover, the details of the used IoT technologies and their complexity are important [22]. This is described within the capability dimension *IoT technology*, including the technical details of the solution that are already present within the organization.

Furthermore, the degree to which IoT is integrated in the design, analysis, configuration, improvement, and evaluation of business processes must be assessed [22]. This incorporates the capability dimensions *system integration*, *behavioral and organizational impact*, as well as *functional and operational impact* [39]. System integration refers to organization's capabilities to effectively use IoT technology within executed business processes. This requires the creation of interfaces and the standardization of data formats. Also, IoT applications have an impact on several facets of the process perspectives [41]. The behavioral perspective refers to the process sequences and workflows, whereas the organizational perspective focuses on the selection of personnel that is involved in the process execution and monitoring. The functional perspective includes the concrete process steps, activities, and events which can all be influenced by IoT technologies. Finally, most of the processes, especially in the manufacturing industry, comprise several facilities, machines, tools, software applications or items which can be described as the operational perspective [41].

For all these capability dimensions, we formulated a set of corresponding capabilities, ordered by increased influence on achieving a beneficial topic of IoT-based BPI. This resulted in a capability matrix with 100 capabilities along 25 capability dimensions and four capability levels. Hereof, capability level 1 has the lowest positive influence on IoT-based BPI, while level 4 has the highest. Due to the limited scope, a detailed description of the capabilities has been omitted. However, the final MM including all details is illustrated in section 6.

5. Maturity Model Refinement

5.1. Delphi Study Setup

To obtain a rigorously developed and evaluated MM, we performed a structured six-round Delphi study to refine the initial MM proposal. A Delphi study is an iterative method to solicit information about a specific topic through the completion of a number of surveys [42]. It has been widely used to combine expert knowledge and find group consent for complex issues that lack empirical evidence [42]. Research experiences revealed that Delphi studies generally result in a higher quantity and quality of idea and knowledge contribution than other group-decision methods [43]. Further, Delphi studies are highly present in information systems research and especially in the research of MMs [42]. The general study process includes the selection of experts with different backgrounds to minimize bias. The experts do not get introduced to each other, which leads to more creative outcomes and reduces conflicts within the group as well as group pressure [43]. The experts are asked to rate, indicate, or validate specific topics in several rounds. After each round, the results of all participants are consolidated and used for model refinement. By iteratively adjusting the model, eventually a final consent can be achieved. According to existing publications about Delphi studies, 10-18 participants represent an appropriate number [42].

Table 1. Expert Panel Description

Expert panel characteristic	Number of experts
Affiliation	
Industry	10
Academia	5
Nationality	
Germany	7
Sweden	2
Netherlands	1
USA	3
China	2
Years of experience	
<5 years	2
5-14 years	3
≥15 years	10
Expertise	
Internet of Things	9
Business Process Management	8
Maturity Models	5
IT Project Management	5

By forming an expert panel of 15 persons, we conform with recommendations. Within the panel, 10 experts are selected from organizations ranging from medium-sized companies to multinational corporations in the chemical and manufacturing industry (see Table 1). The remaining 5 experts are academical researchers in the fields of IoT and BPM. To minimize regional influences, we selected experts from Germany, Sweden, Netherlands, USA, and China. As technological knowledge may differ between persons who have rather recently graduated from educational establishments and persons with many years of experience, we selected experts with different years of working experiences. Eventually, 2 experts have less than 5 years' experience, 3 experts have working experience between 5 and 14 years, while 10 experts have experiences of 15 years or more. Finally, as the survey topic includes several research areas, we included persons with expertise in IoT, BPM, MMs, and IT project management. All experts have at least a bachelor's degree while including 6 female and 9 male persons. Having selected the expert panel, the actual survey has been conducted in six rounds. Figure 3 shows the applied Delphi process including the tasks and information flows between both parties, the research team or *facilitator* and the e*xpert panel*. The capability dimensions and capabilities from section 4.3. served as an input for the study.

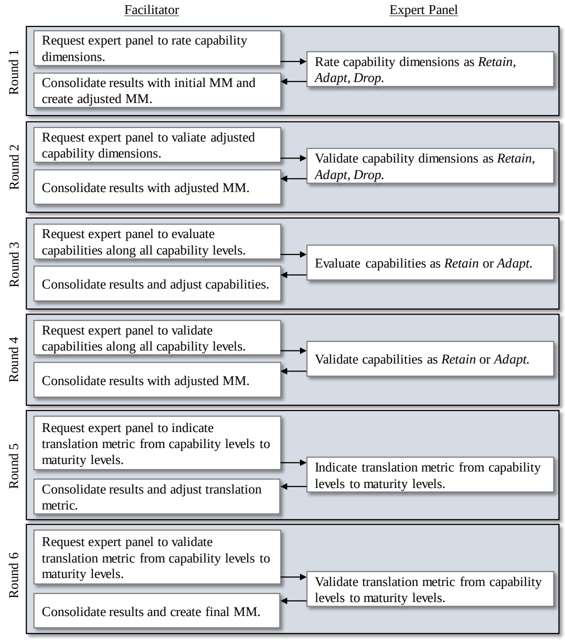

Figure 3. Delphi Study Process

In **Round 1**, the expert panel was requested to rate the formulated capability dimensions as *Retain*, *Adapt*, or *Drop*. In addition, the experts could also suggest new capability dimensions. The results of round 1 were analyzed and consolidated by using a systematic decision tree (see Figure 4), that has already been proven in prior Delphi studies [22]. A capability dimension was only dropped, if more than 60% of the experts agreed on this option. No adaptions were considered, if the percentage to retain was at least 80%, while minor adaptions were performed for a retain rate between 60% and 80%. Major adaptions were needed if the retain rate was below 40% or at least 50% of the experts agreed on the option to adapt a specific capability dimension. The last possible outcome was when the percentage to retain was at least 40% and the percentage to adapt was at least 50% at the same time indicating that there has been a lack of unity in opinion. In **Round 2**, the experts were requested to validate the adjusted capability dimensions, again by using the options *Retain*, *Adapt*, or *Drop*. This was followed by another consolidation phase. In **Round 3**, the expert panel was requested to evaluate the capabilities along the four capability levels with *Retain* or *Adapt*.

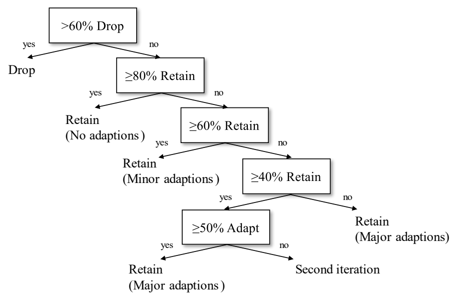

Figure 4. Decision Tree

For a retain rate of at least 80%, no adaptions were considered. Elsewise, for a retain rate between 60% and 80% minor changes were performed, while major adaptions were necessary for a retain rate below 60%. In **Round 4**, the consolidated capabilities were validated by using the same logic. As with rounds 1 to 4 the capability dimensions, and the respective capabilities have been evaluated, **Round 5 and 6** were about creating the translation metric. The expert panel was requested to indicate the translation metric from capability levels to maturity levels. For each of the five maturity levels, the experts needed to indicate the required capability level of every capability dimension. For all six rounds, the participants could add additional comments regarding their indications. The facilitators then consolidated all results by choosing the most frequently selected value for each capability dimension and maturity level. If two or more values were chosen equally often, the median of all values was selected as it considers the trend within all indications. The created translation metric was then validated in **Round 6**, concluding in a final consolidation. After the final round, a discussion with all experts individually helped to get feedback and gain insight into the motivations and background of the individual decisions.

5.2. Delphi Study Results

In **Round 1 and 2**, the expert panel rated all capability dimensions. The results of both individual rounds have been consolidated by using the systematic decision tree (see Figure 4). In total, 13 capability dimensions were retained without changes. Further, 5 capability dimensions were considered for minor changes while 2 capability dimensions were majorly adapted. From the initial set of 25 dimensions, 5 were dropped completely, whereas 1 capability dimension could be added. For the final set of capability dimensions, the individual capabilities have been formulated. In **Round 3 and 4**, the expert panel evaluated the capabilities as *Retain* or *Adapt*. Based on the results of both rounds, 29 capabilities were considered for minor changes, 14 for major changes, while 41 were not changed at all. As after rounds 1 to 4, the main structure of the MM has been evaluated, in **Round 5 and 6**, the translation metric from capability levels to maturity levels was created. Therefore, the expert panel indicated the required capability level of each capability dimension for achieving a specific maturity level. For maturity levels 1 and 2, there has been a broad conformity along the expert panel. However, for maturity levels 3 and 4, as the indications have not been unambiguous resulting in using the median. Especially, the capability dimensions *continuous improvement culture*, *knowledge management*, and *alignment & methods* showed a wide distribution of indicated values. This shows the disagreement of the expert panel and the associated uncertainty regarding the relevance of these dimensions. In general, academic experts tended to emphasize the importance of technical dimensions related to the infrastructure or data processing capabilities of organizations. On the other hand, industrial experts underlined the importance of dimensions regarding the organizations' culture, ethics, employee competences, and strategical leadership. Any other tendencies regarding the results and the expert background could not be recognized. In general, the Delphi study helped to effectively refine the initial MM.

6. Final IoT-based BPI MM

The final IoT-based BPI MM consists of three main components, the capability matrix (see Figure 2), the translation metric (see Table 3), and the maturity level description illustrated in section 4.1. The final capability matrix consists of 21 capability dimensions clustered in

7 focus areas for improved structure. The translation metric determines, which capabilities, are required for each dimension to accomplish a specific maturity level.

Table 2. Capability Matrix

		Capability Levels			
Focus Area	**Capability Dimension**	**Level 1**	**Level 2**	**Level 3**	**Level 4**
Strategy & Leadership	IoT vision	Management has closed attitude towards IoT.	Management understands IoT and its value propositions.	Management is setting up a detailed IoT vision and roadmap.	Management sees IoT as a crucial technology to gain competitive advantage.
	Decision making	No decision making about selecting IoT technology.	Selection based on best-practices.	Selection based on external and internal expert consulting.	Quantitative and qualitative methods and assessments.
Culture, Ethics & Behavior	Technology affinity	Reservations or rejection of new technologies.	Open to learn about new technologies and its potentials.	Active searching and learning about new technologies.	Eager for life-long-learning about new technologies.
	Continuous improvement culture	No intrinsic motivation for improvements.	Basic incentive systems to uncover improvement potentials.	Adaption of further methods, e.g. PDCA, Kaizen, or Six Sigma.	A fundamental continual improvement process is implemented.
	Interdisciplinary, interdepartmental collaboration	No explicit collaboration between different departments.	Communication, coordination, and awareness are present, but treated opportunistically.	Decentralized coordination and shared knowledge, mainly through group artifacts.	Tacit knowledge is shared through ideas, opinions, and experiences.
People, Skills & Competences	Knowledge management	Knowledge is created via training. No formal knowledge management practices are present.	Knowledge-sharing activities are actively encouraged while the benefits are observed and monitored.	Enterprise-wide knowledge management system has been established and knowledge is reused at project levels.	Knowledge sharing becomes an organizational culture and knowledge is a critical asset.
	IoT competences along employees	No experiences with IoT technologies.	Initial experience with IoT based on past and isolated current projects.	Internal and external IoT experiences and knowledge exchange with experts.	Employees are experienced in IoT through targeted trainings.
	Dedicated teams for IoT	No internal structures or specialist departments.	IoT projects are carried out by employees who have been trained.	Design, planning, implementation, and maintenance is handled by dedicated teams.	IoT core competence centers exist that are designed for the corresponding company hierarchies and divisions.
	Dedicated teams for BPM	No internal structures or specialist departments.	Specific contacts for the planning and optimization of business processes.	BPM is performed by specialized personnel structured in teams.	Distributed process managers and a central process management is operated.
Infrastructure and Data	Enterprise software systems	Simple control system architectures (PLCs, SCADA) enabling networked data communication.	ERP systems are responsible for integrated management of main business processes.	Systems, such as MES and BPMS for sharing information and obtaining real-time feedback from functional areas.	Systems including interfaces to each other that provide automated decision-making and data management.
	Networking	Basic wired (LAN) and wireless (Wi-Fi) networking technologies covering most of the enterprise facilities.	Basic and more advanced technologies such as 2G/3G/4G and Bluetooth and covering all enterprise facilities.	Basic and more advanced technologies such as low-energy PAN communication protocols, e.g. ZigBee, BLE or LoRa, are existing.	Enhanced mobile broadband, massive machine communications, and ultra-reliable low-latency communications are existing.
	Data processing	Data can be stored, and simple processing is performed.	IoT is capable of aggregating data into simple context data.	Aggregation of data into complex context data. Techniques for ensuring data quality are applied.	High-frequency event data from heterogenous sources can be processed. Complex event processing is applied.
	Data analytics & interpretation	Data analytics is sparsely implemented.	Basic analysis of IoT data is conducted. IoT data analytics is still mainly ad hoc.	Analyses based on calculations and co-relations. Patterns based on rules.	Predictive analytics is performed using IoT data.
Business Process Management	Alignment & methods	Jobs and organizational structures include a process aspect but remain basically traditional.	Broad process jobs and structures are put in place outside of traditional functions.	Process measures and BPM are deeply embedded in the organization.	Advanced process practices that allow transfer of responsibilities without legal ownership.
	Process performance controlling	Absence of defined metrics.	Basic cost and quality metrics.	Metrics have been derived from the enterprise's strategic goals including time, cost, quality, and flexibility.	Managers review and refresh the process metrics and targets and use them in strategic planning.
	Process documentation	Processes are not structured and lack clear definitions.	Documentation is primarily functional, but it identifies the interconnections among process entities.	Description of interfaces with other processes and enterprise systems as well as the data architecture.	An electronic representation of the process design supports process reconfigurations.
IoT Application Maturity	IoT architecture	If any, the organization adopts a basic IoT layer architecture.	Middleware layer that enables interoperability and device technology independence.	Management of scalability and interoperability.	IoT architecture is prepared to be reused in different applications within the company.
	IoT technology	Possibly some use of RFID or sensors, but with limited functionality.	IoT technologies using existing wired and wireless networking. Cloud computing for vertical communication.	Assets and products communicate horizontally and directly within a closed environment.	The volume of generated data and the processes that are involved in the handling of data become critical and important to manage.
IoT Integration into Business Processes	System integration	If any, monitoring and visualization purposes are in focus.	IoT supports some repeatable tasks within certain business processes.	IoT is used for process control using high-frequency event data.	IoT is successfully integrated within each phase in the management of processes.
	Behavioral and organizational impact	IoT has no impact on the behavioral and organizational perspectives.	IoT data is used to ensure correct process sequences by, e.g., detecting process task deviations.	IoT applications are able to distribute process tasks along process entities.	The IoT system is responsible to effectively allocate process tasks, manage process entity interactions, and guarantee efficient process workflows.
	Functional and operational impact	IoT is not influencing the actual process activities and its execution.	Process activities are changed and improved by implementing IoT technology.	Process task execution is directly influenced by providing user interfaces.	Process activities and interactions with process entities are redesigned by integrating IoT.

Table 3. Translation Metric

Capability Dimension	Required Capability Levels for Maturity Level				
	1	**2**	**3**	**4**	**5**
IoT vision	1	2	2	3	4
Decision making	1	2	3	3	4
Technology affinity	1	2	3	4	4
Continuous improvement culture	1	2	3	4	4
Interdisciplinary, interdepartmental collaboration	1	1	2	3	4
Knowledge management	1	1	2	3	4
IoT competences along employees	1	2	3	4	4
Dedicated teams for IoT	1	2	3	4	4
Dedicated teams for BPM	1	1	2	3	4
Enterprise software systems	1	2	3	3	4
Networking	1	2	3	3	4
Data processing	1	2	3	4	4
Data analytics & interpretation	1	2	3	4	4
Alignment & methods	1	2	3	3	4
Process performance controlling	1	2	3	3	4
Process documentation	1	2	3	4	4
IoT architecture	1	1	2	3	4
IoT technology	1	2	2	3	4
System integration	1	2	2	3	4
Behavioral and organizational impact	1	2	3	3	4
Functional and operational impact	1	2	3	3	4

For example, to achieve maturity level 2, amongst others, the capability dimension *IoT vision* requires capability level 2. Within the capability matrix of Table 2, the information about this specific capability level can be found. As the capability matrix comprises all relevant capabilities, the MM follows a prescriptive approach, which allows the derivation of roadmaps and agendas.

7. Discussion and Conclusion

As the integration of IoT technology into existing business processes constitutes a major challenge for organizations, the proposed MM may be used to determine the status quo regarding necessary capabilities. Industrial organizations can therefore assess their readiness to effectively exploit IoT value propositions. Considering the lack of existing MMs, this paper contributes to the resolution of existing research gaps and tackles the formulated RQs. The MM has been developed according to the framework of Becker et al. [8] which enables a rigorously designed and evaluated model. At first an initial MM has been created based on an extensive literature review on existing MMs of both areas IoT and BPM respectively BPI. The findings were used to identify relevant capabilities and capability dimensions. The initial MM consisted of 100 capabilities aligned to 25 capability dimensions and four capability levels. In addition, five maturity levels have been formulated. To refine the initial MM, a six-round Delphi study has been performed with an expert panel consisting of 15 persons from industry and academia. The final MM is composed of 21 capability dimensions including 84 capabilities along four capability levels.

Due to the nature of the applied methodology, this contribution is not without limitations. Although the literature review has been rigorously performed, the incorporated literature does not represent all existing work of that research area. Moreover, the selection of appropriate capabilities and dimensions can only cover a limited amount of all existing possibilities. Further, the success of a Delphi study highly relies on the expertise of the respondents [42]. Whilst we tried to arrange an appropriate expert panel, the selection of different experts may have led to different results. Furthermore, the technological capabilities of Table 2 could change over time as technology progresses. Therefore, the MM itself needs to be adapted periodically. Finally, the MM has not received practical assessment and therefore a final evaluation. Therefore, steps 5 to 8 of the framework will be addressed within future research.

In conclusion, the IoT-based BPI MM constitutes a valuable tool for organizations to assess their capabilities and create concrete plans for actions. Future research should focus on methods and frameworks to keep the MM assessment updated within organizations. This is highly relevant, as internal capabilities may change over time.

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3 P3: Keeping Your Maturity Assessment Alive - A Method for Capability Tracking and Continuous Maturity Assessment

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RESEARCH PAPER

Keeping Your Maturity Assessment Alive

A Method for the Continuous Tracking and Assessment of Organizational Capabilities and Maturity

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Abstract Maturity models are valuable management tools for assessing and managing capabilities and therefore creating a basis for their identification, prioritization, and further development. Numerous maturity assessment methods have been developed to support organizations in applying maturity models. However, these methods are mostly used for unique assessments and only provide a snapshot of the current state of capabilities and their maturity. Certainly, this does not reflect the continuous change of capabilities within dynamic organizational environments. Moreover, the systematic selection of suitable maturity models and the identification of the actions that should be targeted following the maturity assessment require more attention. To fill these research gaps, this study proposes the generally applicable Continuous Maturity Assessment Method (CMAM) that enables comprehensive and continuous maturity assessments. The CMAM comprises five steps that extend and advance existing principles of maturity assessment and can be implemented as an organizational routine. The rigorous development of the CMAM followed basic principles of the design science research methodology, including an evaluation of six organizations in different industry sectors and an extensive industrial case study.

Keywords Maturity model · Capabilities · Continuous maturity assessment · Maturity appraisal

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1 Introduction

Organizations face dynamic and rapidly changing environments that make the attainment of long-term economic success exceedingly difficult. The pressure to gain and retain a competitive advantage forces organizations to continuously identify means of cutting costs, improving quality, and reducing time to market (de Bruin et al. 2005). According to the resource-based view of organizations (Barney 1991), a competitive advantage can be secured by developing or acquiring valuable, unique, inimitable, and non-substitute resources that consist of assets and capabilities (Wade and Hulland 2004). While assets can be seen as the resource endowments of the organization, capabilities enable these assets to be deployed advantageously (Vorhies et al. 1999). For this reason, it is important for organizations to know their capabilities in depth. Maturity models have proven to be valuable tools that assist organizations in this endeavor (de Bruin et al. 2005). They support organizations in identifying and analyzing their capabilities to assess their overall maturity in specific domains. Maturity models are often applied enthusiastically because the insights that they can provide are highly valuable. However, after the initial application or, at the latest, when a targeted maturity level has been reached, the

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focus shifts to other organizational issues. This constitutes a problem, as organizations in all sectors are liable to change due to the complex and ever-changing technological, organizational, and economic environments in which they are embedded (Nelson and Winter 2004). Thus, capabilities can never be in a final state, as organizations are forced to adapt to this continuous change (Loasby 1998). This permanent transformation and the fact that maturity develops alongside capabilities, implying evolutionary progress, contradicts the notion of a singular and non-continuous maturity assessment (Mettler 2011). In the long run, the accuracy and relevance of maturity assessments can only be ensured by tracking capabilities and, therefore, by assessing current maturity levels over time. Moreover, most maturity assessment methods are specifically designed for certain maturity models and lack principles and phases that enable a generic application. For this reason, many models are tied to proprietary and limited assessment methods, such as questionnaires, which support their application. These methods may guide users during pure maturity assessment activities but eventually disclose how to effectively perform all relevant maturity model application activities (Mettler and Ballester 2021). Accordingly, there is a need for a generally applicable and continuous maturity assessment method (Englbrecht 2021; Frick et al. 2013; Stoiber and Schönig 2022). We define a *continuous maturity assessment* as an iterative and prolonged determination of the maturity level of an organization in a specific domain. In this context, the term *continuous* refers to a repeated maturity assessment that is conducted over specific intervals and which also considers individual changes in specific capability dimensions. Given these research gaps, we formulated the central research question (RQ) as follows:

> RQ: How can any organization be guided through all phases of a continuous maturity assessment?

To answer the RQ and cover all its aspects adequately, we created the Continuous Maturity Assessment Method (CMAM). It supports organizations during all phases of continuous maturity assessments. The CMAM comprises five phases that can be implemented as an organizational routine covering all activities that are necessarily required to keep maturity assessments alive. We anchored the CMAM in the Design Science Research (DSR) methodology and designed it for practical use at all kinds of organizations. To ensure rigor, we followed the established method of Peffers et al. (2007) and complemented it with the Framework for Evaluation in Design Science Research (FEDS) by Venable et al. (2016). Our contribution is based on the inductive analysis of existing maturity assessment methods and considers best practices while addressing known inadequacies and weaknesses. These findings were used to attain the initially formulated design objectives, which are derived from the main RQ. A summative evaluation, including interviews with six market-leading organizations and an extensive case study provided valuable insights into the applicability of the artifact and its effectiveness.

The remainder of this article is structured as follows: in Sect. 2, we present the theoretical background of the research phenomenon under observation. Subsequently, in Sect. 3, we outline the underlying research methodology that we employed to create the CMAM. The CMAM is presented and explained at length in Sect. 4. In Sect. 5, we outline the results of the summative evaluations, which included a survey and an extensive case study. We discuss our contributions, the implications of the study, and its limitations in Sect. 6 and conclude with a summary of the findings in Sect. 7.

2 Theoretical Background

2.1 Organizational Capabilities, Maturity, and Maturity Models

Organizational capabilities can be defined as organizational entities that represent complex bundles of skills, accumulated knowledge, and systems that manifest in organizational processes (Kwon 2021). When deployed purposefully, capabilities enable organizations to perform certain activities to achieve particular goals and outcomes and serve as the fundamental basis of economic success (Kwon 2021). Maturity models have been used extensively to (i) assess the capabilities of an organization in a certain discipline, (ii) to provide a basis for benchmarking against competitors, and (iii) to guide an organization in the acquisition of the capabilities that it needs to improve in that discipline (Serral et al. 2020). In this context, maturity is a specific process that entails the explicit definition, management, measurement, and control of the evolutionary growth of an entity, such as - in this special case, capabilities (Kerpedzhiev et al. 2021; Paulk et al. 1993). Therefore, maturity implies evolutionary progress from an initial state to a final and more advanced one (Mettler 2011). A maturity model is generally structured as a sequence of distinct levels (Pöppelbuß and Röglinger 2011) that follow a path from an initial state of maturity to a potential final state of maturity (Becker et al. 2009). Those models are usually conceptualized as matrices, with maturity levels on one axis and capabilities on the other, while capabilities are mostly arranged along specific dimensions (Lasrado et al. 2015). Maturity levels are phases of development that are arranged sequentially from the lowest to the highest. Maturity models are particularly important for identifying the strengths and weaknesses of organizations by reference to an underlying phenomenon and for the collection of benchmarking information by the organization (Khoshgoftar and Osman 2009). Maturity models, as diagnostic or benchmarking tools, enable the identification of appropriate actions for creating or improving capabilities and, therefore, for reaching higher maturity levels (Kohlegger et al. 2009).

One of the first models was the Capability Maturity Model (CMM), which was designed to assess the maturity of software development processes (Paulk et al. 1993). Many models that followed the CMM were loosely based on it but lacked a comparable scheme. The capability maturity model integration (CMMI) project was initiated to create a standardized framework model (CMMI Product Team 2010). Although many models followed the basic outlines of CMMI, most of their authors did not disclose their research methods or the underlying design decisions (Mettler 2011).

2.2 Perspectives on Maturity Models

Research on maturity models can be viewed from two perspectives, representing cycles that include specific and sometimes overlapping activities. The developer perspective is directed at providing suitable and rigorously designed models, whereas the user perspective is oriented toward their effective and appropriate application (Mettler 2011; Proença et al. 2020). Both perspectives entail the use of different methods and frameworks for the creation, selection, and application of models. Figure 1 shows the two cycles and the associated generic activities.

2.2.1 *Developer Perspective*

The development of maturity models is highly complex and requires patterns to be recognized, structured, and documented so that the organization may improve its performance logically (Kühn et al. 2013; Röglinger et al. 2012). In the development cycle, the identified need or opportunity to develop a novel maturity model serves as a basis for defining its basic scope. This definition influences all parameters of decisions that are made during the design phase. To improve the model sustainably and iteratively, revision, in the form of evaluation, reflection, and appropriate adaptation, is necessary. These three phases, namely scope definition, design, and revision, have been recognized within maturity model research and are, in fact, essential for the developer perspective. Since many maturity models have been subjected to criticism because they are seen to oversimplify reality and lack an empirical foundation, research has approached the problem from a design process and design product perspective (Marx et al. 2012; Röglinger et al. 2012). In this regard, several procedural models have been developed to support the development of structured maturity models (Becker et al. 2009; de Bruin et al. 2005; Maier et al. 2012; Mettler 2011; Solli-Sæther and Gottschalk 2010; van Steenbergen et al. 2010). For example, de Bruin et al. (2005) investigated several maturity models in different domains and identified six distinct phases that guide the design of descriptive maturity models for prescriptive and comparative use (Röglinger et al. 2012). Another established method was proposed by Becker et al. (2009), who derived a procedure model from the well-known design science guidelines of Hevner et al. (2004). Overall, the developer perspective has a sufficient set of tools at hand to create rigorously developed and applicable maturity models. Especially due to the mentioned methods by de de Bruin et al. (2005) and Becker et al. (2009), the developer perspective has not been considered in depth within the study at hand.

2.2.2 *User Perspective*

As far as the application cycle is concerned, the need or opportunity for applying a maturity model must be

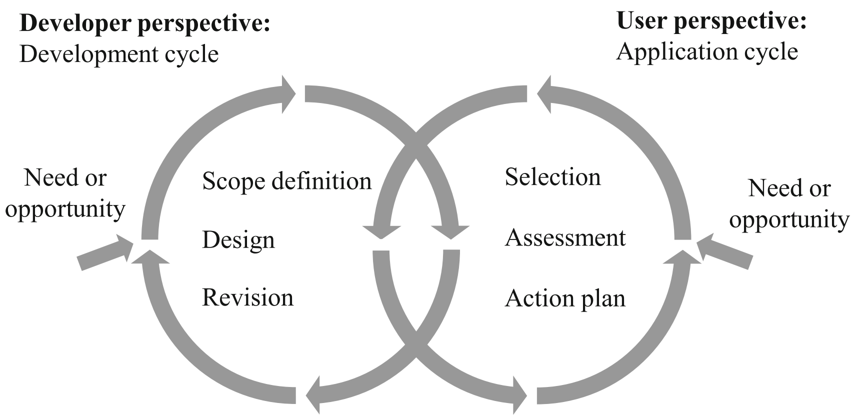

Fig. 1 Perspectives on maturity models according to Mettler (2011)

determined. The intended use of a model may be descriptive, prescriptive, or comparative (de Bruin et al. 2005). This determination is followed by the laborious activity of identifying and selecting a model appropriate for the business. Once a model has been selected, a maturity assessment, in the narrow sense of that term, can be initiated. For most maturity models, a questionnaire supports the analysis of organizational capabilities. The findings of the assessment should then be taken as a basis for actions to improve or create capabilities and to reach a targeted level of maturity. Since the development cycle undoubtedly benefits from the introduction of development methods, potential users are often left to make essential decisions alone during the application cycle. Current assessment methods mainly address actual assessment activities (Mettler 2011). Depending on the internal resources at their disposal, organizations can choose between three approaches, namely self-assessment, third-party assessment, and complete outsourcing (de Bruin et al. 2005). Regardless of the chosen approach, numerous maturity assessment methods (also called "maturity appraisal methods") have been developed. In contrast to the established methods of the developer perspective, no universally accepted maturity assessment method has been presented. Thus, contributions to effectively performing maturity assessments should be in focus within maturity model research.

2.3 Current State of Maturity Assessment Methods

Due to the popularity of maturity models, a potential user is confronted with various heterogenous maturity assessment methods that cover different phases of the application cycle. These include established methods like SCAMPI or ISO/IEC TS 33030, which are the de facto standard for a wide range of models and are updated and refined regularly by their managing organizations. Both methods cover maturity assessment activities and address, among others, the analysis of assessment results. Furthermore, numerous proprietary assessment methods have been developed. Those methods are tailored to particular maturity models and are not applicable generally. The existing maturity assessment methods can be classified along the dimensions of *generality* and *scope*. The term *generality* describes the degree of generic applicability to different maturity models. Methods can be highly specific, with concrete questionnaires, or relatively generic, with structures that are free of specific references to individual models. The *scope* of a method has to do with how the user is supported in all phases of the application cycle. Along both classification dimensions, the methods can be clustered into two disjunct areas (see Fig. 2). Area 1 comprises methods that have been developed for a specific maturity model and cannot be applied easily to others.

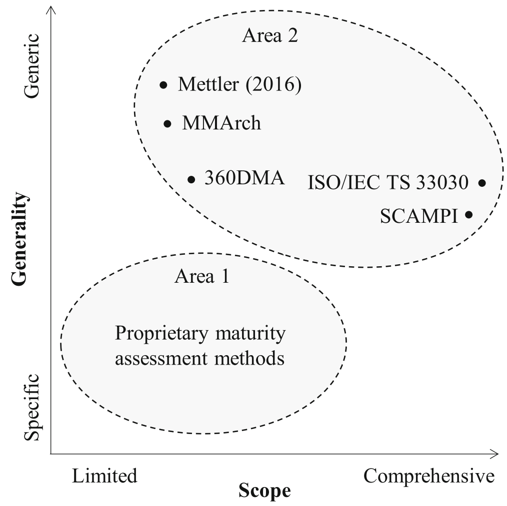

Fig. 2 Classification of existing maturity assessment methods

This area includes limited and highly specific questionnaires that support the user during the collection of evidence and information about capabilities (Akdil et al. 2018; Schumacher et al. 2016) or methods that also describe activities that support the user within subsequent actions (Adyrbai et al. 2021; Rosemann and de Bruin 2005). Area 2 comprises methods that are relatively generic and often more comprehensive. They are designed for well-established maturity model frameworks or sets of related models within a specific domain. The most popular methods of Area 2 are SCAMPI and the ISO/IEC TS 33030. SCAMPI was originally designed for evaluating organizations against the CMMI process model, but the procedure can also be used for a limited number of related process models, such as ISO/IEC 12207 or DIN EN ISO 9001. The ISO/IEC TS 33030 is a revised version of the ISO/IEC 15504, the former Software Process Improvement and Capability Determination (SPICE), which guides users in the assessment of organizational processes and capabilities. Another contribution to Area 2 is a framework defined by Mettler (2011), which describes activities that are relevant for users as well as important decision parameters that they must consider. The 360 Digital Maturity Assessment (360DMA) is a less generic method. It is mainly applied to a range of models for digitalization but also outlines general principles that may fit any maturity model application (Colli et al. 2019). Finally, the Maturity Model Architect (MMArch) by Proença and Borbinha (2018) supports the execution of maturity assessments by using enterprise architecture models, ontologies, and description logics.

2.4 Inadequacies of Existing Maturity Assessment Methods

Despite a large number of existing maturity assessment methods, there are some inadequacies and weaknesses that call for further research. Some of these weaknesses have already been identified in the literature, while others can be isolated by investigating and analyzing the most relevant methods and the activities they include.

2.4.1 Irreconcilability of Generality and Comprehensiveness

The first weakness is the apparent incompatibility of generality and comprehensiveness within established maturity assessment methods that belong to Area 2. In this sense, the proprietary methods from Area 1 are irrelevant because, for the most part, they are neither generic nor particularly comprehensive. Most existing comprehensive assessment methods are tailored to specific maturity models and are therefore not generally applicable (Tarhan et al. 2016). This is true for methods such as SCAMPI or ISO/IEC TS 33030. In this regard, SCAMPI was explicitly developed for CMMI for Development (CMMI-DEV), CMMI for Acquisition (CMMI-ACQ), CMMI for Services (CMMI-SVC), and other CMMI derivatives. The other established method, ISO/IEC TS 33030, is only applicable to SPICE for Software Development (ISO/IEC 15504-5), Automotive SPICE, and SPICE for System Development (ISO/IEC TR 15504-6). Both methods include detailed activities that prevent their application to other models. In principle, there is no generally accepted comprehensive assessment methodology (Frick et al. 2013; Mettler et al. 2010).

At the same time, more generic assessment methods, such as the 360DMA or the framework proposed by Mettler (2011), do not include comprehensive and detailed activities that support users during all assessment phases. They often lack activities that support the collection of capability data and the accurate reporting of assessment results. Moreover, they lack principles that would enable the method to be embedded into an organizational routine and the generated results to be used for action plans. This is important as assessment methodologies should harness the knowledge that is generated from their application (Rosemann and Vessey 2008). In general, there are few rigorous assessment methodologies (Frick et al. 2013) that are both general and comprehensive. A new method must therefore be generically applicable to all maturity models and contain activities and principles that cover all assessment phases.

2.4.2 Lack of Continuity

Existing maturity assessment methods are insufficiently sensitive to the problem of continuity (Proença and Borbinha 2018). Most methods do not require iterative assessments specifically or indicate that such assessments should only be performed over long intervals. SCAMPI assessments, for example, are performed every three years, which is a long period given the rapidly changing business environments (Albuquerque et al. 2019). Moreover, some studies report difficulties with continuous assessments at different organizations (Fontana et al. 2018; Uskarcı and Demirörs 2017). For existing methods, no mechanism is in place for enforcing the general continuity of application (Uskarcı and Demirörs 2017). Existing assessment methods only focus on the collection of evidence to substantiate maturity level calculations without highlighting the importance of a continuous procedure (Proença and Borbinha 2018). However, continuity is critical because capabilities are liable to change, either due to organizational improvements and capability creation or due to deterioration (Loasby 1998). The adoption of a structured and continuous maturity assessment routine is a prerequisite for the effective development and maintenance of knowledge about organizational capabilities. By introducing such routines, maturity models can describe how organizational capabilities develop over time (de Bruin et al. 2005) while evaluating and promoting their continuous improvement (Bititci et al. 2015).

3 Methodology

3.1 General Research Approach

Given the existing inadequacies and weaknesses, we aimed to develop a novel maturity assessment method combining generality, comprehensiveness, and continuity. In line with existing research on maturity models, we positioned our contribution within the DSR paradigm. This decision enabled us to adopt established principles and draw on methodological guidance for the development of the artifact and its evaluation (Peffers et al. 2007). We relied on the well-established process model of Peffers et al. (2007), which is based on the methodology of Hevner et al. (2004) and provides a detailed development process for conducting DSR on information systems. The process model translates the guidelines and DSR principles of Hevner et al. (2004) into an easily applicable process. This translation enables DSR endeavors to proceed in a straightforward manner. Based on the inadequacies and weaknesses of the existing maturity assessment methods, which we described in Sect. 2.4, we defined four distinct objectives.

Subsequently, we executed two development phases that included semi-structured interviews as formative evaluations. These interviews helped us to estimate and evaluate the compliance of the artifact with the design objectives (Stefanou 2001). Once the two development phases had concluded, we conducted two summative evaluations to produce empirically based feedback.

First, the artifact was assessed by practitioners from different domains to elicit interpretations and feedback from different practical contexts (Venable et al. 2016). Second, an extensive case study of a real-world setting was conducted over six months. All evaluations were conducted as part of a comprehensive evaluation strategy in line with the FEDS (Venable et al. 2016). Figure 3 overviews the development and evaluation phases.

3.2 Definition of Design Objectives

Four concrete design objectives could be deduced from the RQ and from the inadequacies and weaknesses of the existing maturity assessment methods that we identified. Those objectives were used for orientation and guidance during the design and development phases. The first design objective (DO1) is that the design and the structure of the artifact must be understandable and easy to apply for practitioners. The second design objective (DO2) reflects the need for principles and activities that enable a continuous maturity assessment. The artifact must refer to activities that entail the tracking of capabilities and thus create a basis for an iterative assessment. The third and fourth design objectives refer directly to the classification of the artifact within the set of existing assessment methods, as described in Sect. 2.3. First, the artifact should be applicable to the largest possible number of maturity models and organizations without having specific links to existing models, that is, it should possess a high degree of generality (DO3). To that end, it is useful to define a generic assessment method that makes use of relevant information when applied at specific organizations. What information is relevant depends on the actual use case. Furthermore, the artifact should provide comprehensive activities that support users during all phases of the maturity assessment (DO4).

3.3 First Development Phase – Structuring What Exists

In the first development phase, we aimed to create an empirical basis, gain insights, and synthesize findings and best practices from past and current research on maturity assessment methods. To identify an appropriate selection of literature, we performed two structured literature reviews (SLR) to investigate both areas that we outlined in Sect. 2.3. These SLRs helped us to create a theoretical foundation for the development of our artifact (Sturm and Sunyaev 2019). The first SLR concerns the methods of Area 1 and thus investigates maturity models that are accompanied by proprietary assessment methods. The second SLR focuses on the assessment methods of Area 2.

We performed both SLRs according to the structured method of vom Brocke et al. (2009) and considered the most relevant journals and conference proceedings in the research domain by querying the databases ACM Direct Library, AISeL, IEEE Xplore, ScienceDirect, Scopus, and Springer Link. A detailed overview of the SLRs, including the search strings, the eligibility criteria, and all analyzed articles can be found in Appendix 1 (available online via http://link.springer.com). During the SLRs, we found 45 eligible articles in Area 1 and eight articles in Area 2, which we analyzed in detail. Subsequently, we extracted the relevant data by using grounded theory, a qualitative research method that seeks to develop a theory that is grounded in data that is systematically gathered and analyzed (Urquhart et al. 2010). We aimed to identify patterns, common attributes and principles, and best practices from

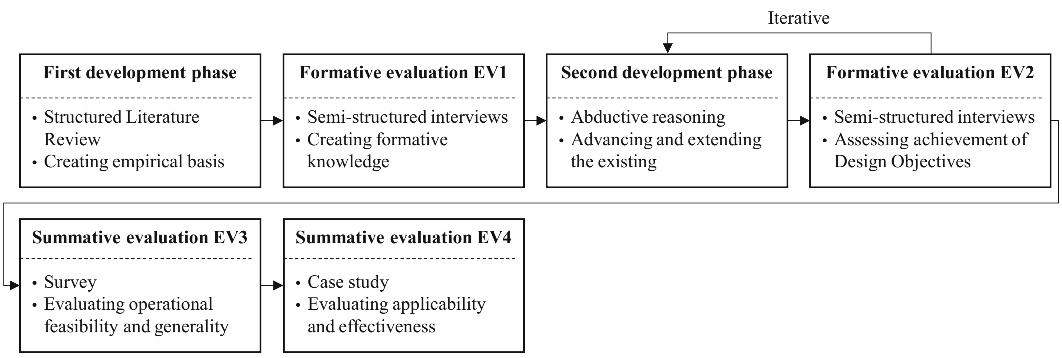

Fig. 3 Development and evaluation phases

existing maturity assessment methods that can be used as a basis for an artifact. Accordingly, we applied the methods of open and axial coding, as proposed by Strauss (1997). In the first round of coding, each of the authors analyzed 20 publications from the sample. Open coding, an interpretative method, was used to disaggregate all assessment methods into their constituent parts analytically. The goal was to develop substantiated codes that would enable those parts to be described, named, and classified. The breakdown of each assessment method into separate activities is an example of this open coding approach. Codes were then assigned to the activities. After this first round of coding, we collated, compared, and contrasted the codes that we had identified. Eventually, we harmonized the individual interpretations of the main codes. In the second round, we applied the method of axial coding to connect the formulated codes to each other. During this process, we organized the codes from the previous round into categories. This categorization enabled the creation of phases within the maturity assessment methods that comprise similar activities. After a second discussion, the results were harmonized again. In round three, the remaining publications were coded with the findings of rounds 1 and 2 to test them against data. Subsequently, we clarified and resolved any remaining coding differences. Following inductive reasoning, as suggested by Hempel (1966), we extensively discussed the created codes and categories to identify best practices and the fundamental principles of maturity assessment. Table 1 shows the identified categories and codes, which are translated into phases and activities that are essential for maturity assessment methods. The table also overviews the descriptive statistics within the underlying articles. In total, we derived five generic phases, which cover all activities that form part of the investigated methods. A central finding that emerged from the coding is that few methods address the selection of models. Moreover, most proprietary methods in Area 1 only cover the preparation, assessment execution, and reporting phases. They do not provide support for adaptations or critical reflection on assessment results. Figure 4 shows how the identified phases can be mapped onto common maturity assessment methods of Area 1. After the SLRs and coding activities, we conducted seven semi-structured interviews with researchers and practitioners. This included two professors, one postdoctoral researcher, and four management consultants completing their doctoral degrees. Those interviews would serve as a formative evaluation episode EV1.

All experts possessed considerable expertise in the field of maturity models, whereas the consultants had already been involved in their practical selection, implementation, and monitoring at different organizations. The experts were presented with the RQ, the design objectives, and the created findings on maturity assessments. Against this background, they were asked which fundamental phases, activities, and indispensable aspects of maturity assessments should be considered for artifact creation. Moreover, they were asked to indicate what extensions would be necessary to achieve the design objectives. Appendix 2 shows the details and the results of the interviews.

3.4 Second Development Phase – Advancing What Exists

The analysis of existing maturity assessment methods made it possible to overview the status quo and to identify fundamental phases, activities, and principles. Furthermore, the results of the formative evaluation EV1 provided us with expert knowledge on the necessary and potential extensions that would make the design objectives easier to attain. This expert knowledge formed the basis of the second development phase, in which we created the final CMAM by extending and advancing existing knowledge about assessment methods. To that end, we followed the method of abductive reasoning, a creative process that enables the introduction of new concepts and ideas (Peirce et al. 1998). Abduction can extend and create knowledge because researchers imagine and analyze all possible theoretical accounts of a given problem or a set of data and then form hypotheses until they arrive at the most plausible interpretation (Charmaz 2008). We built the CMAM iteratively by selecting the most useful phases and activities from the first development phase and extended it by incorporating information from the formative evaluation EV1. After each iteration, we performed semi-structured interviews (EV2) with the expert panel to obtain additional feedback. After three iterations and 21 interviews, we finished the procedure because the experts did not identify further extensions or new issues.

4 Results

The CMAM that we developed reflects best practices and contains elements that are indispensable to an appropriate maturity assessment method. In addition, it extends and advances prior methods to address the formulated design objectives. The CMAM is intended to guide organizations through all the steps of the maturity model application, and its phases can be implemented into an organizational routine.

The CMAM consists of five phases and several activities that are arranged iteratively. Figure 5 shows all phases and contains descriptions of the associated activities, their purposes, and their objects. The first phase, *maturity model preparation*, is the user's point of entry into the assessment

Table 1 Status quo analysis of existing maturity assessment methods

Phases	Activities	Number of articles*	
Maturity model setup	Selection of an appropriate maturity model	6	11%
	Adaptation of the underlying maturity model	4	8%
	Definition of assessment purpose and goals	17	32%
	Creation of capability-development roadmaps	4	8%
	Creation of awareness and highlighting of relevance	5	9%
Assessment preparation	Analysis of assessment requirements	7	13%
	Definition of assessment scope	19	36%
	Clarifying responsibilities and stakeholders	11	21%
	Definition of assessment methods and required data and information	8	15%
	Creation of questionnaires and selection of interviewees	36	68%
	Definition of milestones and schedules	12	23%
	Estimation of resources and capacities	8	15%
	Identification of risks	3	6%
Assessment execution	Data collection and processing	33	62%
	Data validation and documentation	29	55%
	Preparation and conduction of interviews	49	92%
	Translation of data and information into capabilities	11	20%
	Determination of maturity level	46	87%
Reporting	Communication of results to stakeholders	17	32%
	Comparison with prior results and anticipated goals	4	8%
Actions and revision	Derivation of actions to accomplish goals	13	53%
	Adaptation of assessment method	3	6%
	Adaptation or replacement of maturity model	2	4%

*Absolute and relative numbers of articles

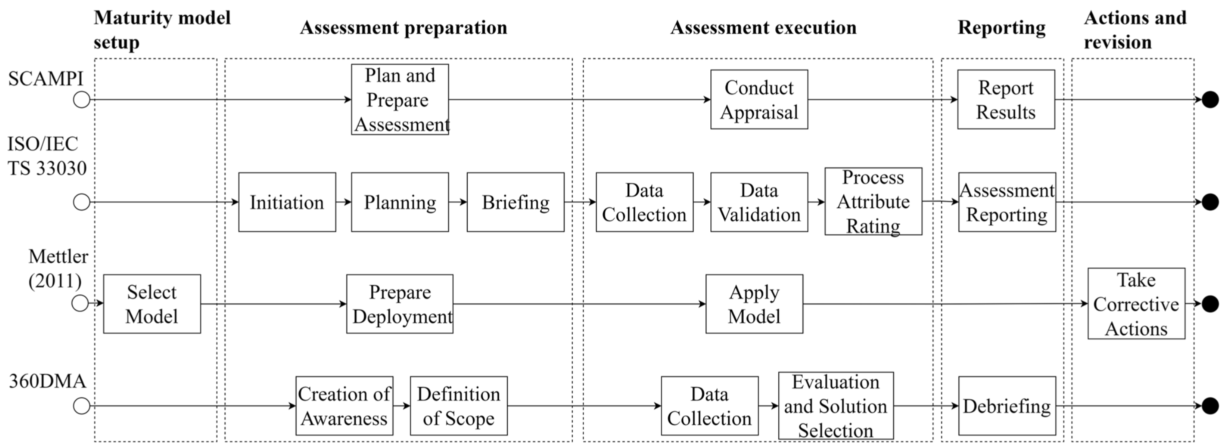

Fig. 4 Phases and activities in established maturity assessment methods

method and contains activities that revolve around the selection of an appropriate maturity model and preparation for its use. It is followed by the phase *assessment specification instantiation*, in which all relevant responsibilities, decision parameters, and assessment details of the method are defined. The users must instantiate a metamodel that results in an assessment specification that is unique to the individual assessment. In the next phase, *capability tracking and assessment*, all relevant capabilities are tracked by collecting associated data in line with a trigger- or interval-

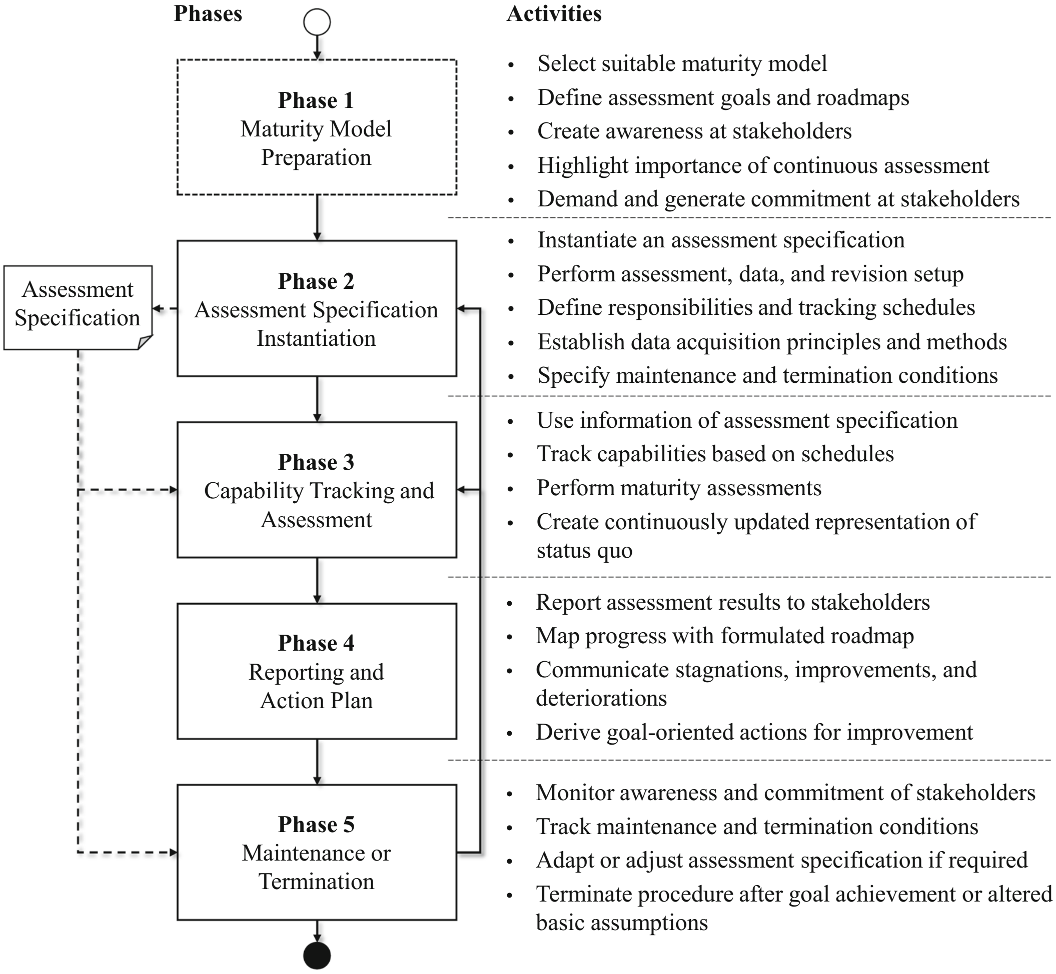

Fig. 5 The continuous maturity assessment method (CMAM)

based schedule. The resulting data is used to define the maturity level, which is then communicated and analyzed further in the *reporting and action plan* phase. Finally, the *maintenance or termination* phase describes activities that are related to the adaptation or termination of the procedure.

4.1 Phase 1 – Maturity Model Preparation

The first CMAM phase lays the foundations for all subsequent ones by having the users select and prepare an appropriate maturity model and formulate basic assessment definitions. For a suitable model to be selected, several decision parameters must be considered. They depend on business needs and situational factors. These factors and needs can include the origin of the model (i.e., academia or practice), its reliability (i.e., evaluation), its accessibility (i.e., cost of use, if any), its practicality (i.e., whether it is problem-specific or more general), and its design mutability (i.e., the convertibility of the model and the ease with which it may be integrated into the existing organizational model base) (Mettler 2011). Furthermore, the assessment approach is highly relevant. For example, much depends on whether the organization can perform all activities as self-assessments or if external support or the retention of certified experts is necessary. The latter can be relevant to assessments that are performed as part of contractor evaluations (Paulk et al. 1993). In addition, the user should become aware of the added value of the continuous application and of the resources and capacities that are required. This awareness depends strongly on the anticipated assessment goals, such as benchmarking against competitors or creating knowledge about internal capabilities (Serral et al. 2020). Thus, creating awareness necessitates a conclusive resolution of uncertainties or ambiguities in the assessment goals (SCAMPI Upgrade

Team 2006). If the selected maturity model cannot be adopted because of the organizational situation and environment, goal-oriented adaptation and adjustment are possible. However, these should not change the fundamental structure of the model or contradict its objectives. Another important prerequisite to enabling an effective CMAM application is the creation of awareness about the relevance and importance of the model. This exercise should also highlight the need for continuity (Stoiber and Schönig 2022). All involved users must understand that continuous assessment is relevant and crucial to arriving at accurate and objective insights into organizational capabilities. Moreover, for the CMAM to be embedded into an organizational routine sustainably, all stakeholders must guarantee their commitment and long-term dedication (Colli et al. 2019).

4.2 Phase 2 – Instantiation of Assessment Specification

Once an appropriate maturity model has been selected and all activities in Phase 1 have been performed, assessment details must be specified to enable the introduction of a systematic and iterative organizational routine. To that end, an assessment specification is created. It includes all vital building blocks, such as responsibilities, a data setup, and conditions for maintaining or terminating the CMAM. In this sense, the assessment specification describes objects, parameters, and characteristics of the real-life application of the maturity model. To facilitate the enumeration of substantiated assessment details, the CMAM provides a metamodel that can be used to instantiate the assessment specification for any underlying maturity model. Figure 6 shows the metamodel, which is presented as a Process Data Diagram (PDD), an approach that includes standards of the Unified Modeling Language (UML) (van de Weerd and Brinkkemper 2008). The PDD has already been used in related research and is sufficiently expressive for creating an appropriate model (van Steenbergen et al. 2010). The process view on the left-hand side of the diagram is based on a UML activity diagram, and the deliverables view on the right-hand side is based on a UML class diagram. The user performs the process on the left side to specify the classes and attributes on the right side. These classes represent all decision parameters and details that are relevant to the subsequent phases of the CMAM. Due to its representation as a class diagram, the metamodel can be implemented in different ways, for example, as a manual routine or as software that includes a database for defined and collected data.

4.2.1 Data Setup

In the first phase, *data setup*, the required data, its sources, and its processing must be specified for the purposes of the maturity assessment. This phase refers to similar data collection and preparation activities in SCAMPI and ISO/IEC TS 33030. At first, a product owner of the CMAM must be nominated to create responsibilities. Then, capability dimensions are selected iteratively, and the corresponding data types, which are used to identify capabilities, are defined. A qualitative acquisition principle must be specified for qualitative data. This principle also refers to participant groups that gather relevant data. In most proprietary assessment methods, data is collected by using questionnaires. If a quantitative data-acquisition principle is adopted, the data source for the capability dimension must be specified. These sources may include the databases of Enterprise Resource Planning (ERP), Customer Relationship Management (CRM), or Business Process Management (BPM) systems. For instance, as far as the supply chain management maturity model of Lockamy and McCormack (2004) is concerned, data for days of supply (DOS) or cash-to-cash cycle times, which is easily accessible, could be used to define and assess relevant capabilities. Since most maturity models contain qualitative descriptions of capabilities, individual metrics can facilitate the translation of the acquired data into specific capabilities or capability levels. Moreover, similarly to SCAMPI, data validation is necessary to ensure that the assessment is reasonable and accurate.

4.2.2 Tracking Setup

In the second process phase, *tracking setup*, the details of capability tracking, and the assessment must be defined. Thereafter, the capability tracking schedule is set. It can be based on events or intervals. In the case of event-based schedules, specific triggers must be identified. Those triggers should indicate that specific capability dimensions ought to be assessed. For time-based schedules, the relevant dimensions are examined over fixed intervals. Subsequently, the capability dimensions must be selected that should be assessed for the set intervals and triggers. For a full scope, all capability dimensions of the maturity model, and therefore all individual capabilities, are tracked by reference to the corresponding schedules. For an individual scope, specific capability dimensions can be selected that correspond to a defined schedule.

4.2.3 Revision Setup

To be applicable over a long period, the CMAM should contain principles that allow for flexible adaptations of its

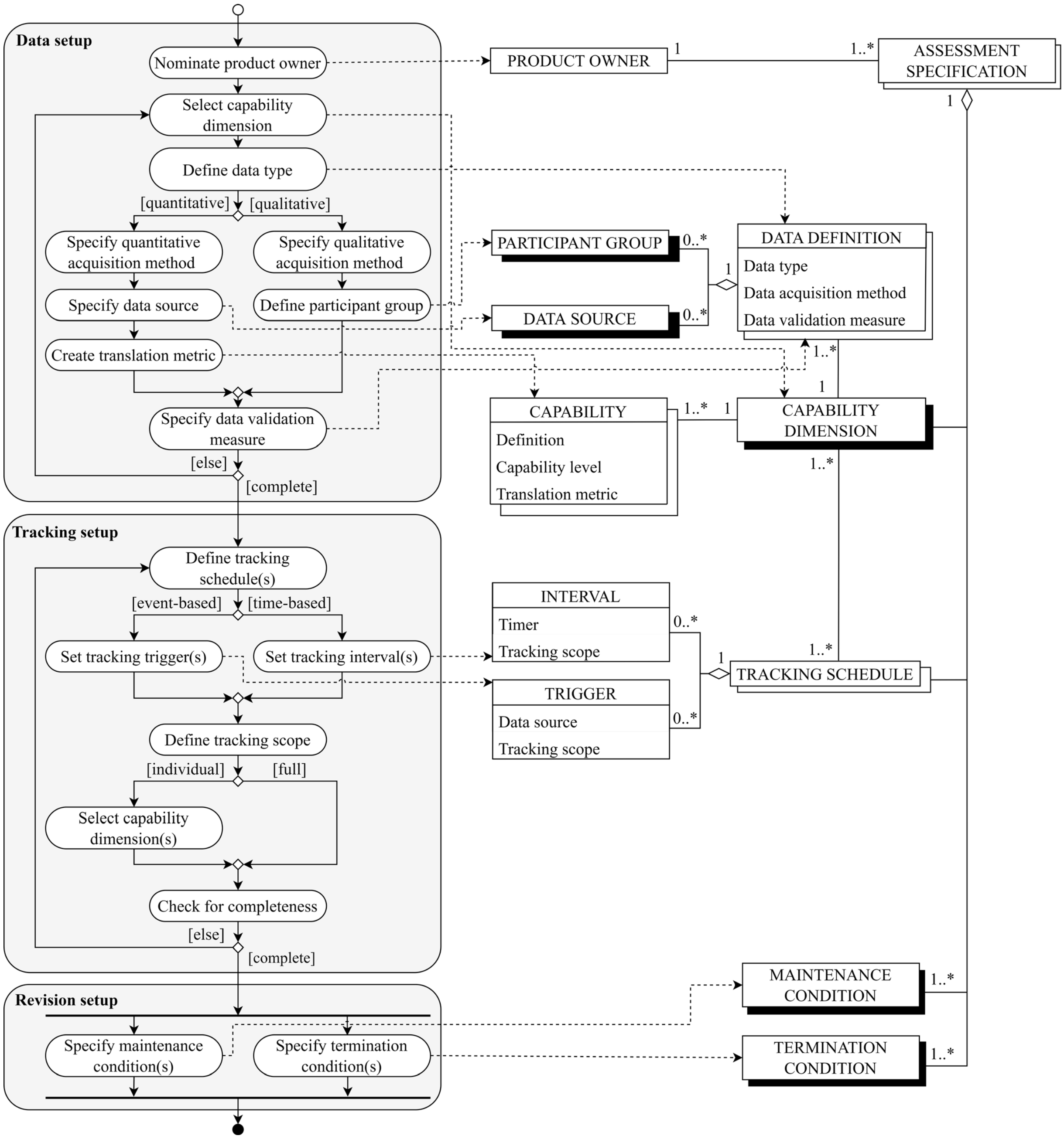

Fig. 6 Assessment specification metamodel

setup. Furthermore, being an iterative procedure, it must have clear termination conditions. Both principles are defined in the *revision setup* stage, in which maintenance and termination conditions are specified. Any changes in responsibilities or data sources need to be adapted to the assessment specification. Moreover, changes in the management of the organization or its structure may lead to the termination of the CMAM. Finally, the introduction of superior maturity models may require the CMAM to be terminated and restarted because Phase 1 is always the entry point of new models.

4.3 Phase 3 – Capability Tracking and Assessment

In the third phase of the CMAM, the predefined assessment specification is used to track all relevant capabilities according to the formulated schedules. The product owner is responsible for either enabling the collection of quantitative data from the data sources and translating it into capabilities or for gathering capability information through qualitative methods, such as questionnaires and focus groups. The tracking results are then used to define the current maturity level. Tracking is also related to the RQ in that it enables the creation of a method for the continuous assessment of maturity through the constant monitoring of organizational capabilities. The information that is obtained thus can be used to determine maturity levels. Stakeholders obtain a more detailed and recent representation of the state of affairs, and the needs of many maturity model users are met, especially in highly dynamic environments (Englbrecht 2021; Stoiber and Schönig 2022).

4.4 Phase 4 – Reporting and Action Plan

In the fourth phase of the CMAM, the results of the maturity assessment are reported to the stakeholders and other focal groups. While it is not described in detail in many existing methods, reporting is an important activity in the SCAMPI, ISO/IEC TS 33030, and 360DMA, as well as in other methods. An appropriate debriefing includes a presentation of results and a comparison with prior assessments, which enable learning and the formulation of action plans. The results must be analyzed critically, and it is necessary to decide whether advances in maturity should be coupled or uncoupled from the regular target system of the organization and if improvement-related activities can be conducted ad hoc or whether specific project initiatives are necessary (Mettler 2011).

4.5 Phase 5 – Maintenance and Termination

In the last phase, the user performs activities to ensure a valid CMAM representation, including an actual and correct assessment specification. Since organizational changes may necessitate the adjustment or adaptation of the specification, the user can decide to return to Phase 2 and rerun the assessment specification instantiation. The necessity of this operation depends on the maintenance conditions from the assessment specification. These conditions could include changes in organizational structures, stakeholders, or information systems for data collection. In some cases, the termination of the CMAM might be appropriate or necessary. The termination conditions may include, among others, the achievement of maturity goals, significant changes within the organization, or the introduction of a new and more suitable maturity model. In general, this phase ensures that the CMAM is validated and updated continuously, and it eventually results in the rationally justified termination of the assessment. If no maintenance or termination condition is met within a given iteration, the user is guided back to Phase 3 to track capabilities and to keep the maturity assessment alive.

5 Evaluation

5.1 Evaluation Setup

Accurate evaluation is a central and critical part of DSR (March and Smith 1995), and its aim is to assess the utility that an artifact contributes to its environment (relevance cycle) and the knowledge that it adds to the knowledge base (rigor cycle) (Hevner et al. 2004). Therefore, we followed the FEDS of Venable et al. (2016), which complements the process model of Peffers et al. (2007) and extends it by introducing detailed evaluation principles. The FEDS complements and details the generic evaluation phase of Peffers et al. (2007) by introducing tools to create an overarching evaluation strategy. In this regard, it supports the (i) explication of evaluation goals, (ii) the development of an appropriate evaluation strategy, (iii) the determination of evaluation properties, and (iv) the design of evaluation episodes. The main goal of the evaluation was to support the achievement of the design objectives (ex-ante) and, eventually, to measure and assess the degree of attainment (ex-post). These two goals mean that a combination of formative and summative evaluations is required. We designed four evaluation episodes, two of which are formative (EV1 and EV2) and two of which are summative (EV3 and EV4). Table 2 presents an overview of the evaluation episodes, including the three guiding questions of evaluation in DSR, namely "*why?*", "*how*?" and "*what*?" (Prat et al. 2015). The formative evaluations EV1 and EV2 were used to produce empirically based interpretations that provided a basis for improving the characteristics and the performance of the CMAM (Wiliam and Black 1996). For the summative evaluations EV3 and EV4, we defined four evaluation criteria that allowed us to conclude the attainment of the evaluation goals.

First, we chose the criterion of *operational feasibility*, which concerns the degree to which managers, employees, and other stakeholders might support the proposed artifact effectively, operate it, and integrate it into their daily practices (Mark et al. 2007). This process is essential because only feasible artifacts can be applied and maintained by organizations. Secondly, we evaluated the *generality* of the CMAM to ensure that the artifact can be used at any organization and for any maturity model. Third, the criterion of *applicability* was selected. Fourth, we evaluated the *effectiveness* of the CMAM, which we defined as the degree to which the artifact achieves its goal in real-life situations (Prat et al. 2015).

Table 2 Performed and planned evaluation episodes

Evaluation episode	Why?	How?			What?
	Function	Environment	Timing	Method	Criteria
EV1	Formative	Artificial	Ex-ante	Semi-structured interviews	Achievement of design objectives
EV2	Formative	Artificial	Ex-ante	Semi-structured interviews	Achievement of design objectives
EV3	Summative	Artificial and naturalistic	Ex-post	Survey	Operational feasibility, generality
EV4	Summative	Naturalistic	Ex-post	Case study	Applicability, effectiveness

5.2 Expert Survey

To assess the operational *feasibility* and *generality* of the CMAM, we conducted expert surveys at six organizations. To cover different scenarios and to collect heterogeneous feedback, we selected organizations from different industry sectors, of different sizes, and with varying experiences of maturity models. The organizations in question included market-leading businesses in the chemical industry, plant engineering, the manufacturing sector, and financial services. At least one interviewee at each organization was responsible for applying a maturity model at a specific business unit. In Step 1 of the interviews, the underlying RQ, the design objectives, and the CMAM, including all its phases and activities, were presented in detail. In Step 2, we proceeded with initial questions that were aimed at gathering information about the position of the interviewee within the organization, their experience with maturity models, and their awareness of the RQ. Subsequently, in Step 3, we administered a questionnaire. It contained 12 statements, and the interviewees were asked to indicate their agreement or disagreement with each. The questionnaire used the well-established Likert scale (Likert 1932), which has interviewees record their level of agreement or disagreement with a statement on a symmetric agree-disagree scale. The statements were formulated in a way that enabled us to draw direct conclusions about the two formulated evaluation criteria. In the final step, Step 4, we conducted a semi-structured interview that helped "*to confirm what is already known whilst at the same time providing the opportunity for learning*" (Kundisch et al. 2021; Recker 2013). Appendix 3 provides a comprehensive overview of the survey details and the results. The survey showed that all organizations were aware of the relevance of continuous maturity assessment and would implement principles and methods that support it. They pointed out that the phases and activities of the CMAM could be adopted as organizational routines within different departments and for different maturity models. The survey results also demonstrated that managers would support the adoption of the CMAM and that they saw the considerable potential benefits of its application.

5.3 Case Study

After the first summative evaluation yielded positive feedback on the operational feasibility and the generality of the CMAM, the artifact was evaluated further in an industrial case study. The case study had the distinct objective of testing the hypothesis that the CMAM is an effective and applicable method for continuously assessing organizational capabilities and maturity.

5.3.1 Case Study Design

Since the CMAM constitutes an iterative process that is applied over time, the case study was designed as a longitudinal study that is sensitive to temporal variations. To that end, the CMAM was introduced at an organization to enable the application of a maturity model over a period of six months. The organization in question already had experience with applying such models, which enhanced the significance of the study. All steps of the application of the CMAM were documented and analyzed. This process covered the organizational implementation of the CMAM and the operational results of each phase. After an application period of six months, the users at the organization were asked for feedback through a survey and during semi-structured interviews. The aim was to determine whether the CMAM is (i) applicable and implementable as an organizational routine, and (ii) an effective method that enables continuous and comprehensive maturity assessments.

5.3.2 Case Study Setup

While all organizations that participated in evaluation episode EV3 agreed to participate in a case study in principle, two of them initiated concrete action after the survey was conducted. Ultimately, the chemical organization was selected for extensive study because it agreed to the documentation of all internal data. The case study was conducted over six months in 2022, between February and August. In the beginning, a project team was set up. It consisted of four members of the organization and the authors. The CMAM was introduced at the *IT Service Managemen*t department of the organization, which was responsible for delivering business applications and IT-enabled processes at the German headquarters of the business. Since 2015, the department has been using an updated version of the original Gartner Infrastructure Maturity Model (GIMM) (Hidas 2006). A detailed overview of the updated GIMM from 2015 may be consulted in Appendix 4. Previously, maturity had been assessed every two years as part of a self-assessment and with limited external support. This self-assessment was conducted based on the descriptions of the GIMM and loosely followed the generic phases of SCAMPI. External consultants had created questionnaires that were intended to enable conclusions to be drawn about the capabilities of the GIMM. The questionnaires would be distributed within the department. At the last assessment, which took place in 2021, a maturity level of "*Rationalized"* had been achieved, which represented no improvement on the previous assessment, which had taken place in 2017.

5.3.3 Implementation of the CMAM as an Organizational Routine

Initially, all relevant phases and activities of the CMAM were discussed with the project team. Subsequently, the first phase, *maturity model preparation*, was executed by the organization-side project team. Despite the last update of the maturity model in 2015, the project team decided to retain the GIMM for the case study because its capabilities were still relevant to the department's goals. However, the project team included a termination indicator that would necessitate the selection of a new model or an updated GIMM if the management demanded a new strategic alignment. The detailed results of all activities are presented in Appendix 5. The second CMAM phase was performed thereafter. The assessment specification was instantiated and visualized in MS Visio. Once the product owner had been defined, the data setup was formulated according to the PDD. Data sources that indicated where to gather information about a given capability were identified for each capability dimension. This process led to the definition of acquisition methods for the dimensions in question.

The data for four capability dimensions was to be gathered through qualitative questionnaires, while quantitative data for the two remaining dimensions would be extracted from databases. Then, translation metrics were created for each capability dimension, which enabled the questionnaire results and the data from the databases to be translated into distinct capabilities. Participant groups were identified for each questionnaire, and schedules were defined within the tracking setup. These schedules included one general interval, whereby a full assessment would be initiated every six months. Two separate automated triggers were determined for the two capability dimensions that were associated with quantitative data acquisition methods. Finally, three maintenance and termination conditions were set. Since the visualization of the assessment specification that was created included structured assessment information, a basic dashboard could be developed. Figure 7 shows the dashboard's home screen, which was programmed by the department and was mainly used for enhanced visualization. The dashboard includes five primary tabs that overview all details of the assessment specification. It can also disseminate alerts if database queries indicate that there have been changes within the two quantitative capability dimensions, and it displays a timer for the fixed six-month interval.

5.3.4 Longitudinal Study

The product manager used the dashboard for six months to execute CMAM Phase 3, Phase 4, and Phase 5 iteratively. Two automated database triggers were activated during the longitudinal study, and one fixed six-month interval passed. The capability dimensions that corresponded to the two database triggers were tracked. This tracking resulted in the identification of capability improvements, which led the department to reach a new and higher maturity level. In accordance with CMAM Phase 4, this change was reported to all stakeholders, and a comparison between the set goals and future actions was discussed. Due to the expiry of the fixed interval after six months, the product manager had to distribute questionnaires to all participant groups. However, the analysis of the capability dimensions did not lead to any further changes. At no point was any maintenance of the assessment specification required, and the CMAM was not terminated. Appendix 6 presents all events that occurred during the six-month study.

5.3.5 Study Results

The implementation of the CMAM and the six-month study allowed us to draw valuable conclusions about the applicability and effectiveness of the method. At the end of the study, we performed a survey and conducted interviews with the project team to collect evidence of the achievement of the evaluation objectives. We followed the procedure that was described in Sect. 5.2. First, we performed a survey. The project team members could indicate their agreement or disagreement with statements on a Likert scale. Subsequently, we asked each team member open questions to collect individual feedback on the applicability and effectiveness of the CMAM. Appendix 7 contains a detailed overview of the questions and the statements.

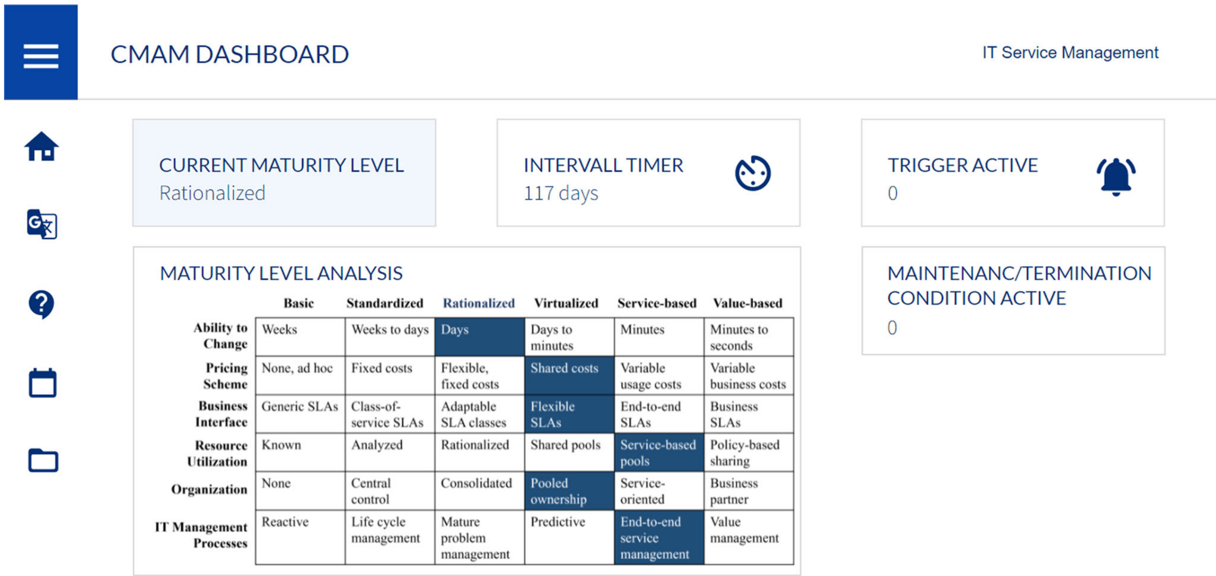

Fig. 7 CMAM dashboard

The project team members stated that, in principle, the CMAM "*[…] was generic enough to be applicable to our GIMM and department environment.*" The generic and instantiable assessment specification, in particular, solved the problems that had been generated using other methods in the past. Those methods had been too specific and did not match the GIMM. The statements of the project team members confirmed the applicability of the method as an organizational routine. Furthermore, the project team confirmed the effectiveness of the CMAM by indicating that it is comprehensive and continuous. The activities pertained to CMAM Phase 1 made it possible to "critically question the existing maturity model" and raise the necessary awareness among all stakeholders. In particular, the appointment of a product manager anchored CMAM as a routine process and gave it additional relevance. The team also stated that "*the clear assessment specification of CMAM Phase 2*" was particularly useful, enabling the visualization of all necessary assessment details. No such structured presentation had been developed previously. The specification also made it possible to develop a software representation because the UML standard of the PDD provided all the necessary information. Moreover, the two quantitative triggers allowed new perspectives to emerge from the maturity assessment. So far, only qualitative questionnaires have been used as bases for capability assessments. The introduction of these triggers and an additional fixed interval enabled changes in maturity level to be detected two months into the study. Under the previous regular assessment method, achieving the same outcome would have taken nearly two years. This circumstance made it possible to "*update stakeholders about the achievements at an early stage and to adjust further goals.*" These statements demonstrate the CMAM's effective principles for continuity, as during six months, two changes within the capabilities and a major maturity level change could be identified. The project team decided to retain the CMAM as an organizational routine because it has measurable advantages over prior methods and because it is conducive to long-time usage, independently of the chosen maturity model.

6 Discussion

6.1 Contributions and Differentiation from Existing Methods

This article proposes the CMAM, a comprehensive method for the continuous tracking of capabilities and the assessment of maturity that can be applied to any model and at any organization. To develop it, we analyzed the existing literature on maturity models, identified inadequacies and weaknesses, and formulated a central RQ. Drawing on the four design objectives that we defined, we extended and improved existing assessment methods on the dimensions of *generality*, *comprehensiveness*, and *continuity*.

6.1.1 Managing Generality and Comprehensiveness

As noted in Sect. 2.4, there is a discrepancy between generically applicable and comprehensive maturity assessment methods. The CMAM addresses this issue and provides generality and comprehensiveness across its activities and phases. First, the CMAM does not refer to specific models and therefore allows for generic and configurable applications. The generic assessment specification metamodel provides means for individual instantiations. The CMAM improves on methods such as SCAMPI and ISO/IEC TS 33030 that are only applicable to a specific set of models. The evaluation episode EV3 showed that the CMAM could be adopted at all the organizations that we interviewed and used to apply the maturity models that they use. Furthermore, the case study confirmed that the CMAM is easy to configure and instantiate.

The CMAM is also comprehensive. It adopts phases that are established in previous methods, such as assessment preparation, assessment execution, and reporting, and it adds features that provide more comprehensive guidance. Phase 1 begins with the selection of an appropriate maturity model, the definition of a product manager, and the creation of sustainable awareness among stakeholders. This is not the case under SCAMPI, ISO/IEC TS 33030, or 360DMA. Furthermore, the definition of maintenance and termination criteria in CMAM Phase 5 is an improvement on existing methods because it introduces activities that ensure sustainable implementation. The case study that we conducted showed that the extended Phase 1 and Phase 5 increased awareness and relevance as well as engagement with the maturity model that is in use. Furthermore, creating a detailed assessment specification (CMAM Phase 2) is not a feature of any previous model. The assessment details can be mapped concretely by defining tracking intervals, automated triggers, and a fundamental data basis. As noted in the description of the case study, it was even possible to develop a digital representation and to track two dimensions automatically.

6.1.2 Enabling Continuity

Another design objective was to enable continuous capability tracking and maturity assessments. The final CMAM maps this through the iterative Phase 3, Phase 4, and Phase 5, as well as through the assessment specification. Previous assessment methods do not permit the continuous tracking of capabilities and do not recommend maturity assessments based on empirical data. For example, SCAMPI only specifies that the assessment must be repeated at least every three years. Far-reaching changes may occur over such a period, especially in sectors that are characterized by frequent innovation. Accordingly, the CMAM enables assessment schedules to be formulated. These schedules can include fixed intervals or triggers that are based on changes within the organization. Improvements and deteriorations can be detected rapidly, and countermeasures may be taken if necessary. The case study showed that changes in organizational capabilities and maturity levels are detected much more rapidly through the CMAM and can be used to adapt goals and action plans.

6.2 Theoretical and Practical Implications

Given the novel aspects of the CMAM, the implications of our research are twofold. As far as theory is concerned, the present paper analyzed existing assessment methods, investigated weaknesses and research gaps, and described a novel DSR artifact. It developed the first systematic analysis of existing assessment methods against the background of *comprehensiveness*, *generality*, and *continuity*. In this way, the analysis of the literature and the existing maturity models identified new perspectives and addressed existing research gaps concretely. The inclusion of *continuity* as an essential aspect of maturity assessments reflects a new perspective on the manner in which maturity must be assessed within rapidly changing business environments. The CMAM is a new theoretical artifact that advances and extends the existing knowledge of maturity assessments. It, therefore, has new facets that can be important to future research on the application cycles of maturity models.

From a practical and managerial standpoint, the article described a new method that can be adopted by organizations of all kinds and applied to any maturity model. The *applicability* and *effectiveness* of that method were validated by a case study, which proved that the artifact is ready for extensive practical use. In particular, the artifact will likely benefit organizations that use maturity models without proprietary assessment methods. The CMAM can be implemented as an organizational routine enabling up-to-date mapping of organizational capabilities. As shown by the study, this type of implementation makes it possible to identify improvements or deteriorations more rapidly, which means that plans for improvement processes and target setting may become more effective.

6.3 Limitations

Although it is rigorous, the presented work is not without limitations. Those limitations are related to DSR, which allows various artifacts to be developed in line with different preconditions and aims at the identification of suitable rather than optimal solutions (Hevner et al. 2004). First, the selection of existing assessment methods within the SLRs and the choice of experts for the formative evaluations influenced the design and the development of the CMAM. We performed structured SLRs in line with an established method to collect all articles that may have been relevant (vom Brocke et al. 2009). While selecting the expert panel, we identified researchers and practitioners from different domains who possessed advanced expertise in the design of maturity models. Another limitation arose from the generic design of the CMAM, which does not provide concrete references, tools, or questionnaires for assessing capabilities in specific fields. However, organizations can easily embed existing questionnaires into the CMAM or create quantitative data-acquisition methods internally. The CMAM is not intended to be too specific. Therefore, the CMAM need not replace proprietary assessment methods; they can be included in superordinate frameworks. Finally, the two summative evaluation episodes were limited to six organizations, and the CMAM was only implemented at one organization. However, despite this limitation, we deem the results of the evaluation to be generalizable because the CMAM is sufficiently generic to be applicable in different scenarios.

7 Conclusion

Given the wide variety and the high complexity of existing maturity models, users require comprehensive support during all phases of the application cycle. However, existing assessment methods do not provide sufficient support in all phases of that process and cannot be applied to all types of models. Furthermore, they do not consider activities or principles that are relevant to continuous assessment. This tendency runs contrary to the fundamental character of capabilities because organizations are embedded in ever-changing environments while their capabilities are liable to continuous change (Nelson and Winter 2004). Therefore, we propose the CMAM, which plugs existing research gaps and contains phases and activities that enable a generic, comprehensive, and continuous maturity assessment for all underlying models and all organizations. Drawing on the research gaps we identified, we formulated a fundamental RQ, which we translated into four concrete design objectives for the CMAM. We followed a rigorous research methodology, which is anchored in the DSR and enabled us to engage in goal-oriented analysis and synthesize indispensable principles and best practices from existing methods. Based on the formative evaluations, we iteratively extended these findings and created the CMAM. A summative evaluation of six market-leading organizations and an extensive six-month case study enabled us to determine that the artifact meets the design objectives. We are confident that the CMAM assists users during all phases of the application cycle and that it extends the descriptive knowledge of maturity assessments. As a general matter, the CMAM affects decision-makers in organizations, so the application of a maturity model becomes not a one-off or a point-in-time process but an embedded mechanism for continuous improvement.

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4 P4: Conceptualizing Industrial IoT-based Business Process Improvements – A Metamodel and Patterns

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Conceptualizing Industrial IoT-based Business Process Improvements – A Metamodel and Patterns

Abstract. Companies of all kinds are increasingly recognizing the Industrial Internet of Thing's (IIoT) capabilities to enable valuable Business Process Improvements (BPI). However, from a theoretical and practical standpoint, it remains unclear how potential applications can be systematically and successfully identified, specified, and implemented. The study at hand addresses this research gap by providing a metamodel that contains all relevant aspects and elements of IIoT applications with BPI propositions. The metamodel can be used to derive generic patterns of IIoT-based BPIs that may support companies to identify and realize beneficial applications. The metamodel and patterns contribute to the descriptive knowledge of both IIoT and BPI and facilitate sense-making, theory-led design, and practical execution of IIoT projects. To demonstrate the metamodel, an initial set of five patterns is presented that has been derived from 34 real-world applications. To ensure rigor, the research endeavor followed fundamental principles of the design science research (DSR) methodology including a comprehensive evaluation.

Keywords: Industrial Internet of Things, Business Process Improvement, Metamodel, Patterns.

1 Introduction

Internet of Things (IoT) applications are omnipresent and influence all facets of everyday life by providing disruptive technologies for private households and businesses of all kinds (Whitmore et al., 2015). Besides various smart home, smart grid, and smart city applications, especially industrial companies can remarkably benefit from integrating IoT technologies into their business processes. In this regard, a paradigm denoted as the Industrial Internet of Things (IIoT) has evolved that leverages the IoT, albeit transcending the concept of the thing toward industrial applications. In contrast to the IoT comprising various applications, e.g., smart home or smart city, the IIoT constitutes an explicit use of IoT technologies within industrial companies and applications. The transformation of analog information into digital data, which can be processed worldwide in real-time, enables new business models, revolutionizes existing ones (Ng and Wakenshaw, 2017), and improves the company's competitive advantage (Li et al., 2012). Moreover, the generation and use of comprehensive process data and the connection of process entities can be used to improve all types of business processes and thus optimize value creation (Del Giudice, 2016). Therefore, the integration of IIoT technology into existing business processes can lead to beneficial Business Process Improvements (BPIs) that are highly relevant for process-oriented companies (Janiesch et al., 2020). For instance, equipping in-stock products with simple radio-frequency identification

(RFID) tags can fundamentally enhance the traceability of warehouse processes and enable manifold further opportunities for improving downstream operations (Fescioglu-Unver et al., 2015). Hence, the pressure on companies to integrate IIoT technology into their processes is growing steadily, to the point that companies which don't adopt IIoT, may not be competitive shortly (Liu et al., 2017).

However, a survey of more than 500 business executives revealed that 90% of industrial companies are remaining in the proof of concept or even early-stage planning phases for IIoT projects (Bosche et al., 2016). This matches the general challenges that companies face when implementing IIoT and other Industry 4.0 technologies (Zhang et al., 2021). Knowing about the relevance of IIoT technology and the benefits that can be expected by companies, indicates the existence of severe barriers and hurdles for successful integration into their process landscapes. One main reason for this lack of IIoT application maturity may be the complexity and heterogeneity of IIoT technology and the underlying business processes. Existing process problems must be investigated, and potential IIoT solutions must be identified (Sethi and Sarangi, 2017). Another reason is the existing discrepancy between the companies' expectations of IIoT projects and actual results (Skaržauskienė and Kalinauskas, 2015). Decision-makers need to have an explicit understanding of the value they can expect and the technical aspects that are required to achieve it (Reijers and Liman Mansar, 2005). This is highly important for the development of detailed project specifications. Finally, the "*Act of Improvement*", i.e., how existing business processes are transferred to the improved target state by implementing IIoT applications, can often not be defined precisely. This reduces the plannability and thus the chance of a successfully performed IIoT project (Forster, 2006). To sum up, companies need to be supported at all three stages of project execution: the identification of potential IIoT applications, *(ii)* the development of application specifications, and *(iii)* the actual implementation.

To tackle these challenges, companies need structured models that display and describe all relevant aspects and facets of IIoT-based BPIs. These models need to be generic enough to be applicable to similar scenarios and detailed enough to effectively guide companies during the implementation of individual IIoT-based BPI projects. In this regard, we define the term "*IIoT-based BPI"* as the purposeful use of IIoT technology within business processes to improve the same concerning predefined objectives. We formulate the following central research question (RQ):

RQ1: How can industrial companies be supported in the identification, specification, and implementation of IIoT-based BPI applications?

One auspicious approach to address this RQ is the development of generic patterns. Patterns are reusable artifacts that address a problem within a certain context by providing a suitable solution (Alexander, 1977). In this context, patterns can represent templates or blueprints for IIoT-based BPI applications and are reusable for different kinds of industrial companies (Forster, 2006). Using patterns can reduce the risk of IIoT projects as well as support companies with the identification of possible BPI potentials and the required IIoT technologies, making them extraordinarily valuable. Furthermore, all relevant application elements such as underlying problems and challenges, industry examples, performance indicators, or specific characteristics of the technical solution are provided. The prerequisite to formulating these patterns is an appropriate metamodel that displays basic design principles. The metamodel ensures completeness and consistency of the pattern descriptions and specifies their structure (Falk et al., 2013). Against this background, we formulate an additional RQ:

RQ2: Which metamodel can enable the illustration of IIoT-based BPI patterns?

The paper at hand addresses both RQs by proposing a metamodel that contains all elements that are required to fundamentally comprehend the phenomenon of IIoT-based BPI. The metamodel design followed basic principles of design science research (DSR), i.e., the procedure model of Peffers et al. (2007). In addition, an initial set of five IIoT-based BPI patterns was derived from 34 real-life IIoT applications and illustrated using the metamodel

The remainder of this study is structured as follows. Section 2 presents the theoretical foundations of the disciplines IIoT and BPI as well as an overview of the concept of patterns and metamodels in information systems research. In section 3, the underlying research methodology is described, which has been applied for developing and evaluating the metamodel. Subsequently, the design and development of the metamodel is illustrated in section 4. In section 5, we present the final metamodel of IIoT-based BPI including all aspects and elements. In section 6, the first set of five patterns is derived by an expert panel. Subsequently, in section 7, the knowledge generated during pattern creation is used to perform a survey on the expert panel as a summative evaluation. We conclude by discussing implications, limitations, and future research opportunities in sections 8 and 9.

2 Theoretical Foundations

2.1 Industrial Internet of Things and Business Process Improvements

There are dozens of different approaches for defining IoT, its components, features and capabilities, and the *things* themselves. The Institute of Electrical and Electronics Engineers (IEEE) combined several different descriptions, explanations, and characterizations towards a universal definition. According to the IEEE, IoT is a network that connects uniquely identifiable things to the internet. Through the exploitation of unique identification and sensing, information about the thing can be collected and the state can be changed from anywhere, anytime, by anything (Minerva et al., 2015). The term thing, therefore, corresponds to the idea of creating a ubiquitous presence of objects which are equipped with sensors, actuators, or tags. On the other side, the term internet refers to the ability of these things to build a network of interconnected objects based on several specific network technologies. These two perspectives can be complemented by a semantic view, which represents the ability of IoT to uniquely identify things and store, process, and exchange data (Atzori et al., 2010). In line with the growing share of industrial IoT applications, a more specified paradigm has been developed, called the Industrial IoT. In contrast to the generic definition of IoT, the IIoT constitutes the use of certain IoT technologies, e.g., certain kinds of smart objects within cyber-physical systems, in an industrial setting, to promote goals distinctive to the industry. The IIoT, therefore, differentiates itself from the IoT by the purposes to which the technologies are put (Boyes et al., 2018). Current research and already-implemented applications show that IoT technology reveals many extensive possibilities for improving business processes (Stoiber and Schönig, 2021).

In this regard, especially redesigning and therefore improving business processes is a timely and relevant topic in both research and the business environment and is considered one of *"the most important and common titles in both literature and applications"* (Coskun et al., 2008). Despite IoT's capabilities to enhance BPI and therefore sustainably optimize the company's overall performance, there is a lack of research regarding IoT-based BPI. Among the limited number of contributions, Janiesch et al. (2020) created an overview of existing research and remaining challenges. Here, especially the need for further research on how to benefit from the integration of IIoT into business processes has been highlighted. This research gap can be tackled by developing a metamodel that enables the creation of patterns and adds to the descriptive knowledge of IIoT-based BPI. This approach has been proven in several other research disciplines and is well-received in companies of all industry sectors (Winter et al., 2009).

2.2 Metamodels and Patterns in Information Systems Research

Patterns, initially described by Alexander (1977), describe a recurring problem or challenge in the real world and the basic features of the solution to this problem. This solution is generic enough to be applied to many similar problems without ever being implemented in the same way. Although Alexander (1977) created this definition in the context of architecture, the idea of patterns is transferable to other domains, especially information systems research (Gamma et al., 1994). In the context of enterprise and systems modeling, Fowler (1996) described patterns as an idea that has been useful in one practical application and is likely to be useful in others. According to Gamma et al. (1994), patterns consist of four essential elements. First, the pattern must have a name for identification. Then there is a description of the problem, i.e., in what context the pattern might be useful. The third element is a description of the problem solution. This must not be done by a concrete solution, because the pattern should be applicable to different scenarios, but by a description of the interaction of different mechanisms that lead to a problem solution. Finally, the consequences of the pattern must be described, i.e., the positive and negative effects that can result from the application of the pattern. Depending on the purpose of the pattern, this basic description can be extended by further elements. There has been considerable research on patterns in information systems for more than two decades leading to several relevant approaches indispensable from a research and practical perspective. Without a doubt, software development is one of the disciplines that benefited most from the creation of patterns (Winter et al., 2009). Here, patterns can support the design of individual object-oriented software components or assist with the composition of software components to applications (Schmidt et al., 2000). As this discipline includes complex tasks, patterns can bridge the gap between high-level integration plans and the actual implementation challenges by providing guidelines to compensate for the lack of experience among decision-makers (Hohpe and Woolf, 2003). This leads to reduced time consumption and cost while improving the quality of project execution. Moreover, patterns can be used for process-related disciplines such as Workflow Management or Business Process Modeling (Kühn and Karagiannis, 2005). For the discipline of BPI, the creation of specific patterns has barely been addressed in research. Reijers and Liman Mansar (2005) described a set of textual Business Process Redesign (BPR) best practices including a framework to classify them. Forster (2006) built up a framework and toolset for creating and structuring BPI patterns while creating the first set of patterns. Another relevant contribution by Falk et al. (2013) proposes a metamodel that facilitates the illustration of BPI patterns. In this respect, patterns constitute models that are derived from an origin metamodel.

In general, a model can not only describe objects that exist in the real world, but also abstract constructs. If the abstract construct described is a model, the describing model is called a metamodel (Gonzalez-Perez and Henderson-Sellers, 2008). The relationship between model and metamodel can also be referred to as a class-instance relationship. This is an analogy to object-oriented programming, where a class describes the attributes and methods of the objects to be formed from it, without itself being an object. By instantiation, objects or instances can be formed from the class, which in turn are mappings of real objects. A metamodel describes the types of model building blocks available, the types of relationships between the model building blocks, the rules for linking between model building blocks by relationships, and the semantics of the model building blocks and relationships (Ferstl and Sinz, 2013). To create a metamodel, a suitable modeling language is necessary to represent and communicate relevant information about a model. Modeling languages are defined by their syntax, notation, and semantics. The syntax describes the elements of a modeling language and how they may be linked together, i.e., it describes the grammatical rules. The notation describes the symbols and characters that may be used to capture a model. Ultimately, the semantics determines how certain information is to be interpreted, e.g., when ambiguities occur in the model (Kühn and Karagiannis, 2005).

2.3 Related Work

As described in subsection 2.2, there has already been researching conducted on general BPI patterns and metamodels that do not particularly focus on IoT or IIoT but consider BPIs of any kind. Especially noteworthy is the contribution of Falk et al. (2013), who created an explicit metamodel that enables the creation and formulation of BPI patterns and can be used as a template and basis for further research. Furthermore, the concept of patterns has also been applied to several topics related to IoT. As IoT technology consists of different layers, comprising perceiving, networking, or data processing technologies, a great variety of different patterns can be formulated that support system engineers with integrating whole applications into business environments. The design and architecture of IoT systems can eminently benefit from patterns that assist in designing scalable and replicable IoT applications (Washizaki et al., 2020). Another focus within this research area is on data exchange and network technology patterns along with multiple connected devices, machines, or process entities (Reinfurt et al., 2016). However, a comprehensive conceptualization of IIoT-based BPI that explicitly describes and specifies the phenomenon has not been addressed yet.

3 Research Methodology

To tackle this research gap and answer the formulated RQs, we developed a metamodel that can be used to create and appropriately illustrate reusable IIoT-based BPI patterns. In addition, we created an initial set of five patterns based on metamodel. To develop the metamodel as a DSR artifact, we followed the structured procedure of Peffers et al. (2007). This proven method is based on the methodology of Hevner et al. (2004) and provides detailed phases to carry out DSR. It consists of six iterative phases in a nominal sequence including *(i)* the identification and motivation of the underlying problem, *(ii)* the definition of objectives of the solution, *(iii)* the actual design and development, *(iv)* the demonstration, *(v)* an evaluation, and *(vi)* the communication to an appropriate audience. Initially, every conduction of DSR is based on a research entry point that necessitates and justifies the artifact development. For the study at hand, the existing problems and challenges that companies face for integrating IIoT into their business processes constitute a problem-centered research entry point. Moreover, the lack of artifacts that support the realization of IIoT-based BPIs necessitates the creation of a suitable artifact. This research endeavor is of special interest, as the integration and use of IIoT technology is an enabler for economic success and becomes increasingly important. The objective of the developed artifact is to provide a basis for the creation of reusable patterns of IIoT-based BPI applications which serve as blueprints and templates for companies. The conducted research is composed of the following phases: *(i)* the design and development of a metamodel, *(ii)* its demonstration to industrial companies, *(iii)* the derivation of an initial set of patterns, and *(iv)* a summative evaluation of the metamodel's conciseness and completeness. Figure 1 gives an overview of the conducted research activities and their section references.

In the first research phase, we designed the metamodel of IIoT-based BPI applications and performed a comprehensive formative evaluation. In contrast to creating a completely new metamodel from the scratch, the improvement and revision of an existing and thematically related metamodel enable the adoption of proven concepts and ideas. Therefore, the metamodel for BPI patterns according to Falk et al. (2013) served as the basis for development. It was generic enough to represent all patterns of IIoT-based BPIs since these represent a subset of BPI patterns.

DSR activity	**Description**	**Section reference**
Metamodel development & formative evaluation	First design iteration: Adaption of baseline metamodel using SLR and grounded theory	4.2
	Second design iteration: Refinement of metamodel using Delphi study	4.3
Metamodel demonstration & pattern development	Demonstration at three companies and creation of five patterns derived from 34 IIoT applications	6
Summative evaluation	Expert survey to evaluate metamodel	7

Fig. 1. Performed research activities.

However, was not specific enough to appropriately illuminate the aspects of the IIoT domain due to its complexity and unique features. For this reason, the base metamodel required adaption concerning IIoT. Like in the original metamodel, a class diagram is used for modeling as it provided sufficient semantic expressiveness for metamodeling. To adapt the base metamodel, we performed two development iterations. Within the first design iteration, an explorative inductive approach has been selected. In this respect, an extensive systematic literature review (SLR) was conducted to investigate literature describing IIoT applications with BPI reference. Subsequently, the identified literature was analyzed following the grounded theory and its methods of open and axial coding (Corbin and Strauss, 1990). This enabled the identification of indispensable aspects of IIoT-based BPIs which could be used to adapt the metamodel. Within the author team, we applied the method of inductive reasoning (Hempel, 1966) to critically discuss the findings and select the most appropriate metamodel adaptions. Within the second iteration, we included additional expert knowledge in the research approach. Hereof, we conducted a Delphi study with nine experts from industry and academia to consequently refine the metamodel. In four rounds, the experts were asked to rate and eventually adapt the metamodel based on their expertise in the research area. Gradually, the metamodel has been adapted by removing redundant elements, adding additional required elements, and retaining or slightly adjusting the remaining elements.

The Delphi study also served as a formative evaluation and supported decision-making that intended to improve the metamodel (William and Black, 1996). In the second research phase, an initial set of five IIoT-based BPI patterns has been derived and illustrated using the developed metamodel. To do so, we demonstrated the metamodel to three multinational companies in the manufacturing, pharmaceutical, and automotive industries. Seven practitioners from different departments were asked to analyze a set of 34 IIoT applications in their different business areas to derive patterns. The industry experts used fundamental principles of inductive reasoning to analyze the applications, identify generic aspects, and derive five initial patterns. Subsequently, we surveyed the industry experts as a summative evaluation. The practitioners were asked to indicate whether the metamodel could be used to create distinct and meaningful patterns. In this regard, we specifically evaluated the metamodel's *completeness* and *conciseness* (Prat et al., 2015).

4 Metamodel Design Approach

4.1 Baseline Metamodel

The development of the IIoT-based BPI metamodel is based on the previous work of Falk et al. (2013). Their designed BPI metamodel is illustrated as a class diagram, whereby each element of a pattern is represented by a specific class. The properties of these classes are described by attributes (Fowler and Scott, 1997), while relationships between the classes are represented by undirected binary associations and their multiplicity. This multiplicity specifies the relationships between the individual object classes. The central class of the metamodel is *BPI Pattern*, which is instantiated by a unique *Name* and an *Example* (cf. Figure 2). The name describes the overall purpose of the pattern and can be uniquely identified.

In addition, there is the class Problem, which is defined by the attributes Name, Description, and the actual Consequences of the problem for the process. Each pattern addresses exactly one problem, but a specific problem can also be solved by different patterns. Furthermore, the Context class is directly related to the class BPI Pattern. It is explained by a Name and context-specific Characteristics and describes the required circumstances for the pattern to be applicable. As with the problem, each pattern exists in exactly one context, but multiple patterns can exist in the same context. Each pattern also contains a Solution, which is described by a Name and the Measures required to achieve the goal. The same solution can again be applied to multiple patterns, but each pattern has only one solution. Bound to the solution are one or more Mechanisms, each defined by a Name and precise action Instructions. In addition, a solution can optionally contain one or more Building Blocks. These building blocks are predefined models that can be implemented to solve the problem without customization. In addition, the pattern is related to an Effect, which is defined by a Name and the BPI dimensions Cost, Time, Quality, and Flexibility (Dumas, 2018). Finally, each pattern is related to one or more Performance Indicators. These are defined by a Name and Performance Measures that can be used to represent the improvement after the pattern has been implemented.

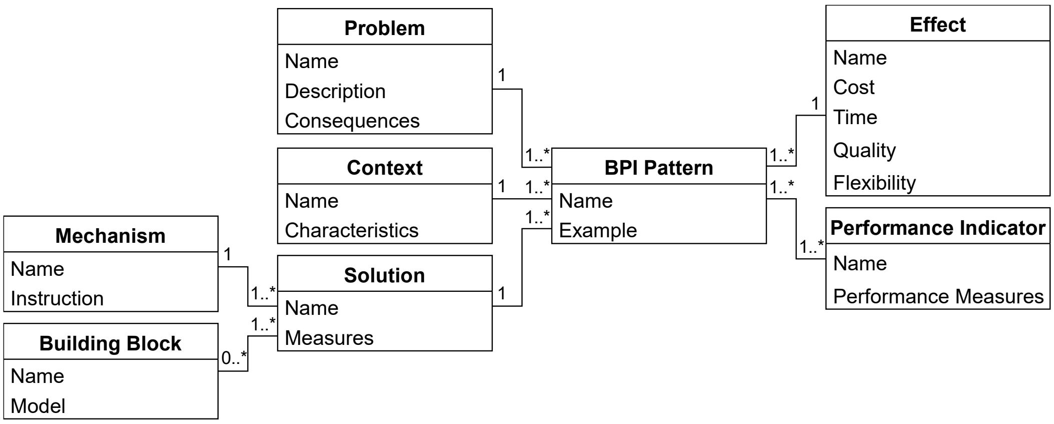

Fig. 2. Baseline metamodel by Falk et al. (2013).

4.2 First Development Iteration

To adapt the base metamodel, we first performed an inductive development iteration. We decided to start with this approach, as a large number of IIoT applications are available in the scientific literature which can be used to identify additional metamodel classes. For inductive approaches, the information processing is performed from subsystems to form a perception of a top-level system. This aggregation of information is suitable to analyze initially unknown data relationships and transfer them to a metamodel. For the identification of literature, we performed an SLR according to the method of vom Brocke et al. (2009). To allow a rigorous search and improve the traceability of the literature selection process, the Preferred Items for SLRs and Meta-Analysis (PRISMA) statement has been applied. Initially, the search string ("IoT" OR "CPS") AND ("BPI" OR "Process Improvement" OR "Process Optimi?ation" OR "Process Automation" OR "Application" OR "Process Improvement") and the written-out forms have been formulated. Figure 3 illustrates the results of the SLR as a PRISMA flow diagram. To incorporate and consider preferably all relevant journals and conference proceedings of the research area, ACM Direct Library, AISeL, IEEE Xplore, ScienceDirect, Scopus, and Springer Link have been queried. According to the PRISMA statement, four criteria were defined that a paper needs to achieve to be eligible for the SLR. The publication must (i) be a peer-reviewed research paper published in a journal or conference proceeding, (ii) propose an evaluated solution or real IIoT industry application, (iii) have clear links to BPI, and (iv) be relevant and up to date. As criteria (ii) and (iii) are assessed in a rather qualitative manner, criterion (iv) is defined as a publication date after 2015 and a minimum number of 30 citations.

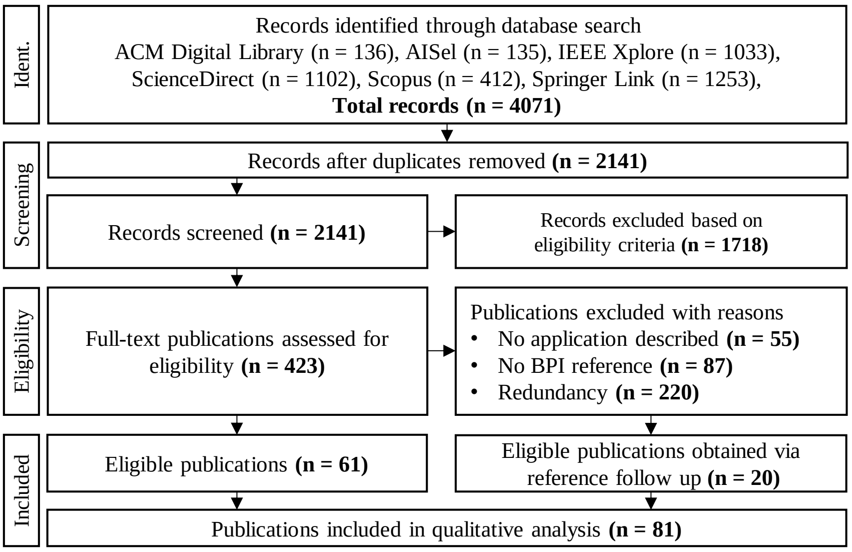

Fig. 3. PRISMA flow diagram.

The literature search and the included reference follow-up resulted in the selection of 81 eligible publications. Having identified the eligible sample of publications, we analyzed it and extracted relevant data using grounded theory. In this regard, we applied the methods of open and axial coding, as proposed by Corbin and Strauss (1990). This approach enabled the derivation of metamodel classes and attributes from the sample of IIoT applications. Figure 4 shows the changes within the baseline metamodel classes during the two design iterations.

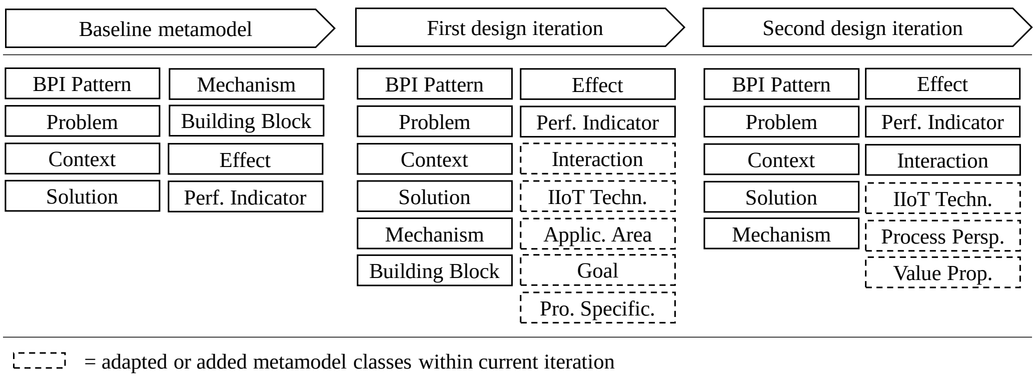

Fig. 4. Design and development iterations.

In the first round, each author analyzed 40 publications of the sample using open coding as an interpretive method to analytically break down all IIoT-based BPI applications. The goal was to develop substantiate categories that enable description, naming, and classifying. After this first round, we discussed the identified categories and harmonized the individual understanding of the main elements of IIoT-based BPIs. In the second round, we applied the method of axial coding to relate the formulated codes to each other. This enabled the creation of further categories and subcategories. In a second discussion, the results were again harmonized. In round 3, the remaining 41 publications were coded with the created set of categories and subcategories to test them against data. Subsequently, we clarified and resolved any remaining coding differences. Following inductive reasoning, according to Hempel (1966), we extensively discussed the created categories and subcategories to select the most relevant ones for the metamodel adaption. These have been used to create a set of classes and related attributes which were added to the base metamodel. Figure 3 shows the resulting metamodel classes during both design iterations.

4.3 Second Development Iteration

To refine the metamodel draft of the first iteration we performed a structured four-round Delphi study. A Delphi study is an iterative method to solicit information about a specific topic through the completion of several surveys. It has been widely used to combine expert knowledge and find group consent for complex issues that lack empirical evidence (Loo, 2002). For this reason, Delphi studies are highly present in the field of DSR research. The study process included the selection of experts with different backgrounds to minimize bias. They did not get introduced to each other, which led to more creative outcomes and reduced conflicts within the group as well as group pressure. The experts were asked to rate or validate the metamodel classes and attributes of the first draft. After each round, the results of all experts were consolidated and used for refinement. We formed a panel of nine experts including five practitioners and four researchers with expertise in the fields of IIoT and Business Process Management (BPM) and BPI.

The five selected practitioners have working experiences ranging from four to 21 years and have accompanied at least one IIoT project within their company. They work as project engineers, project managers, and IT specialists and have at least a bachelor’s degree. The four researchers included two professors, one postdoctoral researcher, and one doctoral researcher. They have been selected based on the impact of their research work. In this sense, all researchers have at least published one scientific article regarding IIoT and BPM in the Senior Scholars’ Basket of Journals. To minimize regional bias, the experts of the panel are based in Germany, the US, or the Netherlands. A detailed description of the expert panel can be found in Table 1. Figure 4 shows the applied four-round Delphi study including all information flows between the authors, facilitator, and the expert panel.

In Round 1, the expert panel was asked to rate the metamodel classes of the initial metamodel draft. They could Retain, Adapt or Drop the individual classes as well as Add further ones. The results of round 1 were analyzed and consolidated using a systematic decision tree which has already been used in different Delphi studies and proved to be appropriate (Serral et al., 2020).

Table 1. Overview of included industry and academic experts during all research activities.

Research activity	Role of expert	Industry/Academia	Employees (2020)
Delphi study and formative evaluation	Manufacturing Technology Specialist	Manufacturing industry	[500-5,000]
	Project Engineer Operations Automation	Manufacturing industry	[5000-10,000]
	Project Manager Digitalization	Chemical industry	[50,000-100,000]
	Head of Digital Operations	Automotive industry	[50,000-100,000]
	Director of IT Operations Management Support	Aerospace industry	[100,000-250,000]
	Professor of Information Systems	University – Faculty of Informatics and Data Science	N/A
	Professor of Information Systems and Business Process Management	University – Faculty of Law, Business & Economics	N/A
	Postdoctoral researcher	University – Faculty of Informatics and Data Science	N/A
	Doctoral researcher	University of Applied Sciences - Faculty of Computer Science	N/A
Pattern creation and summative evaluation	Technical Project Manager Operations	Manufacturing industry	[5000-10,000]
	IT Support Specialist	Manufacturing industry	[5000-10,000]
	Operations Automation Expert	Pharmaceutical industry	[5000-10,000]
	Digital Transformation Expert	Pharmaceutical industry	[5000-10,000]
	Senior Project Manager	Pharmaceutical industry	[5000-10,000]
	Manufacturing Technology Expert	Automotive industry	[100,000-250,000]
	Senior Project Manager	Automotive industry	[100,000-250,000]

A class was only dropped if more than 60% of the experts agreed on this option. No adaptions were considered, if the percentage to retain was at least 80%, while minor adaptions were performed for a retain rate between 60% and 80%. Major adaptions were needed if the retain rate was below 40% or at least 50% of the experts agreed on the option to adapt a class. In Round 2, the experts validated the results of the first round, followed by another consolidation phase. In Round 3, the expert panel was requested to rate the attributes of each class. For new classes, they were asked to introduce corresponding attributes. The consolidated results were validated in Round 4. After this round, a discussion with all experts helped to get feedback and gain insight into the background of the individual decisions. Having refined the classes and attributes, we analyzed relations and subsequently added multiplicities for all classes.

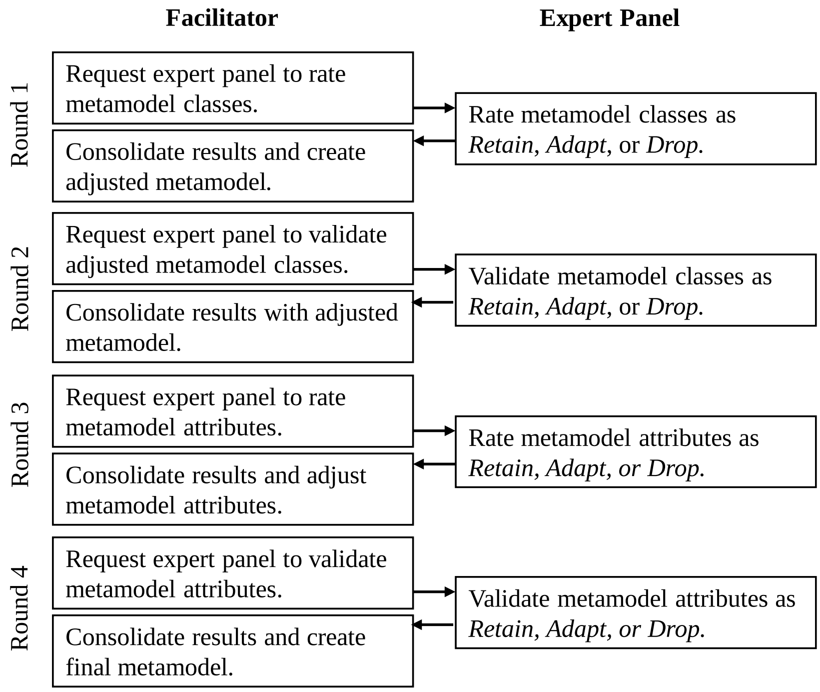

Fig. 5. Delphi study rounds.

5 The Metamodel of IIoT-based BPIs

The final metamodel of IIoT-based BPIs consists of eleven classes and 28 attributes. We added five classes during the first development iteration, namely *IIoT Technology*, *Application Area*, *Interaction*, *Goal*, and *Process Specification*. During the refinement, two further classes *Process Perspective* and *Value Proposition* could be added. The previously created classes *Goal* and *Process Specification*, on the other hand, were removed as a result of the Delphi study. In addition, the class *Building Block* of the base metamodel was removed. Figure 6 shows the resulting metamodel including all classes, attributes, and relations which will be now explained in detail.

According to Falk et al. (2013), the class *Building Block* can be used for result-oriented patterns, i.e., patterns that directly describe the target process, and are models that can be implemented without adjustments. In contrast, procedure-oriented patterns only describe instructions on how to improve the process, but no direct implementation. Since IIoT systems are very complex and cannot provide any benefit without appropriate integration in the process, it is assumed that patterns for process improvement through IIoT can only be procedure-oriented. Therefore, the expert panel agreed to delete this class from the metamodel. Also, we changed the multiplicity of the class

Mechanism. In the base metamodel, each solution contained exactly one mechanism. However, this is an unnecessary restriction that makes it difficult for modelers to create domain-specific BPI models. By removing the restriction, it is possible to define further implementation details of the IIoT application, while the modeler is given greater freedom. The first new class of the extended metamodel is *Interaction*.

As part of the solution, it describes Human Involvement in the IIoT application. This is an essential aspect of describing the integration of the IIoT application into the process and has already been discussed by Patterson et al. (2017). For example, it can describe whether a dashboard is only available to the process owner or whether every actor in the process is always provided with information via wearables, smartphones, or other devices. It comprises interfaces between the IIoT application and humans regarding data input and output. Being a domain-specific element, it constrains the generic BPI metamodel to an IIoT-based BPI metamodel. In particular, the information output or the information transfer to human actors had to be modeled previously using the class Mechanism or could not be modeled at all. Each solution can contain one or more Interactions as there might be several interfaces regarding data input or output, or different groups of persons might be affected. However, the class is not mandatory, as highly automated IIoT systems might not have any human involvement at all.

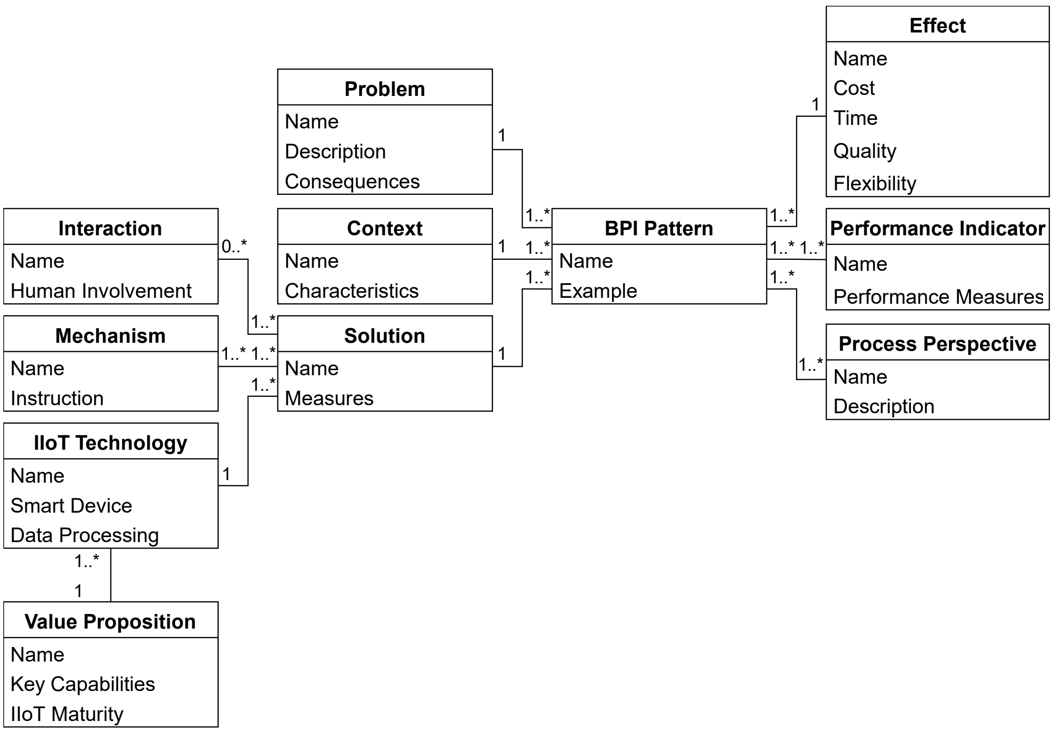

Fig. 6. The metamodel of IIoT-based BPI patterns.

As another new class, IIoT Technology has been added to the metamodel. As the base metamodel could not be used to represent these requirements, the aspects for the basic description of the technical requirements were combined under this generalized class. The class comprises two attributes that explain the necessary technical specification of the IIoT application. At first, the Smart Device type reflects technological and architectural principles. As already described in subsection 2.1, sensors, actuators, and network technologies can turn conventional objects into smart things (or devices). These aspects can be displayed within this attribute. Kortuem et al. (2010), e.g., have already defined three different types of smart devices. Activity-aware devices understand events and activities causally related to the use of the object. Policy-aware devices can reflect whether activities and events are compliant with organizational policies and process-aware devices can place activities and events in the context of processes. A more detailed description of the required hardware, e.g., sensors and actuators, and networking technologies would be too concrete for the creation of generic patterns.

The second attribute *Data Processing* describes the basic features of how the collected IIoT data is analyzed and eventually used to improve the underlying business processes. With cloud computing, for instance, the IIoT device is only responsible for generating the data and does not provide any data processing capabilities. In contrast to centralized data processing, edge computing involves processing and analyzing the generated data (or at least parts of it) directly at the edge of the network by specially designed devices. Depending on the application and the structure of the IIoT system, hybrid approaches can be possible, too. Directly connected to *IIoT Technology* is the new class *Value Proposition*. It describes the actual value that the IIoT technology can provide to solve the addressed problem. It goes beyond the simple description of technological specifications but rather outlines, which disruptive features and capabilities the combination of sensors, networking, and data processing technologies enables. The first attribute that details the class is *Key Capabilities*. The IIoT comprises novel and disruptive capabilities that distinguish it from other technologies. To enable beneficial BPIs, these capabilities must be profitably and systematically exploited. While the combination of these capabilities is often relevant for IIoT-based BPIs, in most cases individual key capabilities can be identified that are particularly relevant. Examples of such capabilities would be universal scalability, comprehensive perception, embedded intelligence, or interoperability. By using specific IIoT technologies and therefore exploiting a set of capabilities, *IIoT Maturity* can be defined. Maturity in this case refers to the complexity of an IIoT application, how deeply it is embedded into the process, and how value is generated. It ranges from simple data collection and analytics to completely automated tasks within the process. Tai Angus Lai et al. (2018) have addressed this topic and identified different possibilities to define this IIoT maturity. They stated situational awareness, decision-making support, information exchange, and autonomous systems as potential manifestations.

Finally, the class *Process Perspective* was added to the metamodel. It describes the perspectives and therefore process aspects that are influenced most by the IIoT application. This is especially useful to illustrate, how the IoT application affects and redesigns the process. Jablonski and Bussler (1996) have stated six process perspectives that can be used in this regard. The behavioral perspective comprises elements of the right process workflow or sequence, legal regulations such as reporting obligations, and internal requirements. The organizational perspective focuses on the personnel that is involved in the process execution. Its main components are responsible process owners, admins, and users. In addition, the underlying system is part of this perspective and represents for example the IT environment. The functional perspective includes concrete process steps, tasks, and events. Most of the processes, especially in the industry, comprise several machines, tools, and software applications that can be described from the operational perspective. The data perspective involves all data and documents that are necessary for process execution. Finally, the locational perspective describes the specific locations of process entities, e.g., machines or workers.

6 Metamodel Demonstration and Design of Initial Patterns

Having designed the metamodel, we demonstrated it and used it to create an initial set of patterns. This delivered valuable insights into the usefulness of the metamodel and resulted in a starting point for a comprehensive pattern catalog. For deriving the patterns, we requested seven practitioners from three multinational industrial companies to analyze the IIoT applications within their business areas. All practitioners have a broad knowledge of IIoT technology and business processes in general and have working experience between five and 18 years. They work as technical project managers, IT managers, automation experts, or digitalization managers and are the responsible persons for conducting IIoT projects within their organizations. A more detailed description of the experts can be found in Table 1. In total, they identified 34 IIoT applications with BPI propositions that were suitable for further analysis. In a joint workshop that took place in the form of a video conference in February 2021, six different patterns could be derived and illustrated using the provided metamodel. These patterns are *Process Guidance*, *Derivation Detection*, *Authentication and Authorization*, *Task Distribution*, and *Activity Automation*.

6.1 Process Guidance

The first pattern *Process Guidance* (cf. Figure 7) generically describes applications focusing on improved user guidance. By capturing situational and process-related data, the actual process state and subsequent process tasks can be ascertained. The next process tasks can then be displayed to process participants, e.g., via wearables. This pattern mainly affects the operational and data perspectives, as the way of performing process tasks is changed by using input and output data. The used smart devices are process-aware as they need to capture process-related data, process it, and provide it to the process participants concerning the current process state. The example given in the pattern is taken from an automotive company where employees get visual instructions and indications that guide them through all process tasks.

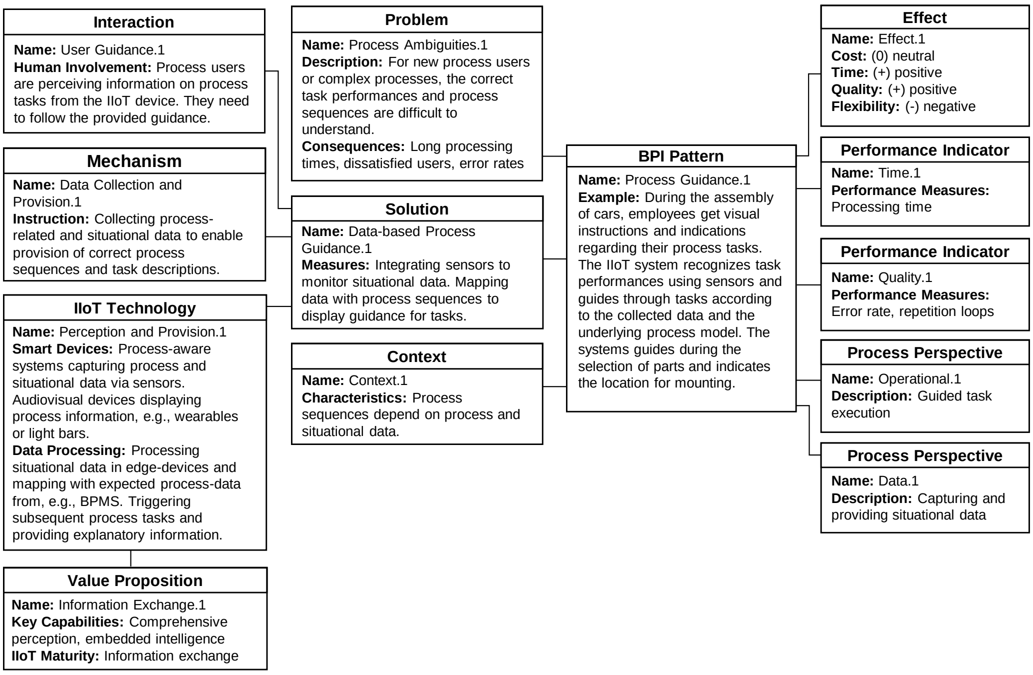

Fig. 7. Process Guidance pattern.

Due to the comprehensive perception of integrated sensors and the embedded intelligence and data processing at edge devices, the IIoT systems can track the actual process flow. This enables the provision of information about the current task using light bars of different colors. The implemented pattern leads to improved processing time, as well as decreased error rates and repetition loops. Another relevant literature application of this kind is the training of new employees in a manufacturing company (König et al., 2019). Employees are guided through process tasks by tracking the current process data and visualizing process descriptions of subsequent tasks. Other companies have implemented applications to guide employees through production or logistic processes by capturing environmental and process data, processing it, matching it with process models, and providing guidance for tasks (De Vries et al., 2015).

6.2 Deviation Detection

The second pattern *Deviation Detection* is exemplarily described using a gas bottle filling process in the pharmaceutical industry, as seen in Figure 8. The main challenge for companies is the detection of process deviations during runtime to identify incorrect task executions and adequately adapt the subsequent process flows. Deviations lead to low process quality, process deadlocks, or the need for process support. After the filling of toxic gas bottles, they must be placed in the right areas according to the process description. Incorrect task executions include high-risk potential. By implementing location sensors that collect task execution data and collating it with expected values from the process description, deviations can be detected.

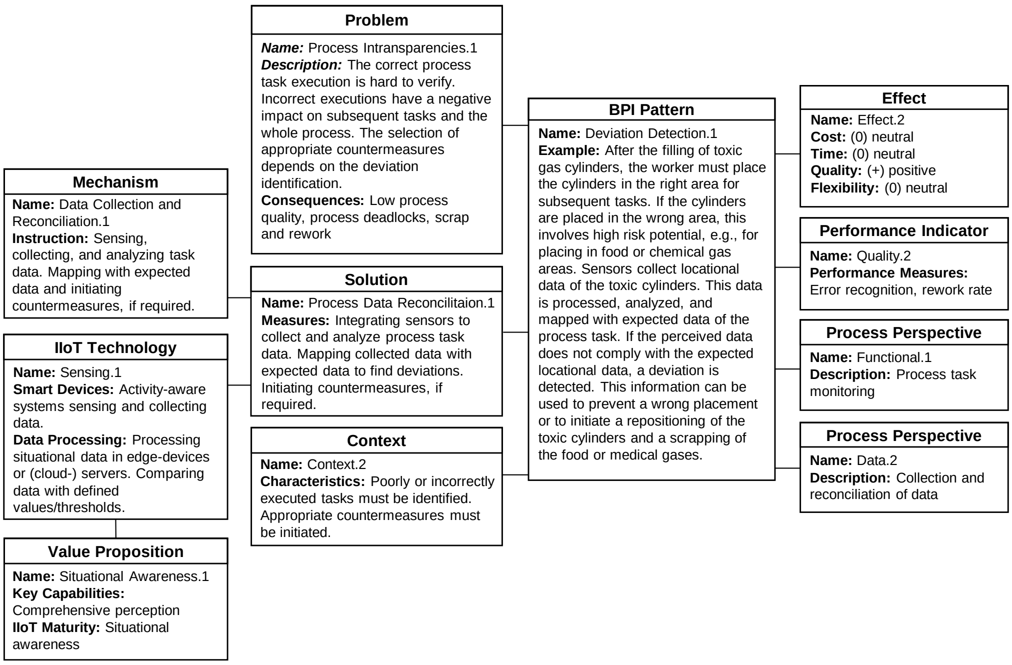

Fig. 8. Deviation Detection pattern.

This enables the initiation of countermeasures and leads to an improved error recognition rate which has a positive impact on the overall process quality. The pattern addresses the functional and data perspectives, as the execution of the process task is monitored. The IIoT technology includes activity-aware smart devices that process situational data on edge devices or (hybrid) cloud servers. To identify deviations of any kind, the key capability of comprehensive perception must be exploited to enable situational awareness of all process details. The implemented pattern improves process quality in terms of increased error recognition rate and decreased rework rate. Similar industrial applications can be found for the detection of machine failures where sensor data is used for diagnostics and detection of deviations, e.g., at leakage detection (Ammirato et al., 2019) or other anomalies (Schneider et al., 2019).

6.3 Authentication and Authorization

Many processes require authorized users to guarantee process safety and quality. Therefore, potential users need to authenticate their identity to check if they are authorized for performing specific tasks. The third pattern *Authentication and Authorization* solves this challenge by illustrating a suitable IIoT-based solution. The exemplary process is taken from a car assembly process of a major automotive company. During the assembly process, the safety-critical anti-lock braking system (ABS) module must be correctly placed, fixed, and connected to the car. As this should only be performed by trained personnel, authorization is required. The employee must authenticate to get access to the respective ABS module storage container. This container is only unlocked if the user has authenticated himself with valid credentials and the location of the employee is directly at the respective car. This can be done using smartwatches or other personal IIoT devices. The pattern mainly influences the organizational and data process perspectives, as user and process data are collected and used for authenticating the process participant. This has a highly positive impact on process quality as it improves the overall process safety. Similar IIoT applications can be identified in several industry applications aiming at checking customer authorization and authenticating employees in the production area or the logistics sector. For instance, the material handling of special products is only allowed for trained personnel, wherefore an authentication is necessary (De Souza et al., 2020).

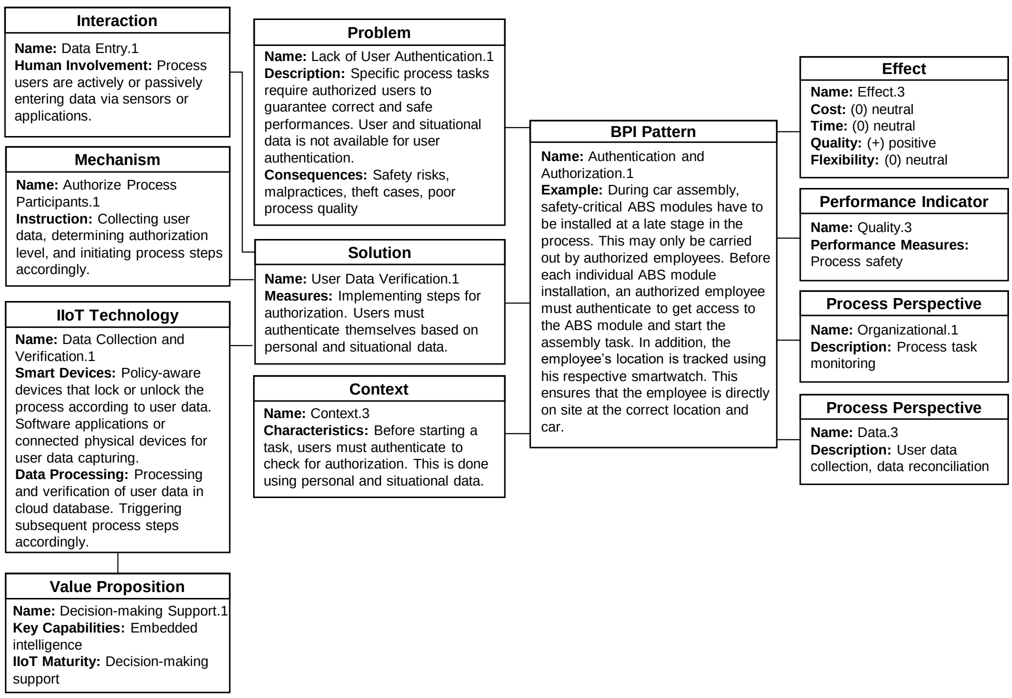

Fig. 9. Authentication and Authorization pattern.

6.4 Task Distribution

The fourth pattern *Task Distribution* originates from the problem of automated and efficient allocation of process tasks to a multitude of process users with specific knowledge and skills. In the corrugation industry, the different production process tasks need to be distributed to workers according to their situational and personal characteristics. This is performed by capturing data on their current location, fatigue, or skills and competencies, and matching it with process task requirements. By processing the data coming from activity-aware systems on edge or cloud devices, the parameters can be mapped with the task data. When distributed to a specific worker, the task can be displayed via wearables, e.g., smartwatches or other audiovisual devices. This improves the process quality, as the most appropriate person is performing the tasks. This pattern can also be identified along whole supply chains to achieve an IIoT-enabled optimization of task allocation. By performing information-driven dynamic optimizations based on IIoT data, the distribution of logistics tasks along the supply chain entities can be significantly improved (Liu et al., 2018).

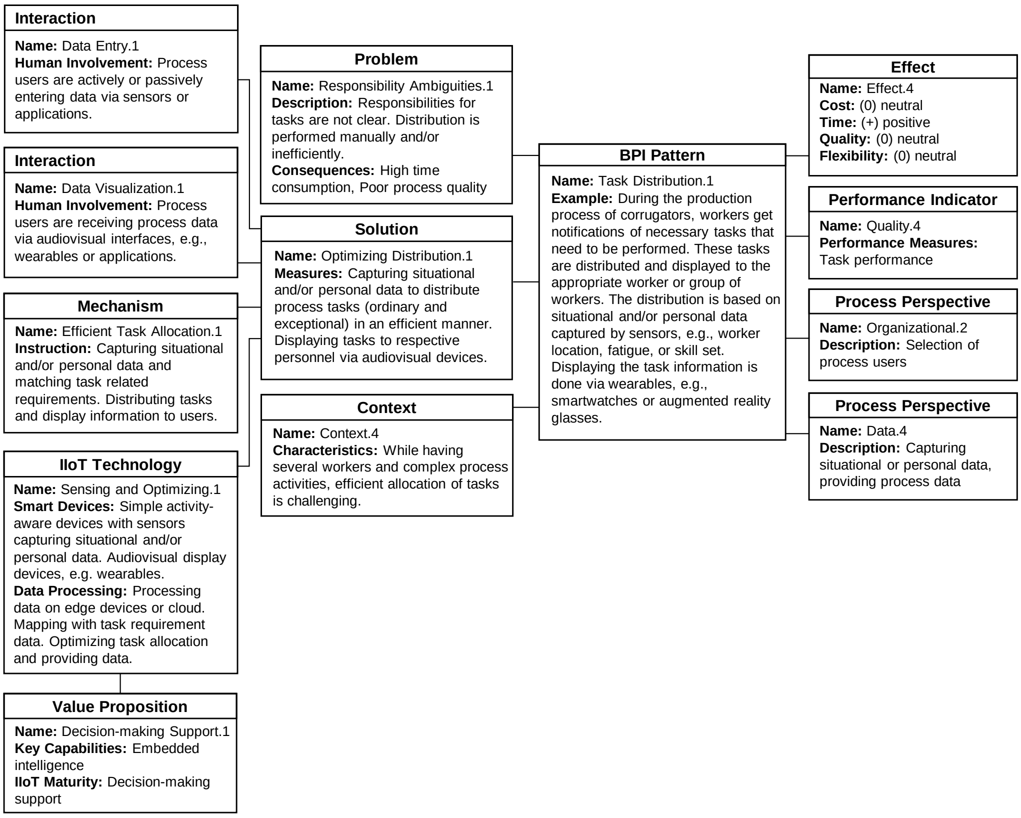

Fig. 10. Task Distribution pattern.

6.5 Activity Automation

Replacing manual process tasks with automated tasks contains major benefits for companies of all kinds. As manual process steps require trained personnel, it is associated with high labor costs and high working time consumption. The fifth pattern *Activity Automation* addresses this problem. The example described in Figure 11 is taken from the manufacturing industry. Here, forklift drivers needed to manually scan pallet barcodes and storage location barcodes to enable effective material tracking. Using location sensors and providing this information to overarching control systems can enable automated tracking and tracing. Sensors capture location data that is processed on edge devices or cloud services. Based on the data input, mechanical or software-based reactions can simulate manual activities. These systems form rather complex process-aware IIoT devices that can reduce labor costs, working time, and overall processing time. As the actual process flow is redesigned by the IIoT technology, it mainly influences the functional process perspective. The pattern has a positive impact on labor costs as well as working time consumption.

Improving business processes by automating activities is one of the most relevant and frequent patterns in the literature. Several use cases have been identified during the literature review describing autonomous systems containing high-complexity IIoT systems. Li et al. (2017), e.g., describe a fully autonomous system in which the production object can automatically coordinate with the production and transportation machines and plan an optimal production process. The object to be processed is equipped with a microchip for this purpose and can receive individual production instructions from the cloud to enable a maximally flexible and fully automated process. Other examples describe the automation of whole activities within food supply chains (Pang et al., 2015). This comprehensive study shows the bandwidth of application possibilities of this pattern.

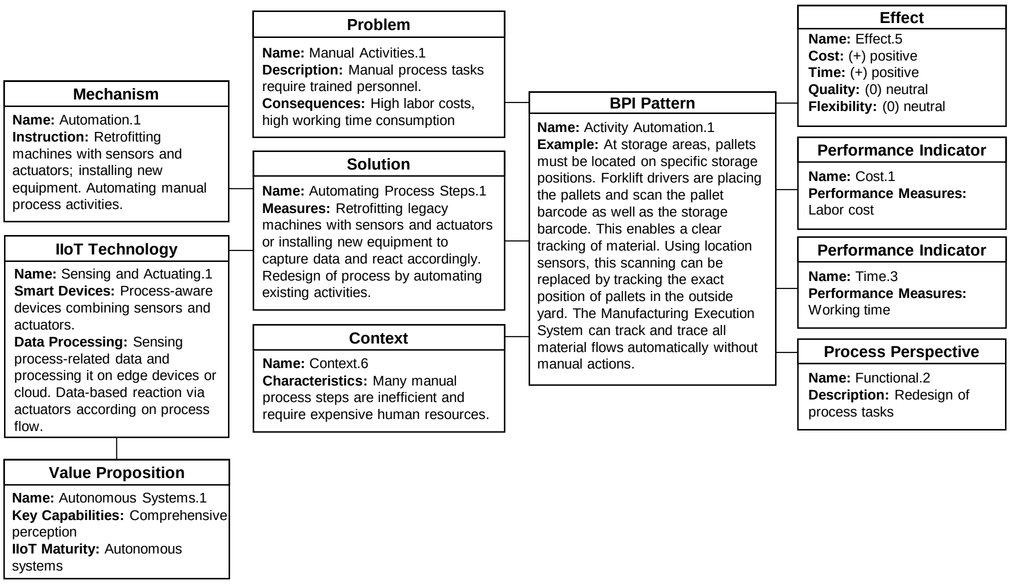

Fig. 11. Activity Automation pattern.

7 Evaluation

The five initial patterns formed the basis for the summative evaluation which aimed to assess the underlying metamodel's *completeness* and *conciseness*. The experts' experiences and impressions allowed us to gain deep insights into the actual application of the metamodel. The heterogeneous composition of the experts along different industry sectors resulted in valuable knowledge of the artifact's value.

Table 2. Expert survey results.

No.	Statement	Strongly agree	Agree	Neutral	Disagree	Strongly disagree
1	The metamodel's classes and attributes enabled an appropriate illustration of IIoT-based BPI patterns.	29%	71%	0%	0%	0%
2	The metamodel's classes and attributes allowed an appropriate degree of abstraction and generalization.	29%	57%	14%	0%	0%
3	The metamodel allowed an illustration and description of generic business process problems and potential solutions provided by IoT technology.	14%	86%	0%	0%	0%
4	Extending the metamodel would contradict its generic design, limit its generality, and decrease the number of applications that can be covered by a pattern.	29%	42%	29%	0%	0%
5	Removing classes and attributes would reduce the expressiveness of the patterns.	86%	14%	0%	0%	0%
6	The metamodel's classes allowed a sufficient differentiation of the represented patterns.	71%	29%	0%	0%	0%

This hybrid evaluation episode includes characteristics of an artificial and naturalistic setting, as the derivation of patterns is based on real-life IIoT applications, but the patterns are not put to use in an industrial setting. The expert panel received a list of six statements for which they needed to indicate their agreement or disagreement. This followed the proven psychometric tool of the Likert scale (Likert, 1932). The statements were formulated in a way that allows conclusions to be drawn about the two evaluation criteria. Table 2 shows all statements and the obtained survey results. For wording the statements, we leaned on the principles of the Technology Acceptance Model (Davis 1989). As a result, most of the practitioners agreed or strongly agreed with all of the statements. Only for the second statement, one practitioner could not specify, if the metamodel's degree of abstraction and generalization is appropriate for the derived patterns. These results proved that the metamodel includes all necessary aspects and elements of IIoT-based BPI and is concise and, therefore, generic enough to be applicable to different companies

8 Discussion

The IIoT is recognized as one of the most relevant and significant paradigms in the industrial domain. It comprises novel disruptive capabilities and is associated with the potential to transform and improve business processes of all kinds. Yet, industrial companies still struggle to exploit their full potential (Bosche et al., 2016). Although the literature on technological aspects of IIoT can certainly be considered mature, the integration of IIoT technology in processes has so far been insufficiently researched which eventually led to a blind spot for practitioners. This explains why companies face difficulties in advantageously using IIoT for improving business processes. A goal-oriented identification of IIoT applications that enable appropriate BPIs is not supported by the research of any means. Moreover, the *"Act of Improvement"*, i.e., how existing business processes are transferred to the improved target state by integrating IIoT, can in most cases not be defined precisely. To tackle these challenges, and extend and advance the knowledge of IIoT, we created the metamodel of IIoT-based BPI and an initial set of five patterns. The most significant theoretical and practical implications that became apparent during the development, demonstration, and evaluation activities are outlined in the following subsections. In addition, we present the existing limitations of the study.

8.1 Theoretical Implications

From a theoretical standpoint, our study provides relevant and new perspectives on the IIoT as an enabler for valuable BPIs. To the best of our knowledge, this study is the first to create an in-depth understanding of the mechanisms and aspects of IIoT as an enabler for BPI. Our theoretical contribution is a well-founded metamodel that comprises all indispensable elements and relations of IIoT applications with BPI reference. The core theoretical implications of our study are twofold, as it adds to the descriptive knowledge of IIoT and BPI and lays the foundation for further research on respective patterns.

As a theoretical theory and design artifact, the created metamodel complements existing descriptive knowledge on both IIoT and BPI (Gregor, 2006). The metamodel deliberately focuses on mechanisms and aspects that explain solutions to process-related problems and not purely technology-related characteristics. This gives the metamodel persistency within changing IIoT environments where novel technologies are developed rapidly. The process-related view on IIoT applications proposes new facets to the predominant technical and engineering focus of IIoT and introduces a novel catalytic idea for further research. Thus, the metamodel provides a foundation for the theory-led design and sense-making (Gregor and Hevner, 2013). We based our study on the existing BPI metamodel of Forster (2006) and advanced it by adding elements specifically related to IIoT. This brings novel facets to the research area of BPI and extends its substance by more technical aspects. Against this background, the proposed metamodel extends and advances both research topics IIoT and BPI by combining them.

The main purpose of the developed metamodel is to provide a basis for the creation and illustration of manifold patterns. In this regard, the creation of an initial set of patterns enabled a summative evaluation and took the first step toward a comprehensive pattern catalog. Such a catalog would represent a critical piece of the puzzle to specify, identify, and implement IIoT applications more successfully and systematically. The proposed metamodel, therefore, builds the foundation for further discourse and the derivation of patterns from real-world applications. This incremental theorizing may also improve the understanding of how companies can succeed in adopting Industry 4.0 and digital transformation, as IIoT is one of the focus areas.

8.2 Practical Implications

From a practical and managerial standpoint, the metamodel and the initial set of patterns are noteworthy and valuable. They provide practically relevant insights as existing studies regarding the IIoT and its technical composition have few practical implications for process-oriented industrial companies. Past research and surveys among managers have shown, that most IIoT projects remain in the proof of concept or early planning phases and often fail to deliver the expected benefits. This necessitates support during the phases of project execution, namely identification, specification, and implementation. In this regard, the demonstration and evaluation of the metamodel have pointed out two major practical implications.

First, the usage of patterns, based on the created metamodel, allows managers to investigate and identify appropriate IIoT applications. As the patterns include a description of the underlying process problems, the influenced process performance indicators, the impact on process perspectives, and a generic illustration of potential solutions, a goal- and process-oriented identification of applications is enabled. With the help of our patterns, companies of all industrial areas can assess their processes, create action plans, and even establish an IIoT strategy for departments or the whole company. The patterns also prevent the development of wrong expectations on IIoT projects, as the benefits of the processes are clearly described. This may also avert the implementation of insufficiently planned and falsely selected projects.

Second, instantiating the *"Act of Improvement"* constitutes a major challenge for industrial companies. This means, that proceeding from a detailed specification to a final implementation includes several intricacies, unpleasant surprises, and hurdles that must be managed. The patterns can support this demanding project phase by describing crucial mechanisms and interconnections between the extant problem and the planned solution. This goes beyond technical details and includes specifying the context and process perspectives that need to be considered. Moreover, the performance indicators give a clear indication, of whether the project reached maturity and the expected goals have been achieved.

8.3 Limitations

Although we have endeavored to be as thorough and rigorous as possible the study is not without limitations due to the nature of DSR. Following an inductive approach for metamodeling is a proven concept that provides several advantages arising from building up on actual observations. However, the underlying SLR cannot cover all existing data on the phenomenon under investigation. The identification of literature is limited to the incorporated databases and formulated queries. To mitigate this subjectivity, we conducted a comprehensive Delphi study. This enabled both a formative evaluation and the inclusion of broad expert knowledge. Another limitation concerns the type of artifact that we developed. A metamodel can structure and illustrate indispensable aspects, facets, and elements of IIoT and BPI. However, it does not specifically provide procedural guidance in the form of methods (Hevner et al., 2004). Further research would do well to create a method as an artifact to provide even more guidance within project execution phases and activities. Finally, the creation of further patterns must be considered a continuous research topic, as technological progress inevitably leads to novel BPI propositions.

9 Conclusion and Future Research

This study proposes a metamodel of IIoT-based BPIs that can be used to illustrate generic yet adoptable patterns of IIoT applications. Furthermore, the first set of five patterns is presented. The research endeavor followed the fundamental principles of DSR and was based on the methodology of Peffers et al. (2007). In two development iterations, the baseline metamodel of BPI by Falk et al. (2013) has been adapted by adding additional classes and attributes and dropping irrelevant ones. At first, we performed an inductive development iteration including an SLR followed by open and axial coding. Additional classes and attributes could be derived and added to the existing metamodel based on the results. The first metamodel draft was then refined by conducting a Delphi study with nine experts from industry and academia. To evaluate the final metamodel, seven practitioners from three multinational companies analyzed a set of 34 real-life IIoT applications in their business areas. They derived five patterns and illustrated them using the metamodel. In a subsequent survey, the experts assessed the metamodel according to the predefined evaluation criteria of comprehensiveness and conciseness.

We are confident, that both the metamodel and the initial set of patterns extend and advance existing knowledge and constitute valuable tools for researchers and practitioners. The patterns can be used by industrial companies of all kinds to identify, specify, and implement IIoT-based BPI applications. We hope that all respective groups benefit from the created artifacts and that further research will continue to establish a comprehensive pattern catalog.

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5 P5: Process-aware Decision Support Model for Integrating Internet of Things Applications using AHP

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Conference Description: The purpose of the International Conference on Enterprise Information Systems (ICEIS) is to bring together researchers, engineers and practitioners interested in the advances and business applications of information systems. It covers different Enterprise Information Systems Applications topics, including Enterprise Database Technology, Systems Integration, Artificial Intelligence, Decision Support Systems, Information Systems Analysis and Specification, Internet Computing, Electronic Commerce, Human Factors and Enterprise Architecture.

Process-aware Decision Support Model for Integrating Internet of Things Applications using AHP

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Keywords: Internet of Things, Decision Model, Business Process Improvement, Analytical Hierarchy Process.

Abstract: Following the trend of Industry 4.0 and Cyber-Physical Systems (CPS), many industrial companies perform costly projects to integrate Internet of Things (IoT) applications aiming at beneficial business process improvements. However, deciding on the right IoT projects is challenging and often based on unilateral assessments that lack the required profoundness. A suitable method for deciding on specific IoT applications is required that incorporates the desired goals and considers the underlying process details. We therefore propose a structured decision model that considers IoT application clusters, anticipated Business Process Improvement (BPI) goals, and details of the process where the application should be implemented. At first, specific IoT application clusters are developed by conducting an extensive literature review. These clusters are examined regarding several characteristic such as their value proposition or technical aspects. Using this information, an Analytical Hierarchy Process (AHP) model is proposed, that incorporates the main objective, relevant BPI dimensions, and the formulated application clusters. To validate our approach, we applied the model to an actual business process of a leading industrial company.

1 INTRODUCTION

With more than 34 billion IoT devices, the number has more than tripled from 2012 to the year 2018 (Burhan, 2018). And although IoT is anticipated to have massive benefits for companies, a survey of more than 500 business executives revealed, that 90% of organizations are remaining in the proof of concept or even early-stage planning phases for IoT projects (Bosche, 2016). This lack of IoT application maturity can be explained by the complexity of IoT technologies and the extent of included components. This complexity is the reason that adopting IoT technologies is quite different compared to adopting other technologies, which leads to a scarcity of decision models and procedures that support a proper selection of suitable IoT applications (Boos, 2013). This challenge will be addressed within the text at hand, by proposing a structured decision model for selecting IoT applications. To determine an appropriate decision basis, it is necessary to be aware, that most companies highly focus on Business Process Orientation (BPO), as this paradigm resulted in significant positive impacts for adopting enterprises (Willaert, 2007). Therefore, a major part of the value generated by IoT applications is based on Business Process Improvements (BPI) and its core performance measures cost, quality, time, and flexibility (Dumas, 2018). Incorporating the underlying process is increasingly considered as an important preliminary for IoT applications. Janiesch et al. (2017) stated process-aware integration of IoT applications as one of the main challenges for companies initiating IoT projects. In addition, while analyzing existing decision support models, it became apparent, that a decision model must be goal-oriented and incorporate best-practice experiences of already implemented applications to find high acceptance among decision makers in companies (Bradley, 2013). As there have already been hundreds of industry-related and domain-specific IoT applications successfully implemented, they should be analyzed and aggregated to serve as blueprints for further applications. These applications can be allocated into distinct clusters according to their main constituents such as the used technologies, their value propositions, and other attributes described in subsection 2.2. This structured clustering can then be used within a quantitative and goal-oriented model to create a priority for possible IoT projects.

To the best of the authors' knowledge, there has been no research that addressed a structured decision

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model for integrating IoT applications, which also considered actual IoT application clusters and anticipated process improvement goals. Existing approaches either focus on on key learnings from other industrial use cases (Bradley, 2013) or suggest frameworks to build up an IoT strategy, which is derived from the company's major business goals (Li, 2012). The work at hand closes this research gap by providing a decision model, that includes two main contributions, *i)* an extensive literature analysis and synthesis of sucessfully implemented IoT applications including a systematic clustering, and *ii)* a decision model based on the Analytical Hierarchy Process (AHP), that supports companies to prioritize relevant application clusters according to their potentials for business process improvement. The model can be used to investigate potential IoT applications for a specific process or a set of related processes. The paper is organized as follows. Section 2 presents the rigorous literature review on IoT applications as well as a clustering. In section 3, the AHP model and its constituents are addressed. After developing an AHP instance for the relevant topic, it is evaluated in section 4, based on an actual process. Section 5 summarizes the contribution and formulates a future research agenda.

2 IoT APPLICATION REVIEW

The methodology to survey the state of research is a structured procedure proposed by vom Brocke et al. (2009). The literature search itself was conducted according to the Preferred Items for SLRs and Meta-Analysis (PRISMA) statement, which improves the traceability of the actual search process (Liberati, 2009).

2.1 Literature Search

Figure 1 shows the results of the literature search within a PRISMA flow diagram. The method gradually reduces the number of publications by assessing the eligibility using predefined criteria.

At first the search string *("IoT" OR "CPS") AND ("BPI" OR "Process Improvement" OR "Process Optimi?ation" OR "Process Automation" OR "Application" OR "Process Improvement")* as well as the written-out forms have been formulated. To incorporate and consider preferably all relevant journals and conference proceedings of the research area, ACM Direct Library, AISeL, IEEE Xplore, ScienceDirect, Scopus, and Springer Link have been queried. According to the PRISMA statement, four criteria were defined that a paper needs to achieve to be eligible for this review. The publication must *i)* be a peer-reviewed research paper published in a journal or conference proceeding, *ii)* propose an evaluated solution or real industry application, *iii)* have relevant links to BPI or BPM, and *iv)* be relevant and up to date. As criteria *ii)* and *iii)* are assessed in a rather qualitative manner, criterion *iv)* is defined as a publication date after 2015 and a minimum number of 50 citations. However, if a publication is assessed as highly relevant, the violation of these quantitative criteria is tolerated. A high degree of relevance is given, when a publication was published in a top journal and offers a contribution that cannot be obtained from other eligible publications.

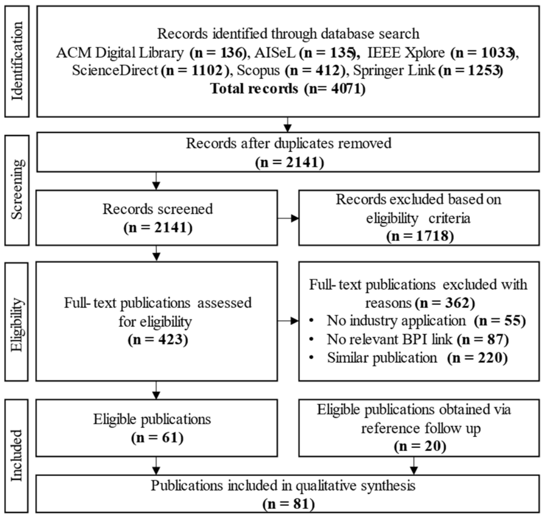

Figure 1: PRISMA Flow Diagram.

Considering criteria *i)* and *iv)*, 1718 records were removed because of a publication date before 2015, low number of citations, or the lack of a peer-review. Eventually, 423 publications were assessed for eligibility based on their abstracts and, if relevant, full texts. Among them, 55 articles did not describe an actual industry solution that can be used for further analysis. Another 87 publications had no specific link to BPI or did not offer any process orientation at all, and 220 articles mentioned a use-case that is remarkably similar to at least another one under consideration. In total, 81 publications were assessed to be eligible including 20 articles obtained from reference follow up.

2.2 Cluster Analysis

After the literature search and selection, a two-step literature analysis framework is applied to derive insights and eventually identify clusters within the set of publications. At first, the publications are categorized in a concept matrix according to Webster and Watson (2002), which gives a first overview of central issues of the contributions. Secondly, a cluster analysis is performed by applying a Multiple Correspondence Analysis (MCA) and a Hierarchical Clustering on Principal Components (HCPC). To categorize all publications according to their main attributes, a concept matrix with five dimensions and 23 subdimensions has been created. The dimensions correspond to concepts for classifying the publications and consist of further subdimensions.

According to Bloom et al. (2018), IoT systems can be fundamentally divided into four areas of application, maintenance, process control, supply chain, and infrastructure.

Table 1: Concept Matrix.

Reference	Dimensions	Subdimensions	Rel. Freq.
Bloom et al. (2018)	Application Area	Maintenance	13%
		Process Control	58%
		Supply Chain	26%
		Infrastructure	3%
Kortuem et al. (2010)	Smart Thing Type	Process-aware	32%
		Policy-aware	24%
		Activity-aware	45%
Tschofenig et al. (2015)	Communication	Backend-Data Sharing	11%
		Device-to-Gateway	55%
		Device-to-Cloud	34%
		Device-to-Device	11%
Patterson (2017)	Human Involvement	Full Automation	3%
		Action Implementation	21%
		Decision Selection	24%
		Information Analysis	42%
		Information Acquisition	11%
Tai Angus Lai et al. (2018)	Value Creation	Complex Auton. Systems	8%
		Inf. Sharing & Collaboration	34%
		Opt. Resource Consumption	21%
		Automation	45%
		Decision-Making Support	45%
		Situational Awareness	50%
		Tracking and Monitoring	39%

Kortuem et al. (2010) have identified three different types of smart things, that reflect basic design and architectural principles. Activity-aware things understand events and activities, policy-aware things can reflect, whether activities and events are compliant with organizational policies, and process-aware things can place activities and events in the context of processes. IoT systems can consist of small local networks up to global networks, while different network architectures are used. The Internet Architecture Board (IAB) has proposed four possible models, in which IoT devices can be networked (Tschofenig, 2015). Patterson (2017) described another categorization dimension, the type of human involvement to classify the degree of automation. The last dimension represents the type of value creation that is provided by the IoT application. Tai Angus Lai et al. (2018) identified eight different areas of value creation by IoT, which serve as subdimensions for the concept matrix. The 81 eligible publications were then categorized according to at least one subdimension of each dimension. The rightmost column of Table 1 shows the relative frequency of the specific subdimension for all analyzed publications. The MCA has then been used as a preprocessing to transform the categorical binary variables from the concept matrix into continuous ones, that are then used within an HCPC to find distinct clusters in the data set, see Figure 2.

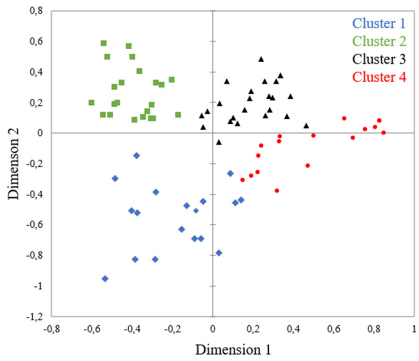

Figure 2: MCA Factor Map.

The data is plotted in a two-dimensional space depending on their similarity to each other. The greater the distance between the individual data points, the more different the items are in relation to the dimensions of the concept matrix.

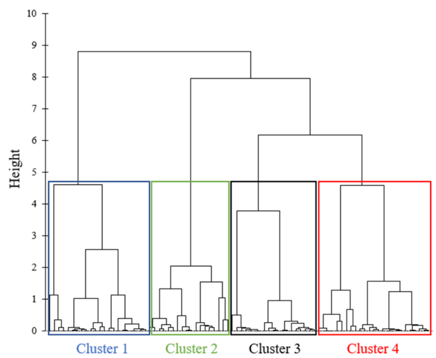

Figure 3: Dendrogram of Cluster Analysis.

The clusters have been created using the HCPC and are visualized by different colours and data point shapes. The results analysis has shown that optimally four clusters can be formed. Another form of visualizing the HCPC results is the dendrogram shown in Figure 3. Here, the different distributions of each cluster are shown in the form of exactly two branches per level. The higher the tree, the higher is the variance between the included publications.

Based on this analysis, the publications of each cluster have been examined again to investigate similarities and interpret them. The results are described in the following subsections.

2.2.1 Improved Information Exchange

The first cluster comprises 20 applications, in which the IoT systems serve to collect information about the process flow and the process environment. The smart devices used for this cluster are mostly process-aware and connected to the cloud via gateway. The gateway only serves to forward data, while the analysis takes entirely place in the cloud. The IoT devices perform a context-sensitive communication and interaction between several process entities such as machines or employees. Due to the strong involvement of people in the process, the benefits of IoT systems is not automation but improved communication and coordination of information, e.g., by using wearables. Schönig et al. (2020) for example described a production process in a cardboard factory and an improved information exchange and visualization using IoT sensors and smartwatches. Moreover, König et al. (2019) illustrated the training of new employees in a manufacturing company with the help of smart devices.

2.2.2 Tracking and Tracing

Cluster 2 comprises 22 publications including IoT systems for mainly tracking and monitoring solutions using simple activity-aware devices, such as RFID tags. The sensed data is mostly sent to a cloud for further processing and provision of IoT services. One focus is process improvement along the supply chain, in which the continuous tracking of the involved resources is particularly important. Chang et al. (2019) describe a smart container for transporting chemical waste products, so it can independently send transport information to a cloud. Other publications show applications in the manufacturing industry that enable location monitoring of products and machines (Valente, 2017) or unique identification using RFID (Rasmussen, 2019). These applications provide an improved transparency and therefore better process quality, since a permanent traceability is guaranteed.

2.2.3 Faster Reaction to External Influences

Cluster 3 comprises 23 case studies, focussing on identifying environmental factors and responding to changes in a rapid way. The used smart things are mostly policy-aware and can independently detect deviations from predefined process rules. As soon as these rules are violated, the things can trigger signals which cause further reactions. Data processing is often performed using cloud services or edge computing. Ammirato et al. (2019) introduced an IoT application to improve the security measures of a bank. With the help of cameras and hybrid data processing or image analysis in real time, threats can be detected automatically at an early stage to initiate countermeasures. Other applications based in the agricultural industry comprise systems that measure the environmental parameters of fields, such as moisture, and can initiate appropriate actions, if necessary (Celestrini, 2019).

2.2.4 Flexible Automated Systems

The last cluster comprises 16 case studies, which are further scattered on the factor map. These applications include more complex IoT systems than those comprised in the other clusters. Li et al. (2017) describe a completely autonomous system in which the production materials can automatically communicate with the equipment and transporting machines to plan and schedule the production. In the case study of Nikolakis et al. (2020), a set of robots and humans can handle production material and are both connected to a mutual network. By performing the production planning and scheduling in a cloud, the work steps can be planned when a new material arrives, and appropriate instructions can be sent to the robots or smart devices used by human. Also, retrofitting and automating machines can be a major step towards flexible process automation and IoT-guided process execution (Murar, 2014).

3 DESIGNING THE AHP MODEL

3.1 AHP Setup

The AHP has been introduced as a theoretical modelling technique for complex decision making (Saaty, 1990). The user designs a multi-layer decision tree including the main objective, relevant criteria that affect the decision, and possible alternatives. Subsequently, expert surveys are performed to collect numerical data for every model layer. The criteria are pairwise compared against each other regarding their importance for achieving the objective. In the same way, all alternatives are pairwise compared against each other for every single criterion. Consequently, the comparison data is processed to get a priority of importance for each alternative.

3.2 Design of Decision Tree

The first step of the AHP is to design the decision tree by defining the decision problem and its objective, decision criteria, and potential alternatives. In the following, these three layers will be specified for our model instance. The AHP model addressed in this paper focuses on prioritizing potential alternatives that may improve the underlying process. The top layer of the AHP therefore is BPI as the main objective. The second layer consist of respective decision criteria, that influence the degree of objective achievement. Popular Process Performance Measures (PPMs) related to BPI are time, cost, flexibility, and quality (Dumas, 2018).

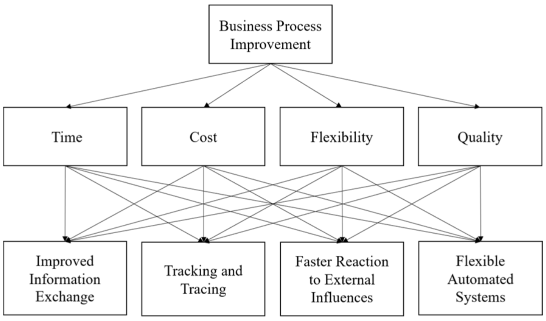

Figure 4: AHP Decision Tree.

Thus, these four components are forming the second layer of the AHP model. The third layer represents possible alternatives to achieve the decision criteria and therefore eventually the main objective. In this case, the identified IoT application clusters are used as relevant decision alternatives, as they are representing aggregated manifestations of IoT implementations. The complete AHP including all layers is shown in Figure 4.

3.3 Data Collection

After designing the decision tree, data needs to be collected by conducting a survey questionnaire for experts and decision makers. This survey consists of two parts, a pairwise comparison of the decision criteria and a pairwise comparison of all alternatives. The criteria must be evaluated in pairs to determine the relative importance between them and their relative weight to the main objective. Analog, the alternatives must be evaluated in pairs to determine the relative importance between them and their relative weight to the decision criteria. The participants need to indicate the relative importance according to a 9-point comparison scale, with increasing importance by increasing numbers. Filling the comparison matrices, the diagonal cells always contain number 1 as they represent the cell value against itself. For a squared comparison matrix with rows i and columns j, each matrix element $a_{i,j}$ has a reciprocal value $a_{j,i}$.

After conducting the survey, a three-step procedure is performed on each matrix including *(i)* gradually squaring the matrices, *(ii)* calculating the eigenvector, and *iii)* repeating step *i)* and *ii)* until the calculated relative weights differ only slightly between two runs. The deviations between the calculated weights decrease with increasing potency, so that an approximation to the actual relative weights is made progressively.

3.4 Results Calculation

At first, criteria weight scores W_C are calculated, which represent the relative importance of the criteria and are mathematically described by the eigenvector. According to subsection 3.3, it is obtained by normalizing the row totals of the squared matrix. The normalization is done by dividing each value by the total column sum. Secondly, the local weight scores of the alternatives W_L are calculated for every criterion. Here, the weight scores W_L represent the relative importance of the different alternatives for the specific criterion. Finally, the global weight of every alternative W_G is determined by multiplying the matrix consisting of all local weights W_L with the vector of the criteria weights W_C. The vector W_G describes the relative importance of all alternatives regarding their importance for achieving the main objective. As the pairwise comparisons need to be consistent respectively transitive, a consistency test must be performed for every matrix to ensure data quality. To do so, the principal eigenvalue λ must be calculated (Saaty, 1990). For a completely consistent matrix, λ is:

$$\lambda = \frac{1}{n}\sum_{i}^{n} x_i \text{ with } x_i = \frac{\sum_{j-1}^{n} a_{j,i}\, EV_j}{EV_i} \quad (1)$$

In this case, n is the order of the matrix and EV represents the eigenvector. Subsequently, the consistency index CI and consistency ratio CR can be calculated:

$$CR = \frac{CI}{R_n} \text{ with } CI = \frac{\lambda - n}{n - 1} \quad (2)$$

The CR and CI are based on the idea, that with perfect consistency of the pair comparisons, to the one maximum eigenvalue λ, which is equal to the dimension n of the matrix, an associated eigenvector EV exists. To decide, if a specific matrix can still be accepted, the consistency ratio CR is calculated. R_n in this formula refers to the so-called random index, which is formed from randomly determined reciprocal matrices. The random index R_n is dependent of the matrix order and can be taken from respective tables that have been created based on empirical tests, e.g., by Saaty (1990). For an exemplary matrix of order four, the corresponding R_n would be 0.89. A decision matrix is sufficiently consistent if CR < 0.1. Before the results can be calculated, all inconsistent matrices need to be dropped. The remaining matrices of the participants are then aggregated via geometric mean to ensure reciprocity.

4 EVALUATION

4.1 Process Description

To evaluate the proposed decision support model, it has been applied to an actual business process of an industrial company. Together with an interdisciplinary group of employees, a specific process has been selected, that does not yet contain any IoT technology and comprises several different entities and interfaces that offer a wide range of possible IoT use cases.

The underlying process is the processing of customer material which is applied for materials that are owned by the customers itself. The process involves four organisational entities, the ERP system, conveyors, and two types of operators, manufacturers and quality assurers. To start the process, a purchase order from a customer, that includes customer material, needs to be received by the ERP system. Fitting customer material is searched in the ERP database. If there is no suitable material from that customer in the warehouse, the purchase order is declined, and the process ends with a request for material to the customer. Having found matching material, a retrieval order is sent to the conveyor system to transport the material to the respective workplace. Simultaneously, an information message is sent to the manufacturers about the imminent arrival. In some plants there are multiple manufacturers wherefore the group needs to first clarify, who will perform the task. As soon as the responsible manufacturer has arrived at the workplace and prepared the machines, the material is processed automatically. After an estimated processing time, the manufacturer is checking the progress. Subsequently, the machines are stopped, and the materials are transported back to the warehouse. The quality assurer gets a notification to analyse the processed material whereupon he moves to the workplace and analyzes the parameters according to the purchase order details. If the analysis results are satisfying, the release order is sent to the ERP system. In case of a failed analysis, rework must be performed.

4.2 Applying the AHP Decision Model

4.2.1 Data Collection

The questionnaire was conducted from July 13th to July 17th, 2020 with an interdisciplinary group of 15 employees of different positions. To cover persons with process knowledge and experiences with IoT technology, the group comprised four project engineers, five process optimizers, three project managers, and three foremen of the specific production area. All employees have knowledge about the process itself as well as experiences with IoT technology acquired at previous projects. They understand the basic value propositions of IoT technology and have insights into potential BPI options for the respective process. The questionnaire consisted of three different steps. At first, the process owner described all process steps and details in a joint workshop to ensure that everybody has the same understanding of general process issues and possible areas of improvement. Secondly, another workshop has been undertaken to discuss general IoT value propositions and possible applications in depth. Furthermore, the literature review of section 2 including the defined clusters and the comprised publications were reviewed to identify first adaption possibilities. Finally, the group had 24 hours to perform the pairwise comparisons. After analyzing the pairwise comparison matrices, two of them turned out to be invalid due to CR values above the rigorous threshold of 0.1.

4.2.2 Results Calculation

According to the structured procedure of section 3, the criteria weights W_C, local weights of alternatives W_L for all criteria, and global weights of alternatives W_G were calculated. Table 2 shows the already squared comparison matrix for the decision criteria. At first, the sum of all row values is added to a total of 108.67. To obtain the eigenvector respectively criteria weights W_C, each row sum is divided by the total 108.67. A corresponding calculation was performed for the alternative matrices for each criterion to get the local alternative weights W_L.

Table 2: Squared Comparison Matrix of Criteria.

	Time	Cost	Flexibility	Quality	∑	W_C
Time	4.50	19.5	9.82	23.00	57.82	0.53
Cost	1.07	3.99	2.41	5.91	13.38	0.12
Flexibility	2.15	9.00	4.49	12.5	28.14	0.26
Quality	0.78	3.30	1.26	4.00	9.34	0.09
				Total	108.67	1

Eventually, the resulting matrix containing all vectors W_L for all criteria was multiplied with the vector W_C. Table 3 illustrates all vectors including the resulting global weight vector W_G and the final alternative priorities.

Table 3: AHP Results.

		Local Weights W_L			
Criteria	Criteria Weight W_C	IE	TT	RI	FS
Time	0.53	0.18	0.33	0.06	0.43
Cost	0.12	0.18	0.34	0.32	0.16
Flexibility	0.26	0.24	0.24	0.13	0.40
Quality	0.09	0.14	0.26	0.14	0.47
Global Weight W_G		0.19	0.30	0.11	0.39
Priority		3	2	4	1

The results show that time is the most important criteria with a weight score of 0.53, followed by flexibility (0.26), cost (0.12), and quality (0.09). The alternative flexible automation systems (FS) reached the highest weight for the criteria time (0.43), flexibility (0.40), and quality (0.47). Tracking and tracing (TT) was evaluated as the most relevant alternative for criterion cost with a weight of 0.34. With a score of 0.39, flexible automation systems is the top priority alternative followed by tracking and tracing scoring 0.30 on the second priority rank. Priority 3 is improved information exchange with a global weight score of 0.19, followed by faster reaction to external influences with a score of 0.11.

4.3 Interpretation and Evaluation

The results of the AHP model have been discussed with the participants in a subsequent workshop. The most favoured decision criterion was time, which stems from several process issues. Firstly, the lead time is suffering from non-transparent transportation and production times. The manufacturer is not aware of the actual transport status and often arrives too early or too late at the designated workplace. Secondly, the production time is not calculated in detail causing loops for checking the processing progress. In addition, the quality assurer is obligated to move to the workplace for analyzing the processing results, which leads to a high time consumption. Tracking the transport orders enables improved data transparency and new possibilities for just-in-time production scheduling. The manufacturers could get better information about the arrival times of materials and therefore obtain improved workflows. Retrofitting machines could help manufacturers as well as quality assurers to simplify their tasks and reduce time consumption. Sensors with connectivity capabilities will lead to reduced loops for progress checking and manufacturers could get relevant information wireless on their wearables. On this basis, the process owners decided on further investigating the IoT project ideas "location monitoring of materials" and "machine retrofitting towards connectivity".

After discussing the results of the AHP, the participants were asked to evaluate the model itself. They should assess its main structure, feasibility, and efficacy in a qualitative manner. All employees highlighted the reasonable setup of the model, that incorporates the underlying process, main BPI goals, and actual application cluster. Three participants resumed, that more clusters would lead to more specific results. Two employees mentioned that technical suggestions for IoT applications would be beneficial. Regarding feasibility, the employees described the procedure including the initial workshops and the pairwise-comparisons as rather easy to perform. However, the data analysis and results calculation of the AHP are quite complex and need to be done by experts. Altogether, the decision model was assessed as highly effective for analyzing the process and finding suitable IoT applications.

5 CONCLUSION

The proposed decision support model tackles the challenge of integrating IoT applications in processes based on best-practice application clusters and goal-orientation. By providing an extensive literature review and clustering, the main application characteristics of industrial IoT applications have been formulated. Based on this information, a structured AHP can be applied to an underlying process or a set of processes to create priorities for application categories that fit best to achieve the main objective. The work contributes to researchers, as it paves the way for further extensions of the AHP and future research regarding process-aware IoT selection models. It also contributes to practical users, as it can be applied to concrete decision challenges. The decision support model has been evaluated using an actual process. The results and final discussion proved the utility of the model and led to further follow up with the identified application possibilities. Future research could extend the model by providing more application clusters and abstracting them to IoT improvement patterns which describe the alternatives in a more formal way. A limitation of the model is its unclear generalizability, as it has only been applied to one process instance.

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Appendix A

Academic Curriculum Vitae

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Professorship for IoT-based Information Systems

Faculty for Informatics and Data Science

University of Regensburg

Universitätsstraße 31, 93053 Regensburg

EDUCATION

Since 12/2019	Ph.D. Student in Information Systems *University of Regensburg, Germany*
10/2015 – 09/2017	M.Sc. in Industrial Engineering *University of Augsburg, Germany*
10/2012 – 09/2015	B.Sc. in Industrial Engineering *University of Augsburg, Germany*

INDUSTRIAL EXPERIENCE

Since 04/2023	Head of Production Digitalization *EagleBurgmann GmbH, Munich, Germany*
12/2017 – 01/2023	Operations Automation Expert *Linde plc, Munich, Germany*
02/2017 – 08/2017	Working Student, Production Digitalization *Hilti AG, Kaufering, Germany*
08/2016 – 12/2016	Intern, Quality and Logistics Management *Volkswagen de México S.A. de C.V., Puebla, Mexico*
02/2016 – 08/2016	Working Student, Product Management *Kuka AG, Augsburg, Germany*
09/2014 – 03/2015	Intern, Logistic Planning *Audi AG, Ingolstadt, Germany*

REVIEWING ACTIVITIES

Since 12/2019	BPMDS2021, HICSS2022, WI2022, BISE Journal, ECIS2023

TEACHING AND SUPERVISION

12/2019 – 03/2022	Supervision of several bachelor's and master's theses
04/2021 – 07/2021	Supervision of the *Honors* seminar
04/2020 – 08/2020	Selected chapters of the lecture *Internet of Things und Industrie 4.0*

Appendix B

Publication List

1. Stoiber, C. and Schönig, S., 2023. Conceptualizing Industrial IoT-based Business Process Improvements - A Metamodel and Patterns. *Springer Nature Computer Science* (2023), (under review).

2. Stoiber, C. and Schönig, S., 2023. The Smart Vending Cabinet: Leveraging the Industrial Internet of Things for Business Process Improvement. In: *vom Brocke, J., Mendling, J., Rosemann, M. (eds), Business Process Management Cases Vol. 3*. Springer, Berlin, Heidelberg, (under review).

3. Stoiber, C., Stöter, M., Englbrecht, L., Schönig, S., and Häckel, B., 2023. Keeping Your Maturity Assessment Alive. *Business & Information Systems Engineering,* (2023).

4. Hornsteiner, M., Stoiber, C., and Schönig, S., 2022. Towards Security- and IIoT-Aware BPMN: A Systematic Literature Review. In: *Proceedings of the 19th International Conference on Smart Business Technologies Security Enumerations for Cyber-Physical Systems, ICSBT*, pp. 45-56.

5. Stoiber, C. and Schönig, S., 2022. Improving Business Processes with the Internet of Things – A Taxonomy of IIoT Applications. In: *Proceedings of the 30th European Conference on Information Systems, ECIS*.

6. Schönig, S., Hornsteiner, M., and Stoiber, C., 2022. Towards Process-Oriented IIoT Security Management: Perspectives and Challenges. In: *Augusto, A., Gill, A., Bork, D., Nurcan, S., Reinhartz-Berger, I., Schmidt, R. (eds) Enterprise, Business-Process and Information Systems Modeling. BPMDS2022. Lecture Notes in Business Information Processing, vol 450.* Springer, Cham.

7. Stoiber, C., and Schönig, S., 2022. Patterns for IoT-based Business Process Improvements - Developing a Metamodel. In: *Proceedings of the 24th International Conference on Enterprise Information Systems, ICEIS*, pp. 655-666.

8. Stoiber, C. and Schönig, S., 2022. Digital Transformation and Improvement of Business Processes with Internet of Things: A Maturity Model for Assessing Readiness. In: *Proceedings of the 55th Hawaii International Conference on System Sciences, HICSS*, pp. 4879-4888.

9. Stoiber C., 2021. Exploiting Internet of Things for Business Process Improvement. In: *Proceedings of the 11th International Workshop on Enterprise Modeling and Information Systems Architectures, EMISA*.

10. Stoiber, C. and Schönig, S., 2021. Process-aware Decision Support Model for Integrating Internet of Things Applications using AHP. In: *Proceedings of the 23rd International Conference on Enterprise Information Systems, ICEIS*, pp. 869-876.

11. Stoiber, C. and Schönig, S., 2021. Event-Driven Business Process Management Enhancing IoT - A Systematic Literature Review and Development of Research Agenda. In: *Ahlemann, F., Schütte, R., Stieglitz, S. (eds) Innovation Through Information Systems. WI2021. Lecture Notes in IS and Organisation, vol 48*. Springer, Cham.