Towards Agile Standardization: Testbeds in Support of Standardization for the IIoT

Claudia Koch and Knut Blind

Abstract—**The Industrial Internet of Things (IIoT) poses multiple challenges to traditional standardization, due to the complexity, dynamics, and accelerating speed of technological progress. The need for a timely availability of standards calls for new approaches and tools to enhance standardization processes for smart manufacturing. Industry and standards development organizations worldwide are seeking new solutions. Testbeds have been acknowledged in innovation policy as a powerful tool for knowledge transfer and the further development of emerging technologies. Lately, they have also attracted increasing attention from the standardization perspective as a promising tool for a more agile standards development process. Proponents of such testbeds expect them to support standardization by providing validated solutions and accelerating the processes to meet the growing demands for faster standardization without any detriment to quality. In an explorative, qualitative approach this article is the first to investigate the operation and impact of testbeds in standardization processes based on a multiple case study on testbeds implemented worldwide in the context of the IIoT.**

Index Terms—**Agility, Industrial Internet of things (IIoT), Industrie 4.0, standardization, standards.**

I. Introduction

WITH the growing complexity, accelerated technological development, and increasing need for interoperability that come with the digital transformation of industry into smart manufacturing systems (Industry 4.0), standardization faces growing challenges to develop timely and high-quality standards [1]. Stakeholders are seeking new tools and approaches that could help meet this challenge. Here, testbeds as controlled experimentation platforms where specific use cases can be implemented [2] are attracting ever more attention [3]. They have been implemented worldwide, and increasingly are pooled in dedicated platform organizations established to support and promote interoperability in smart manufacturing. Testbeds can be used to develop, improve, and validate standards, gaining insights and defining requirements which are then fed into standardization. Although testing has already been part of standards development for some time [4]–[6], the strategic and comprehensive international approach followed by these platforms in this domain is a new phenomenon worth investigating.

Both testbeds and standardization are platforms for coordination and cooperation, in which participants can gain new knowledge and collectively solve problems [7]–[10]. Testbeds as a form of premarket collaborative activity could help to provide tools and mechanisms for faster and more flexible coordination in standards development, while still maintaining high quality. In combination, standardization and testbeds can potentially amplify the diffusion of R&D results and innovations into markets. However, the role of testbeds in standardization has not yet been researched; not much is known about the knowledge flows, emerging processes, and impacts.

In this article, we aim to fill this research gap by conducting an explorative multiple case study on testbeds in the context of Industry 4.0, to find out how they impact standardization processes, principles, and outcomes. The article first reviews the theoretical background in Section II covering conventional standardization processes, the current challenges of standardization in the context of smart systems such as Industry 4.0, and the need for new approaches. The section then introduces testbeds as a tool in innovation policy and outlines the rationale and ongoing trends in their application for standardization. After presenting the methodology and selected cases in Section IV, Section V then illustrates five types of standardization approaches followed by the testbeds in our sample. We discuss our findings in Section VI, before Section VII concludes this article.

II. Theoretical Background

A. Industrial Internet of Things (IIoT)

The IIoT describes an "information network of physical objects (…) that allows interaction and cooperation of these objects" in industrial environments [11]. Applying modern information and communication technologies (ICT), the concept aims to introduce a new stage of organization and control of the entire value chain throughout the life cycle of products, based on connected cyber-physical systems (CPS) [12]. The concept is being discussed worldwide under different terms, for instance, *smart manufacturing*, *Industrie 4.0* in Germany, or *Internet Plus* in China, each differing more or less with regard to their meaning and scope of applications. Applying CPS, these concepts all build on the same enabling technologies such as Big Data, Advanced Data Analytics, Additive Manufacturing, or Cloud Computing [11], [13]. Integrating these shall ultimately

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Claudia Koch is with the Department for Quality Infrastructure, Bundesanstalt für Materialforschung und -prüfung (Federal Institute for Materials Research and Testing), 12205 Berlin, Germany (e-mail: claudia.koch@bam.de).

Knut Blind is with the Technische Universität Berlin, Chair of Innovation Economics, 10587 Berlin, Germany, and also with Fraunhofer Institute for Systems and Innovation Research ISI, 76139 Karlsruhe, Germany (e-mail: knut.blind@isi.fraunhofer.de).

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contribute to realizing the vision of global networks of businesses. With a growing number of interconnected technologies and components, a complex system of systems emerges [11]. This increases the demand for capable standards to ensure interoperability [1], which is a key prerequisite for the vision of IIoT to be realized [13].

B. Standardization

1) Process and Principles of Standardization: Standards serve as a channel for knowledge and information transfer and provide for interoperability and compatibility [14]. The latter function is especially important in the context of the ongoing digital transformation, which demands the interoperation of components and whole systems [1]. Standards can emerge either from a market-based process (*de facto* standards) or as the result of a committee-based approach where stakeholders agree on a solution [15], [16]. In such a voluntary process, technical specifications are developed in specific committees established in standard setting organizations (SSOs) [17], [18]. There, stakeholders from industry, academia, public authorities, and interest groups seek a consensus on solutions that will eventually be adopted as official standards [17]–[19], which are the result of technical discussions and political negotiations [4]. This can be a time consuming and bureaucratic process, which may be problematic in times of fast technological change and the oftentimes quick emergence of *de facto* standards [16]. Consortia, as "private sector-led organizations that create or otherwise support standards" [20], have been addressing these shortcomings of formal standard development organizations (SDOs) providing an institutional platform and mechanisms for faster and more flexible market-based technical coordination [21].

How the standardization processes are organized affects the outcomes of standardization [22]. The governance models, processes, and principles followed in standards development may vary from one organization to the other [23], influencing their respective openness, level of consensus, transparency, and management of intellectual property rights [19]. Standardization in formal SDOs such as ISO and IEC, their national counterparts, but also IEEE and consortia such as IETF or W3C, is a collaborative, inclusive and due process, open to all interested parties [21], [23], [24], which lends particular legitimacy to the processes and outcomes [16]. From an organizational perspective, legitimacy is "a generalized perception or assumption that the actions of an entity are desirable, proper, or appropriate within some socially constructed system of norms, values, beliefs, and definitions" [25]; from a procedural perspective, it is "the aspect of governance that validates institutional decisions as emanating from right processes" [26].

Standardization and standards require a kind of democratic legitimacy, contributing to the acceptance and proliferation of application of the standard [27]. Since standards are not only based on technical considerations, but always involve "commercial interests, political preferences, moral evaluations etc. at the same time [...], the democratic legitimacy of all standards is at issue as a matter of principle" [28]. Especially in network industries such as ICT, legitimacy is paramount, since standards can become quasi-mandatory due to network effects, forcing users to conform to the prevailing standards [28].

Legitimacy can be distinguished in input, throughput, and output legitimacy [27], [29]. Input legitimacy refers to the representation of different stakeholders during the standardization process. This rests upon the requirement that "those who are affected by a decision must be able to take part in the preceding governance processes and have an equal opportunity to engage in the discourse" [27]. Membership in international SDOs should be open on a nondiscriminatory basis at every stage of the standards development process, providing any interested stakeholder the opportunity to participate [30]. However, even in formal SDOs, balanced participation of all interested stakeholders—especially beyond nonindustrial participants—is oftentimes problematic [31].

Throughput legitimacy comprises the modalities of decision making (e.g., the consensus principle as a centerpiece) and the transparency of the development process [27]. Legitimacy requires fair and transparent rules. The accordant requirements for standards development are manifested in the WTO Technical Barriers to Trade Agreement, covering "transparency, openness, impartiality and consensus, effectiveness and relevance, [and] coherence" [30], which are to be adhered to in international standardization and by the SDOs of signatory countries. Although there are many consortia that do not adhere to such principles, e.g., by not considering nonindustry interests or by constraining access [20], and some that adapt them to their specific needs and commercial interests [15], [32], others such as IETF or W3C fully embrace these principles, and have even signed an accordant initiative to support open standards (*OpenStand initiative*). Being based on a consensus process increases social acceptance.

Output legitimacy, finally, concerns the actual result of the standardization process and its problem-solving capacity [27]. It thus "results from the effectiveness and coordinative capacity of a standard and is therefore predominantly related to its diffusion" [33]. Output legitimacy is achieved when a standard is regarded as "good," in the sense of beneficial or acceptable, by those who are affected—regardless of the issuing organization or the development process [28]. However, as *Werle and Iversen* outline, the "benefit" of a standard cannot be demonstrated by its diffusion alone, but rather requires consideration of all relevant technical, commercial, socio-economic and socio-political aspects during development, given the standard's potential positive and negative externalities [28].

In any case, participation in standardization offers the parties involved the opportunity to gain new knowledge and solve problems collectively [7]. Standardization committees serve as a platform for knowledge sharing and production; the outcomes (thus, the standards) are a form of codified knowledge [34]. For markets, the coordination that takes place during standardization plays an important enabling role and can influence business processes and innovations [35]. In the next section, the role of standards and standardization for innovation is examined in more detail.

2) Role of Standards for Innovation and Emerging Technologies: Standardization and innovation are inextricably linked [36] and the important role of standards in the development of innovation is well acknowledged in research [37]–[39]. Standards support the diffusion of innovation and technology transfer by codifying the state of the art in technology and knowledge [35], [36], [39], [40]. They thus represent a technology transfer channel which is integrated into a consensus process, and as a public good are openly accessible to any interested stakeholder [34], [36]. They contribute to bringing knowledge gained in R&D into innovative products and processes, realizing commercial benefits and exerting an economic impact [34]. In addition, the time-to-market of new technologies and innovations can be reduced through standardization [17]. In the stages where markets for new technologies form, standards help to build the necessary cohesion, credibility, focus, and critical mass [40]. Research has also revealed the various roles that different types of standards play within and between the phases of the R&D process, from pure basic research toward market diffusion. The specific contributions of terminology, testing, interface, compatibility, quality, and variety-reducing standards are essential for emerging technologies to progress along the innovation cycle [37]. A failure to standardize in a timely manner can hinder or slow down the diffusion of a new technology [41]. Like R&D itself, standardization is a platform for cooperation and coordination, even between actors who are otherwise competitors [10]. As such platform, standardization and standards are "important elements in the framework conditions for research, development, and innovation" [34].

Given the fundamental role of standards for innovation, the topic has been taken up by innovation policy. Research funding programs have recognized standardization as an instrument for technology and knowledge transfer, e.g., within the EU Research and Innovation Program Horizon 2020 where participation in standardization is specifically considered a research output [23], [34].

3) Current Challenges for Standardization in Context of the IIoT and the Need for New Approaches: Interoperability and compatibility between technologies, devices, machines, and applications across value chains, domains, and countries are the basis of the IIoT. Standards enable this interoperability and guarantee that technologies work together smoothly and reliably [42]. Furthermore, the increasing information flows also require standardized formats, and information security and integrity need to be assured [43]. Yet, the many different technological domains with stakeholders from various disciplines and organizations that characterize complex smart systems, such as the IIoT, pose challenges to standards development and today's standardization ecosystem [1]. Traditional engineering disciplines, automation and IT cannot be viewed separately, but instead need to be integrated—as must their standards. The different standardization cultures of the domains, the diverging innovation speeds, the continuous evolution of the system and its components, and the proliferation of standards add to the complexity of that endeavor [44], [45]. These characteristics form a complex system of systems that requires a coordinated and systematic approach by a variety of stakeholders.

In order to be successful and sufficiently fast, standardization needs cross-sectoral systems thinking [1] as well as multidisciplinary, flexible and comprehensive processes and new tools [1], [46], [47]. Some such new approaches and tools have emerged in recent years, such as roadmaps [1], [48], use cases [49], requirements engineering approaches [50], Reference Architectures [51], standards mapping [52], and anticipation and foresight studies [46]. One tool that has recently attracted global attention is testbeds. Before exploring their role in standardization in more detail, the following section introduces the general concept of testbeds and highlights their role in the life cycle of new technologies as well as in innovation policy.

C. Testbeds and Innovation

1) Definition of Testbeds: Digital transformation challenges the research and innovation landscape and demands new approaches. Experimentation and innovation-based platform ecosystems can bring stakeholders together to collaboratively work on solutions and innovation opportunities for the IIoT and other new technologies. Testbeds can play a key role here [53]. They "provide a platform for cooperation among industry, small and medium-sized companies (SMEs) and academia and facilitate the widespread adoption of solutions by developing prototypes and pragmatically implementing new solutions" [3]. As delimited, spatially confined environments, testbeds allow for experimentation and testing outside real production environments [8], [9] "to think through innovations and test new applications, processes, products, services and business models to ascertain their usefulness and viability before taking them to market" [54].

There are many types of test and experimentation platforms (TEP) and a wide range of accordant terminology. Ballon *et al.* [9] distinguish six types of TEPs, including testbeds, as well as prototyping platforms, field trials, market pilots, societal pilots, and living labs. Other authors categorize the latter as an extension to testbeds in which applications are exposed to users [8]. In addition to these TEPs, there are also so-called "*sandboxes*" in the UK and "*Reallabore*" in Germany: Both concepts provide test platforms for innovation and regulation with the aim of supporting regulation for innovative technologies [55], [56]. They allow for real-time deliberation of rules and regulations for new technologies and applications so that regulation can keep pace with innovation [57], [58].

2) Testbeds as an Innovation Policy Tool: The transfer of R&D results and the diffusion of innovative technologies into marketable products is a major issue for economies worldwide [59]. The challenges associated with digitalization exceed the existing capacities of many national and regional innovation infrastructures [60]. Here, testbeds can significantly contribute to meeting these challenges, providing a new component in the innovation infrastructure [59]. The potential of testbeds as "platforms that generate and share knowledge to address megatrends and support research and innovation (R&I) efforts to increase [...] competitiveness" [61] has been recognized worldwide. Accordingly, testbeds covering diverse technical domains, setups, scales, and objectives have emerged as a new tool for innovation policy [57], [58], [62]. Many of the accordant strategies have in common that they strive to address a weakness inherent to many national and regional innovation systems: the successful transfer of R&D results into innovative products [63], [64]. While it can take years and massive investments of resources to bring an idea to market through long phases of R&D, requiring heavy investments in science, engineering, and problem-solving, the preproduction stages have often been too much neglected [64]. This gap between invention and commercialization—the so-called "*Valley of Death*"—represents a "lack of structure, resources, and expertise" [65]. This phase of the innovation life cycle is characterized by the need for high investments on the one hand, but high uncertainties about the potential market success on the other. With support schemes focusing on R&D phases and neglecting precommercialization, many innovative technologies run the risk of getting stuck in R&D or early demonstration phases [66].

Recognizing this gap, governments are seeking to implement policy tools to help bridge this *Valley of Death*. In the United States, for instance, a National Network of Manufacturing Institutes (now called "Manufacturing USA") has been implemented to support smart manufacturing technologies throughout the entire innovation life cycle up to commercialization, which explicitly involves testbeds designed to connect universities, government, and industry [67].

Considering the maturity of a particular technology using its respective Technology Readiness Level (TRL) [63], the European research funding program Horizon 2020 focuses on funding activities aimed at translating R&D results into commercialization, and thus, specifically addresses prototyping, validation in pilot lines, demonstration, living labs, and testbeds [68].

Testbeds can bring value along the entire R&D cycle, especially in medium-level TRLs, namely those that correspond to the *Valley of Death*. Linking research and innovation with end-users' needs in a collaborative setting supports the transfer of knowledge to industry and society, and the provision of feedback to research, making them an important part of the innovation infrastructure [61]. Testbeds help bring new technologies to companies and users so that they can advance from validation in a laboratory (TRL 4) to prototypes in industrial environments (TRL 7) [69].

Given the increasing complexity of emerging technologies, the importance of testing and improving applications before they are exposed to their real environment is rising [62]. In testbeds, new technologies can be validated, showcased, and demonstrated in relevant industrial environments [70]. Thereby, testbeds help to reduce risks associated with the introduction of new technologies, contributing to an increased acceptance of new products and therefore market success [59]–[61]. Especially for SMEs, which often lack necessary resources, testbeds facilitate access to knowledge and technology. Testbeds can help to provide evidence for the effectiveness of a technology, and to identify potential technical, economic and regulatory barriers. These contributions of testbeds enable and speed up the introduction of innovations to the market and, therefore, help meet global challenges and improve the competitiveness of the respective innovation system [61].

As acknowledged by research, also standards support the diffusion of new technologies [37], [38], [40]. Similar to the *Valley of Death* issue in innovation, standardization, too, faces issues of uncertainty and complexity. Overcoming these challenges would be beneficial for standardization and, therefore, also for the diffusion of emerging technologies. The next section explores the potential and recent application of testbeds for standardization.

III. Testbeds in Standardization

A. Conceptional Background

The EU Horizon 2020 program emphasizes the use of testbeds to lower barriers to market access for innovations. Here, the testbeds are also meant to promote standards and therefore foster trust [69]. However, testbeds are not only used for standards promotion, but have recently come into focus for standards development in the domain of smart manufacturing. As a form of premarket collaboration, their insights are fed into standardization to contribute to define requirements towards a technology [3]. Here, they are meant to support a "more user-driven and participatory-led standards development process" [71].

As the development of ICT has brought about the rise of consortia considered more capable of dealing with the specific challenges, today, a trend towards "multi-mode standardization" is observed by Wiegmann *et al.* [23], in which e.g., committee- and market-based mechanisms and elements are used sequentially or in dynamic interaction when developing standards. Previous studies have shown that companies use activities in consortia to build up connections with fellow members, generating support for their proposals, some of which they then submit to formal standardization [7]. That consortia are used for prestandardization activities outside formal SDOs is also due to the fact that they often have more agile processes [72]—a feature that is also called for in formal standardization in light of accelerating technological dynamics, software-intense systems and shorter innovation cycles of IIoT technologies and smart systems [72].

Agility promotes high responsiveness to changing environments and requirements as well as accelerated dynamics and speeds [73], following development processes that are iterative, incremental, and test-driven [72]. Considering this prominent role of testing, testbeds could potentially contribute to more agility in standards development as well. Testing and enhancing standards dynamically in realistic test cases can help identify and address unforeseeable problems and constraints in changing environments, and also help validate standards [72]. Thus, given the current challenges to formal standardization, agility might become an important characteristic of standardization, supported by the inclusion of testbeds into the standards development process. As observed in consortia, also testbeds could be used as a form of premarket collaborative activity, the results of which are used to develop standards or are continuously fed into formal standardization. Testbeds with relevant use cases and reference implementations could thus change traditional standardization, becoming part of the process, adapting it to the agile technology development processes in industry.

Neither agile approaches nor specifically test-driven standardization are new in standards development. Emerging standards have been tested by designers and developers for many years

[5]. Especially organizations in IT standardization (e.g., W3C or IETF) follow such principles.

Even large-scale trials and testbeds are nothing new in standardization: Since the early stages of 5G, the new generation of cellular mobile communications, standardization has been accompanied by testbeds, prototypes, and experimental trials to demonstrate the feasibility of technologies and whether it is possible to meet the standards requirements as set out by 3GPP and ITU, thereby contributing significantly to progress in standards development [6], [74].

Although testbeds are not a new tool for collaboration, having long been used for joint R&D and even in standardization, the strategic and comprehensive international approach to it and specific application for smart manufacturing are novel. Industry and governments worldwide are implementing accordant initiatives and platforms that aim at supporting standards development with their activities.

B. Testbed Platforms Worldwide

Given the complexity of smart manufacturing and standardization in this domain, more and more attention is being paid to testbeds and their potential contributions to facilitating standards development. In recent years, individual testbed projects and platforms have emerged that pool diverse testbeds. This section introduces some of the most important of these, which, although different in their setup, have all taken up the tool of testbeds as a vehicle that can potentially facilitate the standardization of smart manufacturing technologies.

The Industrial Internet Consortium (IIC) is an industry-driven platform founded in 2014 by large U.S. companies under the umbrella of the Object Management Group standards consortium, with currently more than 240 international members. They work together to identify, compile, and promote best practices and influence international standardization by creating use cases and testbeds [75]. Currently, 24 "controlled experimentation platforms" are run by different IIC members. The testbed partners aim to implement specific use cases and scenarios not only to generate new products and services, but specifically also to explore the interoperability between new and existing technologies. Distinct targets are the generation of requirements and priorities for the development [2] as well as the validation of standards for the industrial internet [54].

In Germany, the nonprofit organization Labs Network Industrie 4.0 (LNI4.0) was also founded by major German companies and industry associations. In contrast to the IIC, however, members do not have to pay membership fees. LNI4.0 uses testbeds as a precompetitive transfer channel for knowledge gained through R&D, specifically addressing SMEs. The members develop and demonstrate Industry 4.0 application scenarios (use cases), which can serve as "important base scenarios to analyze and identify technical requirements for deployment, expansion and new developments of the standards afterwards" [76]. The use cases are implemented in testbeds, which offer SMEs an opportunity to test the technical and economic feasibility of technologies and use cases without risk or competitive pressure, or to work on solutions with other interested stakeholders. Furthermore, the testbeds are used to identify standard gaps and to collect information to support standardization processes, delivering results to standardization organizations in a timely fashion [48], [77].

The LNI4.0 is part of a broader ecosystem concerned with standardization for Industry 4.0. It collaborates closely with the Plattform Industrie 4.0 (PI4.0) and the Standardization Council Industry 4.0 (SCI4.0), which aim to connect the stakeholders in all Industry 4.0 domains, initiating standardization activities and orchestrating them nationally and internationally [78].

Another major initiative has emerged in China, where the government has introduced its ambitious strategy "Made-in-China 2025" intended to make the country a world leader in science and technology and to upgrade China's industry along the entire value chain [79]. The Alliance of Industrial Internet (AII), established in 2016 with the support of the Chinese Ministry of Industry and Information Technology, represents a concept very similar to the German PI4.0. Jointly with industry, this public platform aims to accelerate the development of the IIoT, undertaking joint research and facilitating the application of the IIoT, e.g., through testbeds [80]. These testbeds are run by national and international stakeholders from industry, academia, and governmental institutions, who aim to develop and test technologies and further develop standards. Driven by the motivation to connect companies from different domains and to keep pace with the fast technological development, meanwhile a total of 48 testbeds are running under the AII, with 59 different application cases covering Big Data, Blockchain, 5G and others (as of February 2019) [81].

C. Research Gap

By now there is a broad range of literature on the role and effects of standards and standardization in general from an economic perspective. Especially their role for innovation has been increasingly studied in recent years [37]–[40], [82]. In addition, also strategies and instruments have been investigated that are meant to support standards development, which has become an increasingly challenging task given the rising complexity of today's smart systems [1].

Although the benefits of testbeds for the diffusion of innovations are broadly acknowledged in politics and practice, the existing economic literature on testbeds in general is scarce. Despite a few publications discussing conceptualizations, taxonomies, requirements, and challenges of testbeds [9], [62], [83], scientific publications otherwise predominantly address testbeds with a technology focus. With dedicated platform organizations promoting testbeds for standardization in the context of the IIoT, some white papers and technical reports have recently been published, covering standards related aspects of testbeds [84], [85] and first results from the IIC [54]. A study on cooperation strategies in Industry 4.0, based on interviews with more than 150 international experts, found that these experts, particularly those from Germany and the USA, considered testbeds the most effective instruments to cooperate and accelerate the development of standards [3]. However, the study does not provide further insights into concrete cases or how this works exactly.

TABLE I
TESTBEDS INCLUDED IN THE ARTICLE

ID	Testbed name	Platform	Partners (as of June 2019)
T1	TSN (Time-Sensitive Networking)	LNI4.0	Mittelstand 4.0 Kompetenzzentrum Augsburg, 22 companies (incl. B&R Industrial Automation, Huawei, Microsoft, ABB, Kuka etc.)
T2	PLUG and WORK	LNI4.0	Fraunhofer IOSB
T3	Smart factory OWL	LNI4.0	Parts of the "it's OWL" cluster, Hochschule Ost-Westphalen Lippe, Fraunhofer IOSB
T4	Smart Factory Web	IIC	Fraunhofer IOSB, KETI (South Korea), Microsoft
T5	openAAS	LNI4.0	ZVEI, RWTH Aachen, interested companies
T6	Track and Trace	IIC	Bosch, SAP, Cisco
T7	TSN (Time-Sensitive Networking)	IIC	Belden/Hirschmann, Bosch Rexroth, B&R Industrial Automation, Cisco, Fraunhofer IPMS, Hilscher, Intel, ISW, Kalycito, Moxa, Pilz, SICK AG, SoC-e, Texas Instruments, TRUMPF, TTTech, Xilinx; plus supporting non-members
T8	Smart Manufacturing Connectivity for Brown-field Sensors	IIC	TE Connectivity, SAP, ifm, OPC Foundation
T9	Time-Sensitive Networking (TSN) + OPC UA Smart Manufacturing	AII	Avnu Alliance, Edge Computing Consortium (ECC), Fraunhofer FOKUS, Huawei, Schneider Electric, Hollysys, Spirent, TTTech, National Instruments Corporation, B&R Industrial Automation
T10	BMWi research project	-	3 different testbeds with e.g. RWTH Aachen, KHS GmbH, Fraunhofer, VDI, VDE, BASF, Bayer AG, Claas E-Systems

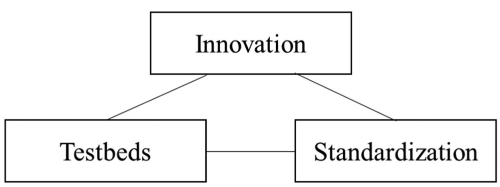

Fig. 1. Testbeds in innovation and for standardization.

Despite the acknowledged role of standards for innovation and the increasing use of testbeds to bridge the *Valley of Death*, as well as the increasing promotion and application of testbeds for the IIoT, the use of testbeds for standardization and the resulting potential for the diffusion of innovation (see Fig. 1) have not yet been addressed in scientific economic literature.

This article is aimed at contributing to close this gap by exploring testbeds and platforms in the IIoT domain as a potential tool to meet current challenges for standardization. We investigate how different testbeds of various platforms operate. The article specifically aims to assess whether and how testbed activities influence standardization processes and outcomes. It thereby addresses opportunities and threats associated with testbed activities, e.g., regarding stakeholder representation and legitimacy.

IV. METHODOLOGY

In view of the scarcity of scientific literature, this article follows an exploratory, qualitative approach. Designed as a multiple-case study, the approach helps to gain a deeper understanding of the phenomenon [86]. It is particularly suitable for new topic areas and allows to derive novel and empirically valid theory from the data analysis [87].

The article investigates nine testbeds run by the three above mentioned platform organizations, the U.S.-based international IIC, the Chinese platform AII, and the German initiative LNI4.0. In addition, the study also includes an independent German testbed project. The selection thus encompasses initiatives with a broad international coverage, including the main industrial economies for which the transition towards smart manufacturing is of major importance. In addition, these platforms are the three most notable and active initiatives worldwide, with a broad spectrum of international members. Since not all testbeds run by the platform initiatives covered deal with standards and standardization, the testbeds had to be preselected in a first step through extensive desk research of the respective platform databases provided on their websites and the corresponding published reports or media releases. Table I displays the testbeds identified and selected for this study along with information about the participating organizations. Information on the single testbeds, the stakeholders involved, processes and standardization activities is gathered through literature research and by conducting interviews. The literature predominantly comprises the websites of the testbed platforms and the respective organizations involved, as well as published technical reports, white papers, and press releases. To gain deeper insights, seven semi-structured interviews with experts from the testbeds, platforms and standardization organizations were conducted from February to April 2019, including researchers from academic institutions, and engineers and managers from companies. The interviewees were chosen to include representatives from the German, U.S., and Chinese platforms and their testbeds, respectively. Each of the interviews took between 20 and 70 min. Based on a questionnaire, the interviews were semi-structured to allow for more flexibility and the elaboration of interesting phenomena that were brought up by the experts during the interview. The focus was on the testbeds' objectives as well as the processes within the testbeds and with relevant stakeholders, including SSOs. Table II provides an overview of the interview partners. In addition, participation in official demonstrations of individual testbeds and platforms as well as relevant industry fairs allowed for further insights and triangulation of the findings. They also

TABLE II
OVERVIEW OF INTERVIEW PARTNERS (IP)

IP	Testbed platform concerned	Organization
IP1	LNI4.0	large international company
IP2	LNI4.0 and IIC	research institute
IP3	-	national formal standards organization
IP4	LNI4.0 and IIC	research institute
IP5	LNI4.0 and IIC	research institute
IP6	-	national formal standards organization
IP7	AII	research institute

provided the opportunity to discuss specific details with other experts. The data collected were then coded and analyzed using the Atlas.ti software.

V. Testbeds as a Tool in Standardization for the IIoT

A. Testbed Cases: Overview and Background

Manufacturing concepts are changing fundamentally with the introduction of the IoT and cyber-physical systems [88]. Networks of devices, machinery, enterprise systems, and production facilities are emerging, in which massive amounts of information are exchanged [47]. Yet, enabling efficient, seamless and reliable communication is complex and challenging, especially as increasingly large IIoT systems are built. Ensuring the interoperability of connected components is therefore crucial [13]. Standards are needed to enable devices to communicate and interoperate. They specify the exchange and processing of information, providing "interoperability, compatibility, reliability, and effective operations on a global scale" [42]. Some such standards exist but need to be extended, others are still lacking [89]. Recognizing the need for advanced interoperability solutions from a technology and standards perspective has therefore driven the implementation of accordant testbeds worldwide.

All testbeds in the sample focus on interoperability issues in the IIoT. The topics range from Time Sensitive Networking (TSN) technologies [*T1,7,9*] through integrated architectures and universal interfaces for flexible adaptation of production capabilities [*T2,3,4*] to data communication channels to higher level IT systems [*T8*]. Furthermore, the testbeds are concerned with data gathering from sensors [*T6*] or demonstrate digital representations of assets [*T5*].

With only two exceptions [*T6* and *T8*], the testbeds have partners not only from industry, but also from research institutes and universities, which even—as in all LNI4.0 cases—provide the physical testbed facilities as neutral infrastructure. The number of partners varies, ranging from testbeds with only three or four permanent members to testbeds with more than 20 partners. In addition, the LNI4.0 testbeds—with their special focus on addressing and involving SMEs—are permanently accessible to interested parties, charging no membership fees—as is the case for the AII platform as well. Costs are limited to the participants' own expenses for personnel and technology. In contrast, the IIC charges membership fees, which vary depending on the size and type of organization.

Some of the testbeds stand out in that they do not have one physical location, but two or even more facilities globally (such as [*T4*] with two model factories in Germany and South Korea each, or [*T7*] with facilities in Texas and Germany).

Initially set up to pragmatically find, implement, test and demonstrate solutions to technical challenges, the sample testbeds automatically also address standardization needs and issues. As one interview partner (IP 1) explained:

> *"When we systematically work out the requirements of the companies in the testbeds, experience has shown that we immediately uncover standardization needs. In fact, internationally."*

Another interviewee highlighted the testbeds' focus on the technical solution, rather than on standardization in the first place: The overarching objective of the testbeds is

> *"interoperability […]. You can not achieve that without standards – they are means to an end – however, not the actual and initial goal of the testbeds."* (IP2)

Implementing, testing and advancing technical solutions, the testbeds address standards and standardization at various levels, covering a broad variety of specific objectives and approaches. The sample of this study provides for five different approaches, which ultimately correspond to the different stages of standards development—from identification of standards needs, through the initiation of a standards project, to the development of a standard and its demonstration [90]. The core contributions of testbeds include the implementation and verification of technical solutions as well as the deduction of requirements which are fed into standardization committees [54], [91]. Recognizing that demonstration and testing are a prerequisite for successful international standardization in the IIoT [92], the work of the testbeds can contribute to paving the way for enhanced standardized IIoT communication and interoperability [93], (IP2). In the next section, the five approaches are explored in more detail.

B. Processes and Approaches Established by Testbeds With Regard to Their Standardization Activities

Given the multiplicity of technologies that the testbeds deal with and the various stakeholders involved, as well as the different set ups, objectives and scopes of the platform organizations, the processes and approaches with regard to standard- and standardization-related issues followed in the testbeds differ.

To begin with, the very approaches for setting up the testbed itself may differ. While in the industry-driven IIC usually a couple of big international corporations collaborate and decide to set up a testbed in order to test and further develop technical solutions, the initiation differs in the German LNI4.0. Like a large part of the German Industrie 4.0 initiative, it has a strong focus on SMEs, striving to support them in the process of digital transformation. Thus, as an interviewee from LNI4.0 stated (IP1), here a testbed oftentimes starts with SMEs, recognizing specific issues when implementing IIoT solutions in their manufacturing environment, that they cannot solve on their own. As soon as several SMEs with similar use cases approach the LNI4.0 platform with these issues, a testbed is set up where interested (vertical and horizontal) stakeholders who are concerned with this issue work collaboratively to find a technical solution. Often these testbeds are anchored in the facilities of research institutions and universities, which contribute their R&D expertise to the project.

1) Identification of Standards Gaps: When working on technical solutions for interoperability within the testbed, the partners might identify a standards gap, which they could then address. In this case, an individual solution is developed experimentally and tested jointly. Standardization options are then explored, and the solution is eventually brought to a standards organization (as e.g., in [*T6*]). There it is assessed whether the identified gap is relevant and whether the proposed solution could be applicable for general use [94]. For this purpose, the single platforms maintain multiple liaisons and active relationships with international SDOs and consortia, and can assist their testbeds in finding the right standardization body to work with on the development of a standard.

2) Development of New Standards: Having initiated a standards project in an SDO or consortium, the testbeds continue to support the development of the respective new standard. The sample provides exemplary cases where two existing standards need to be made work together [*T2, T4, T8*], urging the development of an accordant new standard. An IIC testbed for sensor connectivity and digital interfaces for data exchange [*T8*] e.g., seeks to map two standards necessary for advanced requirements in the IIoT, OPC UA (IEC 62541) and IO-Link (adopted as IEC 61131-9), and implement an accordant usage scenario. This work represented a starting point for the development of an IO-Link/OPC UA companion standard, which will be carried out in a joint working group of the IO Link Community and the OPC UA foundation, the consortia responsible for each of the two initial standards. Since the testbed participants are also members of the consortia, information can be forwarded directly. Not only have the results of the testbeds initiated and supported the standards development process in this working group, the testbed also serves as a reference implementation, which is a prerequisite for final adoption by the consortium [93].

3) Further Enhancement of Standards: Similarly, in other cases, a standard that is already under development in a particular SDO or consortium is implemented and tested in a testbed to further enhance it for the advanced requirements of the IIoT. This is the case, for e.g., in [*T1, T7,* and *T9*] where the current TSN is addressed, a standard that is fundamental for communication in IIoT systems [88]. TSN is a technology that enhances the established Ethernet standard with new capabilities for automation and control systems [91]. The standard is currently being developed at IEEE. All three platforms, IIC, LNI4.0 and AII, run their own TSN testbed operated by several companies and scientific institutions. Some of the participants of one of the TSN testbeds are also active in the TSN testbed of another platform, since all three have different application foci on TSN, as an interviewee explained. With the deployment of early-phase enhancements of the standard, the different vendors have the opportunity to test whether the interoperability of their devices works, can derive requirements for the new standard, and systematically develop software and source code to solve identified issues. In the case of the LNI4.0 TSN testbed, an interviewee (IP1) explained the procedure:

> *"We start the testbed and bring together all vendors and producers (direct competitors, actually). We ask them to tackle the problem systematically. They do this jointly, start developing exemplary software to solve the issues, e.g. around this IEEE 802.1 standard. There are first projects and drafts at IEEE as Word files. And we have started to edit and add single paragraphs and to inform the IEEE about our actions. The added paragraphs are then implemented as source code to test. This is then tested by all vendors, on their devices and machines. And then we run a plugfest in the testbed, where the code is tested across all vendors."*

This real-life implementation helps in the standardization process to more easily and practically provide feedback on what works and where changes are needed [91].

4) Demonstration of Standards: The testbeds not only provide interested stakeholders the opportunity to access the latest technologies and the current status quo of standards under development, enabling them to feed in their requirements, but they can also serve to demonstrate finished standards to those who are meant to implement them. By making such standards accessible and tangible to users through the implementation of relevant use cases jointly developed by industry and research institutions (see e.g., [*T5*]), the testbed helps to diffuse these standards in industry [92].

5) Open-Source Approaches: As a specific fifth case, testbeds provide opportunities for open-source approaches to standards development and the implementation of standardized solutions (see [*T5* and *T6*]). The use of open-source practices has recently raised increased interest in the standardization community to improve processes and meet current challenges [95]. A recent article [96] identified distinct scenarios in which both communities (standardization and open source) complement each other providing the foundation for successful interaction.

While one of the testbeds studied [*T6*] at this time is only considering the possibility of initiating an open-source implementation of a solution created in the testbed, others are already going further. Set up as an open-source project, [*T5*] is seeking to provide a testbed open to all interested stakeholders in order to develop, test and demonstrate an administration shell for Industry 4.0 components, working jointly on an open standard in an open-source process. The results are shared publicly on GitHub, in public workshops and plugfests. Table III summarizes the five different approaches.

To avoid duplication in their efforts and to align the activities internationally, the three testbed platforms and also single testbeds have established cooperation mechanisms between each other as well as with other relevant initiatives and alliances, signing liaison agreements and regularly exchanging information on current activities [97]. Alignment and exchange are further enhanced as many stakeholders are active in two or more of the platforms and testbeds at the same time, facilitating the flow of information for all parties involved. But even single testbeds join forces and cooperate internationally; e.g., the IIC "Smart Factory Web" testbed [*T4*] consists of several intelligent factory testbeds worldwide, among others the LNI4.0 testbeds "PLUG and WORK" [*T2*] and "Smart factory OWL" [*T3*] as well as

TABLE III
APPROACHES TAKEN BY TESTBEDS REGARDING STANDARDIZATION ACTIVITIES

Approach	(1) **Identification of standards gaps**	(2) **Development of new standards (e.g. companion)**	(3) **Further enhancement of standards**	(4) **Demonstration of standards**	(5) **Open source approaches**
	Identification of missing standards during experimental development of technical solutions in testbeds; exploring standardization options; SSOs start project after assessment	Initiation and support for development of (companion) standards suitable for IIoT scenarios direct feedback on requirements and/or direct editing of drafts	Implementation and testing of standards of running projects in an SSO	Making finished standards accessible and tangible / experienceable for users through testbed implementation	Development, testing and demonstration of standards in an open source process open to the public
Example	[*T6*]	[*T1, T7, and T9*]	[*T2, T4, T8*]	[*T5*]	[*T5 and T6*]

South Korean facilities. This enables the individual participants to enhance international cooperation in the IIoT between Europe, the USA and Asia [98].

VI. DISCUSSION

The testbeds investigated in this article all are set up to enable and enhance the interoperability of IIoT technologies through extensive joint testing.

> *"The testbeds are established to keep pace with the fast technological development. […] They basically follow two objectives: to develop and test technology, and to further develop standards."* (IP7)

Given the overall technology and commercialization related goals, bringing insights directly to SDOs and consortia may even not be the initial purpose of the testbeds. Rather, standardization is a "means to the end" in that solutions achieved in the testbeds are sought to be made available and to be accepted by a broad user base.

The cases studied show that demonstration and testing in the testbeds can constitute a supportive tool for international standardization and represent a promising road for standardization to meet current challenges. However, with the increasing importance of testbeds for standardization, certain threats and opportunities need to be considered and effects must be monitored carefully. This concerns especially the effects on the standardization process and the legitimacy of standards and standardization.

A. Testbeds and Standardization as Platforms for Knowledge Transfer

Both, testbeds and standardization, are strategic alliances which involve contributions from their participants, such as resources and technical expertise [19]. Motives for participation are similar for both, since both provide a platform for knowledge transfer, where participants gain access to technological developments by other organizations, enabling knowledge spillovers [14]. Testbeds represent a more direct and practical platform for stakeholders of new technologies and innovations to exchange information and knowledge, express needs and requirements. The cases show that many stakeholders in the testbeds are also members of relevant SDOs and consortia and use their testbed activities to benefit directly from them in the work of the technical committees. In other cases, testbeds can even provide a forum for stakeholders who would otherwise not easily participate in standardization, such as SMEs, to express their requirements, which can then be considered in standards development. In this way, synergies emerge from participation in testbeds and standardization. As stakeholders from research institutes and industry work together, the latest knowledge gained in R&D can be transferred directly between both stakeholder groups and both activities. Another advantage of standardization and testbeds alike is that both help to decrease market uncertainty, reduce technology-related risks, and provide access to markets [19], [61], [68]. The benefits of participating in both activities can potentially amplify their positive effects on the diffusion of innovations.

B. Effects on the Legitimacy of Standardization

With the growing role of testbeds in establishing interoperability and developing accordant standards, the effects of testbed activities on the legitimacy of standardization processes and outcomes, and the adherence to standardization principles, need to be carefully considered. This applies all the more when dominant industry partners cooperate in such facilities, potentially creating *de facto* standards. First preliminary conclusions can be drawn from our observations of the IIoT testbeds studied, which however, need to be monitored in the long term.

Regarding *input legitimacy*, namely the balanced participation of stakeholders, we can see different potential effects. Regular standardization in technical committees, especially in the ICT, is typically dominated by big vendors and service providers [99], who pass on their customers' needs only in a filtered way, if at all [6]. Since participation in technical committees—and even more so in international standardization—requires substantial financial resources, only a few of those who will ultimately be affected by the standard are able to participate directly [28]. In this sense, our cases suggest that testbeds could both strengthen and also inhibit a broader stakeholder representation or consideration of their requirements in standardization, depending also on the openness of the testbeds and their platforms.

In general, as postulated by Niitamo *et al.* [100], testbeds should generally be open to interested stakeholders and neutral regarding technology in order to enable maximum innovation and avoid path dependencies. This applies even more if the testbed is also used for standardization activities and thus contributes to best technical solutions. When testbeds gain more and more relevance in the standards development process as much of the standardization work is performed there, this certainly raises questions about their own openness and inclusiveness. As they are meant to support a "more user-driven and participatory-led standards development process" [71], they need to live up to these expectations. All three major testbed platforms studied (IIC, LNI4.0 and AII) are basically open to any interested stakeholder. However, the IIC charges membership fees, which—though graduated by the type and size of the organization—could act as a barrier to entry for organizations with fewer resources, especially since active engagement entails additional costs. In fact, the membership list shows that commercial members are mainly larger companies which could represent a threat for misrepresentation of SMEs in the testbed work and thus in standardization activities. Strikingly, there was no user interest group or any other stakeholder group besides industry and academia involved in the sample testbeds. Prohibitive financial hurdles in terms of membership fees could act as barriers to entry. The threat could be that the dominance of big players in international standardization could even be enforced if they also dominate in the testbeds—even more so if these facilities and platforms gain more relevance in standardization. The effects are highly dependent on the setup and policies of the accordant platform. Open-source approaches—as followed by [T5], for example—could provide for greater involvement by more interest groups. At least the plugfests in the testbeds conducted to test the developed solutions are described as open to everyone (including non-members of the platforms and testbeds).

The LNI4.0 actively seeks to involve SMEs, providing them the opportunity to come into contact with IIoT technology. Thereby, they can express their specific requirements, which can then be brought to standardization—an additional opportunity for more comprehensive involvement of SMEs in standardization. As an interviewee (IP1) from LNI4.0 outlined:

> *"Standardization is usually Bosch, Siemens, Continental, GE, Philips. Never an [SME] with 18 employees. Never. And now here in the testbed [this SME] can join and exert influence with its expert, basically with no additional effort. Without actually doing standardization work. He does not go to a committee meeting. But he looks: could I, as an SME, implement this thing later? And what could prevent me from implementing it?"*

These insights can then be brought to the technical committees by the testbed co-partners, thus giving those SMEs a voice that would usually not be represented due to their lack of resources [28]. In testbeds, SMEs can benefit at no additional cost: Testing and demonstrating the latest technology as a major driver for testbeds comes with the free additional benefit of bringing one's own requirements into the standardization process. While this may contribute to diminishing the issue of representation, the filtering effect observed in conventional standardization work in technical committees may potentially persist. This, therefore, necessitates accordant communication channels.

With respect to throughput legitimacy, that is, *how* participation takes place and how processes are designed, we also find implications for principles such as consensus and transparency. Transparency, as a major principle of international standardization, requires access to information on the current work programs of the standards organization, on proposals and final results for interested stakeholders [30]. Therefore, when concerned with standardization activities, testbeds should pay careful attention to transparent operations in order to maintain legitimacy and avoid the criticism that many consortia, but also formal SSOs [31], have often faced. In the cases of this study, both LNI4.0 and IIC provide comprehensive information on their websites about ongoing projects and testbeds. The IIC has so far published several white papers and articles on testbed activities, the participants involved and the interim results [54]; the AII has also recently published a white paper covering all testbeds and their activities [81].

What is more, the core principle of standardization is consensus-based decision-making, which can be difficult, especially when the interests within a committee are quite diverse [28]. Furthermore, finding consensus is not necessarily a rational process aimed at searching for the best technical solution, but also relies on negotiations, commercial considerations and politics [31]. Oftentimes, much of this takes place outside the committee meetings [99]. In this sense, testbeds constitute such external fora. As an interviewee (IP1) illustrated:

> *"Consensus must be found. However, this is not found in the formal standardization bodies, but in the testbed. And by developers. These are no standardizers. The work of the standardizers is still to be done. [...] The work of the standardizers is not replaced."*

This again, however, leads us back to the importance of broad stakeholder representation in testbeds as well.

Finally, the findings from our case study indicate that *output legitimacy* could be improved through testbeds. On the one hand, if testbeds succeed in involving otherwise misrepresented users of the standard at stake, the applicability and benefits of the standard can be enhanced. On the other hand, from a purely technical perspective, output legitimacy can be improved since the standards are intensively tested, demonstrated and validated in the testbed by a multiplicity of affected stakeholders. Thus, the quality of the outcome can be increased.

C. *Effects on Processes and Approaches*

As technologies converge and smart systems emerge, the different standardization cultures and paradigms clash [101]. As observed in complex and dynamic markets, there is a shift toward a combined approach of market—and committee-based standardization [102], either sequentially or in dynamic interaction [23]. Yet, the understanding of such multimode standardization is still limited. Given the high technological uncertainties in smart systems, market uncertainties are high as well. In such cases, more market-based approaches gain a more prominent role [103]. Testbeds can take over this role, but in cooperation with SDOs they can achieve the necessary legitimacy required for a broad acceptance of a standard [23].

Since standardization for the IIoT extensively involves IT-related topics, in particular interoperability and connectivity of software and components, consortia play an important role.

As interoperability is at the focus of all of the testbeds studied, they indeed bring their insights and solutions mainly to the relevant consortia. The testbeds covered in this article so far have worked mainly with standards consortia such as the OPC foundation, the Object Management Group, the Eclipse Foundation, but also the IEEE. Their standards are, however, oftentimes subsequently adopted by SDOs such as the IEC. One testbed in the sample [*T2*] even contributed directly to a DIN Spec, a new fast-to-develop specification introduced at the German national standards body to meet the demand for faster solutions (however, with a less broad stakeholder involvement, and hence at the expense of broad consensus). This form was explicitly chosen for its quick and less formal development processes, as an interviewee (IP2) explained

> *"A regular standard takes very long. You have to have a committee, everyone has to agree. A DIN Spec is much faster, more agile. Within 6–9 months you can raise something like this to a publication status that makes it possible to put this into international standardization."*

With SDOs, consortia and testbeds jointly working together to develop the necessary standards for the IIoT, each can add value by contributing its strengths to the process. Whereas testbeds can bring in validated proposals and feedback on functionalities in real-case scenarios, consortia can contribute through their fast and oftentimes agile processes in developing standards, while SDOs guarantee due processes, a consensus-based quality outcome and broad market acceptance. A balanced combination of the institutionalized due process of SDOs with market-oriented practical approaches of testbeds and consortia could help master the challenges of digital transformation and enable efficient standardization while safeguarding valuable principles. Thus, if formal SDOs actively engage with the testbeds and platforms, they can potentially exploit synergies and—as already called for in the case of consortia—"establish a symbiotic co-existence" [21]. The different testbed platforms are working towards the establishment of broad international cooperation and liaisons. The IIC not only maintains liaisons with consortia, but also with formal standardization bodies such as the German DIN and the joint technical committees of ISO and IEC. And also the LNI4.0 is embedded in an ecosystem comprising formal SDOs and consortia.

Testbed work is used to establish continuous feedback loops from the testbeds to the technical committees of these consortia and SDOs along the whole standardization process, providing requirements and validated test results, and implementing and verifying standard drafts. The testbeds thereby can contribute to improving standards from a technical perspective and at the same time speed up the standardization process. This can help to meet the need for accelerated development of high-quality standards for the IIoT.

As outlined by another interviewee (IP3), it sometimes used to take several years and even versions of an interoperability standard before a usable and broadly acceptable version was reached. As the accelerating technological change today does not allow for such time-consuming proceedings, extensive verifications through testbeds with broad stakeholder participation already during the phase of standards development could improve the availability of standards from a time and usability perspective.

From a larger perspective, an interviewee (IP2) summarized the rationale behind the testbeds in standardization as follows:

> *"You cannot make a standard without trying it out first. For that, you need a testbed. You cannot sell this to the industry without having both, a test environment to demonstrate, but also a reference to standardization work so the industry can be sure that this solution will become accepted. Otherwise, it would be just some proprietary work [...]. But this way, you can say there's a bigger community behind it."*

The observations and results from the case studies indicate that testbeds do indeed have the potential to support *agile standardization*, which was affirmed by all interviewees. In the IT domain, agile approaches are already established in standards development, i.e., at the IETF or the W3C [72], characterized by, among other things, parallel implementation and testing of the specifications under development. The cases of testbeds in this study provide a basis for deriving requirements, dynamic real use-case testing and the validation of solutions as well as iterative feedback loops into standardization committees. They can thereby help to identify and address issues early on and validate proposals quickly, thus constituting an important enabler for accelerated and agile standardization to meet the challenges of rapidly changing and complex systems.

> *"We are not replacing the standardizers. We still need them. What we do is a very fast, enabling way to get to very quickly validated standards in this area. That is, to avoid the fact that you need an awful lot of text iterations. You still need iteration. I do believe, however, that it is significantly less so. Because what has been proposed to the standardizers [by the testbeds] in terms of texts is already very mature from a technological point of view. It offers the opportunity to be well implemented. And to be interoperable with other manufacturers. It's actually a kind of an "agility acceleration approach" to standardization.* (IP1)

Fig. 2 illustrates that testbeds could affect standardization at every stage of the standard development process, starting from the identification of a standards gap towards the initiation of a standardization project, to the actual drafting phase. Feedback loops between the testbeds and technical committees at all stages, a constant switch between validation and (re-)editing of the standard drafts, can contribute to achieving better standards faster. But even once the final standard has been published, testbeds can continue to contribute by demonstrating it to users and thereby supporting its diffusion. Furthermore, up-to-date requirements can be generated continuously and fed back to the committees, assessing the need for potential revisions. Thus, the whole process and lifecycle of a standard could benefit from more agility to meet current challenges.

Yet, the corresponding infrastructures and processes in SDOs need to be adapted accordingly to be able to effectively and efficiently exploit the opportunities provided through testbeds. As an interviewee (IP2) outlined, such transformations can be supported by extending current approaches followed with Publicly Available Specifications (PAS) at ISO/IEC or e.g., DIN Spec at the national level, which are more flexible and less formal than regular standards, setting them up as dedicated

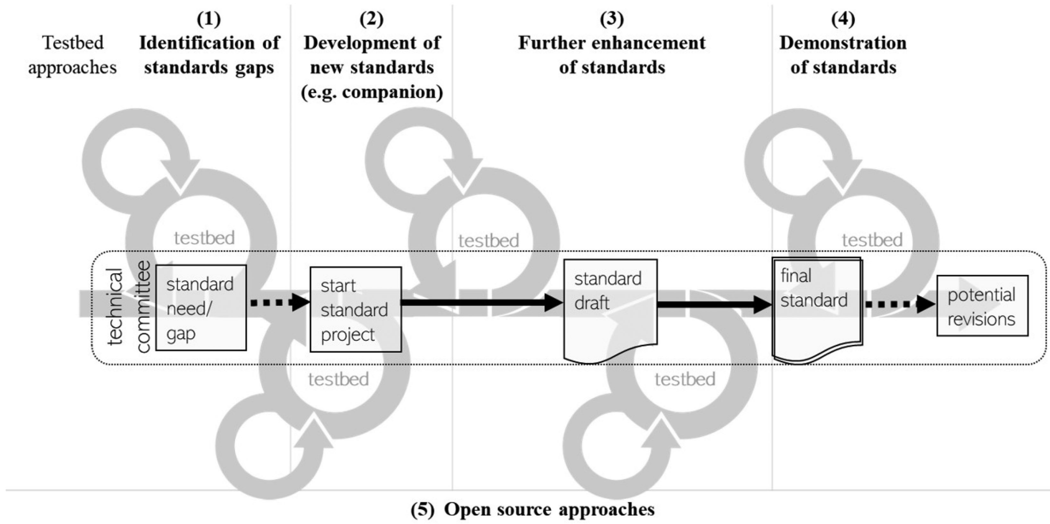

Fig. 2. Agile standardization process enabled through testbeds (standardization process adapted from Blind [90]).

comprehensive projects at the respective SDO. Within such projects, stakeholders could use testbeds to develop and test in parallel and provide results as open-source code to make them immediately usable.

> *"Testbeds could contribute to a more agile standardization. The first effects can already be felt […] DIN Specs are more agile; can also be revised. They can also be backed up in parallel with practical tests. And this would have to go further: that you make real projects out of it, where you then also do real development work at the same time. And even provide the result as open source. Then it can also be used immediately. […] And if you could say: "This has already been implemented, dear industry, there is also an implementation. Please download and use it." This would significantly speed up the spread of DIN Spec."* (IP2)

Another interviewee (IP3), however, highlighted that implementing accordant management structures in SDOs is not trivial, especially on the international level, where complexity is even higher considering the multiplicity of stakeholder interests.

D. Strategic Considerations

Finally, the testbeds and their platform organizations can also serve a greater strategic purpose. They are, e.g., meant to support standards acceptance and diffusion through intensified marketing and promotion activities, as practiced especially by the IIC (according to IP 2, 4, and 5). Here the testbed partners strive to use the generated publicity for general purposes:

> *"This is also new. Now, unlike in the past, with these official testbeds, if necessary, you get a label or attention by operating them and that is advertisement for yourself. […] You invest a lot in the testbed. And [the publicity] helps to find new partners and gain reputation in the community."* (IP2)

Furthermore, there is also a geo-strategic aspect to be considered. The national IIoT initiatives and their standardization-related activities and testbed platforms aim at strengthening the competitiveness of the domestic industry and strong representation in international standard setting. As a German interviewee outlined it from his German and European perspective, testbeds are also considered a helpful tool for instance to meet growing pressure regarding dominance in standardization by China:

> *"The Chinese have recognized that standardization is the essential lever for access to and continuity in markets. […] In almost half of the 32 standardization organizations they have now taken over the chairmanship. We consider this as a real threat. And our answer is that we not only react with Siemens and Bosch, but also actively and consciously approach the topic together with all SMEs in Germany, and go to the committees with our [testbed] validations of standards […]. Thus, bring our point of view and our standards forward […]. That is the real idea behind it: the economic-strategic one. Not just from a German perspective, but an entire European one."* (IP1)

> *"The importance of testbeds will increase, because it is a very valid approach. The relevance of standardization is immense. Thus, it is important to strengthen the European position, not to leave it to others. Not just the European, also the North American."* (IP1)

Nevertheless, the three platforms are in constant exchange on a professional level. In fact, the Chinese AII, the IIC and the German LNI4.0 have signed liaison agreements for cooperation and regularly have official meetings at least once a month to exchange and discuss information on current activities (IP1). In addition, single testbed partners are active in testbeds in all three platforms, which leads to an intensified information flow on a pragmatic and operational level.

VII. Conclusion

Based on an exploratory multiple case study approach, this article contributed a first assessment of testbeds of several IIoT platforms worldwide and their contributions to the development of interoperability standards. The findings indicate that the testbeds fulfill a coordinative function. Set up to jointly work on technical solutions for interoperability, standards, and standardization were taken as a means to make the test results and developed solutions broadly available. Five different approaches were identified in which continuous and iterative feedback loops along the whole standardization process were established with standardization bodies and consortia, and even open source developments were supported. These approaches can contribute to a more agile standardization that meets the requirements of rapidly changing complex technologies. Providing validated solutions to standards development allows for a faster definition of standards with no detriment to high quality. Thus, with testbeds becoming part of the standardization and innovation ecosystem, they can contribute to accelerating standardization and technology diffusion processes. Yet, the medium- and long-term effects of such activities outside formal SDOs need to be carefully monitored regarding, for instance, the representation of stakeholders and the impact of nonformalized activities on the legitimacy of standardization processes and outcomes.

The current coordinated international testbed activities for IIoT have the potential to change conventional standardization processes. Thus, the findings of this article have some implications for practice as well as theory. Concerning the latter, our insights are in line with the concept of multimode standardization as described by Wiegmann *et al.* [23], specifically regarding the combined, dynamic-interactive approach of market- and committee-based standardization. Yet, it extends this view by considering testbeds as another form of market-based alliance besides consortia. As observed in consortia, testbeds can also serve as a platform outside formal committees to achieve pre-standardization consensus and to impact standardization in the committees. Furthermore, the findings indicate that testbeds could contribute significantly to an agile standardization concept needed to face the growing complexity and accelerated technological development of smart systems. Specifically, open source approaches followed in the testbeds could be an important enabler for an agile standardization that allows for broad and open participation.

This is also an important insight for practitioners in standardization. Given the experiences from the investigated testbeds, this tool will potentially gain more relevance in the future. As coordination is increasingly sought in testbeds, stakeholders active or interested in standardization should pay attention to the activities performed in the testbeds, monitor developments, or even consider active participation. This again highlights the importance of testbeds' openness, inclusiveness, and transparency. SDOs, too, should continue to carefully observe testbed activities and actively engage and cooperate with them to take advantage of the new opportunities, benefit from their contributions, and stay involved in these relevant activities. They should further work on establishing their own infrastructure designed to efficiently exploit the opportunities that come with testbeds. In return, regular testbeds implemented to support R&D and market diffusion of new technologies should be alerted and pay attention to the standardization potential of their activities as an additional technology transfer channel which can even enhance their impact.

This is an important lesson for policy makers, who should embrace standardization as a relevant output of testbeds, and include this aspect in their funding schemes and R&D project calls. Testbeds as innovation infrastructure facilitate learning from the latest research results in real-world applications. They offer an opportunity to connect standardization and R&D more closely and practically, potentially leading to better standards faster. This, however, certainly requires ensuring that interested stakeholders have access to this infrastructure, e.g., SMEs which could benefit from dedicated support schemes. This way, SMEs could benefit twofold by getting access to R&D infrastructure and standardization. Given that testbeds are strategic alliances outside formal SDOs, policy makers should pay careful attention to the effects of testbeds on standardization, specifically on their input, throughput, and output legitimacy, including the adherence to the standardization principles set out by the WTO or the OpenStand initiative to guarantee the development of legitimate standards. This entails ensuring broad stakeholder representation, openness, and transparency.

This article has some limitations. First, the topic area is quite new for standardization in the IIoT and Industry 4.0. Thus, the number of cases of testbeds from IIoT platforms with substantial experiences to learn from is still limited. Future studies could include more cases to gain deeper insights and extend our understanding of the emerging impacts and processes. Furthermore, so far, long-term effects on standardization processes, culture and stakeholder representation cannot yet be observed and remain subject to future studies. A comparative study on testbeds and infrastructures in other fields, such as telecommunications or other smart systems, could reveal further interesting insights. Finally, it is worth exploring the framework and possible tools necessary to support the transformation toward agile standardization processes [20].

REFERENCES

[1] J.-Y. Ho and E. O'Sullivan, "Strategic standardisation of smart systems: A roadmapping process in support of innovation," *Technological Forecasting Social Change*, vol. 115, pp. 301–312, 2016.

[2] Industrial Internet Consortium, "Testbed working group," 2019. [Online]. Available: http://www.iiconsortium.org/wc-testbeds.htm

[3] Acatech, "Industrie 4.0 in a global context - strategies for cooperating with international partners," 2016. [Online]. Available: https://www.acatech.de/wp-content/uploads/2018/03/acatech_eng_ STUDIE_Industrie40_global_Web.pdf

[4] M. B. Spring *et al.*, "Improving the standardization process: Working with bulldogs and turtles," in *Standards Policy for Information Infrastructure*. Cambridge, MA, USA: MIT Press, 1995, pp. 220–254.

[5] P. Mannion, "5G: How do you test for a standard that doesn't even exist?," Electron. Des., Sep. 2017.

[6] M. Shafi *et al.*, "5G: A tutorial overview of standards, trials, challenges, deployment, and practice," *IEEE J. Sel. Areas Commun.*, vol. 35, no. 6, pp. 1201–1221, Jun. 2017.

[7] A. Leiponen, "Clubs and standards: the role of industry consortia in standardization of wireless telecommunications," ETLA, Helsinki, Finland, Discussion Papers, 2005.

[8] A. Følstad, "Living labs for innovation and development of information and communication technology: A literature review," *Electron. J. Virtual Org. Netw.*, vol. 10, pp. 99–131, 2008.

[9] P. Ballon, J. Pierson, and S. Delaere, "Test and experimentation platforms for broadband innovation: Examining European practice," 2005. [Online]. Available: https://ssrn.com/abstract=1331557. Accessed on: Sept. 4, 2005.

[10] K. Jakobs, "ICT standardisation-co-ordinating the diversity," in *Proc. 1st ITU-T Kaleidoscope Academic Conf.*, 2008, pp. 119–126.

[11] S. Jeschke, C. Brecher, T. Meisen, D. Özdemir, and T. Eschert, "Industrial internet of things and cyber manufacturing systems," in *Industrial Internet of Things*. New York, NY, USA: Springer, 2017, pp. 3–19.

[12] R. Anderl, "Referenzarchitekturmodelle - Grundlage zur Entwicklung von Industrie-4.0-Systemen," in *Softwarearchitekturen für Industrie 4.0. RAMI und IIRA aus Sicht der Projekte im Technologieprogramm AUTONOMIK für Industrie 4.0*. Berlin, Germany: Kommunikation GmbH, 2016.

[13] Y. Lu, "Industry 4.0: A survey on technologies, applications and open research issues," *J. Ind. Inf. Integration*, vol. 6, pp. 1–10, 2017.

[14] K. Blind, *The Economics of Standards Theory, Evidence, Policy*. Cheltenham, U.K.: Elgar, 2004.

[15] R. Bunduchi, R. Williams, and I. Graham, "Between public and private-the nature of today's standards," presented at "*Standards, Democracy Public Interest" Workshop*, Paris, France, 2004.

[16] P. Belleflamme, "Coordination on formal vs. de facto standards: A dynamic approach," *Eur. J. Political Economy*, vol. 18, no. 1, pp. 153–176, 2002.

[17] K. Blind, "Standardisation as a catalyst for innovation," 2009. ERIM Rep. Series No. EIA-2009-LIS. [Online]. Available: https://ssrn.com/abstract=1527333

[18] D. Breznitz and M. Murphree, "Shaking grounds? Technology standards in China," in *Proc. Nat. Acad. Sci. Symp. Manage. Intellectual Property Standard-Setting Processes*, pp. 3–4, 2012.

[19] K. Blind and A. Mangelsdorf, "Motives to standardize: Empirical evidence from Germany," *Technovation*, vol. 48/49, pp. 13–24, 2016.

[20] B. Biddle, "No standard for standards: Understanding the ICT standards development ecosystem," in *The Cambridge Handbook of Technical Standardization Law: Competition, Antitrust, and Patents*, J. L. Contreras, Ed. Cambridge, U.K.: Cambridge Univ. Press, 2017.

[21] P. A. David and M. Shurmer, "Formal standards-setting for global telecommunications and information services. Towards an institutional regime transformation?" *Telecommun. Policy*, vol. 20, no. 10, pp. 789–815, 1996.

[22] M. van Wegberg, "Standardization and competing consortia: The trade-off between speed and compatibility," *Int. J. IT Standards Standardization Res.*, vol. 2, pp. 18–34, 2004.

[23] P. M. Wiegmann, H. J. de Vries, and K. Blind, "Multi-mode standardisation: A critical review and a research agenda," *Res. Policy*, vol. 46, no. 8, pp. 1370–1386, 2017.

[24] W. Mattli and T. Büthe, "Setting international standards: Technological rationality or primacy of power?" *World Politics*, vol. 56, no. 1, pp. 1–42, 2003.

[25] M. C. Suchman, "Managing legitimacy: Strategic and institutional approaches," *Acad. Manage. Rev.*, vol. 20, no. 3, pp. 571–610, 1995.

[26] T. M. Franck, "Democracy, legitimacy and the rule of law: Linkages," NYU Law School, Public Law Legal Theory, New York, NY, USA, Working Paper, 1999.

[27] R. Hahn and C. Weidtmann, "Transnational governance, deliberative democracy, and the legitimacy of ISO 26000: Analyzing the case of a global multistakeholder process," *Bus. Soc.*, vol. 55, no. 1, pp. 90–129, 2016.

[28] R. Werle and E. Iversen, "Promoting legitimacy in technical standardization," *Sci., Technol. Innov. Stud.*, vol. 2, no. 1, pp. 19–39, 2006.

[29] P. Heß and K. Blind, "Company perceptions of legislation and standardisation and the voluntariness of harmonised European standards," in *Proc. 24th EURAS Annu. Standardisation Conf.*, pp. 185–201, 2019.

[30] World Trade Organization, "Decision of the committee on principles for the development of international standards, guides and recommendations with relation to articles 2, 5 and annex 3 of the agreement," 2002,

[31] E.-M. Forsberg, "Standardisation in the field of nanotechnology: Some issues of legitimacy," *Sci. Eng. Ethics*, vol. 18, no. 4, pp. 719–739, 2012.

[32] R. Hawkins, "The rise of consortia in the information and communication technology industries: Emerging implications for policy," *Telecommun. Policy*, vol. 23, no. 2, pp. 159–173, 1999.

[33] S. Botzem and L. Dobusch, "Standardization cycles: A process perspective on the formation and diffusion of transnational standards," *Org. Stud.*, vol. 33, nos. 5/6, pp. 737–762, 2012.

[34] K. Blind, "The impact of standardization and standards on innovation," in "Nesta Working Paper No. 13/15," 2013.

[35] OECD/Eurostat, *Oslo Manual 2018: Guidelines for Collecting, Reporting and Using Data on Innovation*, 4th ed. Paris, France: OECD Publishing, 2018.

[36] P. Swann, *The Economics of Standardization: Final Report for Standards and Technical Regulations Directorate, Department of Trade and Industry*. Manchester, U.K.: Manchester Bus. School, Univ. Manchester, 2000.

[37] K. Blind and S. Gauch, "Research and standardisation in nanotechnology: evidence from Germany," *J. Technol. Transfer*, vol. 34, no. 3, pp. 320–342, 2009.

[38] M. H. Sherif, "A framework for standardization in telecommunications and information technology," *IEEE Commun. Mag.*, vol. 39, no. 4, pp. 94–100, Apr. 2001.

[39] G. Tassey, "Standardization in technology-based markets," *Res. Policy*, vol. 29, nos. 4/5, pp. 587–602, 2000.

[40] P. Swann, "The economics of standardization: an update," UK Department Bus., Innov. Skills, London, U.K., 2010.

[41] J.-Y. Ho and E. O'Sullivan, "Dimensions of standards for technological innovation–literature review to develop a framework for anticipating standardisation needs," in *Proc. EURAS Proc.*, 2015, pp. 157–174.

[42] L. D. Xu, W. He, and S. Li, "Internet of Things in industries: A survey," *IEEE Trans. Ind. Informat.*, vol. 10, no. 4, pp. 2233–2243, Nov. 2014.

[43] G. Tassey, "The economic nature of knowledge embodied in standards for technology-based industries," in *Handbook of the Economics of Knowledge*, C. Antonelli and A. N. Link, Eds. Evanston, IL, USA: Routledge, 2015, pp. 189–208.

[44] European Commission, Brussels, Belgium, "Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions: ICT standardisation priorities for the digital single market, COM(2016) 176 final," 2016. [Online]. Available: https://ec.europa.eu/digital-single-market/en/news/ communication-ict-standardisation-priorities-digital-single-market

[45] A. Jillavenkatesa, "The changing world of standardization: Trends, opportunities and challenges," Paper presented at the NIST Standards Services Seminar, Sep. 9, 2012. [Online]. Available: http://gsi.nist.gov/global/docs/training/AjitSeminar.pdf

[46] F. Scapolo, P. Churchill, V. Viaud, M. Antal, H. L. Cordova Gonzalez Castillo, and P. De Smedt, "JRC foresight study - how will standards facilitate new production systems in the context of EU innovation and competitiveness in 2025?," JRC, Ispra, Italy, 2014.

[47] BITKOM, "Recommendations for standardization in the context of industry 4.0." [Online]. Available: https://www.bitkom.org/sites/default/files/file/import/Bitkom-Recommendations-Std-I40.pdf

[48] DIN/DKE, "The German standardization roadmap for industry 4.0 - version 3," Mar. 2018. [Online]. Available: https://www.din.de/resource/blob/65354/57218767bd6da1927b181b9f2a0d5b39/roadmap-i4-0-e-data.pdf

[49] J. Trefke, J. M. González, and M. Uslar, "Smart Grid standardisation management with use cases," in *Proc. IEEE Int. Energy Conf. Exhib.*, Sep. 2012, pp. 903–908.

[50] J.-P. Exner, "The espresso - project – a european approach for smart city standards," in *Proc. 16th Int. Conf.Comput. Sci. Appl.*, 2016, pp. 483–490.

[51] BITKOM, "Implementation strategy Industrie 4.0: Report on the results of the Industrie 4.0 platform," Bitkom e.V. Bundesverband Informationswirtschaft, Telekommunikation und neue Medien e. V., 2015. [Online]. Available: https://www.bitkom.org/Publikationen/2016/Sonstiges/Implementation-Strategy-Industrie-40/2016-01-Implementation-Strategy-Industrie40.pdf

[52] DIN/DKE, "The German standardization roadmap for industry 4.0 - Version 2," Jan. 2016.

[53] M. Serrano, N. Isaris, and H. Schaffers, *Building the Future Internet through FIRE*. Delft, The Netherlands: River Publishers, 2017.

[54] Industrial Internet Consortium, "Why we build testbeds: First results," 2017. [Online]. Available: https://iiconsortium.org/ pdf/Why_we_build_testbeds-first_results_091917.pdf

[55] Financial Conduct Authority, "Regulatory sandbox lessons learned report," 2017. [Online]. Available: https://www.fca.org.uk/publication / research-and-data/regulatory-sandbox-lessons-learned-report.pdf

[56] Federal Ministry for Economic Affairs and Energy, "Reallabore: Innovationen ermöglichen, Regulierung weiterentwickeln," Schlaglichter der Wirtschaftspolitik - Monatsbericht, 2019. [Online]. Available: https://www.bmwi.de/Redaktion/DE/Downloads/I/info-reallabore.pdf

[57] OECD, Paris, France, *OECD Science, Technology and Innovation Outlook 2018*, 2018.

[58] A. Wentland, S. Pfotenhauer, and F. Engels, "Test beds as an emerging instrument of STI policy-making. How they approach innovation and reconfigure society," presented at the EU-SPRI 2018, Paris, Jun. 8, 2018.

[59] OECD, "An international review of emerging manufacturing R&D priorities and policies for the next production revolution," in *The Next Production Revolution: Implications for Governments and Business*. Paris, France: OECD Publishing, 2017.

[60] Innolab Livinglabs, Wuppertal, Germany, "Innovation Infrastructures 4.0: A position paper to support germany's innovation infrastructure with respect to networking, development and sustainability," 2017.

[61] T. Malmer, S. Grande, and C. Andersdotter, "Workshop on good practices on increased accessibility of research/innovation infrastructure to industry for testing, demonstration and co-creation. Test beds as drivers for EU growth and innovation," Joint Res. Center Eur. Commission, Brussels, Belgium, 2018. [Online]. Available: http://publications.jrc.ec. europa.eu/repository/bitstream/JRC111308/kjna29177enn.pdf

[62] A.-S. Tonneau, N. Mitton, and J. Vandaele, "A survey on (mobile) wireless sensor network experimentation testbeds," in *Proc. IEEE Int. Conf. Distrib. Comput. Sensor Syst.*, 2014, pp. 263–268.

[63] EARTO, Brussels, Belgium, "The TRL scale as a research & innovation policy tool, EARTO recommendations," 2014.

[64] W. B. Bonvillian, "Advanced manufacturing policies and paradigms for innovation," *Science*, vol. 342, no. 6163, pp. 1173–1175, 2013.

[65] S. K. Markham, "Moving technologies from lab to market," *Res.-Technol. Manage.*, vol. 45, no. 6, pp. 31–42, 2002.

[66] S. O. Negro, F. Alkemade, and M. P. Hekkert, "Why does renewable energy diffuse so slowly? A review of innovation system problems," *Renewable Sustain. Energy Rev.*, vol. 16, no. 6, pp. 3836–3846, 2012.

[67] W. B. Bonvillian, "The new model innovation agencies: An overview," *Sci. Public Policy*, vol. 41, no. 4, pp. 425–437, 2013.

[68] M. Butter, N. Fischer, G. Gijsberts, C. Hartmann, M. de Heide, and F. van der Zee, "Horizon 2020: Key enabling technologies (KETs), booster for European leadership in the manufacturing sector," ITRE Committee, Brussels, Belgium, IP/A/ITRE/2013-01, 2014,

[69] *H2020 Programme. Open Innovation Test Beds: Guidelines for Internal Management and Access Conditions*, 2018.

[70] S. Bøwadt, "Horizon 2020 work programme for research & innovation 2018-2020. Advanced Materials & Nanotechnology with Focus on Open Innovation Test Beds," 2017.

[71] M.-L. Marsal-Llacuna and M. Wood-Hill, "The Intelligenter method (III) for "smarter" standards development and standardisation instruments," *Comput. Standards Interfaces*, vol. 50, pp. 142–152, 2017.

[72] S. Jeschke, *Standardization in the Era of 4.0: How New Types of Artificial Intelligence Change Conceptualization of Rules and Norms*. Offenbach/Main, Germany: DKE-Tagung, 2016.

[73] T. Dybå and T. Dingsøyr, "Empirical studies of agile software development: A systematic review," *Inf. Softw. Technol.*, vol. 50, nos. 9/10, pp. 833–859, 2008.

[74] Leistungszentrum Digitale Vernetzung, "5G Technologies," Project by Berlin Center for Digital Transformation, Berlin, 2019.

[75] Industrial Internet Consortium, "The industrial internet consortium: A global not-for-profit partnership of industry, Government and Academia," 2019. [Online]. Available: http://www.iiconsortium.org/about-us.htm

[76] Plattform Industrie 4.0, Robot Revolution Initiative, and Standardization Council Industrie 4.0, "The common strategy on international standardization in field of the Internet of Things/Industrie 4.0," 2017. [Online]. Available: https://www.bmwi.de/Redaktion/DE/Downloads/G/gemeinsame-strategie-fuer-die-internationale-standardsetzung-im-bereich-industrie-4-0.pdf?

[77] Labs Network Industrie 4.0, Statute of the Association, "Labs Network Industrie 4.0 e.V," 2018.

[78] Standardization Council Industrie 4.0, "Hintergrund des Standardization Council Industrie 4.0," 2019. [Online]. Available: https://sci40.com/de/ueber-uns.html

[79] L. Li, "China's manufacturing locus in 2025: With a comparison of "made-in-China 2025" and "industry 4.0," *Technological Forecasting Social Change*, vol. 135, pp. 66–74, 2017.

[80] Alliance of Industrial Internet, 2018. [Online]. Available: http://en.aii-alliance.org

[81] Alliance of Industrial Internet, "2018 年工业互联网案例汇编-测试床 (Industrial Internet Case Study - Testbeds)," 2019. [Online]. Available: http://www.aii-alliance.org/index.php?m = content&c = index&a = document_download&ftype = 3&fid = 492&fno = 0

[82] R. H. Allen and R. D. Sriram, "The role of standards in innovation," *Technological Forecasting Social Change*, vol. 64, no. 2, pp. 171–181, 2000.

[83] A. Gluhak, S. Krco, M. Nati, D. Pfisterer, N. Mitton, and T. Razafindralambo, "A survey on facilities for experimental Internet of Things research," *IEEE Commun. Mag.*, vol. 49, no. 11, pp. 58–67, Nov. 2011.

[84] G. Gijsbers, C. Stolwijk, T. van der Horst, and M. Butter, "Typologie en standaard voor fieldlabs," TNO, The Hague, The Netherlands, TNO 2017 R10967, 2017.

[85] C. Stolwijk, M. Punter, and C. Montalvo, "Smart industry' and the confluence of standards," in *Handbook of Innovation and Standards*, R. Hawkins, K. Blind, and R. Page, Eds. 2017, ch. 10, pp. 212–226.

[86] R. K. Yin, *Case Study Research: Design and Methods*. Newbury Park, CA, USA: Sage, 2013.

[87] K. M. Eisenhardt, "Building theories from case study research," *Acad. Manage. Rev.*, vol. 14, no. 4, pp. 532–550, 1989.

[88] M. Wollschlaeger, T. Sauter, and J. Jasperneite, "The future of industrial communication: Automation networks in the era of the internet of things and industry 4.0," *IEEE Ind. Electron. Mag.*, vol. 11, no. 1, pp. 17–27, Mar. 2017.

[89] Industrial Internet Consortium, "Smart factory applications in discrete manufacturing," 2017. [Online]. Available: https://www.iiconsortium.org/pdf/Smart_Factory_Applications_in_Discrete_Mfg_white_paper_20170222.pdf

[90] K. Blind, "Standardization and standards as science and innovation indicators," in *Springer Handbook of Science and Technology Indicators*, W. Glänzel, H. F. Moed, U. Schmoch, and M. Thelwall, Eds. New York, NY, USA: Springer, 2019, pp. 1065–1076.

[91] Industrial Internet Consortium, "Results, insights and best practices from IIC testbeds: Time-sensitive networking testbed," *IIC J. Innov.*, 2017, pp. 19–28.

[92] J. Kalhoff, U. Löwen, T. Manger, and K. Schneider, "Open Source Projekt openAAS - mit offenen Standards Industrie 4.0 umsetzen," 2017. [Online]. Available: https://www.zvei.org/fileadmin/user_upload/Verband/Fachverbaende/Automation/Open-Source-Projekt-openAAS-mit-offenen-Standards-Industrie-4.0-umsetzen.pdf

[93] M. Hilgner and E. K. Clauer, "Smart manufacturing connectivity for brown-field sensors testbed – initial deployment – report after completion of phase I," 2018. [Online]. Available: https://www.iiconsortium.org/pdf/Smart_Manufacturing_Connectivity_TB_White_Paper_20181023.pdf

[94] Industrial Internet Consortium, "Outcomes, insights, and best practices from IIC testbeds: Track & trace testbed," *IIC J. Innov.*, 2017, pp. 37–48.

[95] B. Lundell and J. Gamalielsson, "On the potential for improved standardisation through use of open source work practices in different standardisation organisations: How can open source-projects contribute to development of IT-standards?," in *Digitalisation: Challenge and Opportunity for Standardisation*, K. Jakobs and K. Blind, Eds. Berlin, Germany: Verlag Mainz, 2017, pp. T137–T155.

[96] K. Blind and M. Böhm, "The relationship between open source software and standard setting," Eur. Commission Joint Res. Centre, Ispra, Italy, 2019.

[97] Alliance of Industrial Internet, "Testbed working group." [Online]. Available: http://en.aii-alliance.org/index.php?m = content&c = index&a = lists&catid = 51

[98] US-Initiative Industrial Internet Consortium baut mit Smart FactoryOWL Fabriknetzwerk auf, 2016. [Online]. Available: https://www.its-owl.de/newsroom/news/pdf/news/us-initiative-industrial-internet-consortium-baut-mit-smartfactoryowl-fabriknetzwerk-auf/

[99] K. Jakobs, "How people and stakeholders shape standards: The case of IEEE 802.11," in *Proc. Int. Conf. Web Inf. Syst. Technol.*, 2010, pp. 1–13.

[100] V.-P. Niitamo, S. Kulkki, M. Eriksson, and K. A. Hribernik, "State-of-the-art and good practice in the field of living labs," in *Proc. IEEE Int. Technol. Manage. Conf.*, 2006, pp. 1–8.

[101] B. Biddle, F. X. Curci, T. F. Haslach, G. E. Marchant, A. Askland, and L. Gaudet, "The expanding role and importance of standards in the information and communications technology industry," *Jurimetrics*, vol. 52, pp. 177–208, 2012.

[102] F. Vercoulen and M. van Wegberg, "Standard selection modes in dynamic, complex industries: Creating hybrids between market selection and negotiated selection of standards," in *Proc. 1st IEEE Conf. Standardisation Innovation Inf. Technol.*, 1998, pp. 1–12.

[103] K. Blind, S. S. Petersen, and C. A. Riillo, "The impact of standards and regulation on innovation in uncertain markets," *Res. Policy*, vol. 46, no. 1, pp. 249–264, 2017.

Claudia Koch received the Diploma in business administration and the master's degree in business and economic law (L.L.M. oec.) from Martin-Luther-Universität Halle-Wittenberg, Halle, Germany, in 2008 and 2010, respectively, and the Ph.D. degree in the field of innovation economics from Technische Universität Berlin, Berlin, Germany, in 2020.

After several years in industry and research institutes, since 2016 she has been working with the Department for Accreditation and Conformity Assessment, Bundesanstalt für Materialforschung und -prüfung (Federal Institute for Materials Research and Testing), dealing with diverse questions of quality infrastructure.

Knut Blind received the B.A. degree from Brock University, St. Catharines, ON, Canada, in 1990, and the Diploma and the Doctoral degrees in economics from Freiburg University, Freiburg, Germany, in 1992 and 1995, respectively. He studied economics, political science, and psychology at Albert Ludwig University of Freiburg, Freiburg, Germany.

In April 2006, he was appointed as a Professor of Innovation Economics with the Faculty of Economics and Management, Technische Universität Berlin. Between 2008 and 2016, he also held the endowed Chair of Standardisation at the Rotterdam School of Management, Erasmus University. Since 1996, he has been with the Fraunhofer Society (currently the Fraunhofer Institute of Systems and Innovation Research).