A Compilation of Testbed Results:

Toward Best Practices for Developing and Deploying IIoT Solutions

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Testbeds in the Industrial Internet Consortium (IIC) have peculiar field conditions and specific goals tied to their industry domain and the interests of the end users who fund them. Testbeds are producing results towards these goals. They are reported in phased deliverables when a testbed reaches milestones in its lifecycle.

While a significant portion of these results are dictated by initial business objectives, there is a lot to learn from testbeds that can be reused beyond their initial objectives and ecosystem. Lessons learned while developing a testbed can be valuable for other Industrial Internet of Things (IIoT) pilots and projects.

Testbed teams face similar risks and challenges during their deployment process and these are relevant to any IIoT pilot project within or outside the IIC. In this report, testbed learnings that pertain to the IIoT development and deployment process are called *horizontal* learnings. These are often seen as by-products of a testbed, yet they provide valuable insights on how to deploy IIoT, especially when correlated or reinforced by other testbeds.

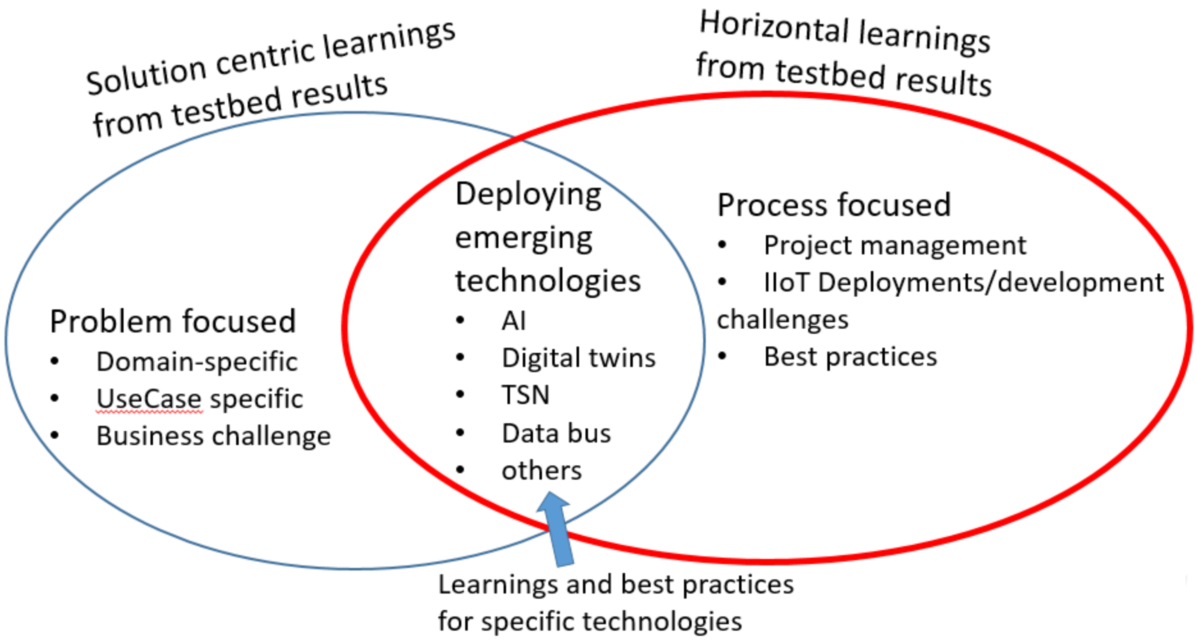

Figure 1: Solution-centric testbed results and horizontal testbed results

These horizontal learnings are different from learnings derived from addressing the business goals: *solution-centric* learnings. Solution-centric results are those that drive the project and initially get the attention of all stakeholders. In contrast, horizontal learnings relate to the process of the testbed project, and challenges that are shared by several – not necessarily all –testbeds. Such learnings are more likely to be of interest to future IIoT projects.

Figure 1 illustrates that the two types of results—solution-centric and horizontal—are not disjoint. At their intersection are learnings that are about deploying technologies common across IIoT testbeds and applications, yet the learnings obtained on how to deploy these depend on challenges that are more or less specific to each testbed.

The following are typical horizontal challenges shared by many testbeds:

- How to initiate an industrial IoT project and get management support?
- What is the best process for deploying industrial IoT?
- How to deal with human factors?
- What are the typical roadblocks and how to deal with them?
- How to handle the mismatch between information technology (IT) and operational technology (OT)?
- What is the best way to deploy specific technologies such as machine learning?

This paper compiles and analyzes published horizontal results from several testbeds. These learnings are expected to be applicable to a broader range of IIoT projects. They represent insights on how testbed teams address their challenges and uncovers tactical patterns for successful outcomes, including mistakes to avoid.

Testbeds have also produced solution-centric learnings (specific to the problem at hand or specific to the particular domain or context of the testbed). These findings have been reported and published by each testbed team over time, and are not considered in this study.

1 The Testbed Program in IIC

1.1 The IIC's Testbed Process

The IIC has paid a great deal of attention to its testbed program and expended significant effort on it. About thirty testbeds have been initiated, many still in progress.[1] Most of these last more than a couple of years. A systematic, yet flexible, process governs testbed lifecycles, beginning with an innovative idea and a proposal to identify testbed concepts, goals, value, potential partners and commercial viability. Each proposal must include at least:

A business case: Testbeds should target applications with potential to deliver a practical path to substantial economic impact beyond a particular application.

Commitment of resources: They should demonstrate adequate funding, engineering support, end user support and interaction time, and understanding of possible disruption to operations when the testbed is deployed in the field.

A deliverable schedule: The proposal should identify tangible deliverables to feed back to the sponsoring companies and the IIC. Results include technologies, best practices, requirements for standards and the testbed itself, which can then be taken into production to generate value and further innovations.

A testbed project team is a partnership between IIC members, which may also include non-members. Each partner has expertise and ownership of some part of the planned development. Such partnerships have diverse roles with different motivations: technology vendors and integrators, end users (often potential customers of the prior), academic experts, government and non-profit organizations, sponsors or advisers from the industry sector and their consortia.

A testbed may involve a significant commitment of resources and time. This makes it comparable to a real pilot project, which it often is. Most testbeds will be judged based on business or operational criteria by its sponsors, which often include end users.

Why We Build Testbeds: First Results [5] provides a rationale for the IIC testbed program, an overview and some examples of learnings from testbeds. This paper complements that and provides a more exhaustive and in-depth review of testbed learnings, insights and best practices.

Recently, new formulas of more lightweight testing initiatives have been introduced in the IIC:

[1] See an introduction on IIC testbeds at https://www.iiconsortium.org/wc-testbeds.htm.

Test drives are short-term, rapid-engagement pilots for end users to employ and adopt IIoT technologies. They address some parts of leading-edge IIoT use cases based upon technology end users' real problems in three-to-six-month-long projects. They are intended to stimulate IIoT adoption across industry through accelerated implementation.

IoT Challenges are competitions for architects and solution providers to design industrial internet solutions that address high-profile, real-world problems. The challenges are conducted over a period of several months, culminating in the announcement of winners selected by a jury. They are open to vendors, organizations, teams and individuals worldwide.

These testbed variants are expected to produce horizontal learnings more geared toward fast prototyping, and we hope they may benefit from the horizontal testbed learnings described here.

1.2 What is a Testbed?

IIC testbeds traditionally address one or more different kinds of objectives, including:

- technology or architecture validation,
- part of a go-to-market strategy and
- brownfield process improvement.

Testbeds typically have two phases: pre-pilot and pilot.

The *pre-pilot phase* evaluates technology adequacy and feasibility of how to apply it in the field. Technical elements of a solution are assessed in the operational context where they are expected to be deployed. In the latter part of this phase, the validity of the planned technology deployment is assessed to answer questions such as:

- How feasible and appropriate is an IoT technology for the problem at hand, within its operational constraints?
- What are the operational issues in deploying a particular technology?
- How will a particular solution be managed in the long-term?

Some examples are:

- Will a particular wireless network protocol support the localization requirements for tracking devices in a large manufacturing plant?
- How problematic is it to add sensors to old equipment that was not designed for this?
- What kind of data to collect for a machine learning engine to produce the best output?
- What changes in the operating context would require modification to an analytic or AI model, and how would that be done?

The expected outcome of this phase is an initial validation of technology choices, how to use the technology in an operational context, and an assessment of the changes required in the host organization and its processes.

The *pilot phase* prototypes (part of) a real solution based on early selections made in the previous phase. The goal is to evaluate it from a business viewpoint, and to assess its operational viability, for example as part of a go-to-market strategy. This phase also validates the solution design and viability in production conditions. The expected outcome is an understanding of the costs, risks, and potential operational disruption with an eye to determining whether developing a fully operational or business solution beyond the pilot will bring the expected value or improvement. While operation experts and engineers are more interested in the outcomes of a pre-pilot, business persons are more qualified for judging the outcome of a pilot phase.

A testbed positioned as pre-pilot such as [*testbed-T&T*] or intended to validate technology such as the Time Sensitive Networking [*testbed-TSN*] will often identify and emphasize the need for requirements for standards. These testbeds initiate or feed the creation of new standards for applying technologies in a compatible and interoperable way across technology providers.

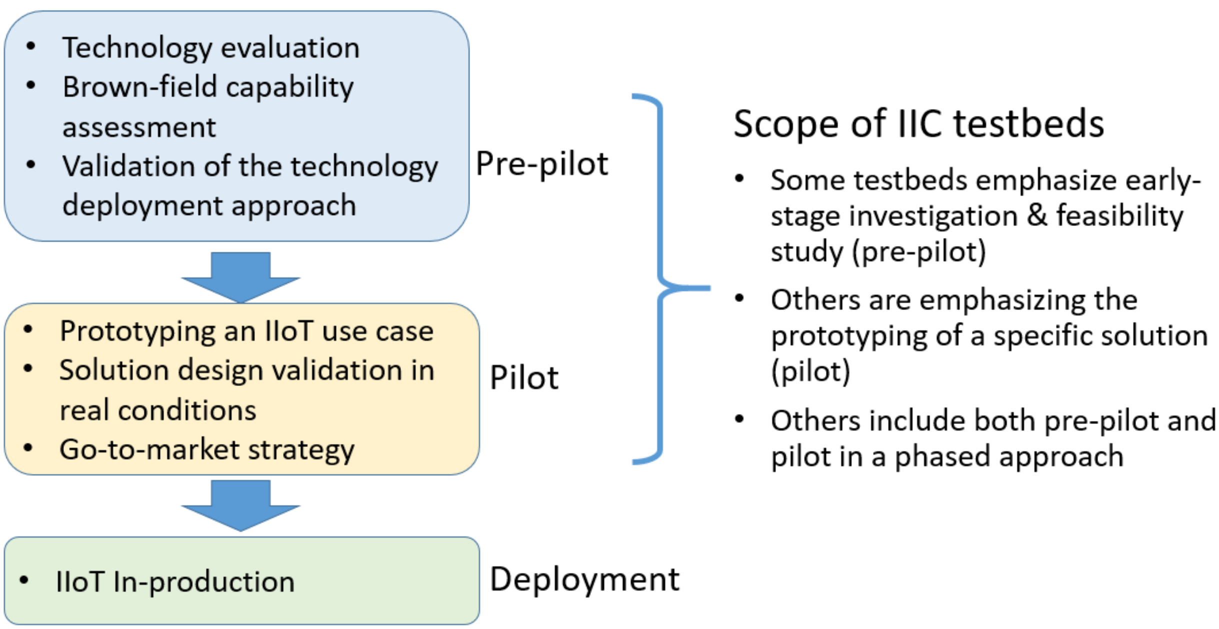

Figure 2: The scope of IIC testbeds

In all cases, starting a testbed implies that some initial challenges have been overcome. Then, deploying and operating the testbed often provides some insights and learnings, should they come from positive or negative experiences. All of these when compiled and compared across testbeds, produces valuable lessons and best practices for starting an IIoT project.

1.3 Some Testbeds That Have Produced Horizontal Outcomes

The following testbeds teams have reflected on lessons learned that qualify as *horizontal* learnings: lessons learned from their testbed process and its lifecycle that future projects could benefit from, beyond lessons learned about how to address the specific business objectives that motivated the testbed in the first place. This section highlights their particular context and motivation but does not provide a detailed record of each testbed objectives and outcomes.

The list of testbeds investigated for this study is listed below, along with their references (detailed in Annex A).

- [*testbed-DER*]—the Distributed Energy Resources (Microgrid) testbed
- [*testbed-DLF*]—the Deep Learning Facility testbed
- [*testbed-FML*]—the Smart Factory Machine Learning for Predictive Maintenance testbed
- [*testbed-FOV*]—the Factory Operations Visibility and Intelligence testbed
- [*testbed-INF*]—the INFINITE testbed
- [*testbed-MQM*]—the Manufacturing Quality Management testbed
- [*testbed-OSP*]—the Open-Standard, Interoperable IoT-Platforms testbed
- [*testbed-SFW*]—the Smart Factory Web testbed
- [*testbed-SMC*]—the Smart Manufacturing Connectivity testbed
- [testbed-S*P*F]—the Smart Printing Factory testbed
- [*testbed-T&T*]—the Track and Trace testbed
- [*testbed-TSN*]—the Time Sensitive Network – Flexible Manufacturing testbed
- [*testbed-UWS*]—the Intelligent Urban Water Supply testbed

A more detailed description of these testbeds is given in Annex A.

1.4 The Business Value of Testbeds: Summary of Profiles

The testbeds were given a profile by their authors, in terms of their expected business value. The high-level dimensions of business value identified for IIoT systems is listed below:

- process efficiency,
- user experience,
- product quality,
- asset management,
- business innovation,
- governance and
- risk management.

Each testbed team expressed their expectations for their testbed project toward improving current operations along any of these dimensions, resulting in a value profile for the testbed. This helps understand their priorities and focus.

Figure 3 summarizes the set of testbeds studied so far (fewer than all IIC testbeds) and gives an overview of their expected business value. In the figure, a large dot indicates a primary business value, while a smaller dot is a secondary value.

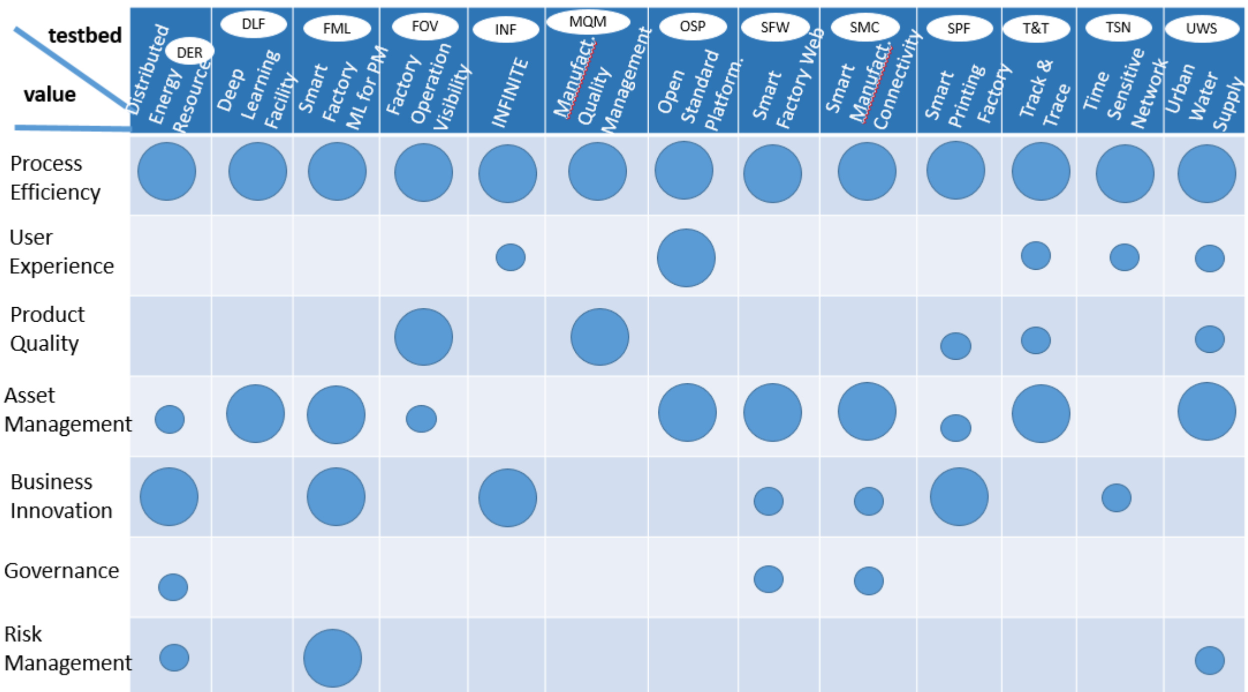

Figure 3: Business value profile for the sampling of testbeds

Process efficiency is a primary value expected from all sampled testbeds, about half of which are in the manufacturing sector (about one third of all existing IIC testbeds). Process efficiency is a common goal in the manufacturing sector to improve any of: agility, speed and reduction in time to market, business process optimization, productivity, labor efficiency, anticipation and predictability, reduction of operation costs and uncertainty, integration with broader operational environment and systems and intra-organization collaboration.

Process efficiency is an objective that requires significant reliance on operational experts and must cope with brownfield conditions and operational disruption in the field. Unsurprisingly, horizontal testbed learnings reported in this study cover extensively some related aspects:

- project planning challenges,
- dealing with human aspects,
- handling brownfield constraints and
- demonstrating value in the field and to management.

2 LEARNINGS ON HOW TO INITIATE AN INDUSTRIAL IOT PROJECT

A challenge faced by a testbed team is how to initiate a project. How can they approach management with an IIoT project with uncertain outcome and involving technologies of unproven value for the particular problem at hand? How can they *sell* a likely disruptive project even before a promising prototype has been successfully demonstrated in production? The following observations give some clues on what has helped testbeds to get funding.

2.1 POSITIONING THE PROJECT AND ITS VALUE

In the business value profile of the testbeds analyzed here, *process efficiency* comes first in most testbeds, followed by *asset management* and *product quality*. This may be due to the heavy representation of the manufacturing sector in IIC testbeds, yet the process efficiency concern shows in other sectors as well.

Positioning a testbed or a pilot toward increased efficiency of existing processes is a popular idea. Efficiency translates to:

- optimized utilization of existing resources,
- lower error, failure or defect rates,
- faster throughput, lead time or turnaround,
- reduced costs and less resources necessary and
- better predictability.

These benefits motivate funding a testbed. Although they translate into financial gain, their primary value is to release resources previously needed by inefficient processes, such as energy, skills, time, equipment and material. These resources are more difficult to increase or renew than financial resources. Their shortage represented an opportunity cost.

The urge to streamline and simplify operations to free capacity so operations can be more responsive to future opportunities and orders is understood and desired by all in the field. This is why the immediate benefit of improved efficiency is quantified in operational terms: reducing an error rate or the number of returned products or the number of late shipments.

The financial quantification is often used to convince higher levels of management, or to compare favorably to some other competing initiative. It is understood that the actual cost reduction or revenue increase may never be easily assessed financially and generally not within the scope of a pilot project as an IIoT solution may affect many operations and resources or have unforeseen long-term effects.

A recurrent expectation for manufacturing testbeds is to expand business operations to handle challenging orders. Such orders were not considered profitable due to their overhead, cost of production and low revenue potential. These obstacles can be overcome with better tracking and optimization capability. Such objectives for a manufacturing testbed make a good business case and demonstrate value. The Smart Printing Factory testbed [*testbed-SPF*] and the Smart Factory Web testbed [*testbed-SFW*] both had a goal to make small orders profitable. The Factory Operations Visibility and Intelligence testbed [*testbed-FOV*] focused on optimizing complex orders with products that could have many variations (*high-mix product assembly*). All of these orders are an optimization and logistical challenge.

While testbeds are motivated by short-term challenges, there is often a longer-term objective for the technology vendors in the team: vendors involved want to assess how well their products fit into emerging IIoT solutions, how these products will be used and in which direction they need to evolve. More importantly, they realize that their products will be part of a solution that requires interoperation with brownfield end user equipment and with other partner products. As the emerging IIoT market will be driven by solutions more than just individual products, products must be demonstrated in the context of these solutions to validate them in this market.

The Deep Learning Facility testbed [*testbed-DLF*] project had a broad set of stakeholders, from technologists to product managers and business types. The team had immediately measurable business objectives (smart building management optimization) and investigation goals regarding emerging technologies, something typically covered by research and development activities in the past. For the DLF team, the algorithmic knowledge and innovations discovered through the implementations of this testbed are also intended to be applied commercially by the participating companies in the future. For example, the testbed dovetailed with some of SAS's ongoing activity.

For the Distributed Energy Resources testbed team [*testbed-DER*], while managing a microgrid was an immediate challenge, technology vendors and integrators were interested in resolving the fundamental and product-focused challenge of distributed control from backend to the edge.

2.2 Visibility of Operations First!

Several testbeds have shown that there is value in improving the visibility of existing operations—in contrast to automating them. The immediate beneficiaries are the field operators of these operations and their opinion is critical for the acceptance of an IoT solution. The field operators are first to assess the validity of a solution, its feasibility in practice, and its actual benefits.

Visibility of operations has been the main goal of the Factory Operations Visibility and Intelligence testbed [testbed-FOVI]. Operators in the field could greatly benefit from better visibility on their work environment, in the form of near real-time visualization of assembly chain operations. Proper monitoring of both machines and products helped to render the processing time and status of each product, visually and immediately helped an operator to detect suspicious delays.

Such a monitoring tool empowers them rather than threatens them. They become more productive and react more quickly to unexpected problems.

One of the goals in the Track and Trace testbed [*testbed-T&T*] was to optimize forklift usage, but recent usage data was missing. The testbed expended significant effort to obtain equipment usage data to increase visibility. Data transparency for the forklifts helped first to analyze the current situation; then, operations could be optimized by increasing equipment utilization.

Enhancing visibility of current operations goes a long way, especially in a brownfield context. When trying to improve process efficiency there is value in helping personnel in the field to:

- detect or anticipate unexpected events and failures,
- identify optimization opportunities (as much as *implementing* these) and
- detect patterns (rather than *bypassing* human expertise and experience).

Visibility of usage and processes is a first step toward process optimization, and often a necessary step on the way to achieving predictive maintenance or automation. By the time such visibility tools enhance the productivity and efficiency of field operators, further automation is less worrisome and more accepted and new opportunities open up for their skills and experience.

For the Intelligent Urban Water Supply testbed team [*testbed-UWS*], visibility into the water quality status was lacking in various parts of the water supply pipeline network. Visibility into the operational state of the remote equipment, such as if and how well it is working, provided immediate value to the operators. Predictive maintenance can come later.

Enhancing operations visibility, especially in process-oriented operations that involve personnel interventions, has great potential for efficiency gains. It reduces the need for manual inspections and unnecessary personal interventions by anticipating or preventing problems, reducing disruptions and stress and improving productivity.

2.3 Giving Non-Functional Requirements First-Class Status

What is the best way to introduce an IoT solution, in particular in a brownfield context where existing equipment, operations and processes are already well established?

For the Manufacturing Quality Management testbed team [*testbed-MQM*], it was useful to clarify the non-functional requirements of concern to management, such as minimizing disruption. Such requirements should be given the same level of visibility as the functional objectives when presenting to management. For the MQM testbed, such a mix was clearly stated in their goals:

- the testbed shall minimize the disruption of the current production process and maintain a non-intrusive approach to test the product (a non-functional requirement of concern),

- an automated objective measure for [product] quality check shall be used (a requirement for automating this part of the process, where human experts were previously involved and needed) and
- the result must be at least 30% better than the status quo (the current objective and criterion for success).

The Intelligent Urban Water Supply testbed team [*testbed-UWS*] successfully mixed measurable short-term objectives known to be technically feasible with more ambitious and uncertain objectives that would get more credence once the short-term objectives were met. It was successful in getting many potential customers willing to sign up to be part of the IIoT initiative.

For a platform project, such as developed by the INFINITE testbed [*testbed-INF*], the primary value for customers in developing their IIoT use cases on the platform was tactical: the value was in minimizing the technology complexity and in making available an ecosystem of key technical expertise and skills so that customers can focus on innovation.

2.4 Building Trust in New Technologies

For the Smart Factory Web testbed team [*testbed-SFW*] the level of understanding and skills about certain technologies had to be increased. Trust in those technologies goes hand in hand with a sufficient level of proven experimentation and best practices on how to apply them. While often not explicitly stated this should be a major objective for testbeds, according to the team. This level of trust is necessary when large production costs and employee well-being are at stake.

The Smart Factory Web testbed team [*testbed-SFW*] found that experimental projects are easier to set up and promote when there is a designated R&D host for them (a *model factory*). This has benefits for the companies operating the model factories—Fraunhofer IOSB and Korea Electronics Technology Institute. Both organizations perform applied research and development for their industry. The SFW testbed is a showcase for products and technologies of participating companies, enhancing their market opportunities. Through the testbed project, team members aim to improve and better market their own offerings in the field of IIoT and automation.

For the INFINITE testbed [*testbed-INF*] team, technology simplification and abstraction through the use of a proven platform gives confidence to their customers and relieves them from the burden of building expertise on these technologies, a distraction from their core business. The testbed team also promotes the community aspect around their platform: the vendor does not need to have the monopoly of technology expertise.

2.5 The Expected Value From a Testbed May Be Changing and This Is Fine

The Intelligent Urban Water Supply testbed team [*testbed-UWS*] believes that the expected outcomes of a testbed should be listed at the start, then later reassessed. Different benefits or additional value from those initially expected may be produced. The end user should be made aware of the possibility of such changes in goals, involving reassessments and re-prioritizations. It is useful to recognize and discuss these early, should the case for a potential change present itself. In this testbed, the benefits shifted from expectations. The initially expected value was:

- more visibility into the legacy process,
- process efficiency: replace the reactive repair process (long turnaround time leading to longer service outage) into a more proactive, faster (prevention anticipation) process,
- energy efficiency, not just a cost issue: small gains are valuable at pilot phase as they will be significant as the project scales up,
- the expertise gained in IoT will help transform the business model (See Section 8) and
- better product (water) quality.

The demonstrated value, sufficient to motivate a change in goal was:

- process visibility (fulfilled),
- remote monitoring (unexpected benefit),
- provide product lifecycle estimates (unexpected benefit) and
- optimize maintenance and repair workflow (fulfilled).

According to the Intelligent Urban Water Supply testbed team [*testbed-UWS*] the benefits of (even partially) automating operations should be stated as a scalability enabler, replicating a testbed solution to other locations without much added personnel resources, not just in terms of productivity and lower dependency on human experts and their skills.

For the Track and Trace testbed [*testbed-T&T*], the value initially expected has been reassessed. The initially expected value was:

- optimization of process, of asset utilization. Testbed to enable this by identifying what data is needed and can be collected,
- localization of the tools and assets in use and
- business innovation: experimenting around the business model itself (for IoT tech providers), not just the technologies: model where the customer appreciates the value of the solution and the partners are designing how they will approach the market together.

The demonstrated value, considered worthy of pursuing, was:

- optimization of process and asset utilization. The main business value derived from this deployment is the increased utilization, the cost savings and overall increased efficiency: process improvement (fulfilled),
- localization of the tools and assets in use (fulfilled),
- quality improvement, more safety and security (unexpected) and
- new geolocation integration standard (unexpected).

What are other challenges in positioning the testbed and its value?

By nature, the Smart Manufacturing Connectivity testbed [*testbed-SMC*] team focuses on technical aspects. A usage scenario was defined and implemented for demonstration and validation purposes only. However, according to the team, the testbed's objectives and message could have been delivered better through the inclusion of multiple business-relevant usage scenarios. Even if phase one has a technical focus, the team realized it is valuable to make the effort to project its effect on broader business-relevant scenarios.

3 Learnings About Project Planning and Management

3.1 At The Start of a Project

3.1.1 Engaging multiple partners

Several testbeds have reported value in a diverse team of partners, even if some only had an advisory role.

As an IoT platform operator, the INFINITE testbed team [*testbed-INF*] developed a use case engagement process that accounted for the multi-vendor and multi-partner composition of the INFINITE ecosystem. This unified process encompassed building a team of different partners, support for all activities in developing a use case solution and operating it over its lifecycle. It included the initial use case engagement with INFINITE customers, requirements specification, design, deployment, results and use case sign-off.

For the Manufacturing Quality Management testbed team [*testbed-MQM*], engaging multiple parties (CAICT, Huawei and China Telecom) in the testbed project was key in convincing the industrial end user customer who was initially reluctant to deploy IoT.

The Track and Trace testbed team [*testbed-T&T*] confirms this pattern of positive reinforcement from involving different partners in helping to start a project.

The Time Sensitive Networking team [*testbed-TSN*] had 12 participating companies, which added credibility and attracted attention early on. It expanded to 25 participants including chip vendors, IACS vendors, network infrastructure/testing vendors and testing/certification organizations. The advice from the Cisco team lead to any organization starting an experimental IoT project involving new technologies is to focus on an area that will drive value and advancement for a range of companies. That will attract a well-rounded group of collaborators who are motivated to invest time and resources toward creating innovative solutions.

For the Intelligent Urban Water Supply testbed team [*testbed-UWS*], several partners brought expertise and credibility: China Academy of Information and Communications Technology (CAICT) contributes to the testbed from the standard and security perspectives. Water Process

Group (the end user) has the water business expertise, Thingswise (now Yo-i Information Technologies) has the IoT analytics expertise.

For the Smart Factory Web testbed team [*testbed-SFW*], it was important that the prospective organization partner was a leading innovator in IIoT in the manufacturing domain and a strong promoter of open standards. Moreover, expertise with the standards used in the testbed was required to participate.

The Smart Manufacturing Connectivity testbed team [*testbed-SMC*] noted that it takes time to establish a diverse partnership. This project started two or three quarters after the testbed's approval. Such project teams need to be nurtured during the project initial phase and every team member must be involved from the beginning. Good team preparation helps overcome typical struggles in the initial phase of a testbed to optimize collaboration.

The Distributed Energy Resources testbed team [*testbed-DER*] started small. In a first phase it had only two or three partners, with informal management to set goals, not a collaboration process. This allowed the team to be nimble. As the team expanded later, the collaboration became more structured. This team recommends to identify a clear lead and contact point in each partner organization and that each lead stays in close touch with other leads.

The Deep Learning Facility testbed [*testbed-DLF*] was primarily driven by large technology vendors as was their partnership. Each had complementary products and technologies to test as part of an integrated solution: Dell's rapid storage system helped establish a distributed deep-learning system platform and Toshiba focused on greenfield instrumentation in smart buildings.

3.1.2 CLARIFYING THE REQUIREMENTS AND CONSTRAINTS IS IN ITSELF A RESULT

The INFINITE testbed team [*testbed-INF*] paid attention to the requirements phase in developing its *Bluelight* use case. It built a better understanding of first-responder requirements, clarified non-functional requirements (a recurring concern across testbeds) of reliability and robustness for mission critical applications, and identified areas for further development.

Requirements are expected to evolve: motivation from users in starting a testbed can often be described as early stage. In the INFINITE testbed [*testbed-INF*] process there are several iterations before a use case pilot is defined and developed.

In the Manufacturing Quality Management testbed [*testbed-MQM*], after an initial investigation on the best approach to provide value, the testbed team set a measurable objective for success. Three requirements were prioritized as shown in section 3.3, which reflect on the key ingredients of a clearly tasked and measurable project milestone:

- What are the field constraints?
- What are the metrics for measuring success?

- What are the objectives to reach based on these metrics to declare success?

The above elements were essential in determining the objectives for each step (see Section 4.3).

In the Smart Manufacturing Connectivity testbed [*testbed-SMC*] the constraints in choosing the edge connectivity solution determined a lot of the final solution and its architecture. An initial investigation period was needed to evaluate three connectivity options on the edge, driven by brownfield limitation in supporting the OPC Unified Architecture (UA) standard, and cost constraints.

3.1.3 Choosing a narrow short-term objective while keeping long-term goals in sight

The Track and Trace testbed team [*testbed-T&T*] started with the localization of the tools and assets in use. Later it expanded from process tools to tools used in logistics such as forklifts.

For the Track and Trace testbed team [*testbed-T&T*], quantifying the business benefits with the customers is an important milestone, but to be addressed later. The team had to keep in mind the viability of a short-term business objective in the long run, even if unable to quantify it yet.

The Intelligent Urban Water Supply testbed team [*testbed-UWS*] observed that connectivity to equipment and collecting data are usually the first focus in an IIoT project. However, the team realized they need to have a longer-term vision of how to ensure data quality and completeness of the data collection. That vision includes a framework to link operational records and apply operational technology (OT) domain knowledge in the analytic model-building process.

3.1.4 Planning for the long haul

According to the Smart Factory Web testbed team [*testbed-SFW*] a testbed should be prepared to operate for a longer time than initially needed. One way to achieve this is to think of it as a part of an ecosystem: the team ensured that there are sufficient accompanying projects to maintain synergy, funding and stakeholder commitment—this brought the testbed from concept to reality more surely and helped maintain it over a period of several years.

A key learning is the value of developing a sustainable, robust and flexible implementation architecture where one can make adaptations and demonstrate new technologies as easily as possible. One of the key enablers toward this goal, according to the testbed team, was to rely on open standards as much as possible.

3.2 The Importance of Keeping the Organizational Perspective at All Times

3.2.1 Operating a testbed in production environment

The Track and Trace testbed team [*testbed-T&T*] opted to deploy the prototype at the site of a customer in a production environment. Moving a testbed into a production environment as quickly as possible is recommended by the testbed team, as frequent customer interaction in operational conditions significantly stimulates innovation. Without taking this step and taking it early, a testbed often remains in a theoretical stage and cannot help quite as much in speeding the solution to market.

For the Smart Factory Machine Learning for Predictive Maintenance testbed team [*testbed-FML*], the deployment of the testbed's technologies in the controlled lab environment is fairly straightforward, but deploying in the real industrial environment involves several challenges. In a real production facility, the window of time available to deploy the technology is drastically limited due to the production schedule of the facility. As a machine is in production, it cannot be stopped or tampered with to run tests. When that short time window opens, the system is connected and deployed, but verifying that it is working properly may take several months, meaning verification must be done during normal production conditions. The team observed that brownfield deployment constraints where IoT technology is deployed along with a new machine is different from when IoT technologies are deployed on a machine that is already in operation. In the latter case, the team believes that the only way to get the collaboration necessary to ensure the robustness of the newly upgraded system is to have a strong relationship with the on-site customer.

3.2.2 Do not separate the technology and the organizational aspects

When discussing a solution, the disruptive aspect of deploying IIoT, its potential benefits and the options for deploying the technology should be part of the same conversation.

A surprise for the INFINITE testbed team [*testbed-INF*] was that although the initial conversations have been exclusively technical, there was a gradual shift toward discussing the business benefits and organizational transformation required for IIoT. The identification of these business benefits helped shift the focus of the conversations in a way that proved key to adoption.

3.3 Planning and Setting Milestone Objectives

3.3.1 The importance of well-defined milestones

The Smart Manufacturing Connectivity testbed team [*testbed-SMC*] noted that the collaboration between heterogeneous partners could create significant overhead, unless a strict project schedule is respected. To reduce the amount of work, proper planning in the testbed preparation phase is required. The schedule must be followed and each testbed team member must understand each partner company's technologies. IT and OT professionals have different mindsets, terminologies and expectations towards other parties that are involved in a testbed. Good team preparation helps overcome typical struggles to optimize collaboration.

In experimental projects such as testbeds, the following questions have proved useful to define each milestone, and to readjust when achieving a milestone:

- What are the constraints under which the solution needs to operate?
- What are the available resources to implement the solution?
- What are the metrics for measuring success?
- What are the targets to reach based on these metrics to declare success?

Answers to these can be summarized as: constraints, resources, metrics and targets.

The Smart Printing Factory testbed team [*testbed-SPF*] realized the importance of agreements on final and intermediate goals with partner companies, including end users. End users wanted to know how soon they could expect some evidence of future benefits during the project. Their support and engagement depended on agreements about clearly defined goals and sub-goals.

3.3.2 Focusing on the Right Objective

For the Smart Manufacturing Connectivity testbed team [*testbed-SMC*], because it takes time to get a cooperation project started they had to be selective on what was the most important challenge to address, with maximum return on investment (ROI) and satisfaction to all partners. In the area of connectivity (the main theme for the testbed), the team decided that a pilot project should focus on the interoperability and security aspects rather than on the development of hardware components. It was best to use available and well-known hardware from participants.

For the Intelligent Urban Water Supply testbed team [*testbed-UWS*], a priority was the scalability of the monitoring solution. When the number of equipment increases to tens of thousands, it is impractical to employ enough staff to monitor the operations manually. Reducing reliance on human operators and manual interventions became key criteria to evaluate the solution.

3.4 Staging a Testbed into Phases

Testbeds have confirmed the value of defining different phases in a project.

3.4.1 Making Room for an Investigation Phase

A pre-pilot is useful to give better chances to a pilot (see Section 1.2) by clarifying which technologies to use, how to integrate these and what are the best directions to maximize ROI.

As several testbeds observed, a pre-pilot should be positioned modestly. It is only a preliminary assessment about technology and its context. A failure or dramatic change in initial assumptions should not be seen as a setback, but as part of the process. The pre-pilot phase assesses the technology, its adequacy and its deployment. It also allows for assessing the commitment from various parties involved and the viability of a deployed solution in the long run.

In the Manufacturing Quality Management testbed [*testbed-MQM*], after an initial dead end (the initial approach proved not to be feasible), the team radically changed directions. That should be considered normal and recognized as part of an initial audit or research phase.

In the INFINITE testbed [*testbed-INF*], the team found that the technology complexities and risks are a deterrent for many organizations (see Section 3.2 for how the Smart Factory Web testbed [*testbed-SFW*] recommends to overcome this). The initial conversations were exclusively technical, but then moved gradually toward discussing the business benefits and organizational transformation required. This validates the phasing of a testbed into a pre-pilot phase for technical and feasibility assessment. Then the pilot phase focused on confirming expected business benefits.

In the Smart Printing Factory testbed [*testbed-SPF*], a preliminary investigation was necessary to decide of the most practical data acquisition method. The scope of this investigation included more than technical feasibility of adding sensors on brownfield equipment or extracting data from a PLC. When initial assumptions proved impractical, the investigation had to be broadened and required a deeper look at operation conditions. A broader collaboration between IT specialists, device manufacturers and a partner company was needed. Evaluation of the new data acquisition approach took time as its testing had to take place at the customer's factory in real conditions under heavy constraints. The investigation typically involved tasks such as (a) in situ study of the deployment site and its operations (this may involve some video recording), (b) inquiry about the brownfield equipment, which involves questions to its vendors and operators, (c) determining how best to perform measurements and data acquisition. Only then could a businesswise meaningful pilot be developed. The equipment investigation (b) may be time consuming in the case of old equipment, and could take up to three months.

The Smart Manufacturing Connectivity testbed team [*testbed-SMC*] has also phased its approach into a technology deployment investigation phase (phase 1), then pilots (phase 2) for real solutions. The phase 1 outcome was a demonstrator for additional data flow collections from physical assets (including testing, selection and integration of new gateways and OPC UA-based communication to enterprise systems). Phase 2 resulted in multiple industry implementations.

The Deep Learning Facility testbed [*testbed-DLF*] on smart facilities was staged into phase 1, which was a pre-pilot phase (see Section 2) and phases 2 and 3 are variants of the pilot phase:

- phase 1 centered around applying AI technology: training and analysis of an AI model for usage scenarios in one smart facility pilot location—specifically anomaly detection,
- phase 2 implemented the new technology into various different facilities, particularly the SAS Smart Campus and
- phase 3 involved deploying into a public facility.

In the Distributed Energy Resources testbed [*testbed-DER*], the team has phased its testbed in two parts:

Phase 1 is the *pre-trial* phase (corresponding to the notion of pre-pilot described here in section 1.2), focusing on the basic infrastructure: the local network and the control aspect combining high speed coordination (for direct current) and supervisory messaging (databus). That pre-pilot was driven by one of the partners in its lab. As the team during this phase had only a few partners, these could remain agile and their collaboration informal as noted in section 3.1.

Phase 2 is the *deployment* phase in real conditions (corresponding to the pilot phase in section 1.2). This phase includes deployment at a utility company site. It addressed integration of multiple microgrids in a hub-and-spoke control system. As the partners' team became larger and a more formal collaboration process was needed, progression was slower and required dealing with administrative issues such as IP agreements.

3.4.2 Planning for iterations and changes in directions

In real deployment conditions, planned solutions may need to be revised at any time.

The initial implementation of the Track and Trace testbed [*testbed-T&T*] was a general-purpose implementation using a standard set of sensors attached to different types of tools. The team has learned that they need different flavors of prototype for different use cases and products.

After evaluation of an impractical initial solution, the Manufacturing Quality Management testbed team [*testbed-MQM*] proposed a solution and convinced management to try a modified process, which they did quickly and returned with better solutions. The team persevered and delivered a solution with outstanding results in the promised time frame. At the end, the testbed team delivered a real IIoT implementation with tangible results for the customer.

In such cases, the constraints, resources, metrics and targets approach (see Section 4.3.1) to define intermediate objectives helps every stakeholder to be on the same page in assessing proposed solutions. Then there should be an assessment phase that may lead to changes in direction.

Iterations are also a way to address scalability needs—generalizing a solution initially developed at small scale, into a larger scale solution. At that time, new constraints and resources may arise that will challenge the initial solution.

3.4.3 Planning for reusability and scalability

For the platform testbed, the INFINITE testbed [*testbed-INF*], there is value in cross-usage of techniques and development that was initially designed for a specific use case. At the enterprise analytics end, the team developed machine learning algorithms for anomaly detection and these machine learning algorithms can be applied to other areas such as monitoring OT elements.

The Smart Printing Factory testbed team [*testbed-SPF*] observed that when designing solutions for several manufacturing environments, a lot of customization and variation in configurations have to be expected. Similar equipment across factories could be customized to accommodate different products and to operate within a specific combination of equipment from multiple manufacturers. It takes time to investigate each site and conduct a preliminary survey of the contact points with each manufacturer. Access to the local technical staff who did the customization was more important than access to the equipment vendors or dealers. The heterogeneity caused by the variety of equipment and machines, each with many built-in sensors, added to the scalability challenge in brownfield environments. A robust preliminary investigation helped significantly to set boundaries to this diversity, and to identify scalability factors such as the right connectivity and architectures.

3.4.4 Results take time and effort

For the Track and Trace testbed team [*testbed-T&T*], it took longer than expected to arrive at the technology decisions and to gather the data about the fleet of equipment. The biggest delay came from the integration of technology into the physical process.

Recurring advice from testbed teams were: be modest in the schedule and make room for investigating options and alternatives. Do not underestimate the deployment hurdles. The end users must understand that their problem is unique or at least its context and combination of requirements are. So will be their solution. All this takes time to investigate and validate.

The Smart Factory Machine Learning for Predictive Maintenance testbed team [*testbed-FML*] believes that the deployment of an industrial machine learning system should follow several phases. A prototype lab phase will cover the development of algorithms, while an on-site factory phase is to test the algorithm in real conditions, followed with an in-production phase to test and tune the algorithm for real environments (noise, etc.). This last phase is the most complex and constrained as the equipment is in production.

4 Common Challenges and How to Address Them

4.1 Hosting the Testbed (or Pilot) Effort on End User Site

For the Track and Trace testbed team [*testbed-T&T*], the first hurdle to overcome was to convince a customer to host the testbed in its production environment. Disruption is expected. Both the expected value and the risks must be clearly articulated so that the end user can make an informed recommendation to its management.

Prior to starting their testbed, the customers in the Manufacturing Quality Management testbed team [*testbed-MQM*] had received much enthusiastic advice about how an IoT solution can help them improve operations, but they never acted on these due to the risk of disrupting their existing manufacturing process.

Successful approaches for reducing the risk of disruption have been:

- To recognize the reduction of disruption as a goal, along with the business and performance goals. Measures to help on this include: defining some metrics jointly with field operators and learning what disruption means operationally, and business-wise. Testbed teams should show end user management that they will pay attention to this.
- To include disruption evaluation in the trial process and solution evaluation.
- Before all of the above, to choose as testbed objectives a specific, well-known problem experienced by field operators, for which it is possible to identify and clearly articulate the potential benefits and risks or downsides, with early evaluation of the latter.

In this way the Intelligent Urban Water Supply testbed team [*testbed-UWS*] had no difficulty attracting potential users to be part of their early IIoT initiative and to volunteer for its testing.

This challenge may be lessened when the testbed team involves large technology vendors, as these businesses are likely to have an internal end user facet in their activities or a branch acting as end user. This is the case for the Deep Learning Facility testbed [*testbed-DLF*] about smart facilities, where the Toshiba participant could make available as the testbed location one of its large buildings while another participant (SAS) later provided its own facility for a second testbed deployment. Because a single campus with multiple buildings was needed for phase 2 of the testbed, SAS was the ideal fit (SAS corporate headquarters Smart Campus, Cary, NC in US).

In Japan, the Fujitsu technology vendor also owns several manufacturing companies for electronic appliances or components. One of them became the on-site location for the Factory Operations Visibility and Intelligence testbed [testbed-FOV].

4.2 Dealing with Brownfield Constraints

4.2.1 Equipment retrofitting challenges

Extracting usage data from existing equipment is often a challenge. Adding sensors is always restricted in brownfield conditions due to technical or physical limits, cost issues, practicality and operational complexities. Testbed teams have observed that:

- with some analysis and creativity, it is possible to reduce the need to add more sensors,
- contextualization, digitization and right models for physical processes reduce the need for increasing data quantity from asset monitoring and
- operational personnel expertise in the field helped narrow in on what to monitor.

In other words, it pays to spend time understanding the OT process and analyzing the meaning of a modest, easy-to-collect dataset before going through the trouble of collecting more data.

For the Smart Manufacturing Connectivity testbed team [*testbed-SMC*], extracting data from legacy equipment posed a variety of challenges. Obstacles needed be balanced: cost, size of sensors and other physical limitations, skills for re-programming PLCs, need to minimize disruption on actual operations. The testbed could choose between three options and settled for two of them to be applied depending on the asset and its technology context, for example where the asset PLC already has an OPC UA server.

The testbed demonstrated the possibility of a non-disruptive and evolutionary approach to retrofitting the factory floor for a higher volume of data collection.

In the Manufacturing Quality Management testbed [*testbed-MQM*], the team discovered it was near impossible to add sensors and a controller to the legacy welding robots. This forced the testbed team to review the whole process, and focus instead on improving the efficiency of the quality control station, which proved to be a more manageable objective for the testbed.

In the Deep Learning Facility testbed team [*testbed-DLF*] the SAS member company had to retrofit a building for experimentation. The testbed mostly covers buildings constructed within the last six years, but there are also projects underway to retrofit some of its older buildings.

In the Smart Printing Factory testbed [*testbed-SPF*], one objective was to collect data on the times a piece of equipment was in operations. The initial approach of reconfiguring PLCs or interpreting signals captured from network activity proved impractical due to brownfield constraints. A better understanding of the operational context led to a less direct yet practical approach to get that information, but an initial investigation phase was needed (see 3.4.1).

4.2.2 Data Collection Challenges

Often, data gathering has proved to be challenging as reported by the Track and Trace testbed [*testbed-T&T*] and the Intelligent Urban Water Supply testbed team [*testbed-UWS*]. Physical assets and equipment deployed prior to IoT concerns are not easy to instrument for collecting data of interest. Creative solutions may help. For example, older tools in [*testbed-T&T*] do not produce utilization data. However, acceleration sensor technology and addition of related sensors can be used to derive information about the usage of the tool. If there is no acceleration, the tool is not used, and vice versa.

For the Smart Manufacturing Connectivity testbed [*testbed-SMC*], improving data collection often interferes with legacy control systems that assume a given latency. Additional data processing (here required for the IO-Link/OPC UA conversion on the Y-Gateway) must have minimum impact on the real-time operations, so that the latency of the cyclic exchange of sensor data with the PLC does not significantly increase. The testbed results include a specification of how to measure the additional delay occurring between a sensor and the governing PLC.

In the Smart Printing Factory testbed [*testbed-SPF*], the context of operations needed to be captured in addition to the operation itself. For example, is the operation taking place during a trial run? Or during some adjustment procedure? Or is it taking place during actual production? Is an interruption due to a voluntary break time from operators, or is it an unexpected incident? Such collateral information is not easily captured because such events are considered part of the normal way of doing things, of organizational nature and never clearly stated by operators. In a first phase, the team recorded the association between the signal coming from monitored physical assets and its operational intent by using video capture. The practice of capturing the operational context with video has also been used by the Factory Operations Visibility and Intelligence testbed team [testbed-FOV]. The team believes that video capture will increasingly be controlled and analyzed automatically in the future.

Generally, data collection under heavy brownfield constraints, such as in manufacturing, required significant understanding of the operational context, and resourcefulness from the teams. A combination of data acquisition techniques proved necessary, such as PLCs reprogramming, dedicated sensors, network signals monitoring and video image recognition. In such environments, collecting data from physical assets and equipment with good technology is not sufficient as noted by the Smart Printing Factory testbed [*testbed-SPF*]. It is critical to contextualize and correlate this data with a broader context including personnel working procedures and style, as well as other business parameters such as the type of product being manufactured and its processing requirements.

4.2.3 Integration and Interoperability Issues

A recurring problem for data collection is the heterogeneity of physical assets to monitor. One challenge the Intelligent Urban Water Supply testbed team [*testbed-UWS*] faced was interoperability—how to connect to the variety of water pumps deployed over decades from various vendors beyond their direct customer (WPG). Data acquisition from instrumenting such a variety of equipment is a challenge. Connecting these to a platform in the cloud is another.

For the Track and Trace testbed team [*testbed-T&T*], one hurdle was integrating new technology with older equipment. This requires more than attaching sensors to equipment. The testbed team had to arrange with the forklift producers to access the forklift data from the embedded software. The safety usage agreement could be violated just by the process of collecting data. The team took time to arrive at the technology decisions and to gather the data about the fleet of assets. The biggest delay came from the integration of technology into the physical process.

The diversity of deployment conditions and of equipment means that functional requirements cannot be addressed by a single technology. The Track and Trace testbed team [*testbed-T&T*]

could not find a single localization technology that would cover all of their localization needs, so several localization techniques were integrated for well-rounded coverage. This uncovered the need for additional localization data standards to bridge and combine these technologies.

4.2.4 Security challenges

The Smart Manufacturing Connectivity testbed team [*testbed-SMC*] observed that by creating a new data path from sensors to IT systems, a door was opened to attacks through this additional connection with the enterprise IT system, which is normally blocked by the PLC. Sufficient levels of endpoint protection for the Y-Gateway and protection of the new communication path were required. The testbed concluded at the value of using a Trusted Platform Module (TPM) as a hardware-based root of trust. The choice was to ensure communication security via OPC UA's own security mechanisms.

4.3 Dealing with Limited Resources Under Uncertainty: Time Pressure and Funding

How to set deadlines when the IoT approach to be used is not settled? Testbed teams often needed to balance a limited but more predictable solution for the problem at hand against using a less practiced and less certain approach that may be more scalable and reusable.

Here a judgement call is needed depending on the context. How critical is the timeline? How useful would a more reusable or scalable solution be with respect to future needs? Can the team afford more investigation time or some uncertainty about timing?

The options need to be presented to the stakeholders and risks and potential benefits discussed. Balancing risks and long-term benefits translated more or less formally into project milestones along the aspects identified in section 4.3 (constraints, resources, metrics and targets).

The Manufacturing Quality Management testbed team [*testbed-MQM*] had to make a choice: they took more risks than needed for solving the immediate problem at hand because the potential of long-term gain was considerable.

An AI-based analytic engine for their acoustic detection problem at first seemed overkill. The process could have used a dedicated machine that did not involve many computations. An analytic engine performed machine learning and deep learning, which required not only the computing power of an ARM processor, but also some other processors like a graphics processing unit and CPU to support it. This was a conscious decision by the MQM testbed team because it could yield an additional benefit: with the AI-based analytic engine, the testbed was not only useful for the simple acoustic detection task, it could also be reused in the future.

Another resource to balance is the funding. How to keep a testbed funded beyond an initial commitment? This was a challenge for the Distributed Energy Resources testbed team [*testbed-*

DER]. Engineers had to limit their time. Participation of an end user organization, the utility company, was helpful. More participation from other end users would have helped.

For the Factory Operations Visibility and Intelligence testbed team [testbed-FOV], funding was secured from a tight collaboration with the end user from the beginning and by aligning with their concrete business needs: the testbed team spent time on integrating existing components for a solution both on the edge and on the platform mostly focused on data processing, but did not spend much time investigating or testing new technologies. This meant enhancing, testing and then deploying this integration before extending the scope to other problems that would require less proven technologies such as AI.

4.4 How to Handle the IT/OT Mismatch

As described in section 4, a partnership, as opposed to the provider-customer model, goes a long way dealing with cultural differences in IT and OT. This divide also extends to technology choices.

As the OT side usually owns most of the requirements, a close collaboration between OT and IT personnel has helped clarify what are the real needs for the IT/OT integration.

For the INFINITE testbed team [*testbed-INF*], IIoT affects many functions within the organization, not just the IT and technology functions. The INFINITE team found that the technology complexities and risks are a deterrent for many organizations. The strategy for them was to use a solution platform so that organizations can focus on business innovation.

On the infrastructure side, there is no one-size-fits-all approach in handling deployment constraints (e.g., brownfield and evolving technologies). Sometimes the best solution is to share an infrastructure, if that infrastructure can support different needs. The Time Sensitive Networking testbed team [*testbed-TSN*] promotes the use of the same network for IT and OT by enabling fine-grained quality of service control depending on the usage. But it can be better to separate the infrastructures, for example due to different security concerns or different upgrade cycles.

On the data side, the guidance from OT experts was critical at all stages of the data processing, as reported by the Intelligent Urban Water Supply testbed [*testbed-USW*], the Time Sensitive Networking testbed [*testbed-TSN*] and the Factory Operations Visibility and Intelligence testbed [*testbed-FOV*]. Only OT experts can:

- identify the most likely useful data sources,
- identify patterns in monitoring data and
- understand what those patterns mean.

This has been observed regardless of the data processing analysis technology (machine learning, statistical analytics or empirical).

4.5 Analytics Models Take Time to Build

Making the case to management for developing a decision model is not easy: decision quality relies on data that can only be gathered over time. Do not be overly optimistic on milestones. Do not expect analytics to be perfect from day one and do not underestimate the time needed to collect enough quality data. That risky and unpredictable part of the project should be balanced with combining it with short-term and more predictable objectives.

For the Intelligent Urban Water Supply testbed team [*testbed-UWS*], much of the hard work was in collecting enough quality data and building robust analytic models so that these models can be applied back to the runtime environment to capture meaningful patterns in near real-time.

Data patterns associated with anomalies and faults are more important than the normal operational states of the equipment, but harder to come by. As a longer-term vision of how to ensure data quality and completeness of the data collection is needed, IIoT projects should start early and have a systematic way to collect and manage data for useful analytic models.

4.6 From Experimental Results to Deployment

Tested IoT technologies must scale when the project moves to an operational phase.

The Intelligent Urban Water Supply testbed team [*testbed-UWS*] had to adopt IIoT technologies in the water supply sector, make them low cost and scalable so it could benefit water supply management for many cities. Measuring these benefits was an important aspect in proceeding toward a more scalability solution.

For the Track and Trace testbed team [*testbed-T&T*], measuring the benefits from early testbed results and insights was key for acceptance of the next steps. Will these insights make an impact—and how big of an impact? Is this useful—and how useful?

5 Learnings on How to Deploy and Use Specific Technologies

5.1 Service Platforms

5.1.1 Establishing the value of an IIoT platform

The testbeds that developed platforms shared the motivation of building an infrastructure open to adding future services, removing the technology expertise barriers for end users and providing a managed-service option that relieved the end user of the burden of managing a solution for IT. Platforms can spread cost across several applications and users can leverage what has been developed before. Because additional investment is needed, these testbed teams had to justify the vision for the long term and establish the value of a platform as opposed to point solutions.

The Intelligent Urban Water Supply testbed team [*testbed-UWS*] realized that basic capabilities deployed initially for one pilot application should be reusable for future applications. The scalability of services and data collection from a large number of communities and cities across China was a major requirement for the urban water company (WPG). These requirements led to a cloud-based service approach. This allowed the collection of large amounts of data from a large number of end user communities and their equipment, usable later for analytics. They developed a service platform for making basic capabilities, data access and data analysis reusable across services. The platform also could share information about equipment and findings with end users across China.

For some testbeds, a platform model was part of the initial intent. The main objective for the INFINITE testbed team [*testbed-INF*] was to develop a horizontal platform. The INFINITE team envisages a converged infrastructure for IIoT where the INFINITE innovation platform can extend and combine advanced cloud virtualization or software-defined technologies to include connectivity, sensors, gateways and analytics to integrate them seamlessly to deliver business, economic and social benefits so that end users can focus on their application.

The Open Standard, Interoperable IoT Platforms testbed team [*testbed-OSP*] demonstrated the value of platforms for providing common services. The testbed is a platform that relies on a standardized infrastructure for the hosting of such services based on a family of standards for the IoT platform infrastructure, including connectivity and services management. This platform supports IIoT applications at different steps in their lifecycles, including the design phase. A service developed on the platform standardized the process of registering an IoT sensor. This sensor can be discovered and accessed by a separate IoT application operating on the same platform or on a peer platform operated by a different user.

Another motivation of the Open-Standard, Interoperable IoT Platforms testbed *[testbed-OSP]* was to address multiple drivers of value, ranging from near term economics to the longer-term potential for business-model innovation. These drivers included:

- Creation of a cost-efficient and common IT infrastructure to make IoT resources shareable by allowing any given IoT application to access data from another IoT application as well as from sensors associated with other applications. This arrangement is fundamental to enabling interoperability between silo solutions.
- Reduced risk of locking users into single-vendor or proprietary solution. By building on an open standard developed specifically for horizontal IoT platforms, users can implement local or cloud-based solutions knowing that the standard supports interoperability across platforms. This enables a smart city use case developed on the platform to scale to neighboring cities or regions.
- Faster application development. The platform creates an abstraction layer that shields applications from devices and other assets on the edge. Developers can focus on the core

application without diluting their efforts on building a full IoT technology stack for each use case. The approach supports numerous applications across many different verticals such as transport, logistics, energy and environment.

- By facilitating application, device and data interoperability, the IoT Platforms testbed *[testbed-OSP]* enables business innovation in shared operating environments. Examples include buildings, cities, industrial sites and transportation hubs. In such environments, several organizations can collaborate in sharing and eventually trading data [1] across operational and organizational boundaries. This becomes possible when IIoT platforms include capabilities that allow data providers to attach licenses to data and to track usage for the purposes of gauging demand and eventually as a basis for monetization.

Carefully selected IIoT platform technologies enable rapid development and delivery of testbeds and IIoT solutions. Selecting from available off-the-shelf platform solutions lets developers focus on the problem at hand rather than struggle with custom solutions, setting up the infrastructure and required standard services. Hence, the testbed program recommends their use. In some cases, platform products are offered to testbed teams, with incentives, to encourage adoption, accelerate development and use of vendor products and open source components. The program also facilitates a smooth transition between testbed phases, such as testing, pilot and solution rollout.

Platform technology is not static. To keep pace, testbed teams periodically re-examine platform technology to accelerate development and deployment further.

In other testbeds the notion of platform was not initially central to the testbed objectives and only appeared in subsequent phases. Such platforms are not designed for enabling a broad set of IIoT applications independently from their industrial area, but instead are specialized on a set of industry-specific business processes or services. The value is about speeding up and facilitating the development of new services in this industry or about enabling collaboration between several parties. For these testbeds, the notion of platform emerged as a key architectural component for enabling domain-specific business processes and operations efficiency, scalability and future business model innovation. The early phases of the testbed help to validate requirements for such platforms.

The Smart Printing Factory testbed [*testbed-SPF*] had the ultimate goal of developing such a platform for processing and analyzing edge data in the printing activities, managing metrics and KPIs, creating optimal manufacturing plans (schedule) and more generally managing data ingestion and the coordination of application components in the industrial printing business.

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[1] There are New Markets for Industrial IoT Data, IIC Journal of Innovation, June 2018, https://www.iiconsortium.org/news/joi-articles/2018-June-JoI-New-Markets-for-Tradeable-Data.pdf

Once the Intelligent Urban Water Supply testbed team [*testbed-UWS*] clarified the water equipment data collection process and usage requirements, the next step was to build a cloud platform as a way to scale up data collection from a large number of water pumps and municipalities across the country. Then in a next phase, the end user (water supply companies) could deploy their water management services, data processing, analytics and business applications in the platform. The scale allows for lower costs, which makes it affordable for the end users to leverage and benefit from the latest technologies.

5.1.2 The importance of use cases for IIoT platforms

Use cases serve as end-to-end scenario requirements for clarifying the desired set of underlying capabilities of a platform, and to justify the platform approach as compared with point solutions.

The strategy for the INFINITE testbed team [*testbed-INF*] was driven by the requirements from selected use cases that were expected to be representative of the requirements from future use cases. For this, the team focused on the initial definition and scoping of solutions. It developed a *use case engagement process* with potential customers. For this platform team, defining and prototyping use cases in collaboration with end users is part of a process for establishing a long-term customer relationship.

A field-trial variant of the Open Standard, Interoperable IoT Platforms testbed [*testbed-OSP*] demonstrates the value of selecting use cases with the involvement of eventual users and beneficiaries. A major use case involved the oneTRANSPORT[1] smart cities and intelligent transport field-trial. The intention was to base pilot activities on use cases that could deliver operational benefits and persuade city leaders to make longer-term implementation commitments. Detailed use case scenarios included:

- transport and traffic management for special events in the city,
- traffic control on a ring road and
- monitoring a park and ride scheme to improve journey-planning advice to tourists and local travelers to the city center.

5.1.3 An IIoT platform means collaboration and community

Platforms developed by testbeds required some form of human collaboration beyond just enabling coordination and communication between automated systems.

[1] Intelligent Transport Solutions for Smart Cities, IIC Journal of Innovation (June 2017) https://www.iiconsortium.org/pdf/June_2017_JoI_Intelligent_Transport_Solutions_for_Smart_Cities_and_Regions.pdf

For their platform testbed, the INFINITE testbed team [*testbed-INF*] realized that collaboration is essential to develop the platform and a community forum was key in managing relationships with their clients. In both cases, focus on collaboration and community offers the following benefits:

- An ecosystem of key domain skills and experts helps remove technology complexity from a solution. An ecosystem of key domain specialists, along with the platform, allows customers to focus on innovation.
- Experience sharing a knowledge base of common questions and challenges that organizations face across all sectors.
- Strong partnerships between leading technology providers and business expertise from different domains and sectors. This is needed when developing and evolving a platform.

The Open-Standard Interoperable IoT-Platforms testbed [*testbed-OSP*] served a community of providers and consumers to register deployed sensors as data sources or to discover registered data sources at different phases of an application lifecycle. The oneTRANSPORT initiative built on the OSP platform features demonstrated how data providers using city sensors could supply a range of data consumers such as facilities management staff, analytics providers and application developers. This provided the basis for an innovative data marketplace business model.

The de facto sharing of platform resources, whether these are based on standards or not, requires some collaboration between users at different levels. The oneTRANSPORT smart city use case illustrated more opportunities for collaboration. As an example, cities need to serve commuter traffic that traverses neighboring regions, each operating under different administrative rules. Harmonization on a larger scale requires agreement between administrations. There are also incentives to collaborate across public and private sector service providers, as micro-services and shared-mobility services add to the mix of available transportation modes. A platform strategy provides a foundation for such collaboration.

One of the goals of the Smart Printing Factory testbed [*testbed-SPF*] was to prototype collaboration platforms between all parties involved in a printing order. Depending on their nature which could vary widely, each printing order may require collaboration between several parties within and across companies. The platform generates task schedules for these parties and most importantly, handles unexpected changes in production plans by offering alternate plans and doing the rescheduling involved.

5.2 Machine Learning and AI

5.2.1 What to use ML and AI for, and what method is the best fit?

Classification is a prime application of AI in testbeds. In manufacturing, quality control for products is a common example.

The Manufacturing Quality Management testbed team [*testbed-MQM*] used artificial neural networks (ANN) for product quality control (QC). The goal was to introduce a consistent and automated way to detect defects that can rival human experts. Such automation will avoid repetitive tasks for skilled personnel and make them available for other tasks.

In its most recent evolution, the Factory Operations Visibility and Intelligence testbed [testbed-FOV] also does quality control with AI techniques (machine learning), with three priorities:

- to reduce personnel needed for visual Quality Control (QC) from two to one person,
- to reduce QC dependency on skills from QC experts to assess product quality visually, as not many employees have these skills, which take some training time to acquire and
- to make the QC process more scalable: currently the ML application is tested in a pilot factory, but if successful will be easier to replicate in other factories and for several other product types, thus multiplying the benefits.

Scalability via automation is a recurring value proposition mentioned by testbeds for AI. For the Deep Learning Facility testbed team [*testbed-DLF*], a concern was the shortage of people in the facility management team of a large building to monitor the control and manage all of the building assets. There was a clear business case for AI ability to support these tasks automatically. This complements immediate payback associated with more sustainable options such as money saved on electricity and energy bills.

However, there is also an experimental technology objective: another area of experimentation was to determine what is computationally feasible and how to apply various high-end technologies to maximize those computation capabilities that are needed for deploying AI.

The Smart Factory Machine Learning for Predictive Maintenance testbed team [*testbed-FML*] realized that the right machine learning method depends on the problem at hand, and that one algorithm cannot solve everything. While artificial neural networks (ANN) excel in classification problems, such as based on image and video inputs, they are not necessarily fit for all dynamic industrial environments. In the presence of data streams from industrial systems and their inevitable concept drifts the team elected dynamic ML algorithm instead of ANN. Stochastic methods were useful to provide actionable insights with a good probability of being valid. Additionally, in industrial environments, the randomness and noise need stochastic algorithms to increase robustness. Given the deterministic character of ANNs the team did not see them as a good fit to avoid getting “noisy” actionable insights.

The testbed team [*testbed-FML*] had another requirement for which ML algorithms were the right choice, compared with other AI methods such as deep learning. Because dynamic algorithms are mathematically well understood and not as opaque as black-box algorithms such as in neural networks, the designer (data scientist) is able to understand what the algorithm is doing internally. This further helps the predictive analytics to minimize false positives and save significant costs.

5.2.2 Keeping field experts in the loop

Especially in the initial phases of an ML deployment, expert personnel play a key role in testbeds. Domain knowledge is necessary to reduce the scope of monitoring to the most likely relevant data and to interpret it (what the data tells about assets and physical processes). Irrelevant or excessive data will burden the project, create overhead and lengthen the training period.

For the Intelligent Urban Water Supply testbed team [*testbed-UWS*] even when quality data have been accumulated, it is necessary both to identify patterns in the data and to understand what those patterns mean—and the latter can only come from the OT side. More specifically, one needs to apply OT domain knowledge to the equipment-generated data.

The Manufacturing Quality Management testbed team [*testbed-MQM*] noted that observing human experts operating during the actual manufacturing process gave clues on the data set that needed be captured. Key to the successful use of ML were hints from human operators.

The Factory Operations Visibility and Intelligence testbed team [testbed-FOV] found it necessary to pre-select the visual data used as input to train the model. For better performance and faster training of the ML engine, QC experts have reduced the visual input by masking some parts of the product pictures that are known to not be relevant. This requires human expertise, extending to validating the model to measure how efficient this data input reduction is.

5.2.3 Correlating diverse data with diverse lifecycles

Testbeds such as the Deep Learning Facility testbed [*Testbed-DLF*] with AI models that process diverse data from various sources are still a minority. Less complex is to apply AI to a confined, homogeneous and fairly independent data set with limited scope, in a classifier role such as for assessing product quality. This is often a realistic goal for a testbed given its time constraints.

However, processing a variety of data and their lifecycles is a common requirement in manufacturing testbeds where operational data often needs to be contextualized with more stable business data such as production plans, delivery schedules or product information. This also requires well-integrated systems where equipment maintenance and repair records can be correlated with the machine operational data and close-loop communication on data lifecycle.

5.2.4 Data quality and acquisition challenges

The quality of data input whether for training of a classification engine or for feeding an analytic model in real-time has been a recurring concern.

In the Manufacturing Quality Management testbed [*testbed-MQM*], the initial trial run of the AI-based analytical engine did not provide satisfactory results: The microphone on the quality check station also picked up additional ambient noise. The analytics were not able to filter out the ambient factory noise effectively. The performance was eventually optimized by placing the tested unit and the microphone in a sound proof chamber at the test station.

For classification types of application requiring supervised learning, such in the Manufacturing Quality Management testbed [*testbed-MQM*] the key to fast and high-quality machine learning is a well-balanced training data set. The testbed team observed that it is not always easy to acquire them. Collecting the failure data sets was difficult because the number of failure cases is small over the short data collecting period; the failure data set size is smaller compared to the 'normal' data set. All data sets are fed into the learning process to train the machine to identify the difference between passed and failed states. The machine eventually established a passing state and failed state for the quality of the product (HVAC appliances) through testing, training and fine-tuning. The development of the analytical engine is important as an appropriate AI-analytic engine is not available off-the-shelf. For users who plan to modernize existing operations in a manufacturing plant, the complexity of the project cannot be underestimated.

Data collection in brownfield conditions has been a challenge in the Smart Manufacturing Connectivity project [*testbed-SMC*]. The testbed provided solutions to collect a higher volume of data from legacy equipment and their PLCs because machine learning algorithms at enterprise IT level require a higher volume of training data prior to running real-time analysis tasks.

In the Smart Factory Machine Learning for Predictive Maintenance testbed [*testbed-FML*] some experimentation led to the development of dynamic algorithms, machine learning algorithms that are not commonly used in state-of-the-art industrial environments but that guarantee the quality of the data coming from the industrial sources in the plant, for example in terms of noise reduction. An important learning for this testbed team was data quality is often wrongly assumed to be sufficient. Quality depends on the use of the data, which may require, for example, a specific sampling rate. A well-designed connection of a sensor to a data acquisition system is no guarantee of appropriate data quality. It took time for the team to realize this. In the future they would prioritize efforts to ensure proper data quality, over developing the machine learning algorithms.

For the Deep Learning Facility testbed team [*testbed-DLF*], one challenge was attributed to the reliance on the domain knowledge of the building facility management team. In typical deep-learning technology, supervised learning is required, and so data must be labeled. An autoencoder reduced the need for supervision by HVAC domain experts, but unsupervised learning cannot do root-cause analysis to detect which device's behavior is unusual. Toshiba's data scientists had to do it.

It has been a challenge in several testbeds to acquire the right data, pre-process and select the variables needed to guarantee the right quality. To achieve this, domain knowledge from field experts is needed, in addition to data scientists' expertise. When building a training dataset for classification, the collection of failure data for well-rounded training was a particular challenge in several brownfield testbeds. Some have broadened their data sources, for example by getting failure data from several factory subsidiaries or plants. Some have considered relying on simulation models.

5.2.5 GETTING ACTIONABLE INSIGHTS

The Smart Factory Machine Learning for Predictive Maintenance testbed team [*testbed-FML*] has observed that producing actionable insights for the end user depends on several factors in addition to new machine learning algorithms such as data flows and data storage characteristics. Actionable insights depend on the question or problem the end users are trying to solve. For predictive maintenance, the questions are related to the degradation level of a specific part of the machine, cell or line that could fail, stopping the production. Goals have to be expressed in terms of downtime reduction or increasing mean time between failures (MTBF). Therefore, the output of the algorithms or the machine learning system is to tell the end user the remaining useful life (RUL) of that particular machine component. The actionable insights provided to the end user is the RUL percentage, helping the end user to make decisions about changing a component during the next maintenance stop.

Usually, the results or outputs of machine learning algorithms are complex and require a lot of experience to be properly interpreted and simplified for the context of usage. This is where operational field expertise is precious (see 5.2.2.). It is also important to realize that the actionable insight given to a machine operator would not be the same as the insight given to the line manager of a production facility.

5.2.6 CHALLENGES WITH LARGE-SCALE DEPLOYMENTS

The Deep Learning Facility testbed team [*testbed-DLF*] perceived several challenges in applying deep learning to large-scale smart building environment such as a set of large buildings on a campus. In this context, field simulation in a lab is not realistic. Differences of operations between a lab and real-world conditions are significant. In real conditions the following is important:

- the neural networks that are generated must be as precise as possible,
- re-training is likely to be required to accommodate changing conditions and
- all compute nodes require simultaneous access to the same data.

Because of this, development and testing of the AI models had to take place under real conditions.

Another challenge for large scale deployments that the Deep Learning Facility testbed team [*testbed-DLF*] had to address was access to and integration of data collected from different building management technologies. Even within one facility on the campus there are multiple vendors who install systems there. To get a decent model of the building, the data from those different systems needs to be brought together. Buildings built at different times further add to the complexity of accessing and integrating that data.

The team has also learned to deploy AI at scale. Employing one large neural network would not give desired results as it would not specify where to take action nor indicate what action was needed. Therefore, the testbed team employed a number of smaller neural network models that could give insight into the individual systems and control them as needed.

5.2.7 OTHER CHALLENGES IN DEPLOYING ML

The following other issues have been identified:

Testing: The Smart Factory Machine Learning for Predictive Maintenance testbed team [*testbed-FML*] realized that a system is not ready when only tested at a home facility. The team may design the best machine learning algorithms, best IoT hardware and best architecture, but many changes take place when moving from a lab to a real industrial environment. If not tested during real production, there will be many false positives. The testbed team strongly suggests conducting tests in real environments rather than limiting results to a proof-of-concept or applications in a controlled environment.

Integration challenge: In the Factory Operations Visibility and Intelligence testbed [testbed-FOV], the ML engine has to be connected to third-party tools such as data cleansing and data visualization tools to be used conveniently. Expertise on these systems was needed and collaboration between AI experts and tool experts was required and could not be overlooked or underestimated.

Lifecycle of the ML model: The process for ML model updates and continuous training is still underreported in several testbed teams. Overall, teams observed that deploying ML and managing it is a process not a turn-key solution. As the context and operating conditions change over time, adjustments and model retraining may be needed.

Data governance and sharing: Another challenge comes into play when accessing data from various systems, under governance from various experts. When working on the smart building application, the Deep Learning Facility testbed team [*testbed-DLF*] realized that the building managers had a contractor responsible for a particular system. The contractor installs the equipment and collects the data, but then hesitated to give out this data as it was not clear who is requesting it and why. A legal agreement had to specify that the contractor must share the detail-level data of the system with the data scientists.

5.3 Time Sensitive Networks

The Time Sensitive Networking team [*testbed-TSN*] demonstrated the viability of enhancing Ethernet (specifically IEEE 802.1 and 802.3) with a variety of functions and capabilities to make it more suitable for industrial applications that require more deterministic characteristics. In particular the testbed team identified diverse types of industrial data traffic and demonstrated the ability to converge both applications and industrial traffic on a single, open network, by defining different quality of services for each. Without TSN, intercommunication between devices and systems had to be controlled with a separate, proprietary networking technology – either not Ethernet or heavily modified Ethernet – that would leave these applications and systems, from an IoT-network perspective, relatively in the dark.

The Smart Factory Machine Learning for Predictive Maintenance testbed team [*testbed-FML*] realized the importance of communication and data flow to ensure proper coordination between decision-making, processing and pre-processing. The deterministic approach of time sensitive networks increases the integrity and timeliness of the data during communication between components, and helped avoid data loss when feeding into the machine learning algorithm.

6 Dealing with Standards and Open Sources

Testbeds have different motivations in using, assisting or promoting standards. The same can be said when relating to open source platforms and their organizations. This section summarizes the value testbed teams have seen in using standards or open source components and identifies different roles played by testbed teams with regards to the standardization process itself.

6.1 The Value of Using Standards

The Smart Factory Web testbed team [testbed-SFW] believes open standards should be followed as much as possible to enable developing a sustainable, robust and flexible implementation architecture where one can make adaptations and demonstrate new technologies easily.

Participants in the Open-Standard Interoperable IoT-Platforms testbed [*testbed-OSP*] are early proponents of the value of standards. Standardization gives users in shared operating environments more confidence about working together. This is true of interactions in smart buildings and smart cities that involve IIoT platforms operated by neighboring regions and external agencies.

The Open-Standard Interoperable IoT-Platforms testbed team [*testbed-OSP*] saw another benefit in horizontal standards. When required to develop an application, implementation teams and application integrators face the choice of either putting resources into developing supportive, reusable features in a platform or, in contrast, spending it all on the priority application at hand.[1] This is a typical conflict between short-term objectives and longer-term goals. The team observed that compliance with IoT platform standards pays off expanding from one to many multiples of applications, which is the eventual destination for city, industrial and transportation scenarios.

Finally, the team [*testbed-OSP*] recognized another benefit of a standard-based solution around the concern of city authorities, for example, in investing large sums of money to deploy proprietary solutions. The use of IoT platform standards alleviates vendor lock-in concerns and creates a pathway to an open marketplace for data and data services.

Closer to use cases, there is a need to standardize the application of technologies and their integration in specific environments or in products as was the case for integrating several geolocation standards such as GPS, triangulation and BLE in the Track and Trace testbed [*testbed-T&T*]. Such an integration of different standards or heterogeneous equipment often manifests as unified interfaces and common data models between components (such as for data transfer and operations). If standardized, these interfaces mitigate interoperability issues and reduce the cost of dealing with heterogeneity without affecting upper layer components. Such standards about integrating other standards or products are different from foundational standards such as a networking protocol and more driven by specific usage environments.

The Smart Factory Machine Learning for Predictive Maintenance testbed team [*testbed-FML*] also incorporates standardized IIoT technologies that help data communication. OPC UA, currently a common protocol to integrate production facilities with superior IT layers, is one example. The Data-Distribution Service for Real-Time Systems (DDS) standard, as implemented in DDS-Secure from RTI, is another example included in the testing. The most critical part for the team was the data structure. The team is starting to use a future standard for machine tools called UMATI (Universal Machine Tool Interface.)

6.2 Producing Requirements for and Feedback to Standards

Requirements produced around standards are diverse and include:

- selection of a standard(s): determine which standard(s) to apply,
- change requirements: how does an existing standard need change,
- need for standard integration guidelines,
- need to profile an existing standard (how to use it to ensure interoperability or portability in practice, for example, what optional features are important) and
- missing standards.

[1] oneM2M's Value Proposition for IoT Application Developers: https://sites.atis.org/insights/onem2ms-value-proposition-iot-application-developers/

Testbeds represent opportunities to validate a standard proposal, an integration practice for standards or a change requirement for a standard. Such sample implementations carry a lot of weight for standard organizations.

However, if they often identify opportunities for standardization or updates to standards, testbeds, in general, cannot factor this in their deliverables because generating a new standard is a long-term proposition of no immediate value to testbed sponsors and to the funding parties.

The Intelligent Urban Water Supply testbed team [*testbed-UWS*] could not afford to wait for standards to be implemented and to upgrade the equipment before implementing the systems. It was essential to be able to adapt to the existing equipment that had already been installed.

As noted in section 4.6, the Track and Trace testbed team [*testbed-T&T*] identified the need for additional data standards to facilitate the integration of several localization technologies. Such a need was only perceived after the testbed solution design had been finalized.

In several instances, best practices on how to integrate existing standards were more important than generating requirements for new standards. The Smart Factory Web testbed team [*testbed-SFW*] relied on standards from the start and knew it had to integrate international standards such as OPC UA and AutomationML to link factories into the Smart Factory Web. Other standards were integrated in the deployed solution (OGC SensorThings API and reference models for service and IIoT architectures) so that information could be exchanged in a standardized way.

In several cases, as shown in the Intelligent Urban Water Supply testbed [*testbed-UWS*], the timeline did not allow for significant contributions to standards let alone initiating new ones.

The Track and Trace testbed team [*testbed-T&T*] realized that even when developing a domain-specific standard, collaboration is needed. They recommended to first implement the proposed data model standard in the solution they have developed. That solution is deployed by the customer and the data model is validated in terms of fulfilling its expected role. Then, the team considers bringing the newly developed standard proposal to a standards organization, using the testbed as a proof of concept implementation. If there is enough interest, a standard group is formed that will generate additional requirements toward a standardization of the model for general use.

The Distributed Energy Resources testbed team [*testbed-DER*] had its end user partner (a utility company) contribute an open-source version of an OpenFMB (Open Field Message Bus) architecture that will support a contribution for a new standard to the North-American Electrical Standards Board (NAESB).

Based on their highly visible testbed on a relatively unexplored area, the Time Sensitive Networking team [*testbed-TSN*] provided inputs to standard organizations such as IEEE, IETF, the OPC Foundation and Avnu that have developed or were developing the standards at the base of time-sensitive networks technology. With the weight of twelve testbed partners, the team could get the attention of these organizations and give them timely feedback, including about integration requirements between TSN-relevant standards. Section 6.4 provides more details on specific contributions of testbed teams to standards-development organizations (SDOs).

6.3 Useful Areas of Standardization

6.3.1 Interfaces and Messaging

In analyzing both horizontal and vertical types of interfaces, the Track and Trace testbed team [*testbed-T&T*] did not find any established standard for the problems at hand (geolocation in diverse environments and with various levels of requirements).

Standards were needed for interfaces that enable integration of functional components or processes, both for horizontal interoperability and vertical integration. This may end up helping integration of existing standards.

Figure 4 illustrates the detected areas for standardization and open-source support in the Track and Trace testbed [*Testbed-T&T*]. On the left side are the various areas of tracking & localization data that is generated on the edge. The elements on the right side reflect the corresponding enterprise system. The arrows between them represent the APIs that need to be standardized. Three horizontal layers have been identified.

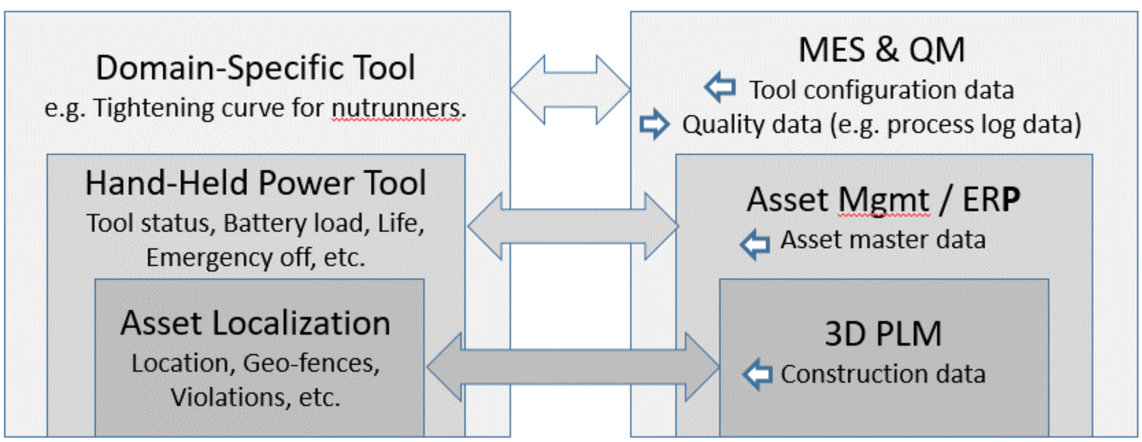

Figure 4: Standardization and open-source areas of requirements in the Track and Trace testbed

The generalization of techniques and interfaces into a standard is generally motivated by the heterogeneity of products and technologies that need to be integrated over time. For the Track and Trace testbed [*testbed-T&T*], multiple localization technologies exist that upper layers of processing should be able to abstract by assuming a common, more general localization data model, which is what the team proposed.

The Smart Factory Web testbed [*testbed-SFW*] testbed, learned that open interfaces based on standards are essential to realizing a system architecture that can be adapted to changing requirements and technologies with reasonable effort.

The Distributed Energy Resources testbed team [*testbed-DER*] based its testbed on the Open Field Message Bus (OpenFMB) standard framework to ensure that the system is interoperable and extensible. This is combined with data models that employ platform-independent configuration overlays to meet the diverse grid-hardware requirements. This combination of standardized data model, real-time data-bus (itself based on the Data Distribution Services [DDS] standard) and RESTFul API-based system allowed for the creation of a generic, adaptive visualization and dashboard for grid operational status and data analytics capabilities that can be easily customized to particular deployments.

6.3.2 DATA

In the Track and Trace testbed [*testbed-T&T*], as more data was collected, data scientists were involved to help build data models and to interpret the data. This complex and ongoing effort is not easily standardized.

Two kinds of data had to be distinguished, as they are not processed or administered in the same way: information—or domain—data models and dynamically generated and transferred data.

For the Track and Trace testbed team [*testbed-T&T*], there are already sufficient communication standards and the testbed team is reusing them, such as MQTT. A testbed will shed light on how to profile a standard for a specific usage in that case.

The Smart Manufacturing Connectivity testbed [*testbed-SMC*] collects and consolidates data from sensors to enterprise IT servers using the OPC UA standard. This mapping to a standardized representation allows for the easy integration with the IT system. It is currently being standardized in a joint effort of the IO-Link Community and the OPC Foundation. The testbed provided essential input and delivers a reference implementation at the same time.

A standards-based solution carries a higher level of acceptance and trust from end users. The German Federal Office for Information Security (BSI) has recently carried out an in-depth security analysis of OPC UA, the results of which confirm that “OPC UA was designed with a focus on security and does not contain systematic security vulnerabilities.”

6.4 RELATIONSHIP WITH STANDARD ORGANIZATIONS

The IIC positioned itself as complementary to SDOs by generating requirements for standards instead of acting as an SDO by creating them. Of course, a requirement for a standard may take the form of a near-complete initial standard proposal.

Testbeds have contributed to SDOs. Some testbed teams have clearly produced advanced standardization proposals and have plans to directly engage SDOs if not already done:

- The Track and Trace testbed team [*testbed-T&T*] initiated a new standardization group in OMG.
- The Time Sensitive Networking team [*testbed-TSN*] has generated a new quality-of-service (QoS) standard requirements to be contributed to IEEE 802.1 as TSN mechanisms to support those traffic types. The team intends to promote TSN to various SDOs, including IEEE, IEC, Avnu Alliance, CC-Link Partner Organization (CLPA), Labs Network Industrie 4.0 (LNI4.0), ODVA, OPC Foundation and more.
- Participants in the Smart Factory Web team [*testbed-SFW*] led the work on the Companion Specification *OPC UA for AutomationML* as a DIN standard. They also contribute to the detailed specification of the Asset Administration Shell of Plattform Industrie 4.0 (PI4.0), a digital representation of an asset by which modular and interoperable digital twins may be built according to the Industrie 4.0 concepts. The team hopes to provide support to this standardization work. Finally, as the Smart Factory Web testbed employs several well-established standards, the team is planning to report to the relevant standards body whenever possible adaptions to a standard are identified. This may involve submitting a change request or undertaking an accommodating process, depending on the standards organization.
- The Smart Manufacturing Connectivity testbed team [*testbed-SMC*] has produced an elaborate standard proposal for a consistent mapping of IO-Link (IEEE) parameters to OPC UA, including mapping of data types from IODD (itself based on an International Standard *ISO 15745-1)*. This will complement the existing range of OPC UA Companion Standards that map existing device profiles or semantics to OPC UA information model extensions of the basic OPC information model. A new standard was produced in 2019.
- The Distributed Energy Resources testbed team [*testbed-DER*] has relied on standards from the Smart Electric Power Alliance (SEPA) and obtained center-stage exposure at the SEPA annual convention.

Testbed outcomes have contributed to standards in a more indirect way. The experience from some testbeds has been processed internally to the IIC by other groups then submitted to SDOs:

- The experience gained on architecture patterns (such as the three-tier architecture pattern referred to in several testbeds) has contributed to the *Industrial Internet*

Reference Architecture/IIRA *[1]* then, in turn, contributed to the IoT reference architecture standard (in ISO-IEC/SC41, WG3).

- The Factory Operations Visibility and Intelligence testbed [testbed-FOV] served as a use case for trustworthiness best practices white paper, which contributed to the for ISO-IEC/SC41 Trustworthiness group.

6.5 The Unique Role of Testbeds Within the Standards Ecosystem

Testbed teams have confirmed what has been observed many times: standards alone do not guarantee interoperability. A common interpretation of standards does. The Open-Standard, Interoperable IoT Platforms team [*testbed-OSP*] realized that the strong interoperability capabilities requirements behind their testbed as a horizontal IoT platform could only be addressed by clarifying and agreeing on a common interpretation of the underlying specifications (primarily IoT platform supportive standards with interworking extensions to complementary standards such as OSGi and MODBUS). The testbed provided the infrastructure to develop and test that common interpretation among the team members. This is an alternative to conventional interoperability plugfest events with heavier logistics.

The emphasis on implementation and testing under end user conditions gives testbeds leverage for advancing their standard requirements. In turn, this gives IIC and its contributions a significant weight in standard organizations.

In the Time Sensitive Networking testbed [*testbed-TSN*], the team considers that its testbed plays a strategic role in promoting TSN technology. There are many architectures, standards and protocols potentially influenced by TSN, meaning many related SDOs and consortiums need be made aware of the requirements and have a perception of their importance and market relevance. A testbed developed within a consortium such as the IIC is more authoritative.

For the Smart Factory Web team [*testbed-SFW*], the testbed supports OPC UA and OGC SensorThingsAPI through open source development contributions that provide a way of trialing the standard and generate practical feedback about the specification. The open source communities can incorporate changes into the latest releases of the software.

In the ISO/IEC JTC1 international standard organization, the architecture work group of the committee SC41 for all standards related to IoT has welcomed significant contributions from the IIC's IIRA. These contributions had a significant weight as they have been validated by several testbeds. In 2019, the SC41 management invited contributions from the IIC in other IoT areas where testbeds provided validation, ranging from security and trustworthiness to connectivity, analytics and more specific technologies (e.g., digital twins and deep learning) or methodologies (e.g., project management and business strategies).

7 Learnings About The Human Side

The success of an industrial IoT deployment depends on the human factor. Expectations must be managed. People may have concerns about the risks and fears about their own job relevance.

As the Manufacturing Quality Management testbed team [*testbed-MQM*] puts it, "While technology is very important, how everyone works together is even more crucial."

7.1 It Is a Partnership

The importance of partnering and teamwork recurs in several testbeds. A testbed offers a collaboration platform, focused on problem solving and free of immediate commercial concerns such as a supporting product to sell. A byproduct is to clarify and refine the actual requirements for a future system in light of insights from end user constraints, technology limits, operational impact, business value and future evolutions to consider. All of these require collaboration between experts, for whom a testbed setup provides the right environment.

No single partner or company has all the expertise needed to deploy an IIoT solution. IIoT projects typically involve a wide range of technologies and practical knowledge from different industries. A team with various expertise areas and from various backgrounds (not all from the same company) gives confidence to the customer that technologies (often rather new) will be properly applied, and that their specific needs will be considered.

The Manufacturing Quality Management testbed [*testbed-MQM*] affected many functions, not just the IT and technology functions. Developing an IIoT pilot is a partnership between several stakeholders: users, industry experts, management and external parties (e.g., organizations and government). Sufficient interest from such partners including non-commercial (CAICT) and commercial (China Telecom) convinced the testbed team to proceed. Huawei submitted some of the IIC testbed results to these partners and helped them during every step of the work.

The Manufacturing Quality Management testbed team [*testbed-MQM*] also learned to help partners who are not familiar with IoT, to build confidence and be willing to participate in this leading-edge IIoT effort.

For the Track and Trace testbed team [*testbed-T&T*], there was no magic bullet or one-size-fits-all approach. A process for collaboration between several experts needed to be defined. Integration with different suppliers was also required, for example for forklifts.

Success, for the INFINITE testbed team [*testbed-INF*], results from the strength in depth and technical capabilities of partners in the team and the quality of the ecosystem, more than a single organization. Such an ecosystem included IT technology providers, application developers, analytics experts, security experts, connectivity experts and sensor providers.

The Track and Trace testbed team [*testbed-T&T*] discovered the importance of a team approach: no one party can solve all of the issues. To fulfill all of the requirements, technology integration is needed. Collaboration between data scientists, IT experts and process experts to develop the models to interpret the data and deliver the business benefit to the customer. The Track and Trace Testbed has been a joint effort with regular meetings conducted with IT scientists from Bosch and SAP, business partners directly from the customer plant and technology partners. Building a small ecosystem with partners and customers enabled them to go to market with their solution more rapidly than they had expected. The ecosystem they developed and the resulting management attention was a powerful combination.

End users were an active part of this partnership: they ran the tests as well as the technology and provided feedback to the testbed team on all aspects of the deployment.

Nearly all testbeds underline that partnership requires time and attention, but is key to their productivity and success. Although the Distributed Energy Resources testbed team [*testbed-DER*] warns about the administrative overhead that a large team of partners may entail. Teams are often heterogeneous: business types, operation managers, technology vendors, government entities, consortiums, external experts all need to adjust to a common process and schedule.

The Smart Factory Web testbed [*testbed-SFW*] testbed has been a major collaboration platform for the two research institutes KETI (Korea) and Fraunhofer IOSB (Germany).

The Smart Printing Factory testbed [*testbed-SPF*] learned the importance of maintaining and sharing knowledge about physical assets in brownfield environments. This requires talking about technology with each equipment manufacturer and vendor and working with them. It is important to collect technical information and cooperate with the maintenance department of each equipment manufacturer, for example to share information on how it is used on site.

For the Smart Factory Machine Learning for Predictive Maintenance testbed team [*testbed-FML*] the most significant surprise has been the relationships formed between partners. In particular, the openness of the collaboration between partners was unexpected, with the team establishing from the start an open and simple mode of communication. When examining the testbed's progress much can be attributed to the effectiveness of these relationships.

7.2 Engaging the Customer Early and Giving Them an Active Role

The Track and Trace testbed team [*testbed-T&T*] received invaluable feedback by involving customers in the early stage of the project—first by setting up the project in a production environment at the location of a customer willing to support and endure the unforeseen consequences. The users were the key to the testbed progress. They provided insightful and timely feedback on the use of the technology and on the ideas from the testbed team.

Eliciting testbed requirements is an iterative process. Customers are not always able to formulate their requirements upfront. That requires constant collaboration, readjustment and discussion.

In the Intelligent Urban Water Supply testbed [*testbed-UWS*], through customer engagement in the development of the testbed, the team has also learned what features the customers would be interested in and not just those planned out by the testbed team. For example, providing visibility to remote assets offers substantial initial value initially ignored by the testbed team. The ability to adapt to customer's needs that can only be revealed over time as technology capabilities and applicability become clearer.

7.3 Addressing the Concern for Disruption

According to the Manufacturing Quality Management testbed [*testbed-MQM*] and the Intelligent Urban Water Supply testbed team [*testbed-UWS*]s, working closely with the customer or end users is key to minimizing operational disruption—usually a major obstacle to an IIoT project.

In [*testbed-MQM*], originally, the client did not favor modifying the existing production line because of the disruption and the additional burden placed on personnel working in the field. For them, the initial collaboration was problematic because any change added to the production line would potentially impair productivity. To gain the trust and cooperation of field operators, the team adopted rules to minimize the impact on the operators. For example, systems could only be tested after work shifts ended.

The system would then be restored before the next shift began. After several iterations, the production line managers became supportive and helped to conduct the testbed in a more constructive manner.

7.4 Early Involvement of Management

For the Track and Trace testbed [*testbed-T&T*] and the INFINITE testbed team [*testbed-INF*], it was also important to involve management as early as possible and develop the plan from the strategic business perspective, not only the user perspective.

The INFINITE testbed [*testbed-INF*] has been influenced by the maturity of the IIoT conversations among business executives. The testbed team understood that everyone has heard of [industrial] IoT yet a lot of organizations are still developing an understanding of how it will affect them.

7.5 Cultivating Trust with End Users

For the Manufacturing Quality Management testbed team [*testbed-MQM*], when starting a new project, it was imperative to understand the real needs and constraints of the end user. During the course of this testbed, the partners' input was solicited, discussed, explored and implemented. They were educated about the process and kept apprised of the results, which fosters trust. End users were in the loop during all tests. The testbed team took the necessary time to cultivate that trust.

The following were factors promoting trust as mentioned by this team:

- Relying on standards and recognized best practices such as developed in the IIC as this helped secure that trust.
- Working with human field operators, not against them. The goal should be to help operators in the field do their job better and faster—not to render them irrelevant.
- Recognizing and respecting human expertise in the field. Their input must be valued in helping to narrow down to the right set of data.

For the Intelligent Urban Water Supply testbed [*testbed-UWS*], a big surprise was on the business side: the team was not expecting to see so many potential customers willing to sign up to be part of this pilot. That experience is unusual for testbeds because there are often challenges getting end users to participate in experiments during the early phases of major new technologies.

7.6 The "Training" Byproduct

In the Smart Factory Web testbed [*testbed-SFW*], the testbed has been integrated into training programs offered by Fraunhofer IOSB and KETI on industrial automation and security, including the application of OPC UA and AutomationML standards.

8 Value Provided by The IIC and for The IIC

There are several ways the IIC as an organization has been reported to help testbed teams. Overall, testbed teams have valued the role of the IIC in providing an ecosystem of partners, of expertise areas and a forum to reach out to a larger audience and potential users. For most testbed teams, it was clear that these IoT solutions need to involve several partners. Partner matching is a crucial aspect of finalizing a solution, and taking advantage of the IIC ecosystem played a significant role in setting the stage for a successful partnership. Testbed teams have reported value in developing testbeds in the IIC in the following areas.

8.1 A Trusted and Legally Protected Environment for Collaboration

Several testbeds have reported the value of the IIC as a trusted ecosystem with clear legal rules for their teams of participants, inclusive of non-IIC members.

For the Time Sensitive Networking testbed team [*testbed-TSN*], the IIC is a trustable environment. Bringing twelve companies together inevitably leads to questions around non-disclosure agreements (NDAs), intellectual property, etc. The participants want to ensure that no vendor takes any of the results to drive commercial advantages for a small group or for itself. The structure of the IIC helps testbed partners to collaborate with enough confidence that sharing or exposing insights and technology is not going to lead to bad press or to someone claiming rights or locking the others out of a marketplace. Then, the IIC helped the TSN initiative to increase awareness and drive adoption. The TSN testbed is also feeding into other IIC work including the IIRA, *Industrial Internet Connectivity Framework* (IICF) and edge architectures.

8.2 A Common Framework for Technologies, Architecture and Practices

Most testbeds have reported benefits in using and applying IIC frameworks at inception and during their lifecycle. IIC frameworks are seen as references for all areas of a testbed including architecture, connectivity, analytics, data and security. In turn, the testbed provided feedback to the frameworks and validated these by showing what works in the field.

For the Smart Manufacturing Connectivity testbed team [*testbed-SMC*] considered early on that their testbed could be described as an application of the IIC's IIRA, which has facilitated its work. The three-tier architecture pattern of the IIRA was helpful in defining testbed overall architecture, its major parts, the functions of its components and understanding how to establish individual interfaces. This pattern was useful in describing where potential testbed partners would extend the current setup.

Similarly, the IIC's *Industrial Internet Security Framework* (IISF) was instrumental in the SMC testbed's work, which recommends that endpoint and communication security are really two challenges that need to be separately considered. For example, the IISF [3] was used as a reference for the testbed's threat analysis and its security maturity [4].

The IIC's IICF was relevant to the testbed as the connectivity stack defined in the IICF provides a structure to explain the properties and interoperability requirements of the communication protocols used in the testbed. For instance, OPC UA's high-level allocation in the stack indicates that it operates with lower-level transport and networking protocols (e.g., TCP/IP), clarifying that OPC UA is addressing semantic interoperability.

When the Deep Learning Facility testbed [*testbed-DLF*] was first proposed, the IIRA and the IISF played a role in formalizing how the system worked. As a standards-based architectural template and methodology, the IIRA enabled the testbed team to design their system based upon common frameworks and concepts in AI and deep learning technology. Similarly, the security design perspective of the testbed is attributed to knowledge gained from the IISF. Finally, the *IIoT Analytics Framework* spells out how companies who want to implement AI for IoT can search through different design patterns and choose those that match their respective cases. This in turn has helped guide the design of the testbed.

In the Smart Factory Web testbed [*testbed-SFW*], the team has also adopted the general terminology used in the IIRA, a crucial step to facilitate clear messaging to their end user industry.

The INFINITE testbed team [*testbed-INF*] aligned its use case facilitation platform to the IIRA and IISF.

The Intelligent Urban Water Supply testbed team [*testbed-UWS*] saw value in IIRA, IICF and IISF.

The Smart Factory Machine Learning for Predictive Maintenance testbed team [*testbed-FML*] has referred to the IIRA for nearly all aspects of the testbed and helped understand which partners may be useful to build the complete architecture of the testbed. With two security companies involved in the testbed, IISF came into play. The two companies combined their points of view in conjunction with the IISF to work toward effective security practices in testbed implementation.

For the Smart Printing Factory testbed [*testbed-SPF*], the IIRA was helpful to guide the overall architecture of the system, and the IISF helped to understand the security issues and how to handle these.

In the Track and Trace testbed [*testbed-T&T*], as the IIRA developed, the testbed team engaged in many helpful exchanges with the IIRA authors. By relying on the base concepts and terminology from the IIRA, the testbed team was able to develop and apply the domain-specific views, which convey the fundamental principles of the IIRA. When phase two began, it was easier to reuse the key concepts that had been developed in the first phase.

More generally, the IIC established a common foundation for terminology [2] and architecture for testbed partner collaboration, including the onboarding phase for new partners. Sharing the same language and the same understanding of the reference architecture moved the collaboration process forward more quickly. The work of the Digital Transformation Working Group about the *plan, build and run* Business Strategy and Solution Lifecycle methodology was also helpful, and, so was the IISF in phase two of the testbed.

8.3 Partnership and Business Opportunities, Along with Visibility

A recurrent observation that gives the IIC a strategic role is that IIoT solutions require a combination of products in hardware, software and domain expertise needed to implement and deploy a complete pilot, close to an IIoT solution as expected by end users. The IIC ecosystem provides the capabilities and ecosystem needed to achieve solution-centric testbed goals.

In the Deep Learning Facility testbed team [*testbed-DLF*], Dell and Toshiba had formed the basis of a relationship. The IIC formalized the relationship into a partnership. SAS came to the team through the IIC ecosystem. The partnering companies have also found that the visibility of their own AI activities improved due to their involvement in the testbed.

For the Distributed Energy Resources testbed team [*testbed-DER*], the IIC publicized the insights and findings from research and related innovation to the 200+ IIC member organizations.

For the Smart Factory Machine Learning for Predictive Maintenance testbed team [*testbed-FML*] the IIC ecosystem played a major role in building the testbed and providing the needed resources. Every partner within the testbed specializes in a different real need used in testbed deployment, whether security, connectivity or cloud integrations.

The testbed team is built on the needs of its architecture and continually improves as needs become clear. The IIC ecosystem is crucial for finding partners able to solve new problems and building the architecture. Partnerships within the testbed expedited processes necessary to build the testbed. The relationship with iVeia and Xilinx, for example, enabled record-time building of the new hardware platform with the latest technology from each company. Such a complex platform was expected to take two or three years to create, but the relationships shortened this process to only six months.

The testbed's first deliverable was published in the *IEEE Internet of Things Journal* in May 2018, covering the results of one of the testbed's first dynamic machine learning algorithms that works with the data stream coming from a machine. The testbed team is now working on a new article for the *Engineering Applications of Artificial Intelligence* for publication in early 2020. This paper discusses machine learning algorithms oriented to predictive maintenance. The team also published a book, *Industrial Applications of Machine Learning*, in late 2018.

For the Smart Factory Web testbed team [*testbed-SFW*], an alliance with an IIC liaison, the International Data Spaces Association (IDSA), brought the implementation of an IDS connector for trustworthy data exchange between factories. Its portal is evolving to address data usage control and data provenance. Moreover, the IIC ecosystem fostered collaboration between PI4.0 and the IIC, which facilitated the international dissemination of the benefits of standards in a testbed and promoted work on the description of assets including the Asset Administration Shell.

The companies taking part in the Smart Factory Web testbed team [*testbed-SFW*] formed an *innovation community* supported by KETI and Fraunhofer IOSB to identify and fill technology gaps by linking the knowledge and requirements of users, companies and research organizations.

NEC has submitted a successful research and development proposal to the Japanese government on AI support for the brokering and negotiation of production and logistic resources in supply chains. This work will be integrated with the concepts of the Smart Factory Web testbed [*testbed-SFW*]. The IIC has announced a new testbed Negotiation Automation Platform, led by NEC, that will apply the results of the Japanese national project and include technologies of the Smart Factory Web testbed [*testbed-SFW*].

The Smart Factory Web testbed [*testbed-SFW*] has been able to procure new projects based on the experiences gained and the marketing support given by the IIC. Visibility and the number of clients in major IIC regions—Europe, North America and Asia—have grown noticeably.

In the initial phase of the Smart Manufacturing Connectivity testbed [*testbed-SMC*], the IIC provided a forum for partnerships. Many contacts were established during the first two or three quarters of the testbed's existence. Individuals from all over the world scheduled meetings just to understand the testbed and offered their contribution, including assistance with the analytics and connectivity side of the testbed so they could provide additional connectors other than OPC UA towards common cloud systems. On the security side, companies were interested in increasing the testbed's communication and endpoint security features. There was a multitude of opportunities that were presented to the team following the introduction of the testbed.

The IIC provided to the Smart Manufacturing Connectivity testbed [*testbed-SMC*] a platform for collaboration between IT and OT companies. The cooperation of companies from different areas and the discussions on the testbed with people with various backgrounds also delivered a better picture of the overall business environment. This included better understanding of requirements from *the customers of the customers*. For instance, one partner primarily provides its components to the *original equipment manufacturers* (OEMs) in the automation domain (e.g., Siemens and Rockwell) and is well connected with them (and through engagements in user groups such as PROFIBUS & PROFINET International and ODVA). Working within the greater IIC ecosystem fosters understanding of the demands of the value chain beyond those well-established relationships such as machine builders.

For the Track and Trace testbed team [*testbed-T&T*], the IIC was a forum to discuss the project, assist in finding partners and share information about the implementation of related technology standards. Hosting the testbed with the IIC gave the testbed credibility and caught the attention of the right levels of management.

For the Intelligent Urban Water Supply testbed team [*testbed-UWS*], the IIC ecosystem enabled participating companies to meet, engage and plan out the testbed, and then find partners. Value is seen at two steps: the IIC as a resource for experts in OT and IT domain expertise, business models, technology providers and system implementers, and the IIC as providing thought leadership and fostering valuable ideas, the significance of which may go unnoticed at times.

8.4 Interface and Mediate with Other Consortia, SDOs and Government Entities

The Smart Factory Web testbed team [*testbed-SFW*] see their testbed as a candidate vehicle for an IIC-PI4.0 collaboration aiming to trial the PI4.0 specification *Details of the Asset Administration Shell* that defines how data exchange shall occur between Industrie 4.0 components based upon international standards. In addition, Fraunhofer IOSB is using testbed results and its own experience to contribute to the whitepaper *Digital Twin and Asset Administration Shell, Concepts and Application* of the IIC-PI4.0 Joint Task Group.

For the Track and Trace testbed team [*testbed-T&T*], hosting the testbed with the IIC gave the testbed credibility and caught the attention of the right levels of management within Bosch and their partners. The IIC assisted in identifying, through its liaison relationships, the standardization bodies with whom the testbed team could work to develop needed standards.

The Manufacturing Quality Management testbed team [*testbed-MQM*] believes that the IIC brought the MQM testbed partners together. It was a good way to coalesce various interested parties from China together. CAICT is a research entity of the Chinese government focusing on new technology trends for China that would provide more global visibility. Huawei and China Telecom, considered two strong IT entities, also discovered that the IIC testbed program is a good platform for helping OT end user entities, by providing connectivity and complete solutions.

For the Smart Factory Web testbed team [*testbed-SFW*], the IIC ecosystem has played a significant role in the planning phase of the testbed. Feedback obtained from several presentations and resulting discussions with IIC members were important factors for continuous discussions and constructive feedback about the testbed's purpose and function.

In establishing alliances for various extensions to the Smart Factory Web Testbed, the IIC ecosystem played an instrumental role. The IIC's collaboration with PI4.0 enabled development of the I4.0 component concept for selected assets in the Smart Factory Web testbed.

In the Smart Manufacturing Connectivity testbed [*testbed-SMC*] testbed, results have been shared with the Standards Task Group (a group within the IIC Liaison Working Group) who had previously expressed interest. The testbed team is working with the Standards Task Group to discuss how to establish a common scheme tying testbeds and investigatory standards together.

8.5 FEEDBACK TO THE IIC

The Smart Factory Web testbed team [*testbed-SFW*] has contributed to several activities in the IIC. The testbed is a candidate vehicle for an IIC-PI4.0 collaboration aiming to trial the PI4.0 specification *Details of the Asset Administration Shell*, which defines how data exchange shall take place between Industrie 4.0 components based on international standards.

Several technology groups in the IIC have benefitted from this testbed's results, for example, the Technology Working Group's Distributed Data Interoperability and Management Task Group.

The Smart Manufacturing Connectivity testbed team [*testbed-SMC*] is contributing to IIC's Networking Task Group in their work on an Industrial Internet Networking Framework by adding specific details on network requirements and implementations of the testbed's usage scenarios.

The IIC offered incentives to testbed teams to provide feedback that they knew would be valuable to others while advertising their acquired expertise. The Deep Learning Facility testbed team [*testbed-DLF*] looks forward to sharing their experiences with the industry so that others may benefit from their findings and launch their own projects in AI and deep learning technology.

The Smart Factory Machine Learning for Predictive Maintenance testbed team [*testbed-FML*] provided feedback on the IIRA, for improving deployment, and to the IISF on security.

9 Other Lessons Learned

9.1 Redefining Business Value and How to Achieve It

Testbed teams such as the Track and Trace testbed [*testbed-T&T*], the Factory Operations Visibility and Intelligence testbed [testbed-FOV] and the INFINITE testbed [*testbed-INF*] have learned the importance of quantifying the business benefits with the customers.

The Intelligent Urban Water Supply testbed team [*testbed-UWS*] helped their customer, WPG, expand their business model from a conventional equipment manufacturer to an intelligent water-supply service provider. WPG now works closely with the water-supply companies to deliver value to them as partners. This gives an advantage in an increasingly competitive market.

By leveraging scale, WPG, the leading water supply manufacturer in China, expects to establish technological capabilities in the cloud and offer them to the water-supply companies as a service.

The Track and Trace testbed team [*testbed-T&T*] seeks to define and achieve the anticipated business value. What is the business value to be provided by this testbed? Can someone in the warehouse interpret these measurements and realize that this information is what they need? The business value lies in the delivery of knowledge that is of interest to that person. Much of this effort is experimenting around the business model, not the technologies. The testbed team is now evaluating a business model where the customer appreciates the value of the solution and the partners are designing how they will approach the market together. Who do they need as partners in this business? How will their business model change in the future? These business-model discussions run in parallel with the technology solution.

9.2 A Continuous Process

By its nature, an IIoT pilot is never really settled. Its major goal is to gain sufficient acceptance and validation to get funding for the initiation of a more complete solution in a next phase. Its goal is not to produce a turnkey solution.

For the Track and Trace testbed team [*testbed-T&T*], one important lesson was the realization that there is no end to improvement opportunities, although business benefits can certainly be attained in a finite time. Once the customer became involved, use cases were quickly added, resulting in specialized extensions.

For the Intelligent Urban Water Supply testbed team [*testbed-UWS*], the design and process should be flexible for late evolution. Discussions with customers may lead to changing priorities. A testbed must be able to reprioritize its features to deliver the best value to the customer.

The Manufacturing Quality Management testbed team [*testbed-MQM*] observed that many end user companies want proven solutions that they can purchase and implement right away. But no matter how ready the off-the-shelf solution may be, additional effort is required to turn any new IoT solution into one that meets the user's needs. The team noted that technology vendors often believe they have a solution for everything: they create a solution in-house and then seek to sell it as a packaged product. The reality is that every user has specific needs.

For the Factory Operations Visibility and Intelligence testbed team [*testbed-FOV*], further automation is not where most of the value resides, as previously mentioned. The expectation from deploying IIoT in manufacturing is process-centric: a major benefit is to assess quickly whether a human-decided process modification is returning the expected improvement or not. This rapid cycle is essential to the success of the continuous improvement of manufacturing operations (i.e., the Kaizen process (see an introduction at: *https://en.wikipedia.org/wiki/Kaizen*)). As different efficiency improvement solutions may need to be evaluated over time, different parts of a process may need to be monitored, and the IoT solution for process visibility may change over time.

9.3 Recognizing Unanticipated Value

The Intelligent Urban Water Supply testbed [*testbed-UWS*] found unexpected value for customers in areas that were not outlined in the testbed proposal. These include features to:

- enhance the visibility to the operational states of assets,
- provide product lifecycle estimates and
- enhance operations (e.g., maintenance and repair) with mobile apps to get real-time insight when traveling.

The Smart Factory Web testbed team [*testbed-SFW*] did not encounter many major technical surprises, but they did in marketing. The level of interest in Smart Factory Web for various application scenarios involving cross-facility collaboration was greater than originally expected. There are many opportunities to transfer its technical learnings to different applications.

9.4 Similarity Between Testbeds and Research Projects

The Smart Manufacturing Connectivity testbed team [*testbed-SMC*] discovered that the amount of work put into developing a testbed is similar to that required when setting up an application for a government-funded research project. That is why it could make sense for IIC members to combine future research projects with testbeds: the practical aspect of a research endeavor could be implemented through a testbed.

9.5 DEVELOPING A TRUSTWORTHY SOLUTION

Trustworthiness in IoT is the degree to which the system performs as expected in the face of environmental disturbances, expected loss of performance quality and accuracy, human errors, system faults and attacks (See the IIC Journal of Innovation issue on Trustworthiness *www.iiconsortium.org/news/journal-of-innovation-2018-sept.htm*]. There are five properties commonly identified as constituting the trustworthiness of an IIoT system: security, safety, reliability, resilience and privacy. Although these properties are usually not prime objectives for testbeds, experts have long known that they must be accounted for early in the development of a solution.

The IIC testbed process gives security and privacy prominent scrutiny. While these are key concerns, it is unsurprising that manufacturing and logistics testbeds have focused on safety.

For the Track and Trace testbed team [*testbed-T&T*] a key learning has been that safety must be factored in from the start when developing a solution.

For the Factory Operations Visibility and Intelligence testbed team [*testbed-FOV*], safety was always a factor in any solution and takes several forms: it is not just about avoiding accidents, but also reducing physical stress on specific machines, which is also linked to human error rates.

For the Intelligent Urban Water Supply testbed team [*testbed-UWS*], IT security had to be assessed based on OT security needs.

The Smart Printing Factory testbed team [*testbed-SPF*] quickly realized that IoT technology vendors do not understand trustworthiness in the operational context of end users. Although engineers in IT technology companies have a fair understanding of how their products can comply with trustworthiness requirements, sales people are less proficient about the topic and have little understanding of field requirements or certification requirements for the industry domain. In particular, reliability and resilience requirements are poorly understood by vendors. On the fundamentals of trustworthiness, checklists and use cases based on the IIC best practices were useful to assess the vendor's proficiency in this area.

10 COMMON MISTAKES AND HOW TO AVOID THEM

Most testbed teams have identified bad decisions they made or could have made. They realized afterwards the importance of some practices that they initially ignored or downplayed. Testbed teams have recurring observations that point to issues that they faced or were lucky to avoid. They are mostly about deficiencies in stakeholder relationships and misaligned expectations.

10.1 Mistake #1: Not Spending Enough Time With the End User Early On

It is tempting for solution providers to design a solution prototype on their side after a cursory gathering of customer requirements. In short, to do what they feel more comfortable about: develop and demonstrate, instead of spending what is perceived as unproductive time in listening and understanding the end user. However, that is deceptive. Many pilots may not go beyond the short-lived successful demonstration phase if they do not address long-term operational expectations and hidden constraints that take time to elicit from the end user.

How to avoid: Spend sufficient time to understand the business of customers and their requirements. Understanding customers and their expectations is essential for developing a solution that is relevant for the long haul. Often without realizing it themselves, customers have key insights into the process that needs improvement or about why current operations are not as efficient as they could be. Besides the main problem or goal of the customer, there is often an unspoken context of constraints, secondary objectives and likely evolution of business and its requirements. For the Manufacturing Quality Management testbed team [*testbed-MQM*], bringing an end user on board early in an IIoT project has proven to be a significant success factor.

10.2 Mistake #2: Treating the End User Just as a Customer and not as a Partner

Customers may not have a clear idea where or how IIoT can help, but they have key knowledge of their operations, a practical grasp on what can be done or should be avoided and the expertise to judge the value of a solution. This knowledge will be ignored if the end users are confined to the passive role of a customer.

How to avoid: A corollary to mistake #1 is that end users should not expect a turnkey solution: it is a partnership. This is about building a solution together with the end user (i.e., the operator in the field, the business manager) or whoever should benefit from the solution. Often, end user organizations are tempted to consider proven solutions that already work elsewhere and which they can purchase and implement right away. However, no matter how ready the off-the-shelf solution may be, additional effort is required to turn any new IoT solution into one that fits a user's needs. The customer should understand that they are a partner in a team and an integral part of its success—or failure. The vendor or technology provider can only provide elements of a future solution. In the Manufacturing Quality Management testbed [*testbed-MQM*], the team decided to familiarize themselves with the production line on-site. The team learned that it is important to clarify to their customers that there is no such thing as a packaged, turn-key IIoT solution that can be bought off the shelf. This led to a solution that no one had previously considered. Finally, only the end user partner could decide on an acceptable solution in regard to hidden requirements and constraints that may manifest late in the process.

10.3 Mistake #3: Committing Too Early to Objectives or Business Benefits

It is tempting to tell the customer and management what they want to hear—especially early on. Overcommitting with insufficient knowledge of the operational context risks disappointing everyone in case of failure, and gives the impression that either the technology is immature or you have not mastered it in real environments.

Experimental projects should have an investigative component on the best way to proceed and represent a learning process for the testbed team unfamiliar with the operational context and processes of the end user. Setting precise business objectives should wait until the means and approach to achieving these have been clarified.

How to avoid: When there are too many unknown variables, plan for an investigative phase in the project. Add a pre-pilot phase to give you time to understand the field conditions, clarify the best way to proceed and define reasonable expectations (See sections 1.2 and 3.4.1). The pre-pilot will define a sound basis for a pilot and will immunize the actual pilot from preliminary failures and delays. Define the pre-pilot objectives toward resolving initial uncertainties and absorbing reversals and turnabouts often associated with deploying new technologies and products. It may be the case that deeper investigation in the field will reveal new opportunities for operation improvements that are much more actionable than the initial plan.

10.4 Mistake #4: Keeping the Objectives Vague and Success Criteria Imprecise

Failure to define clear criteria for evaluating success increases the risks of misunderstanding the goals and misaligned expectations from the stakeholders.

How to avoid: Once the approach to developing a solution has been clarified, clear criteria for success must be defined and agreed by all parties, phase by phase. While it is wise to wait for the results of the current phase before defining the objectives of the next phase, all parties must be on the same page regarding the current phase goals and measurements.

Time must be spent defining the metrics for success and this may require some evaluation step such as monitoring the current operations and clearly defining the scope of the testing (e.g., which operations, when and under which conditions). The project may have motivations clearly related to existing metrics or KPIs, such as in the Track and Trace testbed [*testbed-T&T*], the Manufacturing Quality Management testbed [*testbed-MQM*] and the Factory Operations Visibility and Intelligence testbed [*testbed-FOV*], but that is not always the case. Metrics should encompass effects such as personnel feedback or resilience of the process in case of hardship, in addition to easily measurable factors from common KPIs (e.g., equipment efficiency, lead time, operational performance and cost reduction). The business impact of reaching targets for operational metrics and trial results must be evaluated from the perspective of scaling-up, which may bring unexpected significance to apparently modest efficiency gains. For example, in the

Track and Trace testbed [*testbed-T&T*], when managing a large fleet of forklifts, a small process improvement—a reduction in efforts of running the forklift and a reduction in operating with empty loads—resulted in noticeable direct savings.

11 Conclusions and Outlook

Although testbeds are all different, they face the same challenges in deploying IIoT and have often addressed these in similar ways. Because the IIC has developed a significant body of testbeds, a horizontal study of them is possible and has provided useful insights about deploying IIoT—or sometimes just reinforces what IT/OT project managers already knew. The compiled findings should be helpful to most IIoT pilot projects (IIC testbeds or not).

In a second phase, a larger body of IIC testbeds, and their variants, will be probed. The initial set of testbeds studied here were among those that took the time to reflect on their horizontal learnings. This will help other testbeds and industrial IoT pilots to address common challenges in their process and draw the attention of testbed teams on the value of reflecting on their process, which is often seen less worthy of attention than the business goals that they were originally tasked to achieve.

Annex A Description of the Sampling of Testbeds

A.1 The Distributed Energy Resources (Microgrid) Testbed [*testbed-DER*]

Historically, the electric grid was designed for centralized generation and one-way transmission and distribution, but the emergence of new power generation and storage technologies, such as solar, wind and battery, is challenging that.

Interest in solar and wind power generation continues to increase today because of:

Pollution: Traditional fossil-fuel-based generators cause greenhouse emissions and people are wary of nuclear power after the Fukushima reactor disaster.

Disaster prevention: Renewable energy resources at the edge of the power grid diversify energy generation and make grids more resilient.

Cost savings: After an up-front investment in solar or wind installation, businesses and homeowners can reduce their energy bills substantially over time.

However, existing electric power transmission and distribution systems were not designed to manage large numbers of distributed energy resources (DERs) that produce variable power such as solar and wind at the edge of the power distribution system.

To address the challenge of growing DER assimilation, RTI and Cisco and two additional partners set up a microgrid testbed project under the IIC to experiment with new approaches. The goal is to develop and demonstrate techniques for a 100% DER power-generation-based microgrid with sufficient intelligence to be operationally feasible and support a variety of business models. Creating a testbed under the IIC enabled collaboration with many industry-leading companies and gave the testbed team access to a comprehensive IoT technology framework.

Immediate goals: The goal of the DER Integration Testbed is to prove the viability of a real-time, secure, distributed control framework to facilitate machine-to-machine, machine-to-control center, and machine-to-cloud data communications and control. It combines distributed, edge-located processing and control applications with intelligent analytics. It runs in real-world power applications and interfaces with practical equipment.

Business value profile: The value profile demonstrated through developed use cases pilots on the DER Integration platform: primary value and motivation (bold underline) and secondary value (regular underline):

- <u>**process efficiency**</u> (better understanding and control on grid equipment and response to electricity demand),
- user experience,
- product quality,
- <u>asset management</u>,
- <u>**business innovation**</u> (ability for utilities to market their product better, and address the demand for renewable sources from customers),
- <u>governance</u> (better ability to comply with regulations on the supply of energy source) and
- <u>risk management</u> (ability to reduce risks to the grid infrastructure due to overload and risks of outage).

A.2 The Deep Learning Facility Testbed [*TESTBED-DLF*]

The Deep Learning Facility testbed focuses on smart building management, with objectives from improving energy consumption to managing internal equipment and optimizing users' experience. When started in late 2016, this testbed was a pioneer in using AI among IIC testbeds. This testbed involves several partners including Toshiba, Dell and SAS.

Immediate goals: One objective is to increase energy efficiency by adjusting all power-consuming services in the buildings; another is to optimize maintenance of equipment; a third is to improve the visiting customer experience and employee-resident comfort. It is also an objective to manage the interactions and trade-offs between these various objectives.

These objectives involve a high volume of sensor data from brownfield manufacturing installations to enterprise IT systems in near real-time, and artificial intelligence (AI) deep learning techniques. More than 30,000 data points and sensors were deployed in the trial building owned by Toshiba.

Another goal is to provide a *retrofit solution* for the factory floor. Many older machines don't have sensors integrated for diagnosis purposes, so there is a potential to increase overall equipment effectiveness (OEE) by adding sensors and running machine-learning algorithms.

Finally, the team hoped to gather insights on how to use standards such as OPC UA to streamline the flow of data to servers on the enterprise IT side and deliver a reference implementation to support this.

Business value profile: primary value and motivation (bold underline) and secondary value (regular underline):

- **process efficiency**,
- user experience,
- product quality,
- **asset management**,
- business innovation,
- governance and
- risk management.

A.3 THE SMART FACTORY MACHINE LEARNING FOR PREDICTIVE MAINTENANCE TESTBED [*TESTBED-FML*]

Predictive maintenance is a daunting challenge—the root cause of over 80% of failures for complex equipment is not understood and the conventional approach, taking machines offline regularly, is costly. Actionable insight on failure causes depends on analysis of large volumes of data during normal operations to understand key component anomalies.

Machine learning (ML), residing at the edge and up to the cloud, is a key enabler to predictive maintenance through identifying, monitoring and analyzing critical system variables during operation. Using ML techniques, alerts can be sent to operators before system failure and, in some cases, addressed without operator interaction and without costly unplanned downtime.

However, real industrial scenarios are highly dynamic with elements that last for years before the element is replaced. Normal degradation and failures need to have low false positive (false alarms) rates. To perform this analysis, ML algorithms may be designed to work with data streams that change over time in relation between input data and the target variable (*concept drift*). Nevertheless, there is not much experience in the manufacturing sector on using and testing these types of algorithms for managing industrial equipment under normal operations.

Immediate goals: The testbed's goal is to develop machine learning algorithms and test them in IIoT architectures and real industrial environments. In particular, to:

- evaluate and validate dynamic ML techniques for predictive maintenance on high-volume production machinery, toward optimizing system operation and
- achieve increased uptime and improved energy efficiency using dynamic ML techniques for advanced detection of system anomalies and fault conditions prior to failure.

Business value profile: primary value and motivation (bold underline) and secondary value (regular underline):

- **process efficiency**,
- user experience,
- product quality,
- **asset management**,
- **business innovation**,
- governance and
- **risk management**.

A.4 THE FACTORY OPERATIONS VISIBILITY AND INTELLIGENCE TESTBED [*TESTBED-FOV*]

The initial focus of the Factory Operations Visibility and Intelligence testbed is manufacturing and repair of complex composite products such as IT equipment including notebooks, tablets and network appliances. More generally—at least in the industrial context of this study in Japan—there are two types of manufacturing processes that have significant room for improvement:

High-mix product assembly process: when many variants of a same product need to be manufactured on the same line, there is a need to change the configuration of the machines frequently (often still a manual operation). This entails delays, human errors and other inefficiencies and risks.

Product return and repair process: these tend to escape the *Kaizen* improvement methodology, as they are often considered as exception processes and wrongly assumed not to be significant in affecting the production targets. As a result, they are often left out of related business metrics, and are managed ad hoc. But such processes are costly and there is benefit in improving them.

Immediate goals: The first objective of the testbed is, for the *high-mix product assembly* use case, to visualize the production process status in real-time. Another objective is to accelerate the improvement of factory processes by assisting the continuous improvement method (Kaizen) that is controlled by humans but needs assistance.

For the *product return and repair* use case, the objective is efficiency (e.g., error reduction). The testbed tracks the status and location of products under repair in the work area to avoid shipment delay (scenario 1), and tries to discover the initial errors made during manufacturing procedures and to help analyze these in the repairing station (scenario 2).

Business value profile: primary value and motivation (bold underline) and secondary value (regular underline):

- **process efficiency**,
- user experience,
- **product quality**,
- asset management,
- business innovation,
- governance and
- risk management.

A.5 THE INFINITE TESTBED [*TESTBED-INF*]

This testbed validates the concept of an IoT platform usable for diverse applications, as opposed to addressing a particular business challenge in a specific domain. Described as a use case facilitation platform, it is more precisely defined as a pilot platform. The platform is geared toward use cases that need to aggregate and correlate a variety of data sources.

Immediate goals: to test the concept of such a platform on a limited set of use cases:

The *Bluelight* use case was selected as an anchor use case early on. The aim was to enable intelligent route planning for emergency ambulance services as they are dispatched to an incident and en route to the hospital. The use case poses an analytics challenge: the testbed team obtained tracking data from the ambulance service's network to get a baseline understanding of ambulance behavior. The analytics capabilities of INFINITE were leveraged to combine the ambulance tracking data with publicly available open data relating to road traffic volumes. The data input consolidates application-specific data and public data. The results have helped to deliver service optimizations and drive improvements in service resilience and service flexibility.

The Flood Event Advisory Service use case automates the flood prediction process. Automation requires data collection from many sources in real time, including tidal and river-level gauges, tidal tables and weather forecasts and combines them to develop flood prediction models.

Business value profile: The value profile demonstrated through developed use cases pilots on the INFINITE platform: primary value and motivation (bold underline) and secondary value (regular underline):

- **process efficiency**,
- user experience,
- product quality,

- asset management,
- **<u>business innovation</u>** (for the demonstrated platform itself),
- governance and
- risk management.

A.6 THE MANUFACTURING QUALITY MANAGEMENT TESTBED [*TESTBED-MQM*]

According to its team, the Manufacturing Quality Management (MQM) Testbed from China has been remarkable from several perspectives. The initial approach focused on the production side of the production line, but the initial assumptions and planned approach were not viable. The team then familiarized themselves with the actual production line and discovered that value could be gained by improving the quality assurance by reducing the number of returned products and their costly investigation.

The testbed was considered successful by its end user. The detection of false positives went from 50% to 95%. The testbed also provided insights on the role of human experts in identifying the right data to monitor for the successful application of machine learning and on how to minimize disruption of the existing manufacturing processes, a key factor in adoption.

The testbed had brownfield constraints, and had to avoid disruption in the current manufacturing processes. The customer's management team was so impressed with the results of the testbed that they are now exploring where they may apply this process to other production lines.

MQM triggered the emergence of China Manufacturing 2025 in the smart manufacturing category (an analog to Industrie 4.0 in Germany).

Immediate goals: To improve heating, ventilation and air conditioning product quality and the efficiency of its manufacturing process, in particular to assess the quality of welding on products and to reduce the cost of returned product by improving the manufacturing quality.

Business value profile: primary value and motivation (bold underline) and secondary value (regular underline):

- **<u>process efficiency</u>**,
- user experience,
- **<u>product quality</u>**,
- asset management,
- business innovation,
- governance and
- risk management.

A.7 The Open-Standard, Interoperable IoT-Platforms Testbed [*Testbed-OSP*]

The open-standard, interoperable IoT-Platforms testbed (OSP) has been designed as an interoperability testing platform and developed as a special testbed project intended to create reusable testbed infrastructures and components. The platform supports some basic middleware service functions, allowing IoT application developers to share these across multiple applications without having to build a full solution stack for each one.

Immediate goals: Its immediate purpose was to demonstrate several interoperability capabilities along the IoT stack, with a focus on IoT platform standards. These standards provide a horizontal architecture[1] with a middleware layer between IoT devices and IoT applications. It comprises fourteen common services including device management, data management, security and semantics.

The testbed involved Huawei (Huawei Cloud IoT) and InterDigital (branded as Chordant.io) IoT platforms, gateways and applications. The two organizations first established communications between InterDigital's platform in the USA and Huawei's gateway and devices in China. The first test scenario was to prepare a sensor to publish measurement data to which one or more IoT applications could subscribe. The next part of this was to enable an application to subscribe to published sensor data on an event-driven trigger. The procedures necessary to register IoT applications and devices in a shared operating environment, and to publish/subscribe to data used common IoT platform services and demonstrated interoperability between two platforms and the devices and applications they supported.

This first scenario demonstrated interoperability; the second addressed the need to support new scenarios. In this case, Huawei contributed an OSGi interworking component to demonstrate interworking between OSGi-based devices and gateways to a standardized IoT platform.

Business value profile: primary value and motivation (bold underline) and secondary value (regular underline):

- **process efficiency**,
- **user experience**,
- product quality,
- **asset management**,
- business innovation,
- governance and
- risk management.

[1] Advancing the Industrial Internet of Things, https://www.iiconsortium.org/pdf/IIC_oneM2M_Whitepaper_final_2019_12_12.pdf

A.8 THE SMART FACTORY WEB TESTBED [*TESTBED-SFW*]

The Smart Factory Web (SFW) testbed aims to set up a web-based platform to allow factories to offer production capabilities and share resources to improve order fulfillment in a more flexible way than is currently possible with available technology. It seeks to provide the technical basis for new business models, especially for small-lot sizes, with flexible assignment of production resources across factory locations.

It is designed to be a step towards establishing a marketplace for manufacturing where one can look for factories with specific capabilities and assets to meet production requirements. Factories offering those capabilities can then register to be located and participate in the marketplace.

The testbed is directed mainly towards small-lot size environments because companies working with larger line orders usually have their own supply chain management system and do not need to be as flexible and responsive due to the size of the orders.

The testbed's primary use cases involve manufacturers who seek a factory to produce parts. The manufacturer accesses the SFW system to find a potential target factory with the right capabilities.

Immediate goals: Identify the key concepts, standards application and implementation architecture of the SFW. These concepts can then be adapted and adopted for use by a company.

Another planned output of the testbed is the experience of how to describe asset capabilities, efficiently integrating assets into an overall software architecture.

Ultimately, it seeks to provide the technical basis for new business models, especially for small lot sizes. It is a step towards establishing a marketplace for manufacturing with flexible assignment of production resources across factory locations to meet production requirements.

Business value profile: primary value and motivation (bold underline) and secondary value (regular underline):

- **<u>process efficiency</u>**,
- user experience,
- product quality,
- **<u>asset management</u>**,
- <u>business innovation</u>,
- <u>governance</u> and
- risk management.

A.9 The Smart Manufacturing Connectivity Testbed [*Testbed-SMC*]

The Smart Manufacturing Connectivity (SMC) testbed addresses the discrete manufacturing domain, traditionally characterized by a strict hierarchical structure called the *automation pyramid*. At the control level of the pyramid, programmable logic controllers (PLCs) manage the real-time sub-systems, including sensors and actuators to connect to the enterprise IT systems. In this structure, any data generated by a sensor passes through the PLC. In brownfield facilities, the PLCs are often only capable of running the automation sequence.

Immediate goals: The main objective of the testbed is to provide a high volume of sensor data from brownfield manufacturing installations to enterprise IT systems in near real-time. Other goals are to provide:

A *retrofit solution* for the factory floor. Many older machines don't have sensors integrated for diagnosis purposes, so there is a potential to increase OEE by adding sensors and running machine-learning algorithms.

Insights on how to leverage standards (e.g., OPC UA) to streamline the flow of data with processing servers on the enterprise IT side to deliver a reference implementation.

Business value profile: primary value and motivation (bold underline) and secondary value (regular underline):

- <u>**process efficiency**</u>,
- user experience,
- product quality,
- <u>**asset management**</u>,
- business innovation,
- governance and
- risk management.

A.10 The Smart Printing Factory Testbed [*Testbed-SPF*]

This testbed optimizes printing production planning and improves equipment availability by instrumenting printing equipment and integrating printing ecosystems for production line automation control, cross-site fulfillment and predictive maintenance.

The testbed operates in brownfield conditions. For legacy printing facilities that are not digitally instrumented originally, brownfield sensors are attached and they send data to the Smart Printing Factory Platform to store and analyze.

After equipment instrumentation and data collection are established, the focus of the testbed is a Smart Printing Factory Platform to collect data about job status, machine condition and production quality. The platform provides an optimized job schedule and predictive maintenance plan to users. The Smart Printing Factory Platform aims at establishing an ecosystem that provides several benefits to printing professionals and software vendors.

Immediate goals: The testbed goals in the short term are to establish data collection and storage from brownfield assets and processes in a printing factory. Once the data flow is established, the goal is to define KPIs and metrics for productivity and print quality in the printing industry, identify key data sources and conduct initial control experiments.

An immediate business benefit is to enable new business services such as small orders (small-lot size) with just-in-time order adaptation. Further goals are to increase productivity and flexibility of complex printing production lines, including collaboration across ecosystem partners, through Design → Quotation → Order → Proofing → Print → Post Press → Delivery stages.

Business value profile: primary value and motivation (bold underline) and secondary value (regular underline):

- **<u>process efficiency</u>**,
- user experience,
- <u>product quality</u>,
- <u>asset management</u>,
- **<u>business innovation</u>**,
- governance and
- risk management.

A.11 The Track and Trace Testbed [*testbed-T&T*]

The Track and Trace Testbed was the first testbed approved by the IIC. The notion was to optimize a number of different *key performance indicators* (KPIs) for industrial use cases, through improved physical asset management mostly via better geolocation features.

This testbed clearly distinguished pre-pilot concerns from pilot concerns and positioned itself primarily on the pre-pilot phase.

The testbed team reflected on the business value and gained valuable perspectives on what it really means beyond the usual KPIs. The main business value derived from this testbed is the increased utilization of assets and consequent cost savings and increased efficiency.

The implementation of the testbed has been so successful that it is perceived as a competitive advantage, making them reluctant to publicly describe their successes.

Immediate goals: The original idea behind the testbed was to discover what data could be obtained from sensors that were already built into tools, or retrofitted externally. By using tool-performance data combined with appropriate localization techniques, the team hoped to detect usage patterns and to optimize the use of tools such as forklifts and drilling tools.

The testbed identified the need for and value of standards. It has initiated a new standard[1] through the Object Management Group standards-development organization.

Business value profile: primary value and motivation (bold underline) and secondary value (regular underline):

- **<u>process efficiency</u>**,
- <u>user experience</u>,
- <u>product quality</u>,
- **<u>asset management</u>**,
- business innovation,
- governance and
- risk management.

A.12 THE TIME SENSITIVE NETWORK–FLEXIBLE MANUFACTURING TESTBED [*TESTBED-TSN*]

This testbed is one of the few that focuses on technology refinement and validation (Time Sensitive Networking) but is driven by the industrial context of its usage. TSN is an enhancement of Ethernet as defined by IEEE standards 802.1 and 802.3[2] to bring more deterministic capabilities to the network, in particular, control of its performance and quality of service to accommodate specific usage patterns and needs.

The testbed team is unusually large as many players are involved in establishing a TSN platform. New technology partners are expected to join to test their products and requirements.

Immediate goals: For its sponsors, this testbed is important to prove that TSN is ready for adoption. Priority was given to careful and comprehensive testing through several plugfests, as opposed to a quick proof of concept demonstration.

The main value for all participants—the network infrastructure vendors, the end-device vendors, even the testing tool vendors—has been to learn what it means to implement TSN, where they can enhance, improve or update their product to interoperate. All gained insights on how their implementations work with this new technology.

The focus for an initial plugfest was on establishing time synchronization. Once this was accomplished, devices began to send scheduled traffic over the network. In later plugfests, the focus was on the central, automated configuration aspects of TSN.

[1] https://www.omg.org/news/releases/pr2018/11-06-18.htm

[2] See an introduction in *https://en.wikipedia.org/wiki/IEEE_802*

Another benefit was to generate feedback and requirements to various standards groups working on TSN, in particular enhancements to the Ethernet standards. It is one thing to build a standard and it is another to implement and use it.

Business value profile: primary value and motivation (bold underline) and secondary value (regular underline):

- **process efficiency**,
- user experience,
- product quality,
- asset management,
- business innovation,
- governance and
- risk management.

A.13 THE INTELLIGENT URBAN WATER SUPPLY TESTBED [*TESTBED-UWS*]

The Intelligent Urban Water Supply Testbed is an intelligent water supply management system. In the short-term, its purpose is to determine the best ways to connect to the equipment, and then to build a cloud-based service to analyze large amounts of data collected from a great number of equipment.

Visibility into the water quality is often lacking in various locations of the water supply pipeline network. This is the first technical objective: to provide visibility remotely into the operation of the equipment and then enable a faster response to detected problems.

Immediate goals: The testbed goals are to improve overall visibility into the water processing, then to improve predictability of consumption, of outages and equipment failures. Specifically:

- visibility into water supply operations and equipment (e.g., pumps) in energy usage,
- faster response to detected problems (e.g., water quality and pump failure) and
- optimization.

Business value profile: primary value and motivation (bold underline) and secondary value (regular underline):

- **process efficiency**,
- user experience,
- product quality,
- **asset management**,
- business innovation,
- governance and
- risk management.

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Authors and Legal Notice

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Authors: The following persons acted as editors and contributed substantial content to this document: Jacques Durand (Fujitsu) and Chaisung Lim (Korea Industry 4.0 Association).

Contributors: The testbed teams mentioned above contributed all the basic material and findings collected and compiled in this study.

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