



Cyber-Physical Loops as Drivers of Value Creation in NDE 4.0

Johannes Vrana¹ · Ripudaman Singh²

Received: 28 May 2021 / Accepted: 21 June 2021 / Published online: 3 July 2021
© The Author(s), under exclusive licence to Springer Science+Business Media, LLC, part of Springer Nature 2021

Abstract

Across so many industries, non-destructive evaluation has proven its worth time and again through quality and safety assurance of valuable assets. Yet, over time, it became underappreciated in business decisions. In most cases, the data gathered by NDT is used for quality assurance assessments resulting in binary decisions. And we seem to miss out on value of the information content of NDE which goes way deeper and can help other stakeholders: such as engineering, management, inspectors, service providers, and even regulators. Some of those groups might not even be aware of the benefits of NDE data and its digitalization. Unfortunately, the NDE industry typically makes the data access unnecessarily difficult by proprietary interfaces and data formats. Both those challenges need to be addressed now by the NDE industry. The confluence of NDE and Industry 4.0, dubbed as NDE 4.0, provides a unique opportunity for the NDE/NDT Industry to not only readjust the value perception but to gain new customer groups through a broad set of value creation activities across the ecosystem. The integration of NDE into the Cyber-Physical Loop (including IIoT and Digital Twin) is the chance for the NDE industry to now shift the perception from a cost center to a value center. This paper provides an overview of the NDE ecosystem, key value streams, cyber-physical loops that create value, and a number of use cases for various stakeholders in the ecosystem.

Keywords NDE 4.0 · Use cases · Value proposition · Advanced NDE · Future of NDE · Automation · NDT 4.0 · Industry 4.0 · Cyber-physical loop · Digital twin · Digital thread · Digital weave · IIoT · Industrial revolution

1 Introduction

1.1 NDT Value Perception

In the early industrial days, humans naturally lacked the necessary experience how to safely process raw materials, design and manufacture components and systems, and operate various machines and modes of transportation, which resulted in severe accidents. This is where NDT developments took place. NDT identified potential material imperfections leading to a massive increase in machine reliability. NDT also became a central part of early day feedback loops by identifying potential design and production improvements, through additional knowledge. Growing experience and knowledge in engineering continues to make the world

a safer place while creating economic prosperity through innovation and revolutions.

In the beginning, the business case for NDT was straight forward. At that time, the companies were able to differentiate themselves from competitors by technological performance benefits for the customers. But this position changed over time as competition became harder leading to price wars and every company looked for savings, everywhere.

What does this mean for the current day business case for NDT:

- A *traditional business case* for NDT considers the potential cost which would have accrued in case of accidents. The cost of a single accident can easily be a 7-digit number—not even considering the cost of the loss in reputation. Such costs are way higher than the cost of years of NDT. Most NDT professionals see this traditional business case and are therefore astonished how other groups start to question the cost for any investments for NDT.
- Over the years, as the number of accidents has dropped to a lower level, the credit is being attributed to good quality of design, production, and maintenance, with

✉ Johannes Vrana
contact@vrana.net

Ripudaman Singh
Ripi@inspiringnext.com

¹ Vrana GmbH, Rimsting, Germany

² Inspiring Next, Cromwell, CT, USA

NDT getting the seat behind the scenes. Therefore, *business administrators* start to neglect the costs of potential accidents which results in the fact that they do not see a *business case* for NDT anymore. They only see that NDT must be conducted due to standards and regulations, without the ‘why’. In an extreme case, the value attributed to prevention of accidents completely disappears when the number of accidents drops to zero or if the time span between accidents is longer than the typical employment span of decision makers.

- The *realistic business case* is akin to an insurance model and will be somewhere in-between. We believe, it is incorrect to assume safety without actions required to assure safety even that the potential risk for accidents has dropped. The impact of accidents should be considered, perhaps in the context of ‘not doing NDT’. Suddenly the NDT will appear to be a cheaper and more respectable option. This will in the long run help everybody.

Those different points of view are the reason why NDT professionals believe that NDT is a value center (preventing accidents) while their customers, asset OEMs and asset owner-operators believe that NDT is just a cost center [1]. In some industries this situation has developed to a point that NDT is becoming undesirable. This explains some of the end user pains, perceptions, and remarks captured by a survey [1].

- “You are like my mother in law, I don’t need you... hate it when you are there... you create extra work for the rest of us and I end up paying a ****load of money”
- “It’s all smoke and mirrors; costs too much; bottle neck; non-value-added; only represents negative issues.”
- “If NDT becomes mandatory, our product will be too expensive for the market.”
- “NDT does not have any value at all. It only sorts out parts, that in reality are good. I don’t want it and I would never ever do it, but my customer insists on it. I’d prefer spending the money into further improvement of my production!”

So—how can the NDT Industry ensure its future? Through NDE 4.0! This paper will identify several possibilities, starting with looking into the NDE as an ecosystem, continue with some basic use cases of NDE 4.0, and finally showing how the integration of NDE into the cyber-physical loops opens completely new business cases.

1.2 NDE 4.0

NDE 4.0 has been previously defined as *A Cyber-physical Non-Destructive Evaluation (including testing); arising out of a confluence of industry 4.0 digital technologies, physical inspection methods, and business models; to enhance inspection performance, integrity engineering, and decision*

making for safety, sustainability, and quality assurance, as well as provide relevant data to improve design, production, and maintenance through useful life. [2]. This definition contains several core elements:

- **What** The cyber-physical ecosystem introduced by Industry 4.0 and NDE 4.0 [1–9] with two focus areas [1]:
 - First, the Industry 4.0 emerging technologies can be used to enhance NDE technologies and NDE data processing (“**Industry 4.0 for NDE**”).
 - Second, NDE is the ideal data source for Industry 4.0 (“**NDE for Industry 4.0**”).
- **How**
 - **Technical** Digitization, digitalization, and digital transformation [10, 11].
 - **Human Considerations** a statistical analysis of NDE data provides insight into reliability, inspection performance, training status, consistency, and value of inspections.
- **Why**
 - Safety and economic value, combined into the term **Safety 5.0** [12]
 - **Sustainability**
 - Design, manufacturing, and maintenance improvements
 - Longer asset life, reduced asset cost
 - ...

The *NDE 4.0 business case* creates value twofold:

- It makes NDE more effective (reliable) and efficient (streamline process). It makes inspections more affordable to existing customers and the realistic business case, discussed above, worthwhile.
- It opens NDE to additional customers. NDE data becomes an asset which in itself will carry value.

2 NDE Ecosystem

NDT and NDE are all about the asset to be inspected and evaluated. The NDE Ecosystem is asset centered. The value of NDE for the various stakeholders is defined by the information/knowledge they can retrieve with NDE about the asset. This can be, for example, a GO/NO-GO decision for quality assurance (traditional NDT business case) or the use of the NDE results for engineering purposes (example for an NDE 4.0 business case). The more information stakeholders

can retrieve the more valuable NDE becomes. This is in short how NDE 4.0 creates value. For a more in-depth analysis of the business cases enabled by NDE 4.0, we must start with a detailed view of the ecosystem (including the stakeholders) and the connecting value streams.

2.1 Birds Eye View of the Ecosystem

If you keep an eye on the asset, you can see that multiple parties contribute to its safe and economic operation, in line with the primary purpose of NDE 4.0 [13]. The term asset is used as a generic reference to a physical item—machine, vehicle, system, plant, or a piece of infrastructure that needs inspection for safety and performance assurance. Figure 1 shows the four key stakeholders in the inner circle and the supporting entities in the outer circle. Airplane Asset is just an example.

2.2 Key Stakeholders

There are four key stakeholders, as shown in the inner circle in Fig. 1, presented in the following. Three of them are businesses. We chose to identify inspectors as an individual stakeholder because their personal and professional life is impacted significantly.

2.2.1 Asset OEMs

Asset OEMs (original equipment manufacturers) design, manufacture, assure quality, and prescribe the in-service inspection program, along with standards and procedures for compliance. They leverage R&D out of universities and other research establishments to continuously improve their assets.

The Asset OEMs including the supply chain have the primary responsibility of delivering a product or a system that is safe to operate, affordable over the life span, and requires minimum maintenance. They essentially compete on product performance, cost, and customer experience. To accomplish this, almost every asset is adopting IIoT, from as small as an

electric switch controlling a light bulb to aerospace defense, and home appliances in between.

Asset OEMs are usually bigger players. Therefore, multiple departments should be considered independently—each of them could be a customer for NDE and NDE data. A new product design is usually created by the *engineering* department, the components are ordered by *supply chain management*, inspected and machined by *suppliers, quality assured*, and *assembled*, and the final product *commissioned*. The traditional NDT customer is QA. With NDE 4.0 all departments could become customers/consumers of the results of NDE (the NDE data in addition to binary decisions). With the commissioning, the product is transferred to the owner-operators.

2.2.2 Owner-Operators

Owner-Operators either provide a service to the public using products produced by Asset OEMs or they use those products to enhance their personal life. Examples for the first group: the airlines fly people, oil and gas plants provide energy, and theme parks provide an entertainment experience. Examples for the second group: car owners.

Owner-operators have the primary responsibility of assuring the safe and continuous operation of the asset, in an economically viable manner. They employ asset inspectors or engage them through a professional inspection service provider to guarantee the safety of the assets throughout the operation. They make every effort to optimize inspection programs for maximum asset availability, minimum lifecycle maintenance cost, improve inspection reliability (reduce false calls), stay in compliance with all regulations and inspections prescribed by asset OEMs and regulatory bodies.

We have come across industry peers who believe that safety is the responsibility of the regulatory bodies. It is an unfortunate perspective where ethics are being kept aside because there is a legal recourse to undesirable incidents in form of regulatory compliance.

2.2.3 Asset Inspectors

Asset inspectors perform the physical act of looking at the material to detect anomalies, imperfections, or damage that could lead to failure or performance shortfall. Inspectors are trained by their employer, specialized training service providers, and the manufacturers of the inspection equipment (NDE OEMs). They need certifications as prescribed by regulatory and compliance bodies. They are expected to follow the inspection program and procedures as defined by the Asset OEMs.

Asset inspectors have the primary responsibility of testing the materials or structure for any indication that may cause a failure. They are expected to follow validated and



Fig. 1 NDE ecosystem including its major stakeholders

documented procedures, maintain their inspection skill level indicated by certification, calibrate equipment using prescribed standards and intervals, and maintain the NDT equipment health as prescribed by the NDE OEM. They must see the benefit of adopting new technology and developing new skills. They make every effort to make their job simpler, faster, less physically stressful, improve inspection reliability (reduce false calls), comply with all regulations, and inspections prescribed by asset OEMs.

2.2.4 NDE OEMs

NDE OEMs design and manufacture the inspection equipment (or system), prescribe equipment calibration, and provide application training to inspectors. They also leverage R&D out of universities and other research establishments to continuously improve their equipment.

NDE OEMs have the primary responsibility of delivering an inspection system that is easy to learn and operate, affordable over the life span, requires minimum maintenance, and most importantly delivers dependable inspection outcomes. They essentially compete on equipment performance, cost, and user experience.

Before Covid-19, we used to say that NDE 4.0 provides a competitive advantage in terms of cost and speed through remote access, superior visualization, and data interpretation. Now it is becoming significant with travel limitations, social distancing, and low touch requirements.

2.3 More Stakeholders

The four key stakeholders discussed so far collectively assure safety to the asset consumers (individuals or businesses) and inspectors. They are supported by a few others who can be viewed as a part of the inspection ecosystem.

2.3.1 NDE Research Establishments

Universities, small business research companies, national labs, corporate R&D centers, and defense research centers develop new physical methods, digital technologies, and integration logics to enable NDE OEMs to create systems. Industry 4.0 has created a new pull for research, graduate work, publications, patents, intellectual property, and funding opportunities.

2.3.2 Inspector Training Schools & Certification Bodies

Inspectors need training to develop skills and field experience to get certification. NDE 4.0 means a range of new content, courses, and curriculum; possibly leading up to another set of certifications. These high-tech skills also mean financially attractive programs, which can be delivered in

novel ways, in place onsite, just in time, leveraging extended reality.

2.3.3 Regulatory Bodies

NDE in certain industries is highly regulated. Regulations and innovation work in opposite directions. In general, the regulatory demands for compliance are not easy to meet, where NDE 4.0 is revolutionary in nature with little to no precedence or data-based evidence to back up the value propositions.

Regulatory bodies generally do not enjoy innovation, particularly the revolutionary type. It is also hard to develop regulations when the technology is still maturing, the ill-effects are not yet well understood, there is not enough data to address public health and safety concerns.

Similar is the case with certification bodies. There is not enough evidence to ascertain the level of training, practice, and performance to certify. The NDE community is yet to develop clarity around certification process, levels, domains, etc.

The regulatory bodies can make a pro-active effort to understand the value of NDE 4.0, challenges and risks in adoption, and work cooperatively with innovators in a manner which is good for society and humanity.

2.3.3.1 The Standardization Challenge Standardization assures that the same mistake is not made twice but standards should not be used as an excuse to block innovation. Some existing NDE standards were created years ago. They do prevent “mistakes” but with requirements describing a historic or outdated state of the art, at times designed for NDE 2.0 era— analog equipment, film RT, hand signed reports, manually operated NDE equipment, and for visually performed data interpretation. This hinders innovation, prevents the implementation of NDE 4.0 and its use cases, and disables potential quality increase in inspection technology.

Therefore, existing standards need to be revised regularly and need to accommodate new opportunities. Even more important today is to revise the standards development, acceptance, and governance process to enable adoption of rapidly changing technologies and business models.

First, the technology standardization around data connectivity, exchange, security, analytics, synthesis, and interpretation is still evolving. In fact, some argue that continuous change is the new normal. The underlying technology may just always stay in a state of continuous flux. The German Society for Nondestructive Testing (DGZfP) is making serious effort toward standardization or acceptance thereof with sources from the IT industry for data exchange protocol[3–5]. Soon, we will come to accept one of the interface standards, because this acceptance is a cornerstone for the

industrial success of NDE 4.0, just like in the third revolution, when the community adapted HTML in 1990–1991 to enable the explosive growth of the Internet, originally born in 1969.

2.3.4 Communities and Societies

National bodies and societies, such as ASNT, DGZfP, JSNDI, and ISNT have a major role to play to serve the community as a part of their mission to bring professionals onto a common platform for exchange to ideas, requirements, and shared solution.

2.3.5 IT Infrastructure Providers

As data storage, transfer, security, analysis, and display become prominent part of NDE, cloud storage, SAAS providers, and hardware maintenance services will take prominent place in any operational unit. Most of these businesses are in high growth mode currently as everyone is getting into digital transformation. For them NDE 4.0 is yet another customer persona.

The same applies for Digital Technology Training Schools.

2.3.6 Consultants and Coaches

There is a substantial business opportunity for freelance consultants, coaches, or small firms, specializing in NDE, digital technologies, and entrepreneurship. They can bring Industry 4.0 perspectives, digital knowhow, and innovations, from other domains into NDE.

Authors belong to this element of the NDE ecosystem now and this publication is an effort to bring awareness around Why, What, and How of NDE 4.0 to all other elements of the ecosystem.

2.3.7 Still Unknown

Every revolution has created new business models and additional stakeholders. This one will not be any different. New business models will emerge as data shows promise. The structured data amenable to information extraction can become a commodity with a price tag for data owners because it has value for product performance service life improvement. Who owns the data is a matter of business discussion across asset OEM, asset owner-operator, inspection service provider if different than asset owner, or even

the NDE OEM. Industry will shake this out. There may even be another stakeholder emerging when data is traded as a valuable commodity. Just like in the third revolution where wealth was in the form of company stock, and mutual funds and stock exchanges became major players, in the fourth revolution, Data becomes an asset, *Data-Exchange* the most profitable business transaction, and data traders and enrichers new stakeholders.

2.4 Key Value Streams

The value streams connect the stakeholders with each other in manner to deliver and satisfy the customer. Let us look at the three key value streams.

2.4.1 Asset Value Stream

Generally, the idea and the design for an asset is created by an asset OEM, the individual components are produced and inspected by suppliers, and final inspection done by the OEM, before handing it off to operators (see Fig. 2). The owner-operators start using the product according to the specifications of the asset OEM, including service inspections (NDE) at certain intervals to guarantee problem-free operation. At some point the product reaches its end of life (EOL) and the question regarding reuse, repurpose or recycle arises. This is a great new business area for NDE to support finding the right decision.

Besides the NDE inspections at the suppliers, during operation, and to enable the circular economy non-destructive evaluation with sensors may be performed throughout the manufacturing and service, as planned or as required by circumstances. This could also include sensors monitoring the process parameters within the supply chain, during assembly and during the initial performance tests or sensors used for structural health monitoring (SHM) or condition monitoring (CM). All these generating data of value.

2.4.2 NDE Personnel Value Stream

The personnel performing and supervising the NDE inspections and the personnel writing the standards and procedures, also go through a similar value stream (see Fig. 3). At some point a person decides to become an NDE professional and starts with training, both theoretical and on the job. After the qualification examinations, inspector gets certified and starts working. This could be inspections during the production of an asset, service inspections for owner-operators or circular

Fig. 2 Asset value stream
(Author: Johannes Vrana, Vrana GmbH, Licenses: CC BY-ND 4.0)

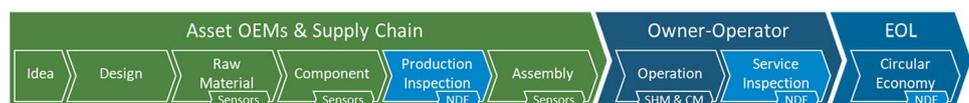




Fig. 3 NDE personnel value stream (Author: Johannes Vrana, Vrana GmbH, Licenses: CC BY-ND 4.0)



Fig. 4 NDE system value stream (Author: Johannes Vrana, Vrana GmbH, Licenses: CC BY-ND 4.0)



Fig. 5 Regulatory value stream (Author: Johannes Vrana, Vrana GmbH, Licenses: CC BY-ND 4.0)

economy inspections. After a while (usually 5 years) NDE personnel needs to demonstrate that their knowledge is still up-to-date and that they can perform the inspections according to the procedures (recertification).

2.4.3 NDE System Value Stream

As shown in Fig. 4 the value stream for NDE system including any software used for NDE is similar to asset value stream, as NDE equipment is essentially a product, another form of an asset. The main differences are that it is produced by NDE OEMs, that the owners and operators of NDE equipment are the companies providing inspection services, and that the service inspections of NDE equipment (recalibration) are usually performed by the manufacturer in yearly intervals.

2.5 More Value Streams

There are probably a few more value streams. In fact, if a new stakeholder such as data traders emerge, there may be new value streams that are hard to conceive at present.

The following gives two additional examples which are important for the NDE ecosystem today.

2.5.1 Regulatory Value Stream

The regulatory value stream (see Fig. 5) starts with the need for a new standard. After a standard is designed, written, and issued, it documents the state of the art which should be used by all stakeholders in the ecosystem. After gaining

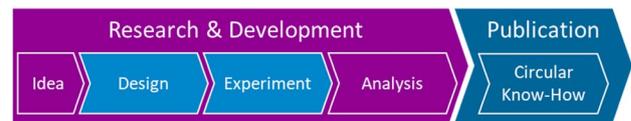


Fig. 6 R&D value stream (Author: Johannes Vrana, Vrana GmbH, Licenses: CC BY-ND 4.0)

experience with a standard, they are revised, normally in 5-year intervals.

2.5.2 Research & Development Value Stream

The R&D value stream starts (see Fig. 6), like all value streams with the initial idea. After the design of the experiment, including hypothesizing, the experiment (practically or theoretically) is conducted and analyzed to prove the hypothesis. The results of public research are usually published in peer-reviewed journals.

This value stream seems to be shorter as it does not contain an operation or experience part. Instead, those values stream usually require iterative work with loops from design to analysis and back. Moreover, scientific work usually should consider the research published before.

2.6 Digital Thread in the NDE ecosystem

The digital representation of the value streams is the digital thread—a time lapse story of digital twins for its users [3].

2.6.1 Digital Thread of the Asset

Since the purpose of NDE 4.0 is around reliability, safety, and economics of an asset, it is best to associate the digital thread to a unique asset.

Like the Asset Value Stream, the digital thread of an asset will start at the Asset OEM and continue through the Asset owner-operator. First the idea for a new product is born, the product is designed, raw material produced, individual components manufactured, the components inspected, assembled to a product, operated including multiple inspections until the product reaches its end-of life (EOL). After its end of life, the product may be disassembled, and the material may be recycled. Events during each of those stages can be captured by a digital twin, which has evolved and used data from the previous event and configuration. All the digital twins over the lifetime of a product are connected to form the digital thread as shown in Fig. 7.

The digital twins during lifetime may come from various companies. Raw materials and components will usually be produced by suppliers, assembly will be performed by an OEM, operation by an owner-operator and the activities after EOL by specialized companies. This means the access to the

Fig. 7 Digital thread of the asset (Author: Johannes Vrana, Vrana GmbH, Licenses: CC BY-ND 4.0)



digital thread needs to be handed from one company to the next during the lifetime of an asset.

The digital thread ownership and transfer model needs to evolve with associated business value. It should be envisioned that sale of a product will include its latest digital thread as an accessory. The lease of the product comes with an obligation to feed data into the digital thread. That means as the asset ages and depreciates in physical value, the digital twin gets richer and appreciates in virtual value.

2.6.2 Digital Thread of NDE System

Once again, every NDE device could have its own digital thread, just like an asset discussed above. Over time this digital thread will include digital twins of all inspections performed as discrete events with outcomes. It will be used by NDE OEM to improve the inspection equipment. It can be used by asset owner-operator to optimize maintenance plans, re-calibration, or even replace the equipment/technique with other options (will be detailed later in the text).

2.6.3 NDE Personnel Digital Thread

This connects the digital twins for all inspection events performed by an inspector (refer also to NDE Personnel Value Stream). Such a thread can be used for training and certification of individuals. It can also be used for training of AI systems (will be detailed later in the text).

2.7 Digital Weave in the NDE Ecosystem

The subject of digital twins is still evolving. In the NDE 4.0 ecosystem, we can clearly see multiple threads from various perspectives of different stakeholders. These connect at discrete events—manufacturing or inspection in our simplified representation.

Think of Fig. 8. The horizontal axis shows the digital thread of an asset and the vertical axis shows the thread for the production machines, which cross the asset twin at a point of manufacturing event. Both the asset and machine may have their nested twins to capture subset details. This leads to a 2D digital weave.

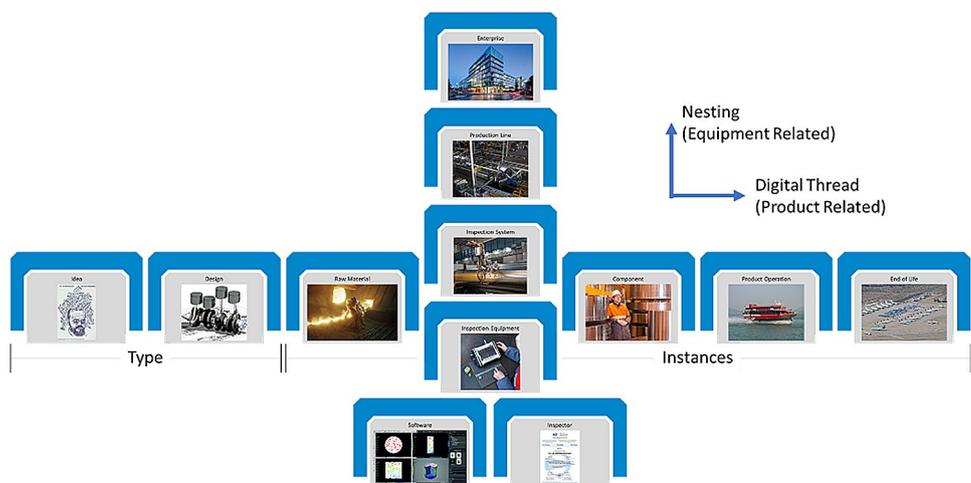
After production, the asset will encounter an inspection event which also belongs to the thread of inspection equipment. The digital weave now has a thread of different color.

The different instances (DTI) of different asset serial numbers (but of the same type (DTP)) constitute a third dimension orthogonal to the paper [3]. As not necessarily always the same machine was used for production or inspection, the digital twins of the various events will interact with different branches of the nested production related digital twins. This creates a 3D digital weave, a little hard to visualize.

Another dimension could be the abstraction layers. Starting with the asset, the functional integration, the user interaction, and business value propositions, as proposed in Reference Architectural Model Industry 4.0 (RAMI 4.0) [3, 14].

The digital weave is a digital thread for the ecosystem. Each of the stakeholders in the ecosystem should only be

Fig. 8 2D Digital weave (On the vertical axis nesting of digital twins is shown and on the horizontal axis the digital thread) [3]. (Author: Johannes Vrana, Vrana GmbH, Licenses: CC BY-ND 4.0)



concerned with relevant digital threads associated with their area of interest, and not sweat about the entanglement.

That ability to pull out the relevant thread from the multidimensional twins is what makes the concept of Digital Weave superior to the RAMI 4.0 model, which is asset centric, considering single instances only, unable to handle interaction with other assets and aggregation.

3 Cyber-Physical Value Creation in NDE

3.1 Basic Cyber-Physical Loop

The value creation in the fourth revolution comes from closing the cyber-physical loop, with the IIoT and the digital twin as the core contributors or enablers (see Fig. 9) [3]. The sensors in the physical world bring digital data, which is then converted into information by semantic interoperability, combined with other information (from the digital thread and weave), processed by the interconnected digital twins to create knowledge, which finally leads back to actions in the physical world.

Human in the loop is a matter of technology maturity, and acceptance. We will continuously see more automation in the loop. Just like we have gone from cruise control to self-driving cars in about 30 years; we will go from human-in-the-loop to human-on-the-loop and eventually human-out-of-the-loop.

Over the life cycle of a product, there can be a number of loops providing a wide range of value to various stakeholders of the NDE 4.0 ecosystem. As shown in Fig. 10.

The cyber-physical loops can stay within one value-creation step, like NDE, they can expand within one value stream including multiple companies and stakeholders, and they can even connect multiple value-streams. Starting with section 3.2 some of those cyber-physical loops will be discussed, beginning with small loops within one value-creation step and getting bigger within the paper. PS: To avoid too much confusion the descriptions are limited to simple feedback connections for key stakeholders.

3.2 NDE Event Loop for Asset Inspectors

The straightforward idea for inspectors and inspection companies are systems which offer the digitalization of the NDE workflow out of the box. This helps optimize resource scheduling, tracking of inspections and inspection results, etc.

The cyber-physical loop in this example (see Fig. 11) starts with the digital order from the customer, translated into a scheduled inspection plan by the supervisor (human with machine assistance), which is converted digitally into a job for a certain inspector at the time and place of inspection. The inspector gets his/her task instruction on the system (say a mobile device). This is where we leave the cyber world and get into the physical world: the inspector performs the physical inspection and stores the results back into the

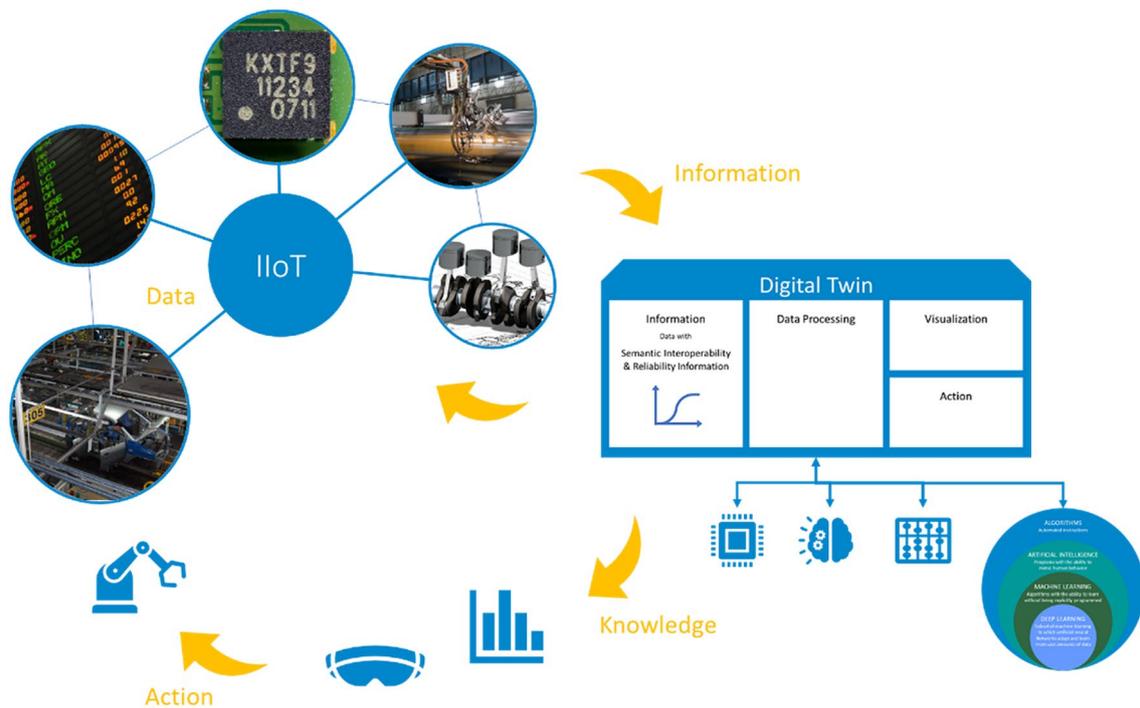


Fig. 9 The digitally transformed cyber-physical loop [3] (Author: Johannes Vrana, Vrana GmbH, Licenses: CC BY-ND 4.0)

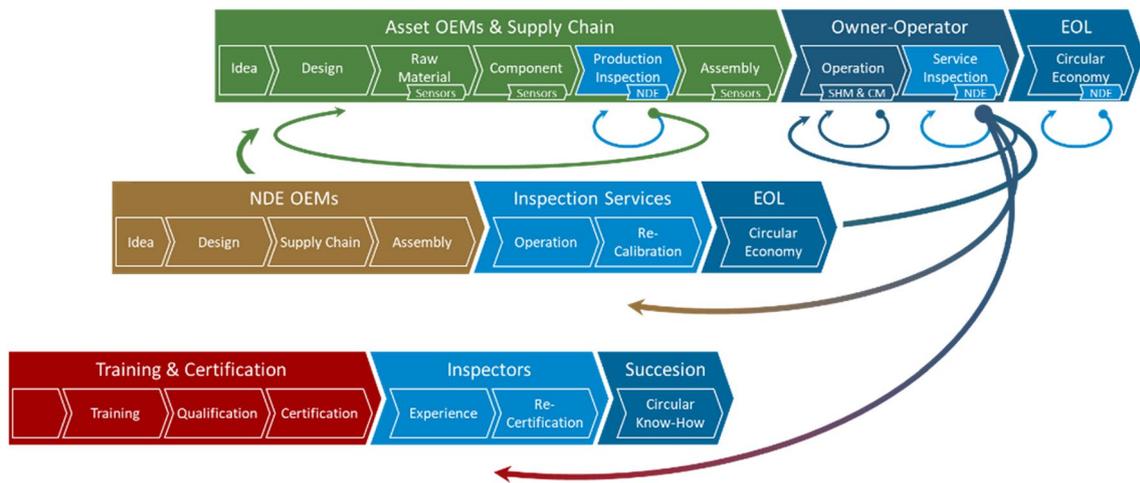
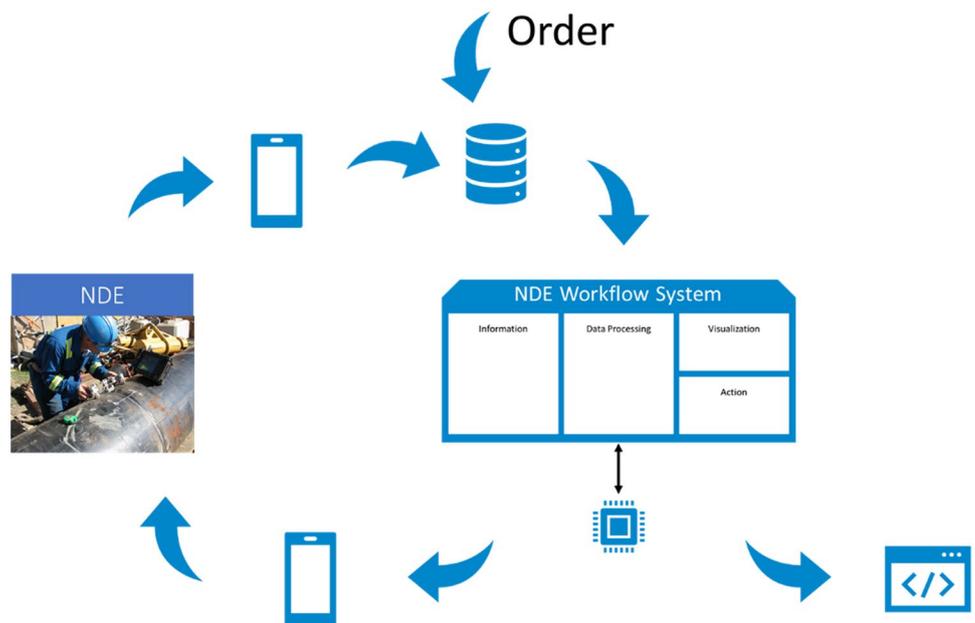


Fig. 10 Cyber-physical loops within and across value streams (Author: Johannes Vrana, Vrana GmbH, Licenses: CC BY-ND 4.0)

Fig. 11 NDE event loop for asset inspectors (Author: Johannes Vrana, Vrana GmbH, Licenses: CC BY-ND 4.0)



digital system, which connects the report with the original instructions closing the loop. Nowhere in the loop did anyone use a paper, or other means of digital communication outside the pre-determined pathway such as an email or popular MS Office programs (Excel, Word, or email).

Such workflow systems can be seen as simple digital twins of the process, they collect information, offer some data processing, and visualization opportunities.

An evolution of this will be when inspection data captured as an event into the Digital Twin, becomes a part of one of the larger loops discussed later. Other ideas to extend such a system include:

- Interface with the customer’s IT systems for receiving orders and submitting the results so that the customer can integrate the inspection into their cyber-physical loops,
- Interface with certification and training agencies,
- Interface with blockchains capturing the experience, the hours, and the certification of an inspector,
- Interface with eyesight testing laboratories (optician),
- Interface with inspection equipment OEM so that the settings of the instrument can automatically be applied and that, at least, some screenshots of the results can be stored together with the report,
- Blockchain to assure tracking of any changes to the data,

- Augmented reality to bring any the real-time information to the inspector,
- Enhanced algorithms for inspector support,
- Ability of the inspector to connect with experts or management for help.

A similar loop (see Fig. 12) can occur for asset manufacturers within their production setup. These cyber-physical loops are the smallest ones and are entirely within the world of NDT/NDE event. In the subsequent sections, we are going to expand the loops step by step and see the increasing value of digital twins with the size of the loop.

3.3 Maintenance Loop for Asset Owner-Operators

The main goal of an owner-operator of assets, like powerplants, oil and gas plants, aircraft, trucks, or trains, is to maximize availability/usage, as smooth and as long as possible, minimize operating cost, and maximize the return-on-invest. Such a desire, led to the development of various operating philosophies:

- Reactive: Fix once it is broken
- Preventive: Maintenance at regular intervals
- Condition-based: triggered by a conditional parameter
- Predictive: Predict when it will fail, and proactively prevent
- Prescriptive: Identify asset specific near-term actions

A major trend for owner-operators is predictive or even prescriptive maintenance. Most implementations for predictive analysis use sensors attached to an asset in operation to predict the remaining life/the point in time requiring the next maintenance by statistical evaluation. Typical sensors: include vibration, acoustic emission, acceleration, speed, oil pressure, infrared,.... Those sensors all work nondestructively and provide a digital sensorial information at predetermined short time intervals—so they should all be considered NDE sensors.

If the data of those NDE sensors gets combined with the results of classical NDE inspections a holistic predictive maintenance can be reached which will allow for an even more accurate prediction of the next potential failure and an even more economic operation of the asset [15].

The cyber-physical loop (see Fig. 13) starts with the inspection event record. Statistical evaluation of these records combined with engineering data and in consultation with Asset OEMs, can help replan the preventive maintenance, start doing predictive maintenance and even take some asset specific prescriptive actions. The loop will close with a revised plan feeding the smaller loop discussed above. This loop integrates the world of NDT/NDE with the world of maintenance planning.

3.4 Design Loop for Asset OEMs

Assets operated by the owner-operators are manufactured by OEMs (like train, turbine, aircraft, boiler, machine, car, truck, boat, or amusement ride manufacturers). Usually OEMs design the asset, get components or sub-assemblies manufactured by suppliers, assemble the asset, test, and deliver the asset to the customer (owner-operator), with accountability and responsibility as per their contracts.

Asset OEMs perform extensive quality assurance, including NDT/NDE to assure that the assets will meet their performance over a promised life. Most of those quality assurance measures are conducted as early as possible in the value-creation chain. Meaning, most of the NDT/NDE is performed at the component suppliers (forging/casting shops, steel manufacturers, ...) and at suppliers specialized in joining operations (welding, gluing, ...). As suppliers are usually highly focused on a narrow product range automated NDT/NDE systems are often used. They may have their own NDE 4.0 loop for the NDE event, at the smallest size/level or the innermost loop.

The next outer value loop could be the data coming from the quality assurance in the supply chain used by the OEMs to enhance the design of the components. For example, by

Fig. 12 NDE event loops (Author: Johannes Vrana, Vrana GmbH, Licenses: CC BY-ND 4.0)

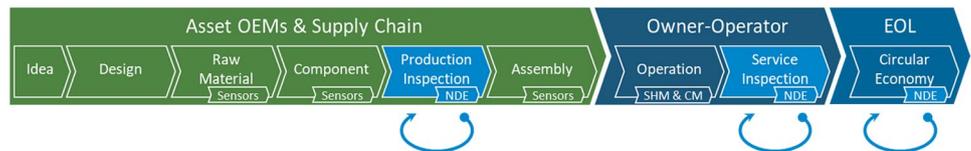
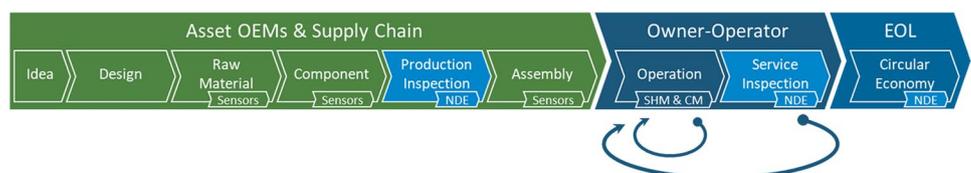


Fig. 13 Maintenance planning loops (Author: Johannes Vrana, Vrana GmbH, Licenses: CC BY-ND 4.0)



analyzing typical defect locations or by incorporating defect size distributions into their lifing calculations [16]. There is also a possibility of a cyber-physical loop taking the data from the NDE during production to enhance the design and the production of the next variant of the components.

The outer most loop integrates the data from owner-operators, both the quasi-continuous data from NDE sensors gathered during operation and the classical NDE inspections gathered during maintenance inspections. This makes the cyber-physical loop even bigger and the results (the potential improvements of design, production, and lifetime) truly remarkable and desirable for a competitive product. This can also enhance the value of NDE engineering in asset development cycle, discussed below.

Such loops (see Fig. 14) are not new. High tech industries such as aerospace and nuclear have been using them, by choice or through regulatory forces. They are generally very weak in terms of data quality and speed of execution. They become highly effective when there is an undesirable incident. With the 4th revolution, they can be a lot more effective and efficient, and possibly proactive, and even continuous. The open interfaces and frameworks will enable much faster implementation, reaching the higher hanging fruits, OEMs do not have to do it painfully in response to a demand for enhanced safety. They can do it proactively for both safety and economic value.

3.5 NDE System Design Loop for NDE OEMs

Companies producing automated inspection systems, no matter whether they are automated ultrasonic, digital radiography, computer tomography, thermography or automated visual inspection systems, need to integrate automation hardware (like robots for automated component feeding and component handling during inspection), NDE Instruments, NDE sensors, sources and detectors, system supporting sensors, software, database access, existing IT infrastructure, The mechanical and electrical components of the system need to be designed and the complete system installed at a customer site, with proper ICT (Information and Communications Technology) connection.

The system design and integration process can be supported by a digital twin [3], allowing the simulation of NDE, mechanics, electrics, interaction, IT connectivity, etc. Such a

digital twin needs information of all components to be integrated—preferably in an open format which can be loaded into the digital twin directly. Such a digital twin could also be used to show the customer the design and integration of the system into their production and allows easy in-factory and onsite customization of the system depending on the customer feedback. Ideally the digital twin of the system relates to the digital twin of the manufacturing environment it is supposed to be integrated so that issues can be determined during the design phase.

The cyber-physical loop in this design phase (see Fig. 15) starts with the designer of the system working in a virtual environment, continuing with simulations of the NDE process and the system. Visualization of the simulation results, and actions how to improve the system. All this to ensure a proper inspection.

The finalized design and the information regarding all the components can be used to automatically issue purchase orders to suppliers and enable automation for assembling the system. This is the point where a digital twin of the type is converted to the digital twin of the event [3]. Once the system gets installed physically, the digital twin of the event can be integrated into the nested digital twin structure of the production floor. This enables an automated storage of the results of the inspection within the IT landscape of the customer.

Moreover, if information from the installed system is fed back to the NDE system OEM the data can be used to improve the hardware and software of the system. This opens more possibilities arising by aggregating the information from multiple systems.

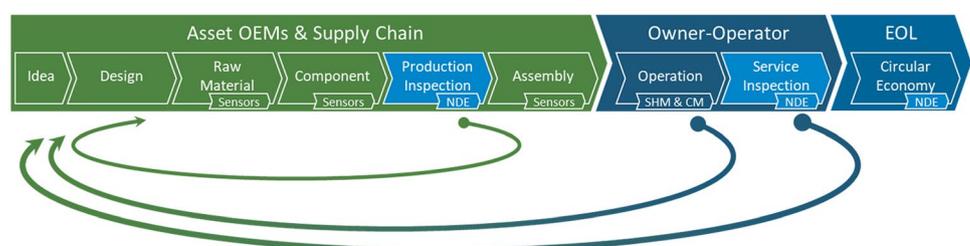
All this leads to improved design of the system, to a better integration, easier assembly for the benefit of the System OEM and the customer.

In principle, all these considerations for NDE System OEMs can be adopted as is to any non-NDE System OEM.

3.5.1 NDE Equipment OEMs

The ideas for cyber-physical loops and digital twins in production of NDE equipment are similar to NDE systems. With the main difference: most systems are highly customized, and most equipment is mass produced. However, a

Fig. 14 Design loop for Asset OEMs (Author: Johannes Vrana, Vrana GmbH, Licenses: CC BY-ND 4.0)



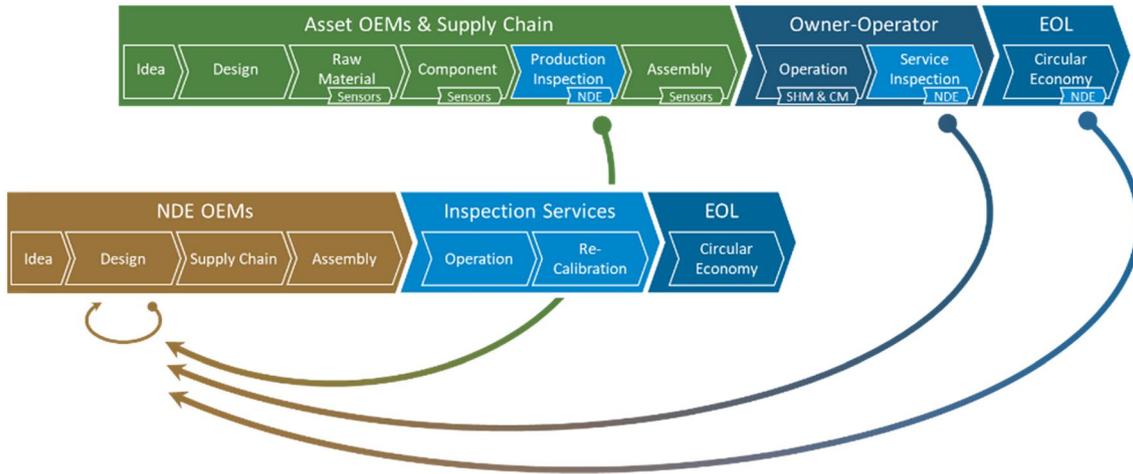


Fig. 15 NDE system design loop for NDE OEMs (Author: Johannes Vrana, Vrana GmbH, Licenses: CC BY-ND 4.0)

good digital twin will also allow a higher degree of customization for mass produced equipment.

Like with all devices in industrial manufacturing, the customers will need to integrate the equipment into their existing infrastructure, no matter whether they are owner-operators, asset OEMs, component OEMs or system integrators. This will lead to the situation that NDE equipment OEMs will have to implement open, standardized interfaces and data formats.

3.5.2 Cyber-Physical Loops for Predictive Maintenance of NDE Equipment

Data from the NDE systems and equipment from all the different inspections during the lifetime of a product can also be used to obtain some information on the equipment status.

Imagine an ultrasonic instrument which is used every day with the same set of probes. The probes are calibrated every day. By performing a statistical analysis on the calibrations and some trending it should be possible to see if the instrument itself is running out of its optimal state of operation. By designing automatic self-tests perhaps even the yearly re-calibrations could be replaced by a cyber-physical loop. In addition, the digital twins can be used for regular checks of probes.

Such systems would have the great benefit that equipment errors could be identified nearly immediately and not at the regular intervals required by standards. This would clearly improve the reliability of the inspections. This will be the predictive or prescriptive maintenance of the NDE equipment (Fig. 16).

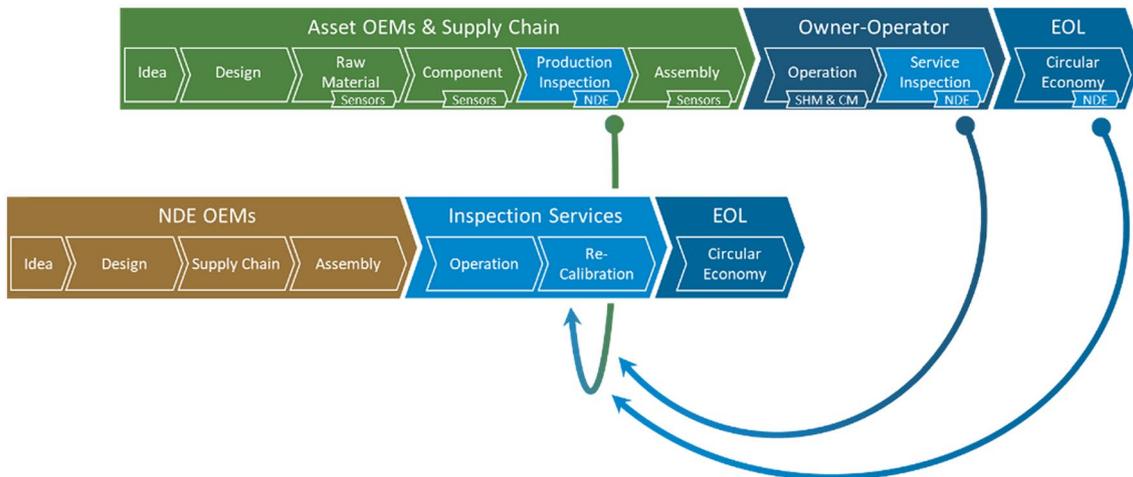


Fig. 16 Cyber-physical loops for predictive maintenance of NDE equipment (Author: Johannes Vrana, Vrana GmbH, Licenses: CC BY-ND 4.0)

3.6 More Loops in the NDE Ecosystem

Others in the NDE 4.0 ecosystem may not have a full loop of their own, but they are a part of the loops we discussed for each of the key stakeholders.

They will perform the necessary R&D (universities and other labs), train all groups within the eco system (training schools), assure standardization while keeping innovation possible (regulatory bodies), communicate and provide platform to collaborate (communities and societies), establish the fitting IT infrastructure, and support companies on their digitalization projects (consultants and coaches). Since they all support the Journey to the World of NDE 4.0, they can all benefit from value coming out of digital twins and feeding back more value into the cyber-physical loops of their primary customers.

Figure 17 shows some ideas for training, qualification, certification, and re-certification, enabling equivalent of predictive or prescriptive re-certification of the individual inspector.

3.7 NDE Engineering Within the Loops

One more group which needs to be mentioned is the NDE engineers. NDE engineers are part of most of the value chains, are employed by nearly all the stakeholders discussed above, and have a significant role to play in the design and outcome of an inspection process.

NDE Engineering is responsible to establish the most appropriate way to inspect an asset in collaboration with other engineering disciplines and to create the fitting specifications and procedures, both for owner-operator and for asset OEMs. For this task, the cyber-physical loops/digital twins enabling the simulation of the inspection process, the inspection physics, and the inspection reliability can be of

tremendous help. Those loops need validated simulation tools, data about the component to be inspected, and a good database of all previous inspections as a baseline. Such tools could for example be used to compare the reliability of classical, conventional UT, to phased array, to TFM, and to SAFT before performing the inspection or to evaluate the effect of certain material or design parameters before manufacturing of the components. Once the components are manufactured and tested this can be used to validate the results. Such a system will over time create growingly more accurate results.

4 Exemplary NDE 4.0 Use Cases and Value Propositions

The loops shown up to the moment already identified multiple use-cases. Moreover, authors have identified multiple use cases using a design-thinking approach [1]. This section presents an explicit look at the authors top 15 value propositions or use cases of NDE 4.0. All of them eventually contribute to social and economic values through safety, reliability, and quality. There is a good possibility that you will be able to relate some of them to your professional activity directly and some others marginally. Final sub section will help you grasp a comprehensive picture through an application matrix across the key stakeholders.

4.1 Enhancing NDE Capability & Reliability

In most industrial situations, the digital systems offer a clear advantage over the analog systems in value from accuracy, productivity, portability, remote access, operator guidance, analytics, and readiness for machine intelligence,

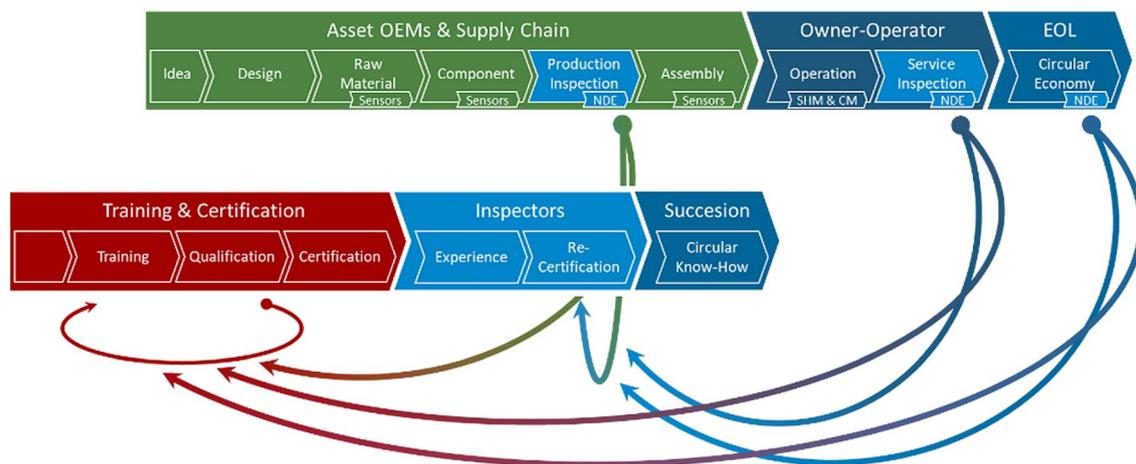
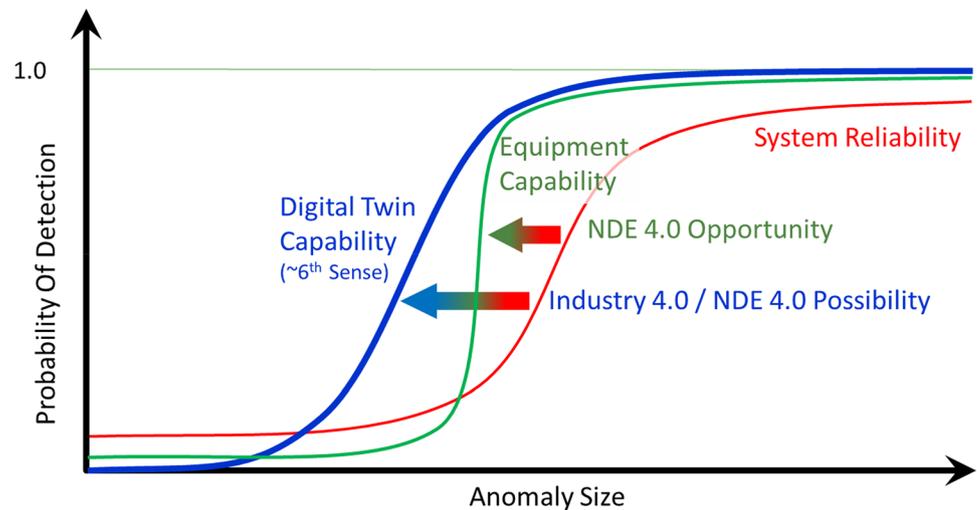


Fig. 17 Personnel loops in NDE ecosystem (Author: Johannes Vrana, Vrana GmbH, Licenses: CC BY-ND 4.0)

Fig. 18 NDE 4.0 not only offers the opportunity to bring system reliability (red) closer to equipment intrinsic capability (green), but it also opens the possibility of exceeding it through use of digital twins using relevant data and processing (blue) (Color figure online)



and it keeps getting better with rapid advances in digital manipulation.

A significant contribution of Cyber-Physical NDE system (NDE 4.0) stems from the better control or partial elimination of human factors in probability of detection [17]. Reduction of human factors through automation, leads to a more reliable inspection system, i.e., better Probability of Detection (POD) and a more consistent POD from inspection to inspection. It can get the reliability curve (red) in Fig. 18 closer to intrinsic capability (green). Virkkunen et al. [18] have shown that using sophisticated data augmentation, modern deep learning networks can be trained to achieve superhuman performance by significant margin in ultrasonic inspections.

When combined with historical data, data from other sources, data from other assets, and holistic enhanced data processing/simulations (e.g. by Quantum Computer enabled AI), it is possible for the digital evaluation system to even exceed the capability (blue) of a standalone equipment. Just like law enforcement agencies can predict a threat from analysis of social media chatter. When this can be achieved, a true revolution in NDE will take place bringing in true superhuman perception which could be perceived as adding the 6th sense to the NDE system (traditionally focused on enhancing the 5 human senses [1]). All this adds to a dependable NDE permitting optimization of inspection program, saving time, money, and improving asset availability.

4.2 Workflow Efficiency & Effectiveness

Digital workflows can enable full value stream efficiency and effectiveness just like so many manufacturing processes on shop floor or logistics in retail distribution. Starting with task allocation from the customer to the inspector and the results transfer back to the customer. Those data transfers are performed using IIoT technologies and interfaces (instead of

Excel files or PDFs using email typical of 3rd revolution). Finally, with the implementation of digital supply chain processes both to customers and suppliers using standard interfaces a complete digital workflow can be established enabling NDE Processes 4.0.

Component traceability becomes easier ensuring that the correct component was inspected, and results retrieved. Revision-safe data storage can be implemented using block-chains and the component identification by digital component files and electronic component identifiers.

From the perspective of inspection service providers or NDT managers, the usage statistics or inspection performance evaluations can show the need for a certain inspection on one hand and identify human factor influence, on the other hand. It helps reduce operator dependence, inspection inconsistencies, and the need for additional training or process change. Such evaluations can also be used to monitor training, experience hours for personnel evaluation, qualification, and certification. If required and permitted by local law, it can even indicate the mental and physical state of inspectors.

4.3 Enhanced Inspector Learning and Certification Experience

The training and certification process usually begins with some theoretical and hands-on learning, includes a vision test, sufficient practical experience, culminating with a successful qualification exam. Most of these steps are still in the second/third revolution era—classroom training, with paper ledgers. Eyesight proofs are paper based with a manual signature from the optometrist. Proofs for practical experience are paper based with the signature of the supervisors. A lot of exams are still paper based; ASNTs exams are computer based with an elaborate scheme for selecting random questions. The final Certificates are paper based.

Digitalization and digital transformation [10] will help to make this system more efficient, effective, and resilient. For example, training by video or mixed reality “classroom”, use of gamification to maintain student attention, using cheap mock-ups of sensors and components and some tracking software to realistically simulate the inspection process at home without the need to send expensive and heavy equipment to the students (practical training). Eyesight test results can be stored in a blockchain which the certification and qualification bodies and the employers can access. Once the practical experience of an inspector is tracked by the NDE workflow system and by employing a blockchain for documentation, the experience could be stored and made accessible in a verifiable and permanent way.

Automatically analyzing the inspector’s performance could even pave a way from hour-based experience records to performance-based experience records. Such an analysis of the inspector’s performance could also be used to personalize the theoretical and practical training needs.

Performance monitoring during practical and theoretical training will track the learning progress. This enables tailored training to the individual needs and once the performance of a student is sufficient the monitoring could be used to amend exams or even to replace them. Again, the documentation of the performance monitoring can be tracked verifiably and permanently employing a blockchain and, if the training is conducted virtually, it can be assured that the student conducting the training is unambiguously identified.

Digitalized exams with AI based learning selection routines for questions and blockchain based performance tracking could finally be used, together with the digital proofs for eye exams, experience, and training, to issue the blockchain-based certifications.

All this will shift the certification paradigm, from training to learning and retention based; even allowing different training, certification, and qualification bodies to cooperate, further enhancing inspector experience.

4.4 Improved Inspector Safety and Support

Remote-controlled robots or drone-based equipment, enabled by extended reality platforms and connected devices, can keep inspectors out of harm’s way and even reduce cost of inspection. Inspector need not go to confined spaces, climb towers, walk into dark and dirty boilers, or hang from a bridge deck, etc.

Remote Support by other inspectors or engineers can help in inspection situations where a second opinion is needed, were an in-depth evaluation of indications identified by the inspector at location needs to be conducted and where local (potentially inexperienced) inspection personnel must be used (for example due to travel restrictions).

The recent pandemic, which led to global shutdown, forcing essential services to continue under stressful social distancing, demonstrated the value of remote NDE. In times of low touch economy, NDE 4.0 enabling technologies is expected to significantly help protect the inspectors.

4.5 Better NDE System Design

We define NDE system as hardware equipment, firmware. The idea to improve NDE system using feedback is simple: provide the data like error codes, system parameters, system status information, software exceptions/errors, or use or misuse back to the NDE equipment OEM, so they can improve the systems.

The statistical evaluation of user behavior helps improve the user interface design, training, and applicability. This feedback loop may also contribute to accelerated troubleshooting and improvements of inspection equipment as a competitive advantage.

It is estimated that every second, 127 new devices are connected to the web. At the end of 2019, the world had 26.66 billion IIoT devices [19]. The projected number by 2030 ranges from 100 to 200 billion. Can NDE OEM afford to stay disconnected? However, what is more important is how to use the connection to generate the value in real-time for the stakeholders. Approaching this challenge now as an opportunity, the NDT OEMs can create a competitive advantage for themselves and their customers—the asset owners and operators. For the ones who decide to follow the market it could almost decide their future.

4.6 Better NDE Equipment Maintenance

Regulations, standards, and company policies require that NDE equipment and systems are periodically checked and calibrated at regular intervals. Such preventive maintenance plans pose multiple challenges. The maintenance plan must be conservative, resulting in over-maintained products causing unnecessary costs. There is still a chance that highly sensitive equipment will break down. Some of the electronic components used could see a drift which leads to a situation that the instrument is working out of its ideal operational state before it is due for re-calibration. This could lead to a situation that indications might be undersized without the operator having any opportunity to notice. During the regular checks such an underperformance could be detected but this would question all the inspection results between the checks. NDE 4.0 can provide a predictive maintenance opportunity to NDE equipment.

4.7 Customized NDE Solutions

NDE sensors and detectors and NDE mobile equipment is usually mass produced. This leads to the unfortunate case that customer is forced to purchase what is available and not what they might specifically need. Digital transformation can relax this constraint, by allowing the customer to submit the edge conditions (either using a good Human–Machine Interface—a website or by opening computer–computer interfaces) and by a highly automated production environment enabling lot-size-one.

NDE devices, which nowadays are software based anyway, mass customization is even easier by allowing the customer to enable certain functionalities or apps on the go, just like on smartphones. Meaning the customer would buy or rent a base unit and based on their actual need they would unlock (buying, renting, ...) the functionalities they need. Automated inspection systems are in a lot of cases already customized. But even here software tools will help to make the customization more manageable for system manufacturers.

4.8 NDE Simplified for Everyone

The highly powerful but widely available electronic devices, such as tablet computers and cellphones, incorporate various sensors in the form of cameras, microphones, vibration sensors and accelerometers. Other smartphone compatible tools are available for purchase like IR cameras, terahertz arrays, eddy current or ultrasonic transducers that can be used for household NDE. The use of these tools is as simple as downloading an app from the App store and attaching the removable device to the phone. That is literally everything that is necessary to start taking measurements. If combined with intelligence augmentation this will make NDE available

to anyone at any time and any place. For the next generation, this technology is self-evident, and they possess a natural flair for it. Merging the highly specialized knowledge of the NDE techniques with today’s technology will open a new market for NDE 4.0. These new hand-held devices will be applied to make NDE available, affordable, and user-friendly to anybody. As a benefit, product inspection at home can become an additional component of monitoring the life cycle of a product. This might significantly increase the acceptance of NDE 4.0 by solving new inspection problems for all day service.

Mobile phone is the wheel of Industry 4.0. Why reinvent?

4.9 Asset Design Optimization

The production and in-service inspection data can be captured in digital threads and shared with design team. NDE results/data processing through statistical analysis and cross-correlations with other data sets provides insight into product performance, not otherwise possible. This is the probabilistic data fusion opportunity and can be used for design improvements, manufacturing processes changes, component reliability estimations, optimum inspection planning, for probabilistic lifing [16, 20], and risk analysis. Large data sets also allow for the training of neural networks and the implementation of AI models to NDE.

What is this connected with NDE: NDE has a certain reliability, a certain Probability of Detection (POD) (red in Fig. 19). In many cases the NDE result is broken down to a GO/NO-GO decision for quality assurance (such as $a_{90/95}$ in aerospace and other sectors). This leads to the fact that engineering is often restricted to using single data point as

Fig. 19 NDE 4.0 enables the probabilistic opportunity for engineering

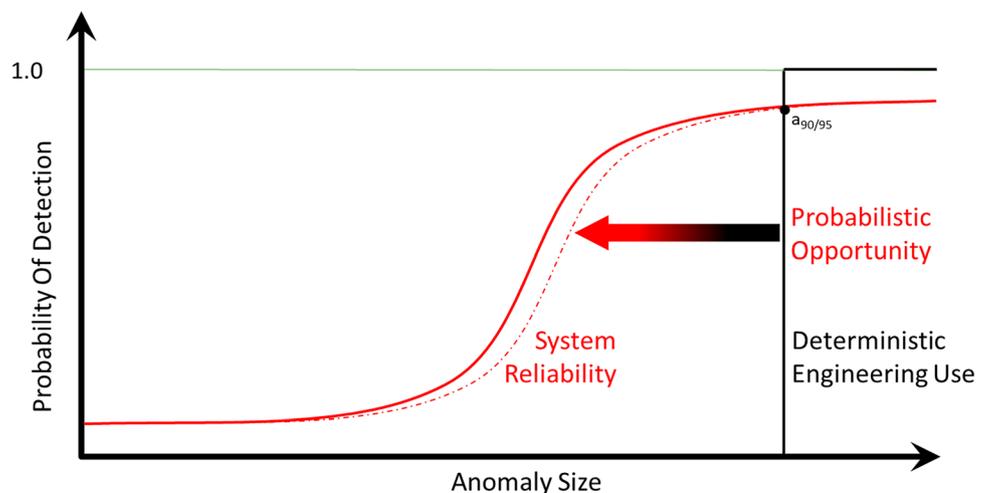


Table 1 Connection of use cases with primary stakeholders and value estimation (H: high; M: medium; L: low)

Use case or value proposition	Asset OEM	Owner operator	Asset inspector	NDE OEM
Enhanced NDE capability and reliability	M	M	H	L
Workflow efficiency and effectiveness	M	H	H	L
Enhanced insp cert experience	M	M	H	L
Improved inspector safety and support	L	M	H	L
Better NDE system design	L	L	M	H
Better NDE system maintenance	L	M	M	L
Customized NDE solutions	H	M	L	H
NDE simplified for everyone	M	M	L	H
Asset design optimization	H	M	L	L
Factory/infrastructure of the future	H	M	L	L
Prescriptive asset maintenance	M	H	L	L
Circular economy and sustainability	L	H	M	M
Additive manufacturing quality	H	M	L	M
Safety of drones and industrial robots	M	M	H	M

if the POD curve is a step function shown with black line in Fig. 19. Meaning the information from smaller anomalies is not used by classic deterministic engineering. By properly identifying the system reliability as a full curve the information about smaller anomalies can be used in a probabilistic manner [16]. This additional knowledge can lead to a more accurate estimation of the lifetime of the asset (Fig. 19).

4.10 Connected Factory or Infrastructure of the Future

A smart factory is a highly digitalized and connected production facility that relies on smart manufacturing. This is also referred to as a factory of the future. The defining characteristics of the smart factory are visibility, connectivity, and autonomy. Through modern technologies, the smart factory systems can learn and adapt in near real-time or real-time, enabling factories that are far more flexible than those of the past. The goal is to identify opportunities for automating operations and use data analytics to improve manufacturing performance. The data comes from [15]

- NDE sensors, providing point-like information at short time intervals for in-situ inspections during manufacturing or operation, such as ultrasonic sensors (like vibration analysis or acoustic emission) and optical sensors (like IR, UV, visual),
- Traditional NDE inspections, providing a view into the component at longer intervals.

Only the combination of the data from both NDE sensors and inspections will provide sufficient data input for predictive and prescriptive maintenance and holistic structural health monitoring (SHM) of critical infrastructure.

As manufacturing gets into mass customization, this would require NDE to adapt to the customized product creating another use case for NDE 4.0.

4.11 Prescriptive Asset Maintenance

NDE 4.0 may soon bring up the possibility of asset customized prescriptive maintenance, which can significantly improve the value derived from Data Analytics Maturity Model, originally proposed by Gartner in 2012. Analytics at various levels, require increasingly specialized skills, with possibility to command increased prices in the data market.

- Analytics Level 1: Descriptive—What happened?
- Analytics Level 2: Diagnostics—Why did it happen?
- Analytics Level 3: Predictive—What will happen?
- Analytics Level 4: Prescriptive—What should we do?
- Analytics Level 5: Cognitive—What don't we know?

Digital thread may even create a new business model for asset manufacturer, one driven by data, and machine intelligence. For certain industries, this could be a shared responsibility with Asset owners. The structured data amenable to information extraction can become a commodity with a price tag, for data owners because it has value for product performance and service life improvement.

4.12 Circular Economy/Sustainability

The life cycle of a product starts with its initial idea, goes through design, production, supply chain, assembly, quality, in service maintenance, and something at the end of useful life. As highlighted above, NDE helps build a database needed to allow for the longest possible lifetime, and

even life extension of high value assets such as in aviation, nuclear, marine industries.

After its lifetime and potentially some lifetime extensions individual components or the complete product reaches its end of life (EOL). The trend these days, rightfully so, is to repurpose, reuse, recycle, as much of the material as possible, in so called circular economy, where we minimize waste to landfill. In a circular economy, environmental sustainability is the purpose.

Circular economy will be a new area for NDE. Firstly, the NDE results during initial production and during operation will provide input for establishing the best options for circular economy. Secondly, the NDE inspections at the EOL will help with this readiness assessment and could also be used as a feedback to enhance the next generation of products. This requires that the results of all NDE inspections, together with the data from NDE sensors, and other data sources are combined to provide the best possible data source. A data-rich digital twin will be a valuable companion to the asset reaching end of life.

4.13 Additive Manufacturing Quality

Components manufactured additively are usually difficult to inspect due to their complex internal structures or complex external shape. This is why the usability of most of the traditional NDE methods is very limited for those components. In most cases, out of the traditional methods, only computed tomography works.

This motivated several groups to start working on in-situ NDE methods which monitor the signal during the additive manufacturing process. The most frequently used sensors are optical sensors monitoring and recording the internal and external dimensions using infrared, visual, or ultraviolet light. The heating and cooling processes, the melting and freezing processes, and the expansion and shrinking processes can be monitored. The feedback control can correct the process to ensure quality in real time. Acoustic emission might be added as an additional in-situ inspection method in the future.

NDE 4.0 can improve the 3D printing process. However, the reduced lot size of additively manufactured components is an additional challenge for NDE, which can be addressed by NDE 4.0 more conveniently.

4.14 Safety of Drones and Critical Industrial Robots

Very soon, society will be in the era where the expensive drones performing everyday functions will need inspection and maintenance programs. For most part, the society reacts to problems when they show up. It is not hard to imagine that one day in near future, a package delivery drone will have a catastrophic failure in someone's back yard, and new

regulations will emerge around inspection of aging drones, and industrial cobots on similar lines. Now this technology and application is changing so fast that it is hitting obsolescence before aging, and so no maintenance plans are created.

4.15 Renewed Respect for NDE

4.15.1 Management Perspective

As mentioned in the introduction, the NDT is seen by some customers as an unnecessary cost factor. For the authors, those statements were quite surprising. Companies are currently installing hundreds of sensors to monitor production and operation to feed the data in cyber-physical loops to enhance production design and maintenance. They are striving for a holistic digital image or representation embedding as much relevant data from an asset as possible. However, they are forgetting one data source, a data source they most likely have already installed in their factory. A data source they are currently only using for a quality assurance decision. A data source they are currently seeing as a cost factor: NDT. NDE 4.0 is the chance for NDT to evolve from a cost center to one of the best value creators for a company—one of the best data sources.

4.15.2 Inspector Perspective

Like any other task, an inspection includes managing administrative workflow in addition to the fun part of data capture and decision making. The automation of mundane tasks is already reducing the burden of the non-value-added portion. This can go a whole new level where the new skill set makes inspectors job high-tech, cool, and highly compensated activity. Every revolution has improved the economic condition of skilled workers (<https://ourworldindata.org/economic-growth>). This is going to be no different. NDE can be Cool, High Skill, and High Paying Profession.

4.16 Use-Case Summary

Table 1 connects the four key stakeholders of Sect. 2 with the use cases in this section.

5 Challenges

5.1 Data Markets and the Connected Industry 4.0 World

The various use-cases and cyber-physical loops show the value of fused data sets. Data itself becomes an asset. There is a market for data and it is important to use it. The way to this market is the interfaces discussed in [3, 4]. How to

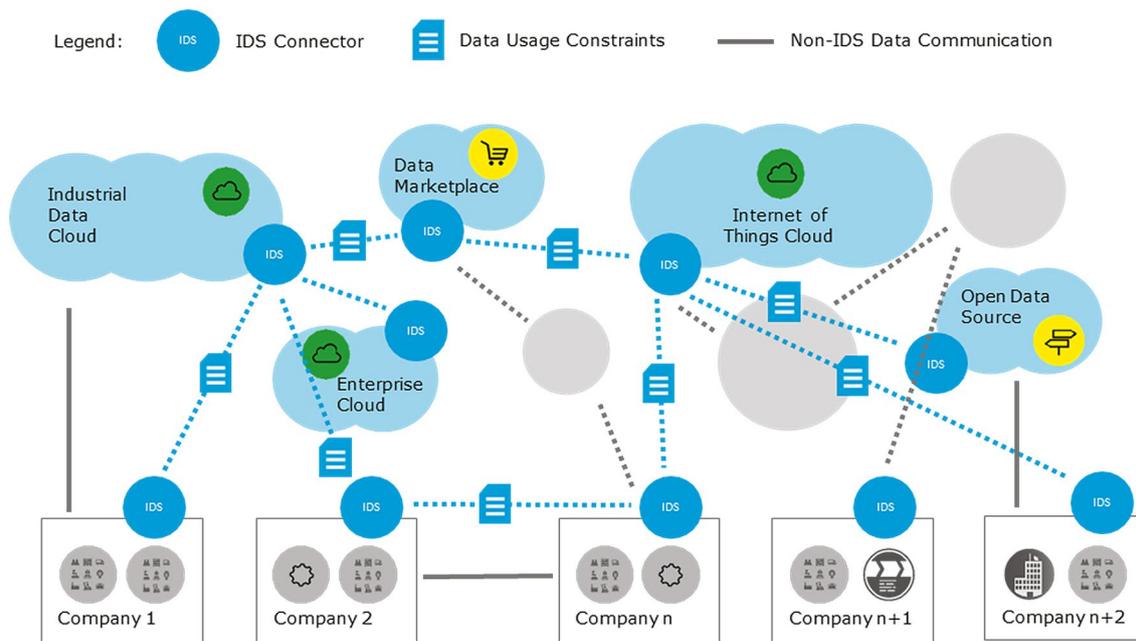


Fig. 20 IDSA: Connected Industry 4.0 World [21]

make this market safe, how to connect data between different companies, and how to establish a data market is discussed in this section.

“The key focus for a data-driven economy and new business models is on linking data.”[Quote: International Data Space Association]

In the future, it will be possible to buy data independent of suppliers. As discussed above this will bring new stakeholders (like data traders and enrichers) and value streams into the NDE 4.0 ecosystem. The aim is to prevent illegal data markets, to create data markets according to crucial values (like data privacy and security, equal opportunities through a federated design, and ensuring data sovereignty for the creator of the data and trust among participants) and to ensure that companies that have generated the data also benefit from their value and not just a few large data platforms.

The International Data Space Association (IDSA) has set itself this goal. IDSA develops standards and de-jure-standards based on the requirements of IDSA members, works on the standardization of semantics for data exchange protocols and provides sample code to ensure easy implementation.

One of the key elements IDSA is implementing are the so-called IDS connectors [21] which guarantee data sovereignty (see Figure 20). Both the data source and the data sink have certified connectors. The data provider defines data use restrictions. The data consumer connector guarantees that

the restrictions are followed. For example, if the data provider defines that the data consumer is allowed to view the data once the data will be deleted by the consumer connector after the data was viewed. This enables also the producer of the data to decide which customer can use his data in which form as an economic good, for statistical evaluation or similar.

Most companies are very reluctant to share data and information with other companies or with cloud systems. As of today, this is reasonable as technical data is only protected by individual contracts. However, it hinders the development and usage of multiple Industry 4.0 technologies (like IIoT, Digital Twin, AI). The IDS connectors, as shown in Fig. 20, create the needed network of trust by ensuring data sovereignty and ownership. This enables the connected world and eventually data markets.

For many, marketing the data will be a new business model. For NDE it is the opportunity to move from the position of an unnecessary cost factor to one of THE data suppliers. This will create a new, larger business case.

5.2 Decision Requirements

In [1] several challenges were identified—including standardization, which is also discussed in section 2.3.3.1. On top several interconnected challenges are getting crucial regarding NDE as data source for cyber-physical loops:

- In a variety of current-day standards, specifications, and procedures the requirements for decision are based on perceptions and experience rather than data. Damage detection of any type causes a fear of failure in the minds of operators and a perception of neglect in the eyes of their customers and consumers. This results e.g. in requirements classifying ALL detected indications as rejectable. By enhancing NDE capabilities more indications would be found which would lead to higher scrap rates. This discourages the use and the development of more sensitive NDE techniques—including the measures discussed in Sect. 4.1. It also prevents the implementation of longer maintenance intervals.
- Vice-versa some standards, specifications, and procedures require NDE methods which do not provide a sufficient reliability for design engineering's requirements.
- Cyber-physical loops promise better designs and products by harvesting and fusing data. This leads to the fact that a better sensitivity and the (automated) reporting of as many indications as possible would be beneficial.
- Decision limits need to be based on design engineering requirements to ensure that quality assurance decision limits are as tight as needed and as loose as possible.
- Sensitivity requirements
 - Design engineering needs to define sensitivity requirements and NDE engineering needs to prove that those requirements can be met with the selected methods.
- Consumer education
 - Asset operators and users need to be educated on engineering analysis and damage tolerance philosophy. They need to be convinced that it is OK to have indication of minor anomaly, where the risk is extremely low and acceptable to continue to use the asset, and monitor is needed.

Those challenges currently contradict each other and hinder cyber-physical loops employing NDE. Moreover, they are a further burden to the general value appreciation for NDT (as discussed in 1.1).

To resolve this, several steps become crucial:

- Differentiation between reporting and decision limits
- All indications should be (automatically) reported so that they can be used for cyber-physical loops.

6 Discussion and Summary

NDE 4.0 is the chance for the NDE and NDT community to provide the vital correction of the value perception. To secure the shift back from being seen as a cost center to being appreciated as a value center.

NDE 4.0 is all about the purposeful cyber–physical ecosystem. We all have seen digital technologies and physical methods continuing to evolve, mostly independently and sometimes interdependently. The real power is in the concurrent design of inspection systems through an appreciation of cyber-physical loops and digital twins.

If data is the new crude oil, then information is the new refined oil,
NDE is the new oil rig,
IIoT the new pipeline,
digital twin the new motor,
and the cyber-physical loop the new machine.

This makes the NDE 4.0 ecosystem like the new energy infrastructure.

These provide an ability to capture data directly from the materials and manufacturing process to usage and in-service maintenance, across multiple assets. The data can then be used to optimize maintenance, repairs, and overhauls over the lifetime of an asset, and even feed back to the original equipment manufacturer (OEM) for design and production improvements.

Acknowledgements Many thanks to valuable conversations with the members of the DGZfP subcommittee “Interfaces for NDE 4.0”, of the DGZfP and ASNT committees “NDE 4.0”, of the EFNDT working group 10 on “NDE 4.0”, and to the members of the ICNDT SIG “NDE 4.0”. Last but not least I have to thank Franziska Vrana for her support.

References

1. Vrana, J., Singh, R.: NDE 4.0.—a design thinking perspective. *J. Nondestruct. Eval.* **40**, 8 (2021). <https://doi.org/10.1007/s10921-020-00735-9>
2. Vrana, J., Meyendorf, N., Ida, N., Singh, R.: Introduction to NDE 4.0. In: Meyendorf, N., Ida, N., Singh, R., Vrana, J. (eds.) *Handbook of Nondestructive Evaluation 4.0*. Springer, New York (2021). https://doi.org/10.1007/978-3-030-48200-8_43-1
3. Vrana, J.: The core of the fourth revolutions: industrial internet of things, digital twin, and cyber-physical loops. *J. Nondestruct. Eval.* (2021). <https://doi.org/10.1007/s10921-021-00777-7>
4. Vrana, J.: NDE perception and emerging reality: NDE 4.0 value extraction. *Mater. Eval.* **78**(7), 835–851 (2020). <https://doi.org/10.32548/2020.me-04131>
5. Vrana, J.: ZfP 4.0: Die vierte Revolution der Zerstörungsfreien Prüfung: Schnittstellen, Vernetzung, Feedback, neue Märkte und Einbindung in die Digitale Fabrik. *ZfP Zeitung* **165**, 51–59 (2019)
6. Vrana, J.: Welcome to the World of NDE 4.0. YouTube. <https://youtu.be/MzUKHmp4exE>. accessed 24 Mar 2020 (2020)
7. Vrana, J.: The Four Industrial Revolutions. YouTube. <https://youtu.be/59SsqSWw4b0>. accessed 30 Mar 2020 (2020)
8. Vrana, J.: The Four NDE Revolutions. YouTube. <https://youtu.be/lvLfy4zfSYo>. accessed 14 Apr 2020 (2020)
9. Singh, R.: NDE 4.0 the next revolution in nondestructive testing and evaluation: What and how? *Mater. Eval.* **77**(1), 45–50 (2019)
10. Vrana, J., Singh, R.: Digitization, digitalization and digital transformation. In: Meyendorf, N., Ida, N., Singh, R., Vrana, J. (eds.) *Handbook of Nondestructive Evaluation 4.0*. Springer, New York (2021)
11. Vrana, J.: Digitization, digitalization, digital transformation, and informatization. YouTube. <https://youtu.be/8Som-Y37V4w>. accessed 21 July 2020 (2020)
12. Singh, R.: Purpose and pursuit of NDE 4.0. *Mater. Eval.* **78**(7), 785–793 (2020). <https://doi.org/10.32548/2020.me-04143>
13. Singh, R., Vrana, J.: NDE 4.0—why should “I” get on this bus now? *CINDE J.* **41**, 6–13 (2020)
14. DIN SPEC 91345:2016-04: Reference Architecture Model Industrie 4.0 (RAMI4.0) (2016)
15. Vrana, J., Singh, R.: NDE 4.0: NDT and sensors becoming natural allies by digital transformation and IoT, *Proceedings Volume 11594, NDE 4.0 and Smart Structures for Industry, Smart Cities, Communication, and Energy*; 1159404. <https://doi.org/10.1117/12.2581400> (2021)
16. Vrana, J., Kadau, K.: Smart data analysis of the results of ultrasonic inspections for probabilistic fracture mechanics. *VGB PowerTech* **7**, 38–42 (2018)
17. Singh, R., Palumbo, D., Hewson, J., Locke, D., Paulk, M.D., Lewis, R.R.: A design of experiments for human factor quantification in NDI reliability studies, USAF ASIP Conf., San Antonio, TX, USA (2001)
18. Virkkunen, I., Koskinen, T., Jessen-Juhler, O., et al.: Augmented ultrasonic data for machine learning. *J. Nondestruct. Eval.* **40**, 4 (2021). <https://doi.org/10.1007/s10921-020-00739-5>
19. Maayan, G.D.: The IoT Rundown For 2020: Stats, Risks, and Solutions. *Security Today*. accessed: 8 May 2021; (2020). <https://securitytoday.com/Articles/2020/01/13/The-IoT-Rundown-for-2020.aspx>
20. Kadau, K., Enright, M., Amann, C.: Probabilistic lifing. In: Meyendorf, N., Ida, N., Singh, R., Vrana, J. (eds.) *Handbook of Nondestructive Evaluation 4.0*. Springer, New York (2021)
21. International Data Spaces Association: Reference Architecture Model, IDSA, Version 3.0 (2019)

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.