Principles for Successful Deployment of NDE 4.0

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Abstract

Digital Transformation is at the heart of the current industrial revolution, and it won't spare the non-destructive evaluation (NDE) sector. It is changing the value proposition of inspection processes from 'an undesirable quality check' to a 'much-needed source of data, information, and knowledge' from manufacturing to service life maintenance. Non-destructive assessment has changed significantly from the early days of 'enhancing human senses' to 'equipment that can assess the condition' and remotely support sustainment decisions. The current trends in cyber-physical technologies offer new possibilities wherein the inspectors will be able to see the anomaly on a digital twin before it can be detected on conventional NDE equipment, by fusing data from multiple sources and leveraging the history captured in digital threads. To convert such a possibility into reality, organizations need to embark on a journey where the endpoint is not very clear. This puts a set of guiding principles, a compass, at the heart of execution to make correct choices, help prioritize processes, and minimize the possibility of conflict.

This paper provides a structured model of twelve principles in three synergistic perspectives with a responsible foundation. They are designed to serve as a guide to meaningful development, deployment, and leveraging of the next generation of inspection systems, as well as creating, capturing, and distributing value from the data they generate.

Keywords: *Industry 4.0, Digitalization, Inspection reliability, Digital Transformation, Roadmap, Value Creation, Innovation*.

1.0 Recap of NDE 4.0

1.1 Historical Evolution

Historians split recent times into three industrial revolutions: mechanization (steam power), technical (electric power and mass production), and digital (computing and microelectronics). The world of NDE has seen a parallel: first - tools to sharpen human senses, second - wave applications to view inside the components, and third - digital processing and automation.

As the industry goes through the fourth revolution powered by interconnections and enhanced digitalization, NDE is also on a new horizon with the addition of information transparency, technical assistance, machine intelligence, decentralized decisions, and much more. The line between non-destructive evaluation (NDE) and the fourth industrial revolution is getting blurred since both are sensory data-driven domains. This multidisciplinary approach has led to the emergence of a new capability for non-destructive evaluation, now termed NDE 4.0. The NDT community is coming together once again to define the purpose, chart the process, re-align the organizations, and address the adoption of emerging technologies.

NDE 4.0 is defined as a *Cyber-physical Non-Destructive Evaluation; arising out of a confluence of Industry 4.0 technologies and traditional NDE physical methods, to enhance inspection performance, decision making for safety and quality assurance, as well as provide relevant data to improve the design, production, and maintenance* [1,2].

This fourth revolution integrates the digital tools (from third) and physical methods of interrogating materials (from second) in a closed-loop manner reducing human intervention and enhancing inspection performance. Within the context of the physical-digital-physical loop of NDE 4.0 [3,4,5]; digital technologies and physical methods may continue to evolve independently, interdependently, or concurrently. The real value is in the concurrent design of an inspection system through the application of Digital Twins, Digital Threads [3,4], and an expanded perspective of the human role in NDE evaluation processes. This provides the ability to capture and leverage data right from the materials themselves and from the manufacturing processes up to the stages of usage and in-service maintenance, creating value across the ecosystem [3].

1.2 Need for guidance today

In [1] the digital technologies relevant to NDE were covered in a design thinking approach. In [3] the value proposition of NDE 4.0 for various stakeholders in the eco-system was discussed and in [4] the core technologies to enable NDE 4.0, like Industrial Internet of Things, Digital Twin, and Cyber-Physical Loops. Those publications covered the WHY and WHAT for NDE 4.0. An extensive description in the context of NDE has been published in the book "The World of NDE 4.0" [6]. The state-of-the-art in NDE 4.0 has recently been captured in the Handbook of NDE 4.0 [7]. All these publications create a suitable vision of the future of NDE and a good indication of personalized sets of seemingly complex technologies suited for specific industries or geographies. What is missing from the published literature on the topic is HOW to plan it out that makes business sense.

There is an extensive suite of digital technologies [1], and their impact is reasonably well understood as standalone pieces. However, their combination adds to the complexity of the technical systems and uncertainty in the business environment. Nonetheless, the synergies and value embedded in their combination are worth the extra effort of a deeper understanding of the principles, perspectives, and mindsets required to manage uncertainty and complexity.

The enormous leap in technology application and value realization tied to the fourth industrial revolution or digital transformation [8] can also be termed as massive transformation purpose (MTP). This is easier said than done. It requires leadership commitment, serious planning, and investment over a sustained period. It requires a roadmap that defines the HOW, starting with actions now and here. An explicit need for such guidance has also been highlighted by the recently formed Special Interest Group on NDE 4.0 (SIG NDE 4.0) within International Committee for NDT (ICNDT). This paper provides a set of guiding principles adopted from Industry 4.0 and interpreted in the context of inspection systems.

2.0 The Three Facets of NDE 4.0

Different NDE practitioners and managers see NDE 4.0 differently. To reduce the confusion, we must classify various facets of NDE 4.0 from the digital adoption perspective. This clarity emerges when we accept an intermediate step (digitalization) between digitization (Industry 3.0) and digital transformation (Industry 4.0).

2.1 Digitalization of NDE

Initiatives directed at the application of Industry 4.0 principles, technologies, and frameworks to improve and expand the realm of NDE solutions available in the world. Examples: Autonomous drone/robotic NDE for bridges, towers, pipelines; and Digital RT/UT/ET along with Augmented Intelligence for integrity assessment of in-service high-risk assets, such as Turbine parts.

2.2 NDE of Digitalized Systems

Initiatives directed at the application of existing NDE principles, technologies, and frameworks to create and mature solutions for Industry 4.0 needs, pains, and gains. Examples: Manual UT/ET at the end of an automated manufacturing line, or Digital RT/UT for an additively manufactured part after printing, or PT/UT/ET of an autonomous drone or a surgical robot.

2.3 Digital Transformation of Industry/NDE

Initiatives directed at integrated development of digitalized NDE capabilities within digitally transformed systems to fully deliver the promise of Industry 4.0. This is not to be viewed as a mere combination of the above two, rather it should be seen as a seamless integration of both, a digitally transformed industry that integrates digitally transformed NDE solutions. Those NDE solutions are a combination of hardware, embedded software, platforms, and enriched human participation through new digital competencies. Example: NDE technologies integrated within smart manufacturing

for inline quality assurance with no human intervention; or In-situ real-time NDE within additive manufacturing process to control the process for part quality assurance; or NDE and SHM digitally fused to assure service performance and safety.

3.0 A Dozen Principles for NDE 4.0

Figure 1 shows the twelve principles that can serve all three facets of NDE 4.0. They are categorized into four buckets corresponding to three perspectives (a) infrastructural, (b) value enhancers, (c) outcome, and a responsible mindset that makes up the foundation across the other three.

3.1 Interoperability

The ability of systems (assets, instruments, sensors, devices, inspection equipment) to connect and communicate with each other via the Internet of Industrial Things (IIoT).

There are three main types of interoperability. (a) Syntactic interoperability: where two or more systems can communicate and share data, thus allowing different types of software to work together. This happens even if the interface or language is not the same. (b) Structural interoperability: this defines the data exchange format, which specifies the standards used to format messages sent from one system to another. This is essential for users to be able to understand the information's purpose clearly. (c) Semantic interoperability: two or more systems connect and share data that each system understands in a meaningful way.

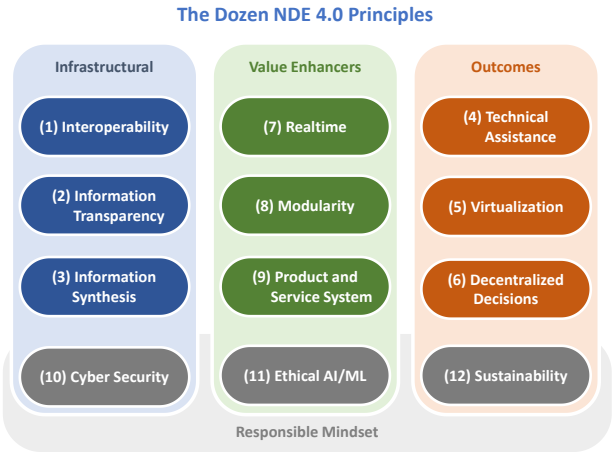

Figure 1 Key NDE 4.0 principles derived from the Industry 4.0 philosophies, industry expectations, and technology trends to provide guidance in selecting, developing, and integrating technologies, products, data, services, and competencies, for a myriad of purposes.

3.2 Information Transparency

The ability of systems to share information (with semantic interoperability), facilitating interpretation, training, and visualization.

The transparency afforded by NDE 4.0 technologies provide operators, inspectors, and NDE engineers with vast amounts of useful information needed to make appropriate decisions, in time. It begins with interconnectivity, which permits the collection of large amounts of data and information from all points in the manufacturing process and service life usage, thus aiding quality, safety, and design improvements. Transparency also helps identify key areas that can benefit from innovation and improvement.

3.3 Information Synthesis

The ability of systems to synthesize information obtained from the materials, environment, and usage history, of several comparable assets and provide intelligent forecasting.

Information synthesis is all about gathering and analyzing information to gain valuable, actionable insights. Conducting this kind of activity and sharing knowledge across time and location leads to advancements guided by purpose. It goes beyond summarizing or reporting; it goes to connecting and interpreting information obtained from diverse sources referenced within a relevant context.

3.4 Technical Assistance

The ability of systems to assist with inspection automation, workflow management, decision-making, and traceability.

NDE 4.0 shifts the role of humans from an inspector of assets to a problem solver and decision maker for the sustainment of assets. Assistance systems are designed to support inspectors and engineers that need to make informed decisions to address urgent needs for operation or maintenance, regardless of whether it's corrective, preventive, or predictive, on short notice. This could be on an asset or from a remote location.

3.5 Virtualization

The ability of systems to create virtual models of themselves and of other assets in their environment that can facilitate the creation of digital-twins, threads, and weaves.

Virtualization allows a "copy" of the physical system to be created digitally by merging sensor data acquired from monitoring assets and inspection equipment with virtual simulation models. The virtual view through a 3D interface helps to monitor physical materials, structure, and processes, allowing operators and managers to better manage growing complexity, and achieve their purpose.

3.6 Decentralized Decisions

The ability of systems to make decisions on their own and perform inspection tasks independently; and to seek human intervention in case of exceptions, interferences, or conflicting objectives.

Interconnection and information transparency permits inspectors and engineers to make decisions both inside and outside of production or maintenance facilities. This ability to combine local and global information at the same time helps to drive better decision-making and increase overall productivity.

3.7 Realtime

The ability of systems to generate and retrieve datasets in real-time to support or substantiate decentralized decision-making processes.

For high-value continuously operating assets such as power plants and transport systems, the concept of real-time condition monitoring is not new. It however becomes essential to fully leverage decentralized decision-making processes and is enabled by transparency and interoperability.

3.8 Modularity

The ability of systems to flexibly adapt to different requirements by virtue of design characteristics.

Essentially, modularity offers advantages in the move to digitized inspections by promoting greater flexibility, interconnectivity, interoperability, data-sharing, and information transparency, allowing much higher levels of technical support and decentralized decision-making.

3.9 Product Service System (PSS)

The ability to synergistically merge a specific set of products and services to create, capture, and distribute enhanced value for purpose.

Digitalization helps to realize product-service integration as business models providing higher profits through a supplementary set of added values. It comes in various forms. (a) Function-based PSS: where you add new functions to increase product value in the competing market, through real-time remote monitoring and technical assistance services. (b) Evidence-based PSS: where you periodically use big data analytics to achieve the purpose.

3.10 Cyber-security

The ability of systems to protect themselves from disruption or misdirection, and protect the data from theft, damage, or unauthorized disclosure.

While the implementation of NDE 4.0 appears to solve many issues, new cybersecurity concerns may be introduced. The use of sensors and remote access may provide entry points for hackers, cybercriminals, or industry competitors to gain access to inspection systems and even assets. Before implementing new technologies, a cyber risk assessment must be performed to provide a full understanding of the system's cybersecurity needs and capabilities. NDE system developers and users should understand the benefits and the potential cybersecurity risks implementing NDE 4.0 may introduce. Cybersecurity standards generated by organisms such as ISO or NIST are valuable resources to enrich and strengthen the security of NDE 4.0 solutions.

3.11 Ethics

The ability of the systems to reduce bias, warn users when operating outside design parameters, and shut down before causing any harm.

NDE 4.0 technologies with automation, robotics, data traceability, and workflows can help reduce many of the existing concerns in NDE and human factors that create difficult situations. However, Artificial Intelligence and Machine Learning require some additional precepts to the existing Code of Ethics. We must address the concerns around responsibility and accountability of decisions made by machines learning from multiple sources. Can smart machines outthink us and, if they can, whether we should worry about

this? Are our traditional business practices of privacy and confidentiality compatible with other principles of information transparency and synthesis? A sound ethical foundation is paramount for any NDE 4.0 solution created, regardless of the decision processes being guided exclusively by human intervention or supported by digital technologies.

3.12 Sustainability

The ability of systems to self-optimize energy consumption and data generation for sustainability.

Just like ethics, sustainability and sustainable development need conscious effort. Digital transformation affects materials and their energy life cycle depending upon how the engineering community approaches design optimization. Data generation and storage are having a profound impact on carbon footprint. Digital technologies shall also be used to minimize and compensate for the impact of the digital transformation of NDE processes and systems.

4.0 Application of these principles

The list of dozen items above is not to be treated as a compliance checklist. But a reference for awareness, education, and guidance applications.

4.1 Organizational Alignment

One of the challenges leaders face is keeping the organization aligned and focused on meaningful actions. A set of guiding Principles helps them with this desire. As we are getting more and more dispersed globally, delegating authority and responsibility across cultures, it is important for managers to have clarity on what is acceptable and preferred. These dozen principles make a useful leadership tool.

4.2 Building a Strategic Roadmap

NDE 4.0 is a transformation journey. You need a roadmap in pursuit of a purpose, with sustained leadership commitment, and a dashboard to track execution. All this requires changes in governance and mindset. A set of principles help align various facets of organizational change and reduce conflict through the transformation. This has been extensively covered in a recently presented paper [9] and also published as a book [11].

These principles can help with assessment processes before and alignment after a merger/acquisition. Hence, these dozen principles also make a useful management tool.

4.3 Developing New NDE Products and Services

These principles help define requirements for the new product and service systems. There will be times when it will be difficult to meet all of them concurrently. In such situations, principles help make the right choices, prioritize the proper selection of alternatives, and reduce internal conflict. These principles are becoming increasingly important to fully support the innovation management process [12,13].

4.4 Regular NDE Activity

Digital Transformation is sweeping every sector. We all talk about it from our own experiences and perspectives, and look at it with different emotions, from anxiety to enthusiasm. The non-destructive evaluation as a cross-sector industry is neither immune nor trendsetting in this rapidly evolving change. One common area of concern for managers is where to start and how to progress, with limited resources and unlimited uncertainty in this vast and increasingly complex ecosystem.

These principles enhance the value extracted from NDE 4.0 activities, be it in-production inspection on the shop floor or In-service inspection of a high-value asset.

4.5 Talent Development

In the dawn of NDE 4.0, training and workforce reorientation play a central role in shaping the professional path of new talent, providing stability and development opportunities for active practitioners and contributing to preserve and transmit the accumulated knowledge of experienced generations of NDE practitioners.

Industry 4.0 is compelling to revise the roles of NDE practitioners, trainers, and mentors who are immersed not only in the accelerated technological advancements but also in profound social, environmental, and cultural transformations [14,15]. NDE itself is transitioning from a niche role as a quality control support instrument to an invaluable knowledge-generating process for creating value through substantial improvements in business sustainability, quality, and safety [3].

This profound transformation is shaping how

Education 4.0 for Industry 4.0 will deliver disruptive modifications in education models, training processes, certification schemes, and support tools. These principles shape those instances and transform how we recruit and develop NDE practitioners in alignment with an NDE 4.0 roadmap.

4.6 Adopt and Adapt

When you look deeply, you will see the intent behind the organized structure to support the applications. These are focused on the responsible use of technology for a profound transformative purpose. With that in mind, you are welcome to tailor this set to your business situation, your supply chain, your customer expectations, and your desire to push innovation. You can even add some of your own to the mix. Dropping any one of them permanently is not advisable.

5.0 Summary and Outlook

NDE 4.0 is a case of a massive transformation in a specific realm of human activity. It shall require that digital technologies be integrated into the inspection systems, the digitalization of workflows, and the integration of NDE workflows within value streams. This paper is all about a fundamental framework of principles that help align an organization through the transformation, while creating new products and services.

NDE 4 0 must be viewed as a journey and not a project or a single deliverable goal. It could take a few years, depending upon the organizational internal and external context, resources, and commitment to sustainable growth through change. Where does the journey end will not be clear in the beginning, but you will know when you get there.

To some, the world of NDE 4.0 appears overwhelming, but a roadmap that breaks down the holistic view into achievable goals provides a means to successfully take on this journey. When the end is not clear, the set of guiding principles become a very important, acting as a compass or a navigation instrument to arrive at a good destination.

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