Guideline for the Development of an NDE 4.0 Roadmap

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Abstract

'*What you don't know can't hurt you*' does NOT apply to Digital Transformation, as it is changing the value proposition from 'competitive advantage' to a 'must do initiative'. NDE has seen revolutions somewhat parallel to industry. The current trends in cyber-physical technologies offer new possibilities wherein the inspectors can see the anomaly on a digital twin before they can see it on the conventional equipment, by fusing data from multiple sources and leveraging history captured in digital threads. To convert such a possibility into reality, organizations need a roadmap, particularly when the ecosystem is still evolving. Roadmaps are instrumental for guiding and thrusting sociocultural, economic, technological, and even political changes around the world.
This paper provides a guideline to the various stakeholders of the NDE ecosystem to develop a roadmap for NDE 4.0. Meaning this paper provides the necessary support regarding HOW to realize the value propositions of NDE 4.0, which have been developed in earlier publications [1,2,3,4,5].
Keywords: *Industry 4.0, Digitalization, Inspection reliability, Digital Transformation, Roadmap, Value Creation, Innovation*.

1 INTRODUCTION: The Genesis of NDE 4.0

1.1 Historical Evolution

Historians identify three industrial revolutions since the second half of the XVIII century: 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 as NDE 4.0. The NDT community is coming together once again to define the purpose, chart the route, 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]. The 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 and Digital Threads [3,4]. This provides the ability to capture and leverage data right from materials and

manufacturing processes to usage and in-service maintenance, creating value across the ecosystem [3].

Readers new to this subject are highly encouraged to use [1,3,4] as companion documents that provide the technical context in more than sufficient detail.

1.1 The ineluctable necessity of guidance

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 nice vision of the future of NDE and a good indication of seemingly complex technologies. 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 not only adds complexity, potentializing value generation but requires a deeper understanding. An increased bi-directional permeability of NDE and digital competencies in the workplace generating competency gaps that are real and have a profound impact, particularly at the union of digital and NDE skills. The two communities speak different languages, exhibit diverse demographics, learn differently, and more importantly have different viewpoints on technology adoption. A serious question today is - should you train an NDE expert on digital skills or an IT expert on NDE skills, while we wait for NDE schools to develop individuals on multidisciplinary competencies. The changing role of inspectors adds another level of complexity and resistance to the adoption of what can be hugely beneficial for everyone. An unsatisfied demand of highly specialized NDE technicians in specific niches runs parallel with the irruption and democratization of NDE technologies contained in digital direct-to-consumer products, such as IR sensors attached to mobile phones.

NDE, as a professional discipline, serves almost every industrial sector with infrastructure, and some of them are heavily regulated. Regulations inhibit transformation, provide friction to change, and need to be addressed if we were to leverage the digitalization of inspection processes. Quite often, the role of NDE is perceived to be a necessary evil and hindrance to operations. Thus, it gets relatively less attention during business investment decisions. The change agents, who can see the value in digitalization of NDE need help to overcome inertia and internal friction. They need tools to manage limited resources to unleash unlimited potential because NDE is transitioning from a niche role as a quality control support instrument to an invaluable knowledge-generating process able of creating significant value through substantial improvements in business sustainability, quality, and safety, that is why NDE 4.0 roadmaps are required to provide purpose and guidance for transforming the role of NDE in several regions of the world and industries.

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). It is easier said than done. It requires leadership commitment, serious planning, and investment over a sustained period of time. It requires a roadmap that defines the HOW, starting with actions now and here. An explicit need for such a guidance has also been highlight 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 guideline to develop an executable roadmap for NDE 4.0.

2 KICKOFF

2.1 Leadership Commitment

All transformation efforts begin with the identification of a leadership team and it sustains as long as the leadership stays committed. To kick off an NDE 4.0 initiative, the organization must first identify a leadership team, that includes top executives and external experts, with oversight from Advisory Boards. There should be one champion to guide the roadmap development and execution. This champion needs to be passionate about safety and quality through inspections and supported by other leadership level team members including the finance, IT, and business development. The leadership team should quickly establish the following high-level items for the roadmap

initiative.

2.2 Purpose

The leadership team should define and communicate the Massive Transformative Purpose (MTP) along with priorities for NDE 4.0. This MTP should provide a clear and aspirational point of reference to the intended roadmap initiative. This could be in form of enhanced safety, quality, reliability, performance, talent, technology, economic value, or sustainability through digital-physical integration. The NDE 4.0 purpose must align with the organization's primary business strategy. Several use cases were captured in [1,4]. Sustainable development and sustainability should be a consideration or constraint at the least.

This Purpose definition, in the form of an MTP, should consider the following attributes:

a) Grounded in sound engineering, science, and management principles
b) Being massive and aspirational in its scope
c) Must demonstrate a clear "why"
d) Clearly focused on large-scale transformations
e) Unique to the organization(s) or communities involved
f) Wildly aspirational to ignite the passion and unify the action.
g) Aimed at achieving profound transformations
h) Forward-looking

2.3 Eco-system Context

The context of NDE is anchored around the asset being evaluated, be it a single part under inspection in a manufacturing line or an infrastructure undergoing in-service maintenance. Any and every entity that comes in direct or indirect contact with an asset to assure its safety and quality can be thought of as belonging to the NDE eco-system. A typical representation is depicted in figure 1. Primary or core stakeholders (inner blue circle) have a substantial influence over the roadmap initiative. Support stakeholders (outer green circle) may or may not influence the roadmap initiative. Leadership needs to define the context for their organization. This figure has evolved compared to [3], in a spirit of continuous learning and improvement.

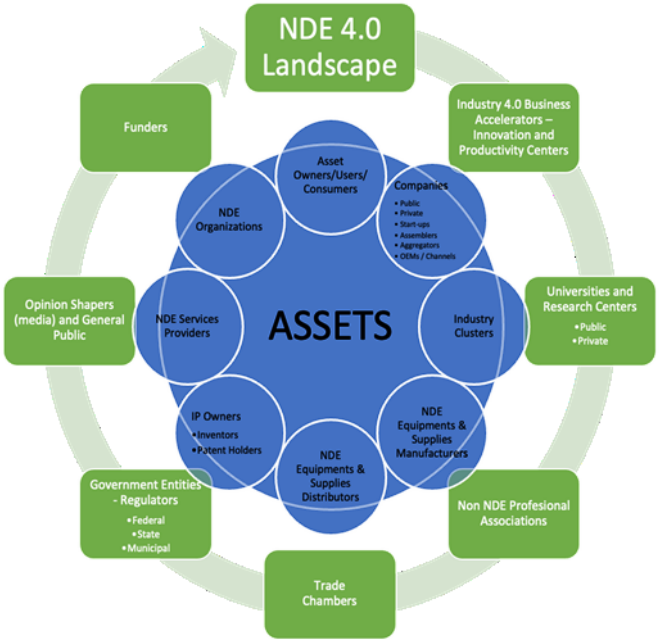


Figure 1: *NDE Eco-system with 'asset to be inspected' at the center.*

2.4 Vision

Once the leadership team has captured the context, it must establish a vision of a digitalized inspection system or a digitally transformed quality/safety assurance solution with a time horizon to accomplish the purpose. A good vision has many of the following characteristics:

a) **Graphic and imaginable**: Paints an accessible picture of the future, the organization strives for.
b) **Compelling and inspiring**: Moves people to act, igniting desire and personal connection.
c) **Focused**: Provide guidance in making decisions and allocating resources.
d) **Feasible and realistic**: Within the realm of resources and timeline, without undue stress.
e) **Desirable**: Indicates why the chosen path makes sense for the long-term interests of stakeholders.
f) **Addresses** triple bottom line growth – profit, people, and planet.
g) **Simple**: Brief, clear, easy to communicate and understand.

These characteristics also flow down to the roadmap.

2.5 Policy

The leadership team should develop and implement

a digital transformation policy if it does not already exist. The policy should

a) Demonstrate commitment to digital transformation strategy, objectives, and activities.
b) Define the purpose and context for digitalization in support of its strategic direction.
c) Provide guidance with conflict resolution, resource prioritization, and escalation.
d) Support human development, re-skilling, and new competencies integration.
e) Balance the human-machine co-working, keeping each one in areas they are best at.
f) Consider eight innovation management principles, described in ISO 56002.
g) Show commitment to ethics, sustainable development, and continual improvement.

The digital transformation policy should fit the organization's culture. The policy should be circulated as documented information to all key stakeholders, including employees, contractors, and relevant external interested parties, as appropriate. The ethics portion of the digital transformation policy may be integrated with an existing ethics policy or code of ethics, and prominently displayed in common areas.

2.6 Roadmap Team

With clarity of purpose, context, vision, and policy, the leadership team should identify individuals who should develop and maintain the roadmap. The Roadmap Initiative Team (RIT) should be knowledgeable about digital technologies, inspection methods, data sciences, business models, and human considerations. The leadership team should define the charter for the roadmap team. For a small business, the leadership team can be the roadmap team, or leverage consultants and partners.

3 FRAMEWORK

With leadership commitment as evident from the purpose, vision, preliminary external context, and charter, the RIT is ready to get to work and create the roadmap. Just to be on the same page; a roadmap is a "Document that visually describes the activities, timeline, and resources necessary to achieve a strategic objective, such as digital transformation in case of NDE 4.0" and a Roadmap Initiative is "an internal effort by a dedicated team to create the roadmap and keep it current."

3.1 Context

The RIT must define the context along three dimensions with reasonable details and confidence.

The internal context of an NDE 4.0 deployment refers to all elements that lie within the organization, and can be controlled by the leadership, as primary elements of the roadmap, to pursue strategic objectives. It includes products/service offerings, business models, technology portfolio, intellectual property, infrastructure, physical assets, data assets, employee skills, competency gaps, human factors, diversity-equity-inclusion, code of ethics, financial capacity, risk tolerance, partnerships, geographical location, and to some extent preferred suppliers and consultants.

The external context of an NDE 4.0 deployment refers to all elements that lie outside the organization and cannot be controlled by the leadership. The roadmap should provide guidance to continuously monitor the external context and to modify the internal context in response to any changes in the external context. Industry 4.0 or Digital Transformation is the key external driver for the emergence of NDE 4.0. External context includes all the stakeholders in the ecosystem that were not a part of the internal context. The most significant are the market forces within the sector – customers, competitors, and regulatory bodies. It also includes changes in political, environmental, social, technological, economic, legal, Innovation, and pandemic aspects (PESTEL+I+P), that are even broader than discipline of inspection or the industrial sector. With globalization, one needs to consider global trends, even if the internal context is geographically local.

The prospective context of an NDE 4.0 deployment refers to internal and external elements that will emerge over the future whether controlled or uncontrolled. The roadmap should provide guidance to continuously monitor the evolution of desirable, anticipated, and unanticipated items and to modify the internal context towards the desirable prospective context. The core of the roadmap is that portion of the prospective context which includes planned development of products/services, technologies, talent, physical and intellectual assets, and resiliency. Prospective context should also consider items broader and far-reaching than business. Such as professional obligations, ethical awareness, industry regulations, social

responsibility, sustainability, and sustainable development. A simple well-articulated prospective context can be indistinguishable from vision.

3.2 Principles

It is now time for RIT to agree on principles keeping the purpose and context in mind. Here is the starter list derived from Industry 4.0 principles [9]. These principles should guide the team in the selection and development of products, technologies, and competencies.

a) **Interoperability:** The ability of assets, instruments, sensors, devices, inspection equipment, and people to connect and communicate with each other via (IOT)
b) **Information transparency:** The ability of assets and inspection systems to share information (data with semantic interoperability), facilitating interpretation, training, and visualization.
c) **Technical assistance:** The ability of assets to assist in workflow management, inspection automation, and traceability
d) **Decentralized decisions:** The ability of automated cyber-physical inspection systems and assets to make decisions on their own and perform inspection tasks independently; or to seek human intervention in the case of exceptions, interferences, or conflicting goals.
e) **Virtualization:** The ability of assets to generate virtual models of themselves and of other assets in their environment that facilitate the generation of digital-twins.
f) **Real-Time:** The ability of assets to generate datasets that may be retrieved in real-time to support and substantiate decentralized decision-making processes.
g) **Modularity:** The ability and design characteristics of assets to flexibly adapt to different requirements.
h) **Product-Service Offering:** The ability of NDE 4.0 solutions to synergistically merge products and services to create, capture, and distribute substantially enhanced value in order to achieve the purpose of NDE 4.0

3.3 Governance

The leadership team is responsible for the overall governance of digital transformation, which is a little different than traditional governance approaches. A well-governed NDE 4.0 program must satisfy different stakeholders across an organization and be flexible enough to accommodate multiple types of initiatives while ensuring enough rigidity to achieve strategic alignment with purpose and efficiency in execution.

The following principles should be considered while identifying initiatives that go into the roadmap [10]

a) Centralize information about digital initiatives rather than the initiatives themselves.
b) Move from centralized to decentralized governance of digital initiatives as digital maturity grows.
c) Decentralize ideation but centralize idea evaluation and prioritization.
d) Make sure that KPIs and Metrics measure the real impact you want to achieve with each initiative.
e) Avoid siloed solutions by ensuring data compatibility, technical consistency, and continuous integration of new initiatives with existing systems.
f) Implement a “fit-for-purpose” mapping system that recognizes value potential and degree of feasibility for each initiative.
g) Evaluate different scenarios to proactively steward digital initiatives toward full-scale impact.

These principles are in addition to whatever governance system is in place for everyday operations addressing the use of internal standards, alignment with international standards, risk mitigation, transparency, relationship with stakeholders, internal and external communication, chain of command structure, and policy deployment.

3.4 Ethics

Any transformation roadmap must include instances and guidance devoted to providing sound ethics foundations to all the categories included in it. The leadership team is encouraged to engage an external expert on ethics in digital transformation, as the subject is still evolving. This ethical dimension must be an integral part of the governance and aligned with the attributes specific to humans, and human-machine integration.

There are five fundamental considerations on the human side of ethics:

a) **Responsible**: The accountability of all instances involved in the digital transformation should be clearly established in the organizational operations.
b) **Equitable**: All organizational and individual participants should have equal access to the instances and support resources that constitute the ethics foundation of the roadmap initiative.
c) **Traceable**: Accountability for decisions and actions should be clearly established. Records should be generated to properly support any traceability requirements.
d) **Reliable**: The reliability of ethical implementation should be sustained by codes and guidelines, personnel training and auditing, and an ombudsman program.
e) **Sanctions**: Ethics code and guidelines once established should have clearly defined instances, processes, and resources to positively inhibit and sanction ethical behavior violations.

These five considerations are altered in the context of the Human-Machine side of Ethics, where the machines learn and act autonomously, such that the machine output is not entirely in human control.

a) **Responsibility**: NDE personnel will exercise appropriate levels of judgment and care while remaining responsible for the development, deployment, and use of AI/ML in NDE capabilities.
b) **Equity**: The digital inspection system developers will take deliberate steps to minimize unintended bias in AI/ML-based NDE capabilities.
c) **Traceability**: The AI/ML capabilities will be developed and deployed such that relevant NDE personnel possess an appropriate understanding of the inspection technology, development processes, and operational methods applicable to AI capabilities, including transparent and auditable NDE methodologies, data sources, inspection procedure, and documentation.
d) **Reliability**: The AI capabilities will have explicit, well-defined uses, and the safety, security, and effectiveness of such capabilities will be subject to calibration, validation, and POD assessment within those defined uses across their entire life cycles.
e) **Governance**: The digital inspection system developers will design and engineer AI capabilities to fulfill their intended functions while possessing the ability to identify and avoid unintended consequences, and the ability to disengage or deactivate deployed systems that demonstrate unintended behavior.
f) **Data Management**: The NDE personnel will honor the data acquisition, transfer, storage, analysis, processing, security, and ownership/sharing rights as determined by organizational policy and contractual obligations.The leadership team also needs to communicate ethical considerations to all employees, periodically.

4 ROADMAP

4.1 Scope and Objectives

The scope of the NDE 4.0 roadmap could be the development of one or more of the following applications depending upon leadership purpose and vision.

Digitalization of NDE (Or Industry 4.0 for NDE): Initiatives directed at the application of Industry 4.0 principles, technologies, and frameworks to improve and expand the realm of NDE solutions in the world. For example: 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.

NDE for Digitally Transformed Systems (Or NDE for Industry 4.0): Initiatives directed towards establishing NDE as one of the major data sources for Industry 4.0 needs, pains, and gains [3]. For example: Digital RT/UT/… for an additively manufactured to gain feedback regarding the manufacturing process or Manual UT/ET with digitalized reporting at the end to fuse the data with the data of an automated manufacturing line.

Fully Integrated NDE 4.0 and Industry 4.0: Initiatives directed at integrated development of digitalized NDE capability within digitally transformed systems to fully deliver the promise of Industry 4.0. For example: NDE technologies integrated within smart manufacturing for inline quality assurance with no human intervention; 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.

4.2 Planning Horizons

Based on the purpose, vision, scope, and objectives; and the rate of change in the external context, the roadmap team can define three planning horizons,

Horizon-1 (Operational or H1): This includes projects and initiatives to bring tangible value in a "now and here" timeframe. These tactical-term projects and initiatives may be 3 to 24 months in duration. It is important that H1 initiatives are fully funded through completion.

Horizon-2 (Strategic or H2): This includes projects and initiatives to bring tangible value in a "Near future, embracing emerging trends" timeframe. These strategic-term projects and initiatives may be 1 to 5 years in duration. Strategic-term projects and initiatives are intended to generate and capture significant stakeholder value when implemented. H2 initiatives may have proof of concept or demonstrator technologies identified and funded under H1.

Horizon-3 (Visionary or H3): This includes projects and initiatives to bring tangible value in a "Pursuit/tracking technology evolution in line with purpose" timeframe. These long-term projects and initiatives may exceed a period of 3 years. These should address ambiguity and uncertainty, particularly in an external technological context. H3 Initiatives may have demonstrators identified under H2 and exploratory studies funded under H1.

Leadership must assure alignment and continuity of H1, H2, and H3 outcomes through funding mechanisms.

Caution: The three-horizon model when applied to transformation or any significant change, needs special care because it is hard to see clearly that far. The H2 and H3 planning carries a significantly higher level of uncertainty and will likely require major modifications and pivots, both technological as well as business models, as it evolves.

4.3 Dashboard

The leadership team should identify a set of KPIs and metrics, in an integrated dashboard or scorecard, aligned with the MTP. The performance should be monitored by the leadership. These KPIs should cover the four prominent categories in line with a balanced scorecard viewpoint.

Value Creation perspective: These are tied to the internal processes supporting the primary purpose of implementing NDE 4.0. It could be in terms of performance, safety, capability, reliability, speed, workflow efficiency & effectiveness, accelerated learning and certification experience, Asset design improvement, asset quality, waste reduction, etc.

Customer perspective: These are tied to the value delivered to the customer – enhanced safety, turn time, cost of operations, etc.

Employee perspective: These are tied to renewed respect for NDE, employee learning and development, as well as improved inspector safety and support.

Financial perspective: This is the traditional quantification of impact on top line and bottom line. This most popular set of metrics should not be looked at in isolation, but through the natural and profound interconnection with the other three perspectives.

In addition, one may choose to add tracking of strategic progress and risk management as add-ons. Ineludibly, all MTPs and metrics defined for roadmap initiatives should take into consideration any human perspective of NDE 4.0, including ethics. H1 initiatives should have tangible and definable metrics. H2 initiatives should have a measurable metric without a target assigned. H3 initiatives should not have any measurable goals, other than total investment limits. The KPIs represent quantitative or qualitative parameters that show how effective are the operations in achieving the objectives. Metrics represent quantitative or qualitative parameters that serve to monitor the status of any specific process.

4.4 Draft Roadmap

Roadmap essentially constitutes a custom portfolio of technologies and enabling initiative, specific to the target markets – including industries and geographical regions. It should consider the following elements:

(a) **Synergistic planning horizons**: Proper balance and blend of H1/H2/H3.
(b) **Digital technologies readiness**: Based on technology adoption curves and technology

surveillance process for the state-of-the-art in R&D and practical applications.

(c) **Smart workflows**: Integrating devices and communication protocols to accelerate the value generation process.

(d) **Smart NDE Applications**: AI permeation or readiness for AI should be a part of the technology portfolio.

(e) **ICT infrastructure**: should be specifically addressed as one core element in any roadmap deployment initiative.

(f) **Decision support systems**: Technologies that generate relevant knowledge to support decision-making processes should constitute a desirable element in a technology portfolio. Dashboards and scorecards with adequate UX design and relevant KPIs may serve as interfaces to guide and facilitate those decision-making processes at all relevant instances.

(g) **Pilot programs**: Devoted to field validation of innovative solutions to decide which ones can be refined and which ones should be pivoted.

(h) **Deliberate frequent reviews**: which can be built in as an integral part of activities to account for uncertainty in planning, execution, and outcomes; and create opportunities for revisions at a frequency higher than the normal strategic cycle.

Based on the diverse requirements of the NDE domain, the landscape of technologies discussed is graphically shown as a mind map in figure 2. Industrial Internet of Things (IioT) and Digital twin are at the core. They connect, manage, import, and export data across various technologies and applications through data acquisition, managing, processing, visualization, and physical action.

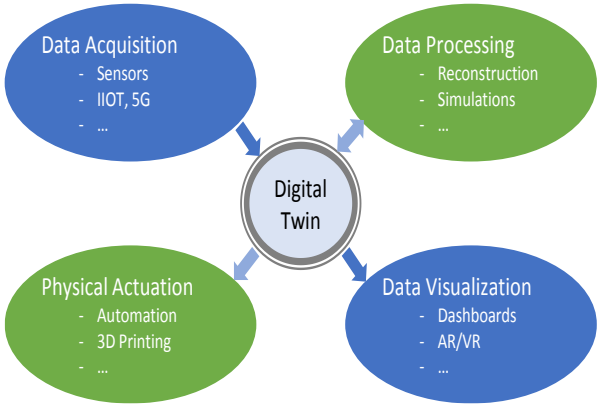


Figure 2: *Mind map for NDE 4.0 technology landscape [6]*

Data Acquisition and Handling includes Industrial Internet of Things, Digital twin, thread, and weave, Semantic interoperability and ontologies, 5G, Blockchain, Data security and Sovereignty, Data integrity, Traceability, Revision safe data formats and storage, Data Transparency, etc.

Data Processing and Computing includes Big Data, Cloud Computing, CAD/CAM/CAE/BIM, Simulation, Reconstruction, and inverse engineering, Smart Handheld devices, Edge Computing, Quantum computing, Artificial intelligence, Machine Learning, Deep Learning, Generative AI, Algorithms (heuristic, model-based and statistical), Image analysis/signal-information-raw data processing, Sound analysis/signal-information-raw data processing, etc.

Data Visualization includes Extended Reality (AR/VR/MR/PR/XR), Dashboards, Volumetric Displays, etc.

Physical Actuation, includes Automation, robotics, drones, Automated Inspection Systems, Additive manufacturing, etc.

In addition to these, the RIT must consider need for **Enabling Hardware,** such as: Special Hardware for AI, Telepresence, Biodegradable sensors, DNA Computers and Storage, Smart Dust, Neuromorphic Hardware, Carbon-based transistors, Nanotube Electronics, Customized analog/digital sensor development, etc.

Vertical and Horizontal Human-Systems integration of all these requires the inclusion of Virtual Personal Assistance – Conversational, Gesture, Smart workspaces and UX Design, Interface Layers and Standards, Brain-machine interfaces, Responsible AI, Intelligence augmentation and Machine assisted decision making, Cryptography, (Symmetric-key, Quantum, Public-key, Post-Quantum)

RIT should not discount the role of **new protocols and interfaces**, and any **new regulatory constraints**.

4.5 Roadmap Validation

Every roadmap needs validation. This is a two-step process.

Internal Validation comes in form of a review of the roadmap conducted by the leadership team and grounded in past experience. One of the possible ways is to view the alignment in inverse order, initiating with the learning and growth, and moving upward toward the financial perspective. Another is to play what-if scenarios. Third could be cross-check with historical performance or know-how of the advisory board.

External Validation requires engaging with key external stakeholders. One possibility is to engage with trusted customers on what-if scenarios. Another one is benchmarking with non-competing organizations.

Supplementary insights to improve the roadmap content may include a) Team structure, roles, and membership expertise, (b) Sponsorship and funding requirements including number, profiles, and amounts to be obtained, (c) Inclusion of specific initiatives under current R&D activity to improve their alignment with MTP, (d) Supplementary partnerships or alliances, and (e) NDE 4.0 Ethics Check.

5 EXECUTION

Now the rubber meets the road. RIT must execute according to the validated roadmap with the realm of principles agreed upon with the leadership team.

5.1 Resource Allocation

Leadership commitment essential to support NDE 4.0 for it to be successful, is exhibited through the allocation of resources and progress reviews. Leadership should be prepared to provide resources, further development of new skills and competencies, as well as new tools and methods. These resources are categorized as follows and should be identified in the roadmap.

General Resources: This refers to all tangible resources excluding people.

(a) **Financial**: Funds the projects and activities, which may come from internal or external sources.
(b) **Partners/suppliers**: Support network with capabilities that do not exist in house.
(c) **Infrastructure**: Tangible or intangible assets for installation, operation, and deployment of projects or initiatives. This includes (i) physical equipment and systems, (ii) digital devices and systems, (iii) information systems, and (iv) communication.
(d) **Equipment**: Tangible assets required to develop the required knowledge and technologies in support of the projects and processes. IOT-enabled equipment should be preferred over stand-alone units.
(e) **Technologies**: Access to a portfolio of proven fundamental technologies for developing prototypes. Annexure-C provides a starter list.
(f) **Knowledge**: Know-how and know-why of existing products/technologies in a documented form.

Human Resources: This refers to people with relevant skills, competencies, mindset, and capacity to support the roadmap [11,12].

Skills refer to a person's ability to perform a certain task, such as an NDE UT practitioner's skill to scan a weld using a phased array transducer within a pressure vessel. Skills may be classified as:

(a) **Trade Skills** (or Hard Skills): They provide the foundation for the deployment of NDE 4.0 projects and initiatives. They include (i) NDE-specific physics, (ii) General Science and Mathematics, (iii) Electrical, mechanical, and systems engineering, (iv) Technology integration & application.
(b) **Digital Skills**: They provide the capability to integrate commonly available digital systems with foundational NDE systems. They include using devices and handling information, programming, creating, and editing digital content, digital communications, digital transactions, and online security.

Data Skills: They provide the capability to establish data organization and reliable statistical and deterministic data processing. commonly available digital systems with foundational NDE systems. They include converting data to information, fusing information, and training artificial intelligence solutions.
Soft Skills (or people skills) : They allow improved performance both on an individual basis and as a workgroup to manage a project or initiative successfully. They include: (i) Mindsets - self-awareness, character traits, and attitudes; (ii) External relations - social awareness, team effectiveness, interpersonal people skills, social

skills, communication skills, career attributes, emotional intelligence skills, and responsible online behavior (iii) Management Skills - planning, communicating, decision-making, delegating, problem-solving, conflict resolution, motivating and negotiating (iv) Balancing and blending human-machine coworking at both physical and intellectual levels.

Competencies refer to the capability of applying or using knowledge, skills, abilities, behaviors, and personal characteristics to successfully perform critical tasks, specific functions, or operate in each role or position (See figure 3). Competencies are thus underlying characteristics of people that indicate ways of behaving or thinking, which generalizes across a wide range of situations and endure for long periods of time. Performing the role of an NDE Level III to manage all NDE-related processes within a company is an example of a competency.

Figure 3: *Performance depends upon several factors [13].*

The roadmap team should identify roles and their description with all relevant skills and competencies necessary to perform it successfully in the context of the roadmap initiative. These role descriptions should be integrated by each operative area and aligned with the objectives of the roadmap, validated by the leadership team. A role often missed is that of a Chief Engineer, who acts as a systems integrator and understands technology, application, and evolutions. The role may not be necessary but, it helps significantly to have a technical focal at the leadership level. Once those role descriptions are established and validated, a gap analysis should be performed for everyone assigned to the role to define his/her development plan.

For specific projects and initiatives, the completion of particular certification(s) may be required. Those requirements should be identified and integrated into the consolidated training program where there is an already available certification program. For certain instances, where no generalized certification programs are available, the development of a tailor-made certification program should be considered, or a well-documented exception justification by appropriate stakeholders.

5.2 Technology Management Process

Projects and initiatives on the roadmap should be managed with rigor of technology or innovation management depending upon the degree of uncertainty. The steps include:

a) **Technology surveillance/vigilance**: The search in the environment for signals and indications that allow the identification of threats and opportunities for technological development and innovation. This may include benchmarking, Markets/Customers research studies, and technological monitoring.

b) **Technology planning**: The development, review, and revision of a technology portfolio that allows the organization to select lines of action to achieve a competitive advantage.

c) **Technology alignment**: The organized integration of technology in all the organization's operations. It also includes the alignment of the technology plan with the business strategy.

d) **Technologies and resources enablement**: The procurement, inside and outside the organization, of technologies and resources necessary for the execution of the projects in the portfolio. This may include a) Technology acquisition (purchase, licensing, alliances, and other applicable methods). b) Technology assimilation, c) Technology development (technological research and development, technology up-scaling, and other applicable instances), d) Technology transfer, e) Technological projects portfolio management, f) technology-involved personnel management, g) financial resources management and h) knowledge management.

e) **Technology patrimony protection**: The safeguarding and care of the organization's technological patrimony, generally by obtaining intellectual property rights. This includes activities intended to capture, transform, protect, and preserve the intellectual property generated.

f) **Technology deployment**: The implementation of innovation projects until

the final launch of a new or improved product/service/experience to the market, or the adoption of a new or substantially improved process within the organization. It includes the commercial exploitation of such innovations and the organizational expressions that are developed for this purpose.

NDE 4.0 also requires significant innovation management which entails a match-making between needs and ideas. Guidance for innovation management can be found in ISO 56002 [14] and InnovatePedia [15].

5.3 Operations

Operations enable the transformation of intentions and plans, into securing resources, to produce verifiable results. An organization may already have them in place and should be able to use as many of the existing processes as practical. All processes to facilitate digital transformation should align with success metrics (KPIs) defined under the primary dashboard perspectives.

Financial: These processes manage the generation and use of funds that make the digital transformation viable. Financial management may include, but is not limited to:

(a) **Data monetization**: that allows a business proposition around the transfer of data.
(b) **Portfolio approach**: for aggregation and diversification of investment portfolios.
(c) **Intangible assets**: generation, maturity, integration, and protection for a competitive edge.

Customer: These processes manage the relationship with the most significant stakeholder group, to obtain the intended outcomes of the roadmap initiative. Customer relationship management may include, but is not limited to:

(a) **Customer insight**: through continuous empathic feedback intended to capture valuable insights for improvement of (i) the roadmap and resulting value creation for the customer, (ii) relationship, and (iii) internal processes for value creation.
(b) **Impulse value generation perception**: using communication processes intended to close the perception gap between the true and perceived value delivered, aimed at minimizing the risks for the deployment and adoption of the roadmap initiative.
(c) **Customer education**: to provide support through the guided diffusion of knowledge, skills, and competencies and facilitate the deployment and adoption of the roadmap initiative.

Value Creation through internal processes: These processes enable the creation, capture, and distribution of value to satisfy stakeholders' needs, including customers, and meet business strategic goals. Value management may include, but is not limited to:

(a) **Value chain management**: is the basic traditional approach to the creation, capture, and distribution of value and is at the core of almost all management perspectives.
(b) **Value network management**: expands the value chain management to a wider ecosystem, and how tangible and intangible value is managed through knowledge sharing, sometimes in real-time.
(c) **Technology management**: as described above.
(d) **Ideation and Innovation Management**: process and techniques at the core of design-thinking initiatives to stimulate creativity and value through novelty.
(e) **Validation/Qualification**: constitute the assurance that processes, systems, facilities, equipment, and people contain the elements required to properly perform their functions.
(f) **NDE-specific processes**: starting from the data acquisition through sensors, networked within NDE systems, that provide information from assets, and their environment, and enable decision making.
(g) **NDE certifications**: which guide validation and provide evidence that NDE systems and personnel have the necessary competencies based on standardized certification requirements, (such as ANSI/ASNT CP-189, ISO 9712, etc,) or based on industry/company/application specific requirements.
(h) **Regulatory compliance**: with all the applicable regional legislation and industry-specific requirement within the roadmap scope, monitored continuously, and used to update the portfolio and so it is always relevant and useful.

Learning and Growth: These processes help formulate and implement the development of human resources and organization knowledge base - the intangible assets of the organization to support value creation. Learning management may include, but is not limited to:

(a) **Talent management**: from the development of individual skills and competencies, and organizational career tracks, to succession planning, including incentives to retain and reinforce talent.
(b) **Knowledge management**: from development and containment of documented know-how and know-why, including procedures, and databases, to performance and organizational learnings.
(c) **Continuous improvement**: seeking to improve every process by enhancing the activities that generate the most value for the stakeholders, while removing waste. It completes the value creation loop that transvers the four perspectives

Risk and Uncertainty Perspective: These processes help assess and mitigate risk in technology development and market capture. Risk mitigation may include, but not limited to

(a) **Portfolio Management**: as discussed above
(b) **Technology reviews**: using a phase-gate process with competent experts as gate keepers.
(c) **Marketplace benchmarking**: to assess the needs, gaps, and competitive position.
(d) **Customer-shared vision**: to assure certain market share and investment recovery.

5.4 Roadmap Diffusion

The roadmap needs acceptance across the organization and communication to relevant external stakeholders. This requires structured communication to promote and garner support for success.

Internal Diffusion refers to topics within the organization, where the leadership team has a relatively higher degree of control.

(a) **Overcoming internal barriers**: such as adverse organizational culture, inadequate organizational structure, internal politics, attitudes, or communication barriers. Analysis tools such as force-field diagrams may be used to identify and prioritize actions.
(b) **Transparency**: through mechanisms aligned with the purpose of the roadmap initiative and in adherence with applicable company policy on information sharing.
(c) **Authority and autonomy**: to execute specific activities as deemed essential for success.
(d) **Employee engagement**: through communication, alignment of personal growth with company growth, incentives, and inclusion in decision making.
(e) **Teamwork engagement**: through an environment of mutual trust among engaged employees.
(f) **Ownership commitment**: as demonstrated through their personal involvement in the roadmap**.**

External Diffusion refers to select engagement with external elements through networking and influence. The roadmap communication strategy should integrate an analysis of all relevant stakeholders in order to properly diffuse the messages to each type of stakeholder and prevent adverse impacts to the roadmap initiative derived from the action of ill-intentioned social agents.

(a) **Overcoming external barriers**: such as legal, regulatory, market perceptions, industry level politics, IP rights, etc.
(b) **Go to Market**: strategy with limited exposure of the roadmap to select customers.
(c) **Marketing, diffusion, and adoption**: strategy to capture share early.
(d) **Customer engagement**: to capture their requirements and improve their utilization of your products/services.

Regulatory engagement: An early and active participation in relevant regulatory instances is strongly recommended to guide and positively influence the evolution of regulatory elements relevant to the roadmap scope.

6 IMPROVEMENT

The roadmap must continuously improve to fully capitalize on opportunities and minimize risk. This requires a periodic performance evaluation of leadership, planning, support, and operations, with full awareness of changes in external and internal context, and reassessment of prospective context.

This can be achieved as follows.

6.1 Acceptance

Information and knowledge required to evaluate the acceptance of the roadmap should be regularly compiled and analyzed. This information and knowledge may take the following form:

(a) **Massive Transformation**: performance as noted by KPIs, and metrics aligned with the Massive Transformative Purpose and scope, as well as stakeholder feedback on progress.
(b) **Full KPI dashboard**: with quantitative parameters for the objective performance assessment of various processes categorized under Business or ESG KPIs and metrics.
(c) **Barriers and limitations**: that impede the advancement of roadmap initiatives should be identified, documented, and addressed adequately.
(d) **Organizational structure:** that constrains the execution of the roadmap should be identified and addressed.
(e) **Resource constraints**: that limit the execution of the roadmap should be identified and addressed.
(f) **Setbacks and Failure**: when properly focused by leadership constitute important opportunities to derive learning processes and to generate improvement opportunities.

6.2 Analysis

Roadmap deployment, review, and changes should be data-based. The leadership Team should implement and institutionalize a structured analytical approach to process and analyze the KPIs and metrics.

(a) **KPI Analysis**: of data captured on pre-determined items over a period. It includes Business indicators, and ESG/SDG indicators. The analysis may include causality validation, context validation, benchmark validation, or segmentation validation.
(b) **Root cause analysis**: of KPIs, their trends, or unintended discrete events to support any decision-making process derived from it.
(c) **Impact scope analysis**: to deeply survey the KPIs and metrics for value created by roadmap. The impact can be analyzed from two perspectives – business value and social value, even if they go in opposite directions.
(d) **Trends and projections**: using appropriate numerical methods, statistical analysis methods, and algorithms to generate projections and improve planning processes.
(e) **Scenario-based forecasting**: for critical to business KPIs, to generate response protocols and contingency plans. Uncertainty may be accounted for by making estimates from conservative and aggressive assumptions.
(f) **Best practices spotlight**: that support the roadmap development, execution, and diffusion; from internal or external sources. Note: Best practices do not imply that they are not subject to improvement.

6.3 Review

Review complements the analysis to extract the necessary knowledge and decide on actions for improvement and sustainability of the roadmap initiative. The review process should consider, but not be limited to:

(a) **Periodic reviews**: at a frequency predetermined by the leadership team, with a formally defined agenda and participation.
(b) **Contingent review**: triggered by an event that significantly alters the external or internal context making a part of the roadmap irrelevant. Leadership should define the focus, agenda, and participation for the specific review.
(c) **KPIs review**: integrated with the periodic or contingent review to assure that dashboards are designed to capture what matters.
(d) **Communication review**: to detect opportunities for improvement in creating stakeholder's perception.

6.4 Refine

The roadmap should include a category of activities devoted to learning and improvement, associated with the planning horizons.

Continuous Improvement: This first improvement category in the roadmap achieves small changes in specific roadmap projects, all the time based on simple feedback. Those small changes should be based on the same objectives and the same technology used to define the initial roadmap initiative. These improvements can be executed at

the operations level, and are typically limited to H1.

Technology Pivot: This second improvement category in the roadmap may be in response to the perceived or foreseeable evolution of the technological environment and include projects devoted to achieving use case learning and alternate options generation. Those changes should be based on the same objectives, but with alternate technology options. These improvements can be executed at the leadership level, and typically for H1/H2.

New Direction: This third improvement category in the roadmap include projects devoted to new focus, new use cases, a revised technologies portfolio, and/or revised business models and value propositions. Those changes should be based on new objectives, and they may or may not comprise changes in the technology used in relation to the initial roadmap initiative. These improvements are decided by the leadership team or key stakeholders on the recommendation of the leadership and may constitute a significant change to the roadmap. These changes start with a revision of H2/H3, and then trickle down to H1. Sometimes this even calls for change in the leadership team.

A well-tuned review and improvement cycle is a sign of committed leadership, and just as important as a well-defined roadmap. Considering that technology evolution is so rapid and investment capacity for any organization is limited, this step plays a significant role in accomplishing the desired change.

7 EXAMPLE: Next Generation NDE Equipment

This is an example to demonstrate how an NDT OEM can build the roadmap to bring Industry 4.0 class NDE equipment using guidance from this book.

7.1 Orientation

The Vice President of Engineering happened to attend the basic course on NDE 4.0 at a conference, which built an anxiety to do something as the world appeared to be changing. His conversation with the CEO led to the start of this program. They included VP of engineering and VP of business development to form the 4-member leadership team.

7.2 Setup Leadership:

CEO initiates: The leadership team motivated a few managers and engineers to read the books "World of NDE 4.0" and the draft version of an ICDNT roadmap guidance document – a predecessor to this paper, with intent to transform the product portfolio

Purpose defined: Leadership team defined the purpose of their roadmap initiative as **"***Create next generation of NDE systems with digitally enhanced capability and reliability*."

The objective is to disturb the competitive landscape in their primary market (nuclear, oil, and gas), increase market share in other secondary markets (aerospace and transport), and provide entry to market in at least one additional industry.

External context framed: Extensive list of known and likely aspects were identified, dominated by increasing demand for (a) inspector safety in hazardous environments, (b) rapid data acquisition, and (c) reliable interpretation.

Vision drafted: Based on the purpose and external context, the leadership drafted the vision as "*Autonomous inspections with dependable decision support system*."

Company policies enhanced: Policies were revised to include managing and securing data as tangible property, ethical considerations around use of AI, employee learning and development for the future, engagement on use of customer owned data, data breach, and business continuity.

Roadmap initiative team identified: The Chief Technology Officer was identified to lead the team with Chief Engineer as deputy. Included in the team were the Director of IT, Director HR, three subject matter experts, and a newly hired programmer. The CEO will continue to be the executive champion.

Internal diffusion: This intent was shared with a select few employees only for the confidential nature of the activity. Those exposed were sworn to secrecy until further notice.

7.3 Setup Governance

Internal context identified: Team took a couple of weeks to understand the current state of the

company in context of the vision. Gaps in performance capacity and competencies were identified as critical to success. Years of six-sigma had eroded all surplus capacity. Their training was traditionally focused on jobs at hand. The only positive outcome from too much lean is that the company had financial resources to invest. The culture of ethics just needed an expanded awareness around new issues with digital transformation. The team discussed all the normative references for relevance.

External context refined: Another couple of weeks were invested in analyzing the external business environment. Starting with extensive market insight, benchmarking, eco-system mapping, and in-depth PESTEL+I analysis, the team identified one serious political change, one socio-economic shift, one legal concern, and three new external stakeholders with a possibility of one new business model - *servitization* (access to the company's product as an on-demand service).

Prospective context defined: Team held a 2-day workshop to speculate the future based on PESTEL trends and market insights, with an external facilitator, professional at this. It focused on dual transformation – digital and sustainability, with business resiliency as an important consideration. After some deliberation the social responsibility was kept out of scope for the purpose identified.

Several undesirable incidents were identified as possible with two of them likely to occur, needing upfront attention in the roadmap.

This was the most useful exercise during this step of governance setup.

NDE 4.0 Principles accepted: All principles were found to be usable as described, with highest emphasis being on cyber-security, for the need to manage customer data and trust.

Governance guidelines prepared: A new formal document was created to document the above aspects, compatible with the existing operating system. This was reviewed with the leadership team, and marked for annual review, to keep it current.

Code of Ethics revised: It now includes digital aspects, with appreciation that data and algorithms for automation will likely be biased. All the suggested guidelines in this book were acceptable as described.

Digital Transformation Review Board was setup to assure governance and adherence to principles, as documented. This is based on a design review board and materials review board. The new board, which is essentially a subset of the roadmap team, was tasked to draft their expectations.

7.4 Create Roadmap

Roadmap initiative kicked off: The team identified roadmap template, held three facilitated ideation sessions to generate data, and established quarterly review cycle. Only one business unit was involved.

Deliberation led to a strategic decision to have 25% of the investment into 2-3 visionary trendsetting projects, 40% for smart forecasting class of development, and 35% at the agile following level. This is unusual, but desirable in this case, given the external context, an opportunity to bring mature digital technologies to the NDE sector, and available financial resources as well as risk capacity.

Scope defined: The primary focus is on digitization of the inspection product and digitalization of NDE processes. This came with an understanding that there will be some digitalization of the manufacturing process along the way. All of this should pave way for total digital transformation later.

Horizons and objectives defined: Horizon-1 objectives included identification and validation of core technologies on existing inspection platforms within 6-18 months. Horizon-2 objectives included autonomous inspection systems and decision assist as separate capabilities within 24-36 months. Horizon-3 objectives included integration of autonomy and intelligence.

Dashboard established: Several suggested KPIs were already in use at this company for business operations. From product standpoint, the additional metrics included autonomy and decision accuracy as outcome indicators and portfolio ROI and digital skills as leading indicators.

All technology options were kept on the table at this point, with intent to build asset digital twins on 'as you go' model.

Roadmap developed: The roadmap is developed using a proprietary tool, with the capability to export as Excel or PowerPoint for external sharing.

Roadmap reviewed and revised: Digital transformation Review Board took a deep dive into the roadmap and did not approve it in the first round. There was poor alignment with several of the NDE 4.0 principles agreed upon upfront.

The roadmap team went back and revised the roadmap to include additional technologies to the planned products. This led to an increase in resource requirements that CEO was not prepared for.

Another round of revisions led to the inclusion of some very creative approaches: (1) Moving some of the newly added technologies to address NDE 4.0 principles into horizon-2 for the subsequent revisions of the product. (2) Adding digitalization to manufacturing process for productivity improvement. (3) Using state government grants for investment in specific manufacturing technologies to offset the cost of productivity improvements. (4) Using supplier financing for introducing their tech into the product. (5) Making advance sales at discounted price to the trusted customer. All this also assumes that initial release of products will generate profits to meet the promises along the supply chain and also fund the subsequent investment. This was an additional financial risk item in the roadmap.

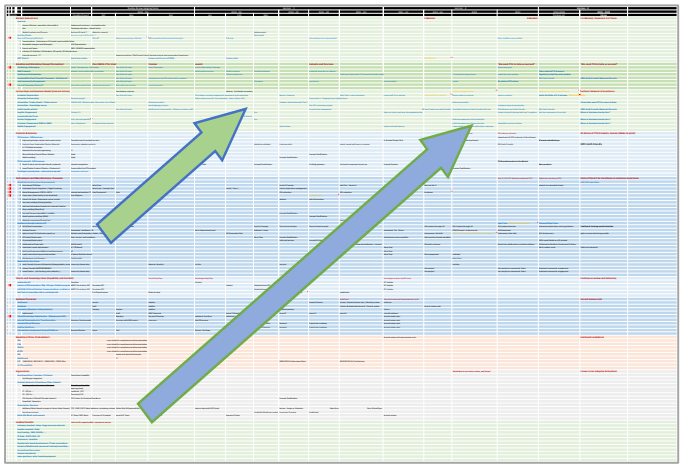
Essentially, the team learned what makes the transformation hard to accomplish and how to address them in a manner of small steps, supported with a serious and solid risk analysis and mitigation plan.

Roadmap validated: Internally, a different set of individuals was tasked to review the details from bottoms-up and top-down view. They identified three assumptions that were high risk. CEO added risk mitigation actions to the roadmap with additional resources.

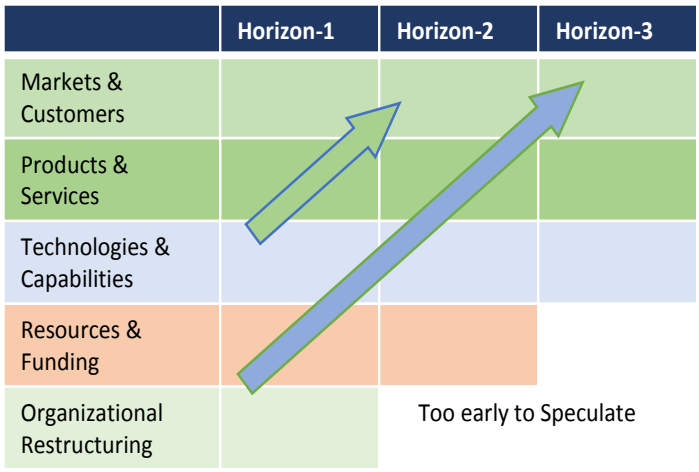
The trusted customer was engaged for external validation. She had already addressed a few unknowns and refined the priorities during funding conversations. This was a very fruitful exercise. It also alluded to a new role for Digital Products Director in the company.

Roadmap approved: Leadership signed it as approving body. Entire team signed it as show of commitment. It was marked confidential – NEED to KNOW BASIS.

Here is a snapshot of the roadmap that deliberately hides proprietary details.



The graphic here provides a high-level view of the structure, showing meaningful connection from lower left to upper right.



7.5 Prepare Organization

Technology Management process exists in the company. Patrimony protection was added. New roles connected with digital competency were added to the review team for stage gates. Review check lists were enhanced with NDE 4.0 principles and digital ethics checks as per the approved governance guidelines.

General resources estimated. Funding, the biggest one, was estimated based on technology plans, and plausible sources. It forced some reprioritization in favor of low hanging fruit to make the entire

program sustainable. Several new suppliers were identified for digital technologies, which also required adding an addition line item in roadmap for supplier qualification. The existing infrastructure was found to be adequate. The biggest gap was in knowledge, particularly the integration piece. The review process was strengthened with additional risk mitigation actions. There is no data set either to try out the AI/ML side of development.

Human talent estimated: This was a bit of a challenge since there is no guidance on the quantification of human talent requirements. This guide only provides a list of skills. An initial swag indicated the need for 3-5 additional engineers with digital and data management skills. It also identified a need for leadership training on the digital side of organizational behavior.

Another major gap identified was in integration skills, since there is no single person who had all three skills - inspection method, diverse applications, and data skills. This firmed up the opinion to create a new role for Digital Products Director. With not enough understanding for such a role in the marketplace, senior leaders created a provisional position description and began the search for a close match. No new certifications were identified at this point.

Leadership demonstrates commitment: Budget was allocated and a weekly cadence for meetings was setup to track progress. These meetings were set up for early in the morning when the CEO is likely to be available in person as well as mentally. A separate room was dedicated to managing operation with visual dashboards/whiteboards.

7.6 Transformation

Value management: Since the focus is more on creating autonomous products and not in the automation of manufacturing process, the value creation is embedded in innovation, design, and technologies of the deliverables. The important items addressed in this section are technology management, validation, and qualification, followed by certification and regulatory approvals. The procedures are being revised to include extensive digital context. Each process change will go through single pilot use before formal approval as standard work.

Customer engagement: The trusted customer now plays the role of an advisor and has also offered to be the beta user.

Risk and uncertainty management: Traditional risk matrix is being used considering likelihood, impact, and prevention opportunity to prioritize. Additional rigor was added to the technology reviews at phase-gate process. An external IT form has been engaged for cyber-security aspect of the product and likely a series of cloud-based applications. The business development team is on high alert for early market entrants and value perceptions for such products, so they can be priced fairly.

Financial management: Most systems are in place. The team still needs to figure out data monetization models.

Learning and growth: The team is continuously learning through online courses, and they discuss subjects over weekly lunch-n-learn meetings. They have also identified a set of courses for others to take when it becomes a company-wide initiative. The HR and IT directors have been tasked to continuously refine the processes in place to detect the need for specific skills. This will evolve over the next many months as learning continues.

7.7 Learn and improve

This is a new initiative, and the improvement cycles will likely begin in a year or so. The leadership team does understand the need for different levels of analysis and change.

8 SUMMARY AND OUTLOOK

NDE 4.0 is a case of massive transformation. It requires digital technologies to be integrated into the inspection systems, digitalization of workflows, and integration of NDE workflows within value streams. This paper is all about **HOW** to digitalize and digitally transform the NDE system. [1] elaborated **WHY** is it important for almost everyone in the NDE eco-system to embrace it and [3,4] elaborated **WHAT** digital technologies in NDE can help improve design, manufacturing, maintenance, and safety.

Roadmap for digital transformation does have some

parallels with traditional roadmaps and transformational efforts, just with the added complexity of uncertainty, major resource investment in technology and talent, and discipline-specific attributes. This paper is guidance document, and every user can adapt to their context, purpose, and limitations.

Fernandez, Hayes, and Gayosso in [12] envision how NDE systems are being disrupted by digital transformation processes as follows: "*In the first NDE lessons often apprentices are still taught the four indispensable elements in a NDE test system (An energy source, a test object, the interaction between that energy source and the test object and a recording medium for this interaction) and while analyzing how the test system does not function in the absence of one or more of those four elements ineludibly a fifth presence, human intervention, often not addressed for its explicit omnipresence which needs to assimilate and capitalize a rising sixth presence, (digital technologies, (including elements such as telepresence, digital aides-de-camp or assisted analysis based in) artificial intelligence, which may be a source of extraordinary opportunities and an unmistakable ally, if properly assimilated, to assist humans to unleash the power of their talent and ingenuity to create and deploy the next generation of NDE systems in the following years*" This transformation has the potential transform for good our discipline and the world.

The NDE 4.0 vision can now become reality with advanced computing and big-data capabilities, using an approach proposed in this guideline paper.

Most importantly, this transformation needs to 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.

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