



Understanding the importance and impact of network digital twins

White paper

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The rapidly developing field of network digital twins (NDT) has the potential to revolutionize network capabilities and operations. In this white paper, we will discuss how digital twin technologies can be used to increase the efficiency and agility of future networks. We present the four-layer digital twin concept, as well as how it delivers situational awareness, what-if predictions, and closed-loop automation. We evaluate the capabilities that enable NDT-value generation and highlight the general benefits. We examine the use cases for NDT applications, covering the phases of sales and design, deployment, operation and maintenance, network service development, testing and retirement. Learn how digital twins present challenges while also bringing benefits to organizations and their operations.

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Digital twins

Digital twins are reaching mainstream status in industrial sectors like discrete manufacturing and processing industries, as well as smart buildings and smart cities. They have proven their value with significant reductions in both CAPEX and OPEX, but also reduced time to develop, test and deploy twinned assets and increase uptime of twinned assets in the operational phase. The global digital twin market is expected to grow at a compound annual growth rate of 37.5% from 2023 to 2030 to reach USD 155.84 billion by 2030 [1].

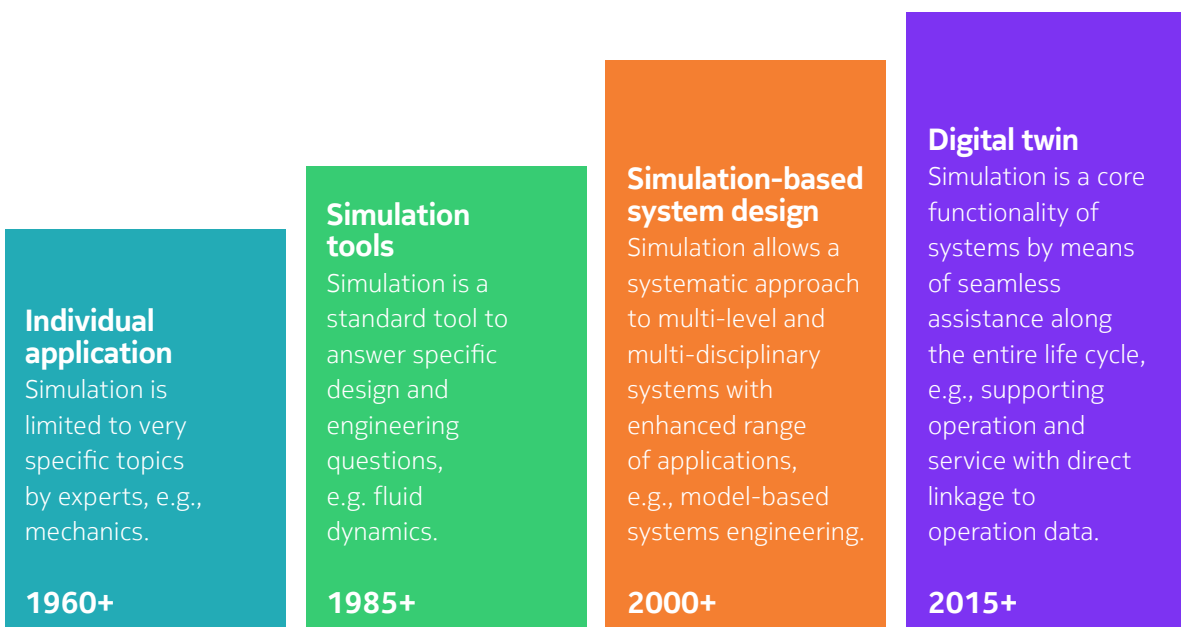
A digital twin is broadly understood as a fit-for-purpose digital representation of an observable element with synchronization between the element and its digital representation. The Digital Twin Consortium [2] offers the following more precise definition:

A digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity:

- Digital twin systems transform business by accelerating holistic understanding, optimal decision-making, and effective action
- Digital twins use real-time and historical data to represent the past and present and simulate predicted futures
- Digital twins are motivated by outcomes, tailored to use cases, powered by integration, built on data, guided by domain knowledge, and implemented in IT/OT systems.

Digital twins are engineered to share information across organizational silos to make all actors more productive. Shared situational awareness enables efficient decentralized self-synchronization because authorized actors across all organizations have timely information. This minimizes uncertainty and achieves increased operational tempo and efficiency. Loose coupling within digital twins enables flexible usage to maximize agility and innovation.

Figure 1. Digital twin as evolution of simulation (Boschert & Rosen, 2016)



As shown in Figure 1, digital twins can be considered the next step in simulation. They focus on supporting business outcomes via robust models, use real-time linkages to physical entities for monitoring and control, integrate big data analytics and AI, and offer flexible user interactions and what-if predictions. [3]

Network digital twins

With the growing popularity and demonstrated benefit of industrial digital twins, the telecommunications industry has begun to explore their potential applications in networks. The International Telecommunications Union (ITU) defines a network digital twin (NDT) as a virtual representation of a physical network. It is useful for analyzing, diagnosing, emulating, and controlling the physical network based on data, model and interface to achieve real-time interactive mapping between the physical network and the digital twin network.

Figure 2. Network digital twin hierarchy

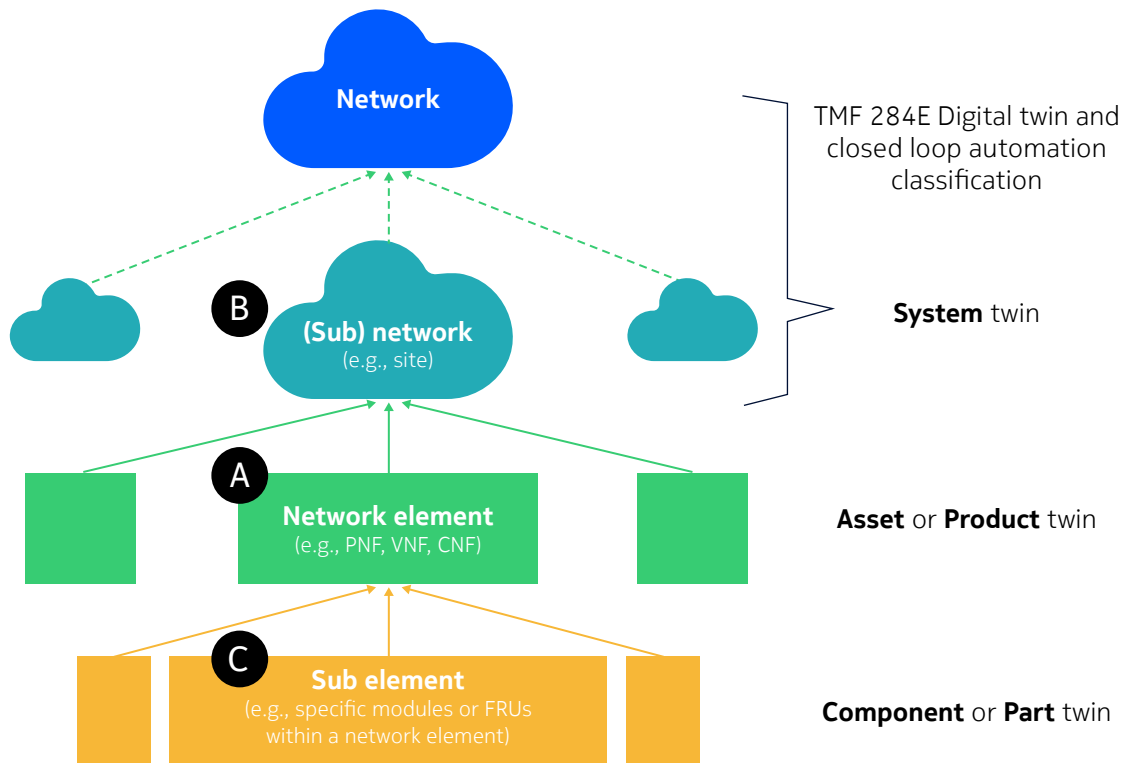
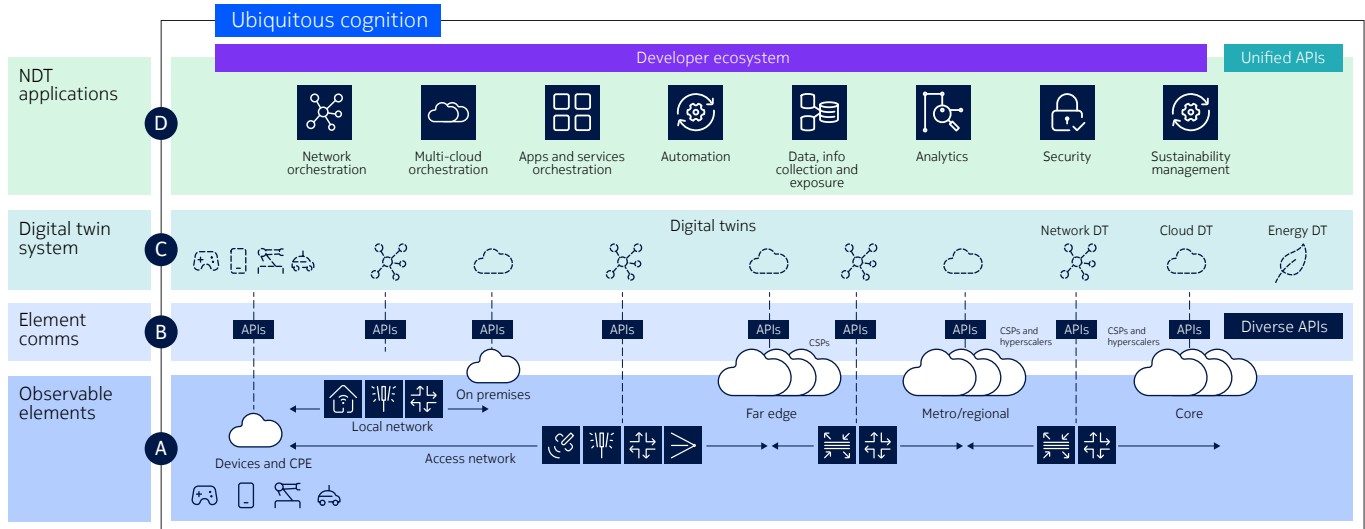


Figure 2 depicts how portions of a network infrastructure digital twin instance can be resolved to various levels. Twinning individual network elements (A in Figure 2) indicates that a discrete digital twin corresponds to some target physical network functions (PNF), virtual network functions (VNF) or containerized network functions (CNF). Individual network elements and interconnections are organized into subnetworks and networks (B in Figure 2), such as a base station site, radio access network (RAN) or other access networks. In some cases, an NDT can resolve to the sub-element level (C in Figure 2) like a field replaceable unit (FRU) or optical module, allowing for fine-grained awareness and control of network element behavior.

Four-layer digital twin framework

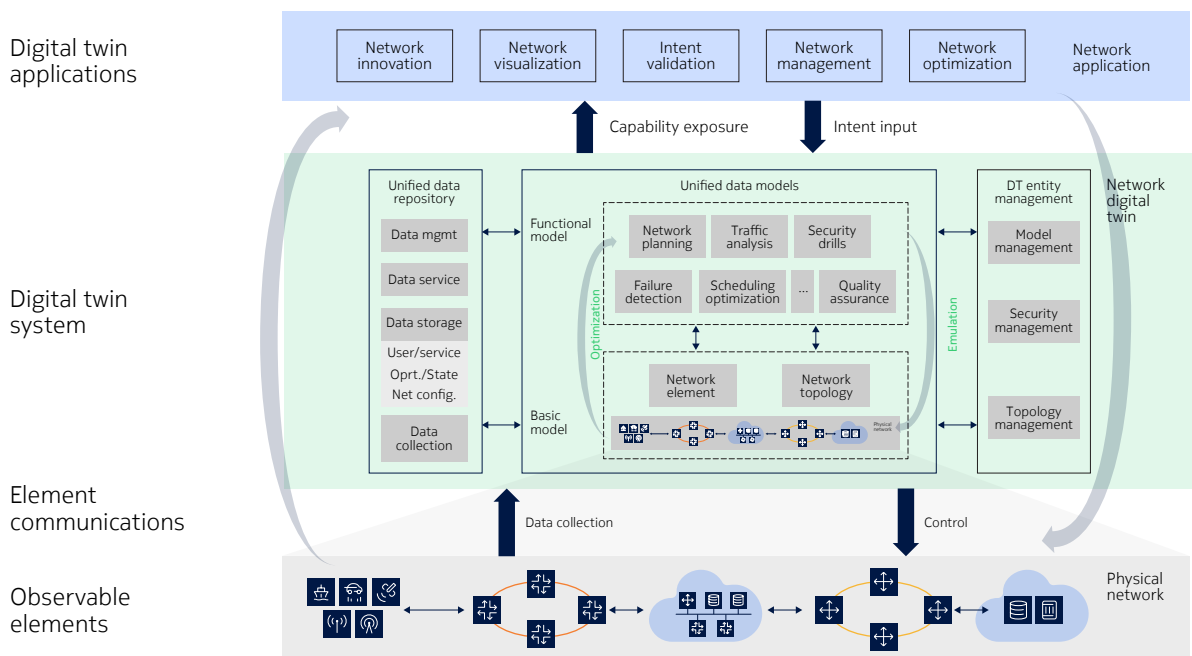
The Nokia network architecture for 2030 and beyond incorporates NDTs through the digital twin system layer (C in Figure 3) which connects observable elements (A in Figure 3) such as PNFs, VNFs and CNFs (via the element communications layer (B in Figure 3) and digital twin applications (D in Figure 3).

Figure 3. Digital twins in future network architecture [4]



This four-layer digital twin framework VNF is consistent with the ITU DTN in Figure 4 [5], the Internet Research Task Force (IRTF), Zhou et al [6], ISO 23247-1 [7] and the Digital Twin Consortium.

Figure 4. ITU-T Y.3090 Digital Twin Network in four-layer digital twin framework [5]



Observable elements

Network digital twins represent observable elements like PNFs, VNFs and CNFs that deliver value in the real (i.e., physical) world.

Element communications

Element communications provides synchronization between observable elements and the digital twin systems. Element communications for network equipment like PNFs, VNFs and CNFs is handled via the domain management systems. Element communications to general purpose sensors and equipment often flow through an IoT platform.

Digital twin system

Digital twin systems fuse data from observable elements into the shared, digital representation of those observable elements, which is used by digital twin applications to deliver business value to digital twin application users. The digital twin system includes a data repository of observed and historic data (A in Figure 5). Behavioral models (B) support the estimation of both current and previous states of observable elements, as well as predicting future states (C). Service mapping models (B in figure 5) are usefully categorized into the functional twin types of Figure 6.

Figure 5. Simplified NDT architecture

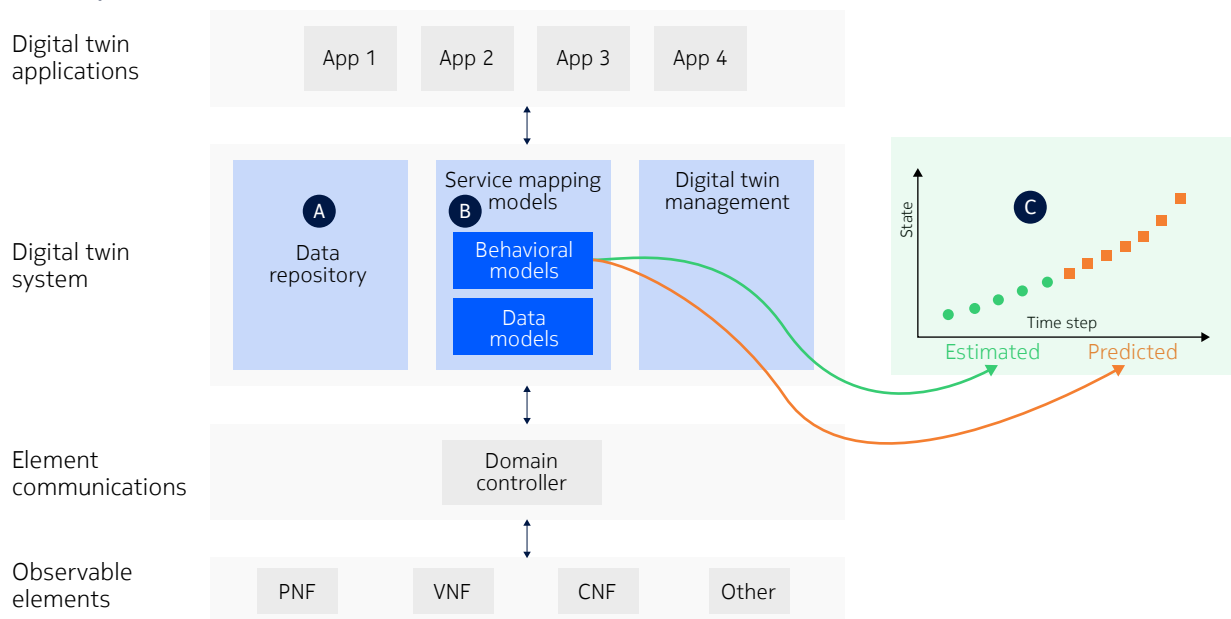


Figure 6. Digital twin functional twin types

Functional twin type	Description	Sample use cases
Descriptive/informative	Organize information on current and past performance for analysis	• Visualization of network status • Forensic analysis • CircleChain sell-side frontend
Emulation	Executes production software in virtual environment	• OSS/BSS integration sandbox • Network operator training • De-risking software changes to production networks • Network pre-sale and demonstration tool
Estimation	Estimates key performance indicator, like current power consumption	• Dynamic energy management • CO₂e estimation
Behavioral	Predicts behavior of mirrored elements	• Anomaly detection • HW predictive maintenance • Network resiliency testing tool
3D/Geospatial	Geospatial/3D model of racks, equipment, sites, coverage areas	• Site planning • Smart glasses for field engineers • Wireless coverage planning
Workflow	Models of processes or workflows to understand and optimize operations	• Deployment coordination

Digital twin applications

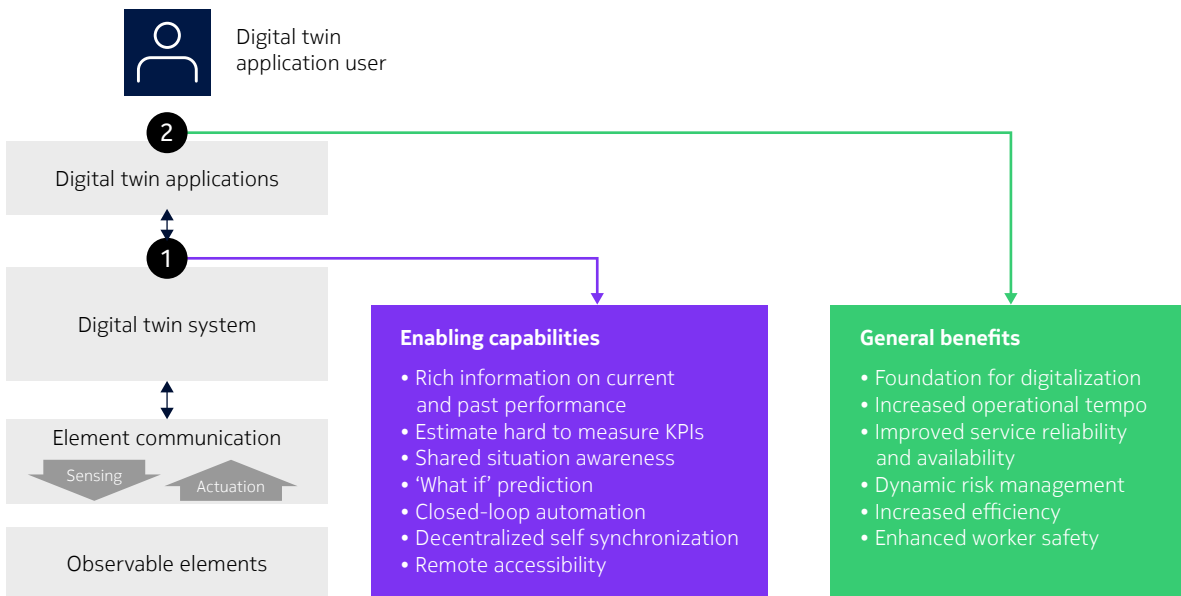
Digital twin applications apply business logic to historic, current and predicted states of twinned elements to create business value for digital twin application users. They are discussed in a later section, “Application use cases”.

Digital twin benefits

Digital twin value creation model

Digital twins create value by linking situational awareness and what-if predictions to relevant actors at the appropriate time to support better decision-making [8]. Digital twin applications combine business logic with what-if predictions and other information from the digital twin system to deliver the general benefits of digital twins to digital twin application users. Figure 7 visualizes the general digital twin value creation model.

Figure 7. Digital twin value creation model



Capabilities enabling digital twin value creation

A digital twin forms a foundation for value creation via the following mechanisms.

- **Rich information on current and past performance:** digital twin systems record rich data from observable elements like PNFs, VNFs, CNFs, and service probes like performance, fault and alarm data, which support online and offline analysis.
- **Estimate often hard-to-measure key performance indicators (KPIs):** digital twin models can integrate rich information on current and past performance to estimate network performance attributes and indicators, including those that are hard to measure, like available bandwidth and CO₂e emissions.
- **Shared situational awareness:** digital twin systems are engineered to break down silos so that situational awareness from a digital twin model is shared with all authorized digital twin applications and digital twin application users.
- **What-if predictions:** enable one to safely explore potential courses of action to de-risk decisions.
- **Closed-loop automation:** Observable elements like PNFs, VNFs and CNFs generate data-like traffic, alarm and fault data. Models in the digital twin system fuse current and historical data to both comprehend the current situation and project likely future states. Digital twin systems can then apply policies set by human operators via digital twin applications to automatically make decisions and pass appropriate commands down to the relevant network elements.

- **Decentralized self-synchronization:** shared situational awareness enables efficient self-synchronization and collaboration by decentralized actors.
- **Remote accessibility:** digital twins enable remote visibility and operation of physical equipment, which reduces the need to expose workers to dangerous or unpleasant situations. The remote accessibility capability of digital twins also enables network operator training environments to be flexibly delivered wherever and whenever engineers are available.

General benefits of digital twins

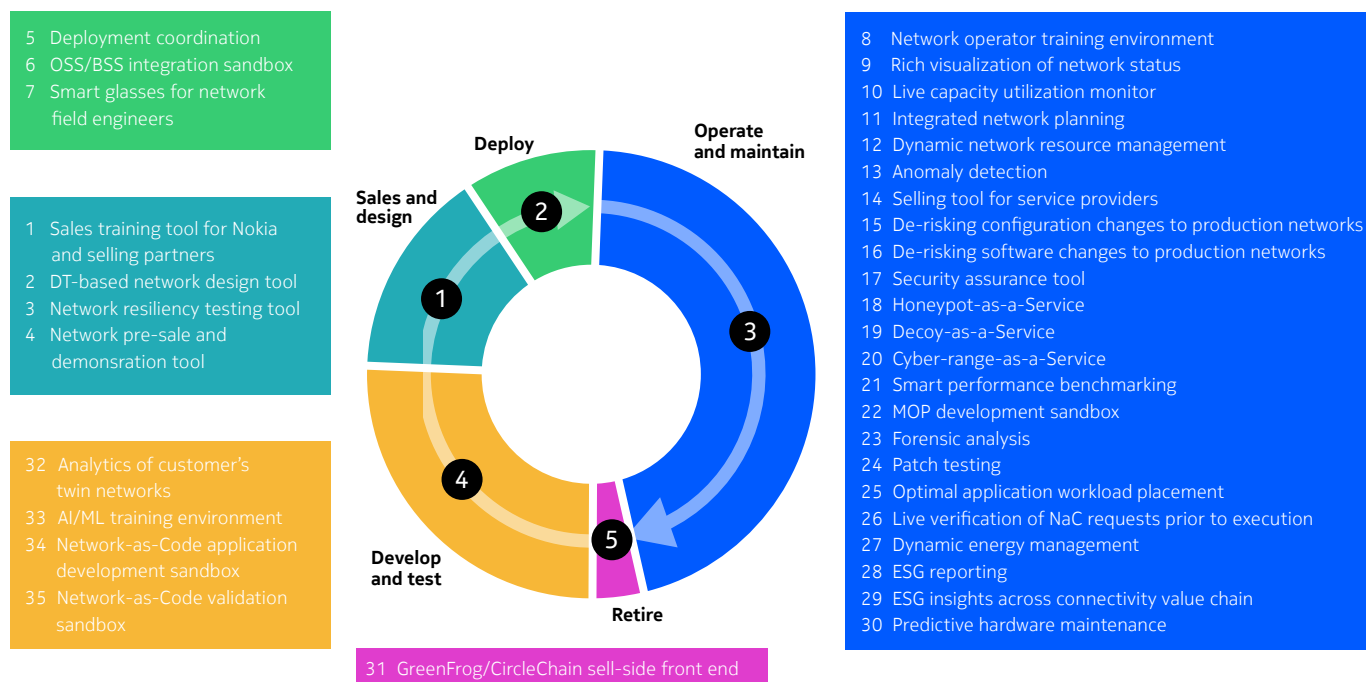
The following benefits of digital twins broadly cover core values delivered by those digital twin applications.

- **Foundation for cyber-physical integration:** a digital twin underpins the physical-digital-physical loop, which is a foundational element of cyber-physical integration. In addition to twinning physical network elements like PNFs, NDTs will eventually twin workflows and processes used by network operators. They will also be integrated into twins of end-to-end value webs utilized by enterprises that consume network services.
- **Increased operational tempo:** shared situational awareness and decentralized self-synchronization enable efficient coordination across ecosystems to minimize waiting time.
- **Improved service reliability and availability:** accurate situational awareness of operational status and performance of all network elements enables fast and accurate fault detection and isolation. Accurate digital twins enable procedure changes (e.g., method of procedure (MOP) development sandbox) and configuration changes (e.g., de-risking configuration changes to production networks and de-risking software changes to production networks). Changes can be verified in simulation before execution on real world elements to reduce the risk of service outages.
- **Dynamic risk management:** digital twins directly address:
 - Uncertainty in the state: As digital twin systems assimilate more sensors and other data, there is uncertainty in the accuracy of the digital representation.
 - Uncertainty about consequences: Digital twin system predictive models can project the likely future consequences of potential changes to a network. Clever ‘what if’ analysis with digital twin system predictive models enables uncertainties around potential network changes to be methodically analyzed to evaluate options, characterize sensitivities and make better-informed decisions.
- **Increased efficiency:** NDTs will guide optimizing workflows and increase efficiency via several mechanisms:
 - Better scheduling to minimize wasted time while maximizing resource utilization
 - Better collaboration, especially across silos and organizational boundaries
 - Better capacity planning using rich situational awareness of resource capacity and projected future workloads to enable better decisions about growing and degrowing resource capacity
 - Reduced network downtime due to better first-time quality. Accurate situational awareness of network status and accurate what-if predictions reduce the risk that service creation requests will be unsuccessful (i.e., not right the first time)
 - Less unplanned maintenance because accurate situational awareness of network status enables predictive and proactive maintenance actions to be taken before impairments cascade into service outages
 - Optimized asset management through better monitoring and management of individual asset instances across their lifecycle, from deployment and commissioning to operate and maintain and finally to retirement.
- **Enhanced worker safety:** Remote accessibility mechanisms of digital twins enhance worker safety by removing human workers from unsafe situations and dangerous locations, thereby minimizing the risk of worker injury.

Application use cases

Digital twins enable better and automated decision-making across a wide range of use cases through the entire lifecycle of the twinned network. This section discusses selected digital twin application use cases (see Figure 8) by network lifecycle phase.

Figure 8. Network digital twin application use cases



Sales and design phase

Sales teams can use a digital-twin-based sales training tool to develop expertise with the products they offer. Digital-twin-based network design tools enable sales teams to efficiently design bespoke network solutions for customers, and digital-twin-based network resiliency testing tools can test those designs for extensive robustness to assure they will meet or exceed customers' expectations. A network pre-sale and demonstration tool can present digital twins of proffered network designs and network elements to prospective customers.

Deploy phase

Having approved a network design, the NDT is used for deployment coordination to establish shared situational awareness for all actors involved in the network's deployment, commissioning and acceptance testing. Rather than relying on human project managers in one firm to call or email status updates to partner firms, all actors have shared situational awareness via the NDT so actors can better schedule work. Eliminating dead time between when one deployment task completes and the next workflow task begins delivers increased operational tempo, so networks are turned up faster.

Installation professionals who physically rack, stack and cable the new network equipment can use digital twin information conveyed by smart glasses to guide their actions and ensure installation is completed right the first time.

In parallel with network deployment, the network owner's IT organization can use the OSS/BSS integration sandbox to pre-integrate the new network elements with the operator's existing systems.

The network operations team can also spin up digital-twin-based network operator training environments even before the network is operational to familiarize the engineers who will perform acceptance testing and have initial operational responsibility.

Operate and maintain phase

Rich visualization of network status gives network operations engineers situational awareness of the current network status. Integrated network planning and dynamic network resource management use what-if predictions to improve decisions about when and how to alter network configurations to maximize efficiency and service quality. AI/ML applied to extensive past performance information can enable sophisticated anomaly detection.

The ability of the digital twin models to estimate often hard-to-measure key performance indicators, like instantaneous power consumption, enables sophisticated dynamic energy management and CO₂e reporting applications.

Quality engineers use forensic root cause analysis to study rich information on current and past performance and hypothesize plausible root causes of inevitable service outages and impairment events. Many of those hypotheses can then be tested via a network resiliency testing tool run against a twin instance configured as the network was immediately before the service outage or impairment event.

Service providers can sell an NDT-based tool that can enable network exposure to enterprise network users or public network customers. The tool can grant them on-demand access to service creation and service monitoring. For instance, a user-oriented, rich visualization of network status capability could give customers the live status of their slice, VPN, or connection across the network. NDT-enabled tools could also let customers design network slices and services and use what-if predictions to estimate service quality KPIs, and directly instantiate those services on-demand via self-service.

Network service development and testing use cases

NDTs enable more agile development, testing and deployment of new network services with features such as:

1. Analysis of rich information on current and past performance and usage of the network to identify opportunities for new and innovative service offerings
2. Emulation-based NDTs offered by the network-as-code validation sandbox to safely and easily develop and test network-oriented applications
3. Live verification of network-as-code requests prior to execution using what-if predictions to assure that a new network-as-code application is safe to deploy onto their production network.

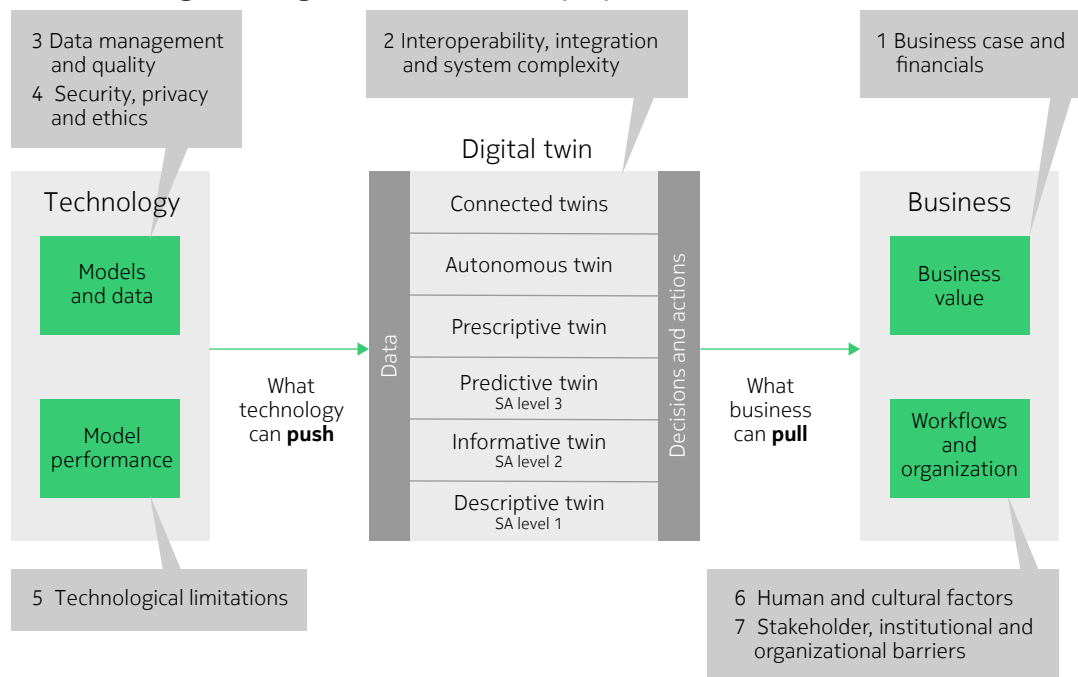
Retire phase

Physical network equipment eventually reaches end of life or becomes obsolete, so it must be retired from service. NDTs capture information across a physical entity's lifecycle, which can be leveraged to maximize the residual value of that equipment when it is eventually retired from service. Appropriately sharing detailed information on the current and past performance of equipment being retired reduces uncertainty about the equipment's true state, so operators, refurbishers and recyclers who buy used equipment are more likely to pay more for the gear.

Digital twin challenges

The primary challenges for successful NDT deployments can be mapped onto the digital twin value framework of Figure 9 (inspired by (Hakimi, et al., 2023)).

Figure 9. General challenges facing successful NDT deployments



1. **Business case and financials:** NDT financials are inherently challenging because a significant up-front investment is required to construct an NDT instance that represents an actual production network configuration, including integrating live data feeds and engineering security policies. Once the digital twin system is online, the operating cost to deliver accurate situational awareness and what-if predictions to digital twin applications should be modest. Note that sustainable value exchanges must be established across the ecosystem so that equipment manufacturers are incentivized to continuously improve the fidelity of their digital twin models as PNFs, VNFs and CNFs evolve.
2. **Interoperability, integration and system complexity:** creating a system is inherently a complex integration challenge. Multi-vendor networks spanning multiple technology domains, immature standards and emerging use cases increase that complexity.
3. **Data management and quality:** ingesting and curating quantities of live data from myriad observable elements raises practical and data quality challenges that must be addressed, especially accuracy, completeness, consistency, credibility, precision, and currentness.
4. **Security, privacy and ethics:** appropriate policies, governance and technical mechanisms must be in place to assure robust security, privacy and ethical use of data from observable elements as well as predictions and knowledge gleaned by models processing that data.
5. **Technology limitations** may prevent digital twin models from achieving the accuracy levels necessary for what-if predictions to robustly support key application use cases.
6. **Human and cultural factors** may complicate achieving the benefits of digital twins, such as:
 - Accountability for bad outcomes: for example, fear of being blamed for decisions made based on inaccurate or incomplete situational awareness or what-if predictions
 - Job losses: as NDTs drive increased productivity fewer employees are required
 - Devaluation of skills: NDTs digitalize many routine tasks previously performed by skilled humans and demand new skills, which some staff currently lack
 - Opaque what-if predictions: if human decision-makers do not understand how and why an NDT model projects an outcome, they may be reluctant to use that prediction when making decisions.
7. **Stakeholder, institutional and organizational barriers:** situational awareness and what-if predictions offered by digital twin systems enable decision workflows to be streamlined, meaning that some humans or organizations may be removed from the decision-making process, which they may be reluctant to do and may cause them to resist or obstruct the deployment and use of NDTs.

Conclusion

Network digital twins integrate rich information on current and past network performance to estimate KPIs and characteristics and make what-if predictions to de-risk decision-making. Applications that leverage NDTs enable organizations to increase the operational tempo, efficiency and mitigate risk of network operations. Digital-twin-enabled applications can improve service agility, quality, reliability, and availability enjoyed by network users.

Nokia Bell Labs researchers, as well as Nokia's world-class technologists and developers, are actively creating the technologies, standards and offerings that will deliver the benefits of NDTs to service providers and industrial customers. Nokia can be your trusted advisor on your journey to embrace the full benefits of NDTs.

Abbreviations

CNF	Containerized network function
CO ₂ e	CO ₂ equivalent
ITU	International Telecommunications Union
MOP	Method of procedure
NDT	Network digital twin
PNF	Physical network function
RAN	Radio access network
VNF	Virtual network function
VPN	Virtual private network

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