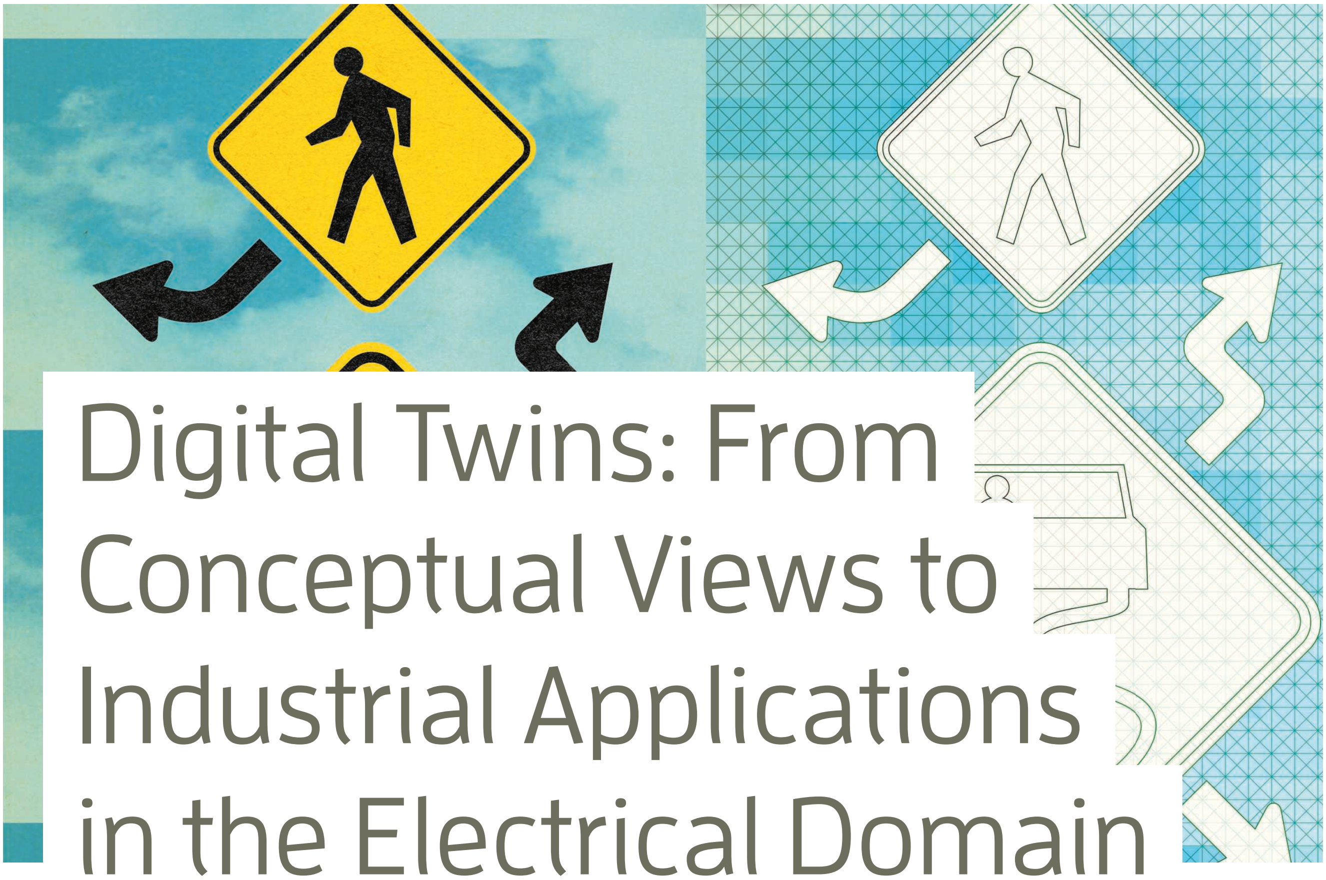

Digital Twins: From Conceptual Views to Industrial Applications in the Electrical Domain

Giovanna Di Marzo Serugendo and Anne-Françoise Cutting-Decelle,
Computer Science Center, University of Geneva

Laurent Guise, Energysemantic.com

Thierry Cormenier, Imran Khan, and Luc Hossenlopp, Schneider Electric

This article reviews various conceptual views behind the digital twins paradigm, highlights software technologies to develop digital twins, analyzes the use of digital twins during the lifecycle of industrial assets, and discusses a generic scenario from the electricity domain.

There is increasing interest from industry to develop and exploit digital representations of physical products, systems, and assets. Such representations, called *digital twins*, aim at inheriting the benefits of the software paradigm—flexibility, configurability, reusability, specialization and upgradability, and autonomy and intelligence—to improve the use of a considered asset. The expected benefits of digital twins cover various aspects of the lifecycle of an asset, from modeling to exploitation and maintenance. Exploiting digital representations of physical assets reduces design time, increases performance and lifespans, and reduces the costs of operation and maintenance.

The concept of digital twins is being worked out from different angles and communities: 1) the academic and

Digital Object Identifier 10.1109/MC.2022.3156847
Date of current version: 29 August 2022

Authorized licensed use limited to: Carnegie Mellon Libraries. Downloaded on October 06,2022 at 14:24:14 UTC from IEEE Xplore. Restrictions apply.

research side develops new digital twin features, pushing boundaries from static models to active entities working hand-in-hand with physical assets[1]; 2) the industrial side, undergoing a profound digital transformation, increases tenfold the potential of the approach to gather corresponding benefits[2,3]; and 3) the standardization side aims at easing the industrialization and deployment of digital twins.

In a previous article,[4] we discussed issues raised by the deployment of digital twins of electrical assets from a data management perspective. In this article, we focus on conceptual views and the use of digital twins in a large set of industrial domains. We discuss enabling software techniques, in particular, software agents and ontologies. We show how industrial stakeholders exploit digital twins throughout the lifecycle of physical products, systems, and assets. Finally, we provide a scenario from the electricity domain and conclude with requirements for digital twins.

GENERAL OVERVIEW AND DEFINITIONS

Conceptual views: From predigital twins to intelligent twins

Based on digital twin reviews and descriptions,[1–3] this article provides advanced conceptual views combining academic and industrial approaches in Table 1.

Digital twins: Various industrial domains

Initially framed in the manufacturing systems domain, digital twins are now found in a variety of other areas, such as health, power, and construction (building information modeling), with different views and definitions. See Table 2 for an inexhaustive list.

Digital twins: Standards

Digital twins are addressed by various standardization committees: International Organization for Standardization (ISO) Technical Committee (TC) 184 (Automation Systems and Integration), with the ongoing development of the ISO 23247 standard; International Electrotechnical Commission (IEC) TC 65 (Industrial Process Measurement, Control, and Automation); the IEC System Committee on Smart Manufacturing; and ISO/IEC Joint Committee 1: Advisory Group on Digital Twin. Other committees, dealing with construction at the international (ISO TC 59) and European levels (European Committee for Standardization TC 443), railway applications, smart cities,

TABLE 1. The conceptual views of digital twins.

Type of twins	Use before a physical asset exists (predigital twin)	Use after a physical asset exists
Static twin: Model with only static properties	List of digital properties of future products (for example, catalogue data); static model	List of digital properties of an actual product; static model
Functional twin: Static twin including some dynamic behavior capabilities (also called a *mirror*[1])	Model usable for simulations of what is likely to happen; useful when prototyping a physical asset	Model usable for simulations of what is likely to happen and smart features, comparing the behavior of a real physical asset and the simulated version from the twin
Self-adaptive digital twin: Functional twin with capacity to acquire real-time data and update the model (also called a *shadow*[1]); needs a digital thread[1] keeping track of evolution and communication with physical twin and following the lifecycle of the digital twin	Model with adaptive capabilities in regard to system level test conditions and scenarios to optimize an asset choice	Synchronization with real-time data to refine a twin's capabilities and expected behavior and make it as close as possible to the real asset; model usable for predictions, maintenance, and simulations of what is actually happening with the physical twin
Intelligent digital twin: Self-adaptive digital twin with autonomy, learning, reasoning, knowledge, and acting capabilities; able to communicate with other twins (also called an *extended digital twin*, *cognitive digital twin* or *physical avatar*[1]); needs information exchange between physical and digital twin in both directions	Selection and prototyping of the right asset; could take the place of physical asset-to-be in prototyping and simulation involving an ecosystem combining other physical assets and twins	Twin becomes an autonomous software agent equipped with learning, sensing, acting, and autonomous capabilities; exchanges data with a physical asset in a feedback loop and with other twins, takes actions alongside or on behalf of physical twin or complements it; could even discover on the fly new capabilities and lead to better use of a physical asset or replace the asset itself (for example, self-healing)

Authorized licensed use limited to: Carnegie Mellon Libraries. Downloaded on October 06,2022 at 14:24:14 UTC from IEEE Xplore. Restrictions apply.

TABLE 2. The digital twins in various industrial domains.

Industrial domain	Typical twins and use	Type of twin (Table 1)
Manufacturing	Modeling and simulating the infrastructure of an industrial process plant[5]	Functional twin
Cyberphysical systems, Internet of Things (IoT), and Industrial IoT	Modeling and simulating the infrastructure Maintenance, monitoring, optimization, security of the physical asset Autonomous actions Providing real-time information from the physical space for performance analysis, maintenance and monitoring of a physical asset (for example, connected objects), and optimization	Functional digital twin Self-adaptive digital twin Intelligent digital twins Self-adaptive digital twin
Health	Agent-based digital twin for trauma management[6]	Intelligent digital twin
Building	Digital model and digital monitoring of building construction	Self-adaptive digital twin Intelligent digital twin
Power	Data model exchange between control center and substations [International Electrotechnical Commission (IEC) 61850 remote terminal unit interface model]	Static digital twin
	Dynamic data model update and validation between advanced distribution management system (ADMS) and geographic information system electrotechnical and automation simulators regarding grid voltage and frequency control, network reconfiguration, and so on (ADMS application based on common information model/grid model)	Functional digital twin
	Operation and control of electricity distribution system for simulation and data analysis[7] Power systems controllers	Functional digital twin Functional digital twin and self-adaptive digital twin
	Grid edge simulators; forecasting power generation and demand on different time horizons, including distributed energy resources (DERs); and demand response impact (DER management system application based on IEC 61850 models)	Adaptive digital twin
	Distributed energy management system[7]	Self-adaptive digital twin
	Forecasting future energy consumption based on past and real-time measurements[8]	Self-adaptive digital twin
	Real-time grid simulation through an active model receiving real-time sensor data, alerting utility operators to cyberattacks and other disruptions[9]	Self-adaptive digital twin
	Analytics with physics-based models, artificial intelligence, and next-generation sensing technologies[10]	Self-adaptive digital twin
	Grid self-healing decision analytics (ADMS app based on common information model/grid model)	Intelligent digital twin
	Exchange of energy among neighbors in a smart grid; contract establishment among consumers and producers; regulation of total energy consumed and produced; prediction of consumption and production[11]	Intelligent digital twin
Automotive	Vehicle development: functional description of vehicles and simulation, including virtual reality[12] Vehicle production: control and maintenance of physical production plant[12]	Functional digital twin Self-adaptive digital twin

Authorized licensed use limited to: Carnegie Mellon Libraries. Downloaded on October 06,2022 at 14:24:14 UTC from IEEE Xplore. Restrictions apply.

and even health, are also developing standards for digital twins.

SOFTWARE TECHNIQUES TO SUPPORT DIGITAL TWINS

Software technologies

We identified various technologies for implementing digital twins and linked them to the conceptual views in Table 1. Biesinger et al.[12] discuss several technologies for production systems: digital models, radio-frequency identification chips, QR codes, real-time coupling, and controller backups (static and functional digital twins). Barthelmey et al.[13] propose a digital twin represented by a data file. The digital twin of each component is stored as an Automation Markup Language file, containing dynamic (the actual status) and static data (the model) about the physical component under control (static and functional digital twins).

Other authors propose cloud-based digital twins that build and update models in real time (functional and self-adaptive digital twins). Barricelli et al.[3] identify necessary digital twin characteristics: networking connections, sensing capabilities, describing and storing static and dynamic physical twin data as well environmental data, and communicating with physical twins, other digital twins, and human experts. They also highlight the importance of exploiting a proper ontology for leveraging data and information with semantics. Finally, for continued improvement, digital twins need learning features and self-adaptive characteristics (intelligent digital twins).

Digital twins and software agents: Insights

Software agents are autonomous entities with sensing and acting capabilities, collaborating and interacting with one another. They vary from purely reactive to more advanced, with modeling, reasoning, and cognitive capabilities as well as advanced interactions.[14]

Various proposals. In manufacturing control systems, early proposals use multiagent systems as virtual counterparts of physical entities to provide short-term forecasts based on the intentions of agents.[15] Other proposals involve the use of software agents linked with robotics modules to design new assembly systems in response to product descriptions.[16] Agents offer an alternative to client/server, cloud-based, and centralized solutions for Internet of Things scenarios involving millions of objects. In advanced visions, things form a collective adaptive system working as a single "superorganism"[17] and "spatial services"[18] to provide complex functions arising from spontaneous interactions among heterogeneous devices and connected objects.

Implementing digital twins as software agents. Software agents, as described previously, provide several if not all the characteristics of the conceptual views highlighted in Table 1. They are particularly well suited for implementing functional, self-adaptive, and intelligent digital twins. Some authors already made this link and used agent-based digital twins in health care[6] and smart grids.[11] A digital twin becomes a software agent when it acquires sensing, acting, reasoning, and autonomous capabilities. It can locate and acquire data, develop new capabilities, aggregate and analyze information, take appropriate actions, and even work jointly with a physical twin, all while communicating and interacting with peer digital twins and human experts.

Enhancing digital twins with ontologies

Given the number of data formats and semantic interpretations digital twins (and digital threads) must manage among the different applications and systems through the lifecycle, it makes sense to use shared and formal semantics for data exchange and semantic interoperability. Ontology models are essential enablers of this. Although the concept of ontology came from philosophy, in 1993, Grüber[19] used *ontology* as a technical term by defining it as "a formal, explicit specification of a shared conceptualization." In other words, ontologies promise to provide a shared and common understanding of a given domain for data exchange among people and application systems, thus providing common access to information.

Törsleff et al.[20] leverage ontologies for reasoning and interoperability among software agents in smart factories and energy grids. Barricelli et al.[3] highlight the need for using ontologies to develop advanced capabilities of digital twins. However, there is still work to do to create standardized ontology models. Similar to the Industrial Ontologies Foundation initiative (https://www.industrialontologies.org), an organized approach is necessary to define relevant ontology models.

DIGITAL TWINS THROUGH THE ASSET LIFECYCLE

A digital twin exists before a product is identified because it arises from functional needs identified through a functional analysis. Functional analysis requires the consideration of the whole life phase of an asset, while use cases mainly focus on the application life stage. At each life phase, relations to the environment, various stakeholders, simulation and production tools,

Authorized licensed use limited to: Carnegie Mellon Libraries. Downloaded on October 06,2022 at 14:24:14 UTC from IEEE Xplore. Restrictions apply.

TABLE 3. The typical twins used during the asset lifecycle.

Lifecycle step	Typical twins	Type of twins (Table 1)
Product ecological design	Product models and associated simulation, if any (thermal, electrical, and mechanical)	Static digital twin or functional digital twin
Product manufacturing	Product assembly model and product identity card (QR code), including traceability	Static digital twin
Product documentation	Multiple-rendition digital model of product characteristics (paper, web, apps, and so on)	Static digital twin
Product procurement	Product purchase model, including everything needed for transactions (retailer models, e-purchasing models, and so on)	Static digital twin
User's conceptual system design	Product/function model	Functional digital twin
System ecological design	Product/function generic characteristics model (thermal, electrical, and mechanical; possibly product simulation models	Static digital twin or functional digital twin
System sourcing	Aggregation of function models to reflect the desired physical function allocation in products for sourcing purposes	Functional digital twin
System analysis	Product/function/communication models to evaluate expected system behavior based on expected physical architectures	Functional digital twin
System documentation	Product/function requirement model; to be used in all downstream phases as a reference	Static digital twin
Service procurement	Twin comparison from the manufacturer's and user's perspectives	Static digital twin
Distribution, transportation, and storage	Product transportation traceability model, including changes of ownership	Static digital twin
Construction, commissioning	Product model for configuration and testing purpose	Functional digital twin
Use	Digital twins of a product exist in all layers and applications of a user's system to cover all use facets (system operation and asset management); possibly present in the supply chain for traceability/maintenance purpose	Functional twin or Adaptive digital twin and even intelligent digital twin
Maintenance	Digital twin of product dedicated to specific maintenance phases (including functional testing, spare parts models, and traceability models)	Functional digital twin, adaptive digital twin, and even intelligent digital twin
Deinstallation	Twin reflecting product deconstruction/ dismantling properties	Static digital twin

and normative and regulatory requirements should be considered for structuring a digital twin. Such an approach will optimize the quantity and quality of data carried throughout the lifecycle, focusing on need-based asset management and extending life spans in a world increasingly seeking material and energy efficiency. A digital twin should include all the functional properties and schematics necessary to understand the behavior of an asset for better utilization. These properties contribute to shaping a product, revealing its needs.

Once a product exists, its identification, technical performance, dependability, environmental, and economic characteristics enrich its digital twin. Functional properties are identified as generic (the environment and cybersecurity); common to families and categories of products generally covered by the same standard; specific to product ranges, according to manufacturers and applications; and even customized, in the case of a single product. More than 70% of the properties do not concern the digital twin of an asset but, rather, the asset's environment, management, and technical and economical optimization. It becomes necessary to standardize properties of assets to improve data interoperability. Table 3 provides an overview of digital twins throughout the lifecycle of assets.

Twin issues: Type of data

The value of a digital twin directly depends on the quality of the input data and thus on the confidence one may have in the outcome of the twin. The management of data quality (data in, collected data, and data out) affects not only the value of a digital twin but also the twin's ability to be easily tested and integrated into a system. It concerns various aspects, such as missing data,

Authorized licensed use limited to: Carnegie Mellon Libraries. Downloaded on October 06,2022 at 14:24:14 UTC from IEEE Xplore. Restrictions apply.

bad patrimonial data, data transparency (with respect to its quality), and data consistency among different twins.[4] Data needed to feed a digital twin come from many sources and need different refreshment processes, depending on the type of information, as depicted in Figure 1.

Setting up a digital twin means providing communication services and processes to ensure that data are of the necessary quality/trust and appropriately connected to the digital twin interface. This is very demanding: some data may be updated only once at the beginning of a process, some may need to be updated in case a product instance changes (for example, after repairs), and when the context of an operation changes. The actors allowed to update depend on the type of data. The triggering of such updates is error prone (how does a twin know that an update is needed?). A lot of care related to the digital twin interface must be taken to facilitate the evolution of twin-related data throughout the lifecycle.

Twin issues: Security

From a model perspective, different data exchange services with various security rules may be required for the digital twin interface: patrimonial data are normally read-only from the asset database serving as a source of trust, and real-time data may be read and write and possibly directly connected to the field of operation as well as upper-level operational systems. Cybersecurity applies differently depending on the circumstances.

Twin issues: Abstraction level

The Smart Grid Architecture Model includes different abstraction views (process, field, station, plant/operation, company/enterprise, and market), each provided by as many digital twins as levels of abstractions.[4] Abstracting from a given asset does not systematically mean that a corresponding digital twin will be simple. For instance, an "asset management" system—which helps plant owners optimize asset lifecycles and financial investments—is normally located in the highest abstraction level, which is known as *enterprise*. Digital twins feeding such an application need detailed parameters to run properly and provide the expected value.

Twin issues: Composition and interoperability

Like service composition, we consider digital twin composition. In the same way that assets are composed of several others and additional features resulting from the possibility to mutualize the capabilities of subassets, twins may be composed of subtwins representing physical assets as well as additional functions. A typical example is a system or factory represented as a digital twin formed by the aggregation of multiple digital twins. The composition of digital twins is a largely unexplored area. We outline a few ideas that should be explored further.

First, the twin of a system is more than just the composition of the twins

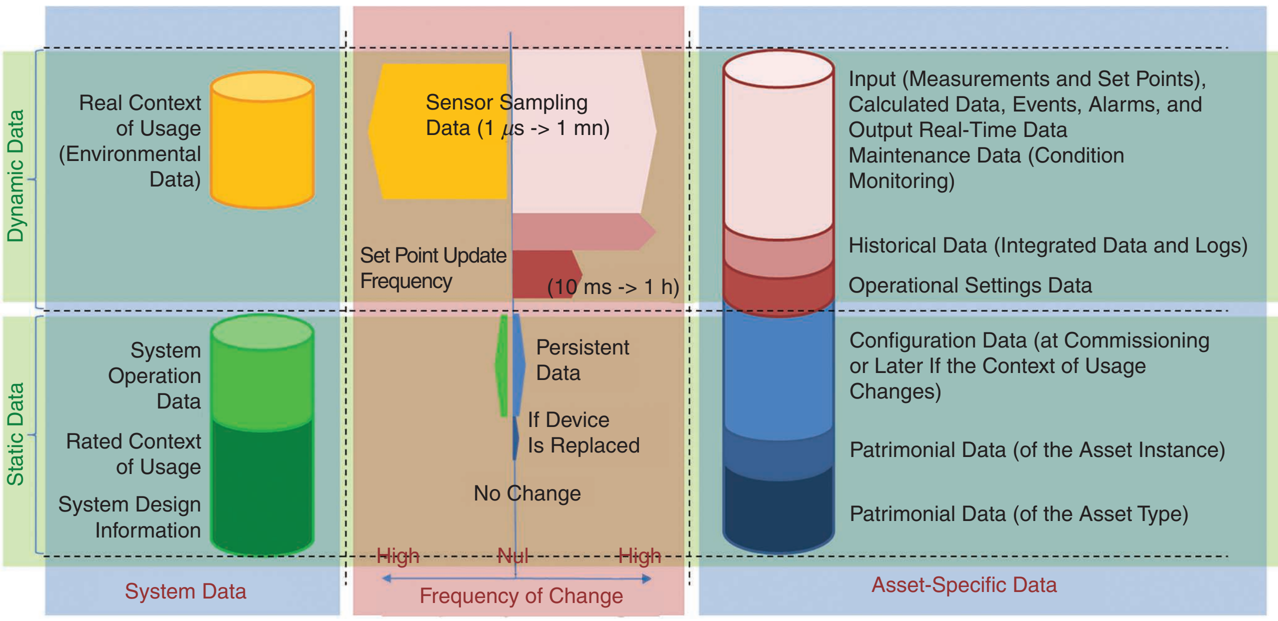

FIGURE 1. The types of data associated with digital twins.

Authorized licensed use limited to: Carnegie Mellon Libraries. Downloaded on October 06,2022 at 14:24:14 UTC from IEEE Xplore. Restrictions apply.

of the components of sublayers. There should be a placeholder for the twins of system-level functions/added value, interacting with the components and other systems. Second, a twin of a component needs, for its own functioning, system-related data (for example, the outside temperature is system-related data shared by twins of the components of the system) (Figure 1). Third, not all digital twins are created equal (Table 1). Different types of digital twins may exist, with varying features and capabilities. This makes it challenging to create a composed digital twin. Fourth, we need to make sure digital twins become part of composed digital twins along various facets. For example, a digital twin of a speed drive may become part of a composed digital twin of a heat exchanger twin in a milk processing plant twin, whereas the same digital twin of the speed drive may become part of the electrical system twin that powers the milk plant. In the former, the speed drive twin exposes process capabilities, whereas in the latter, it exposes electrical capabilities. Therefore, it becomes important to properly define and expose the capabilities of each digital twin so that the twins are easy to use.

Fifth, standard and recommended ways to create, deploy, and manage composed digital twins are missing. In truly autonomous systems, composed digital twins can be choreographed and even self-organizing, but until then, orchestration will be the norm. For this, we need to have platforms that coordinate and manage digital twins. Sixth, structuring the descriptions of digital twins and their capabilities as graph data needs further exploration. This, with the use of formal semantics, will ease finding, exploring, and composing multiple twins together. Existing approaches based on Yet Another Markup Language or XML may prove insufficient for this purpose. Seventh, all these possibilities depend on our ability to treat data and system relationships as first-class citizens of our digital world. A radical data management approach that treats information as a product is the way forward. Traditional techniques, such as data lakes and warehouses, have a narrow scope and have failed to deliver on this front. In addition, "twins" may also be composed of potential future assets and functions. So, it is a clear value of twins to have the capability to anticipate future/potential evolutions of assets, without needing a physical asset/function to be present.

Twin issues: Scalability

The French distribution grid hosts more than 300,000 twins, each representing an individual substation and collectively feeding the model of the entire network.

USE CASE SCENARIO FOR ELECTRICAL INDUSTRY

The electrical industry has been using twins for more than 20 years, for at least four reasons: 1) it has a large quantity of expensive assets, 2) it requires interoperation among various parties, 3) it needs multivendor interoperability, and 4) it has a limited set of function types (hundreds) and information objects classes (thousands), possibly instantiated up to millions of times (for example, smart meters). The twins are supported by international standards [namely, the IEC Common Information Model (CIM), which includes the IEC 61970, 61968, and 61850 series] that define interfaces for supporting data exchange among primary stakeholders throughout the grid lifecycle. Even if applied at the interfaces of the twins, it appears more and more common that the twins are natively handling these data. The CIM is widely used by electrical utilities across Europe.

Use case: Electrical substation

Since 2004, digital electrical substations have involved digital twins, thanks to the use of the IEC 61850 series, which provides the vocabulary, grammar, and processes to define and manage a comprehensive digital twin of a substation, its components, and their composition throughout the lifecycle. The series defines three facets of the system: 1) the "function" facet of the substation twin, including its electrical single-line diagram, expressed as the hierarchical composition of electrical functions linked with connectivity constraints; 2) the "physical" facet of the substation twin, expressed as a collection of communicating components that perform the operations in the "function facet"; and 3) the "communication facet" of the substation twin, specifying the different communication networks, possibly redundant, and the way the communication ports of intelligent electronic devices (IEDs) are connected.

Figure 2 shows the components of digital twins in the following stages:

- The IED configuration description reflects the twin corresponding to the type of selected component: this twin must be provided by the manufacturer of the physical device (static twin).
- The IED instantiated description reflects a later stage of configuration of a given instance of the type of selected component, within the context of the targeted substation (static twin).
- The configured IED description reflects the twins once they are "fully integrated" into the system (functional twins).

Authorized licensed use limited to: Carnegie Mellon Libraries. Downloaded on October 06,2022 at 14:24:14 UTC from IEEE Xplore. Restrictions apply.

One key aspect resulting from this experience is the way that twins of components are integrated with the twin of the upper system level, the substation. The resulting twin, hosted in the system configuration description, includes the three facets of the electrical substation as well as the twins associated with each component in the system. Originally designed with the goal of supporting a smart configuration of a digital electrical substation, the IEC 61850 twin has reached such a sophisticated level that it can support most of the full twin features, including simulation (functional/self-adaptive twin). The IEC 61850 series approach now extends to the whole smart grid application, including power generation plants and distributed energy resources (photovoltaic panels, generation sets, combined heat and power systems, stationary batteries, and even electrical vehicles).

At the system level, there is a software agent acting as a functional twin guiding the operator in complex situations, for example, a loss of generators (self-adaptive/intelligent twin). Ontologies are a key element to achieve interoperability in such a use case (for instance, among electrical substation system twins and their component twins as well as among twins relating to product design, system configuration, and system operation). Additionally, an ontology-based approach enables defining, verifying, and enforcing constraints found in the real world, especially through software agents representing twins.

Digital twins facilitate optimized decision making at every stage of the equipment lifecycle, in each zone of a given system, and within each market domain where the asset is used. Data quality and trust are fundamental issues and challenges to ensure the dependability of digital twins, and they also have a direct impact on cybersecurity. Actors providing data on which digital twins base their computations must provide accurate and reliable information so that systems exploiting digital twins can trust the results.

To achieve interoperability, ontologies are necessary to analyze the semantics and distinguish the "essential elements" of data (common features) for the implicit contingencies of every standard. Digital twins strongly benefit from artificial intelligence advances, due to better analytics and computing power. Software agents bring autonomy and actions to digital twins, working in an ecosystem alongside physical

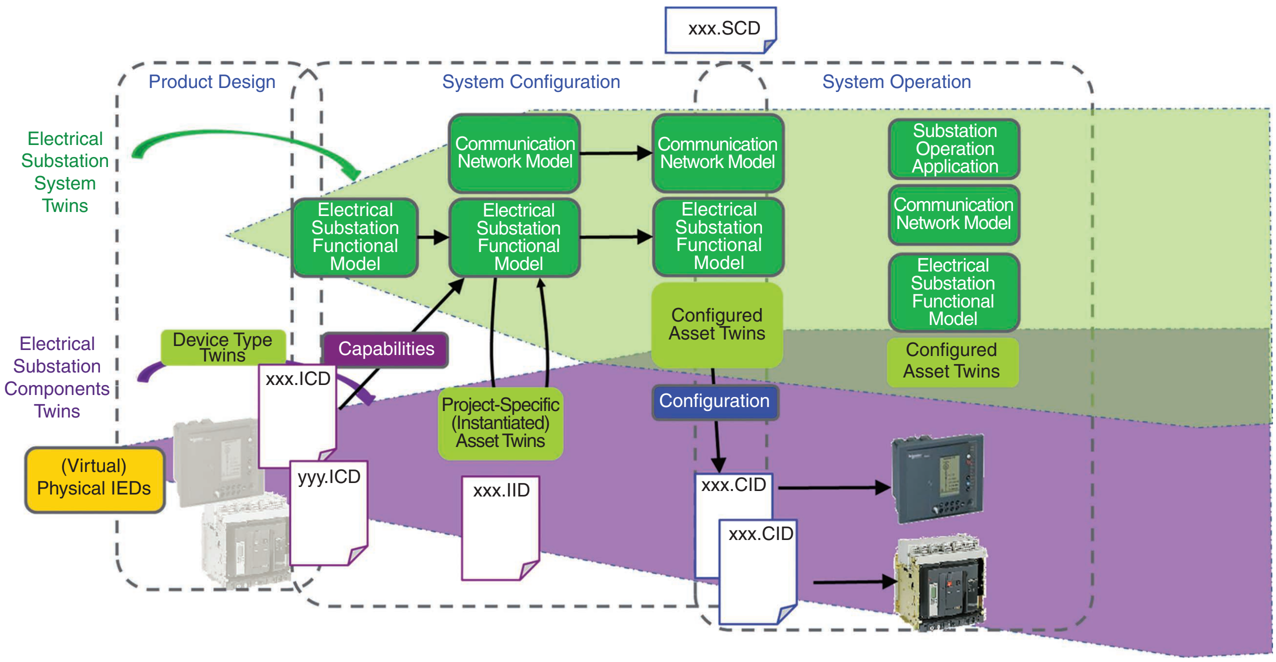

FIGURE 2. Twins in an IEC 61850 electrical substation. SCD: system configuration description; ICD: IED configuration description; IID: IED instantiated description; CID: configured IED description.

Authorized licensed use limited to: Carnegie Mellon Libraries. Downloaded on October 06,2022 at 14:24:14 UTC from IEEE Xplore. Restrictions apply.

ABOUT THE AUTHORS

GIOVANNA DI MARZO SERUGENDO is a full professor at the University of Geneva, Geneva, 1227, Switzerland, where she is the director of the Computer Science Center. Her research interests focus on the engineering of decentralized software with self-organizing and emergent behavior and involves studying natural systems and designing and developing artificial collective systems. Di Marzo Serugendo received a Ph.D. in software engineering from the Swiss Federal Institute of Technology Lausanne. She cofounded *ACM Transactions on Autonomous Adaptive Systems*, of which she served as editor in chief from 2005 to 2011. Contact her at giovanna.dimarzo@unige.ch.

ANNE-FRANÇOISE CUTTING-DECELLE is a researcher at the Computer Science Center, University of Geneva, Geneva, 1227, Switzerland. Her research interests include the adaptation of knowledge engineering and information extraction techniques to improve the understanding and interoperability of international standards in industry through ontologies and natural language processing techniques. Cutting-Decelle received a Ph.D. from the University of Savoie Mont-Blanc, Chambery, France. Contact her at anne-francoise.cutting-decelle@unige.ch.

LAURENT GUISE is an energy consultant with EnergySemantic.com, Grenoble, 38000, France. His main research interest is the impact of the digital transformation on international standardization (including digital twins), which focuses specifically on the energy sector. Guise received a Master's degree in electricity and automation from the Ecole Supérieure d'Electricité. Contact him at laurent.guise@energysemantic.com.

THIERRY CORMENIER is a senior expert with Schneider Electric, Grenoble, 38000, France. His research interests include standardization, environmentally conscious design, material efficiency of circular economy, and environmental footprint reduction of electrical power systems. Cormenier received a Master's degree in automation from the Conservatoire National des Arts et Métiers. Contact him at thierry.cormenier@se.com.

IMRAN KHAN is a senior principal architect with Schneider Electric, Grenoble, 38000, France, where he leads the ontology program for the company's Internet of Things (IoT) platform. His research interests include the IoT, knowledge graphs, data and information management, cloud and edge computing, and intelligent systems. Khan received a Ph.D. from Institut Mines-Télécom and Télécom SudParis in conjunction with Pierre and Marie Curie University. He is a Senior Member of IEEE. Contact him at imran@ieee.org.

LUC HOSSENLOPP is a digital chief technology officer fellow and project design lead fellow at Schneider Electric, Grenoble, 38000, France. His research interests include the various parts of the value chain, from sensor to asset management, with a focus on software and automation, and IEC 61850. Hossenlopp received an M.S. from the Ecole Nationale de Techniques Avancées. He is a member of the International Council on Large Electric Systems, the International Electrotechnical Commission, and Transmission and Distribution Europe. Contact him at luc.hossenlopp@se.com.

infrastructure. They help digital twins change behaviors according to the phases of the lifecycle. Various levels of abstraction, composability, scalability, repeatability, and security are aspects to consider when using digital twins in industrial applications.

Digital twins are present in most domains and accompany their physical counterparts throughout their whole lifecycle. Opportunities provided by ontologies and software agents have the potential to transform the role of digital twins, from mirror models evolving in real time with their physical counterpart to active entities participating in system maintenance and operation. Leveraging these technologies, the industrial domain can develop and exploit these concepts even further and faster than other fields. ■

REFERENCES

1. R. Saracco, "Digital twins: Bridging physical space and cyberspace," *Computer*, vol. 52, no. 12, pp. 58–64, 2019, doi: 10.1109/MC.2019.2942803.

Authorized licensed use limited to: Carnegie Mellon Libraries. Downloaded on October 06,2022 at 14:24:14 UTC from IEEE Xplore. Restrictions apply.

2. A. M. Madni, C. C. Madni, and S. D. Lucero, "Leveraging digital twin technology in model-based systems engineering," *Systems*, vol. 7, no. 1, p. 7, 2019, doi: 10.3390/systems7010007.
3. B. R. Barricelli, E. Casiraghi, and D. Fogli, "A survey on digital twin: Definitions, characteristics, applications, and design implications," *IEEE Access*, vol. 7, pp. 167,653–167,671, 2019, doi: 10.1109/ACCESS.2019.2953499.
4. L. Guise, L. Hossenlopp, T. Cormenier, A-F. Cutting-Decelle, G. Di Marzo Serugendo, and I. Khan, "How to overcome difficulties met in deploying digital twins of electrical assets over their whole life cycle? a data management perspective," in *Proc. Int. Conf. Electricity Distribution (CIRED)*, 2021, pp. 322–326, doi: 10.1049/icp.2021.2197.
5. G. Santillán Martínez, T. Karhela, R. Ruusu, and J. Kortelainen, "Automatic generation of simulation-based digital twins of industrial process plants," ERCIM News, Sophia-Antipolis, 2018. [Online]. Available: https://ercim-news.ercim.eu/en115/special/2097-automatic-generation-of-simulation-based-digital-twins-of-industrial-process-plants
6. A. Croatti, M. Gabellini, S. Montagna, and A. Ricci, "On the integration of agents and digital twins in healthcare," *J. Med. Syst.*, vol. 44, no. 9, pp. 1–8, 2020, doi: 10.1007/s10916-020-01623-5.
7. S. Uemura, "Development of digital twin technology for operations and control in distribution system," in *Proc. 25th Int. Conf. Electricity Distribution (CIRED)*, 2019, pp. 1–5. [Online]. Available: https://www.cired-repository.org/handle/20.500.12455/400
8. "Siemens electrical digital twin," Siemens AG, Erlangen, Germany, Tech. Rep., 2018. [Online]. Available: https://assets.new.siemens.com/siemens/assets/api/uuid:66c9013092b493265e091c154a33f9dd38d36c20/electricaldigitaltwin-brochure-final-intl-version-singlepages-no.pdf
9. R. A. Kerekes and M. J. Rice, "Seeing double: Digital twin for a secure, resilient grid," Oak Ridge National Lab., Oak Ridge, TN, USA, Tech. Rep., 2020. [Online]. Available: https://www.ornl.gov/blog/seeing-double-digital-twin-secure-resilient-grid
10. "Digital twin: Analytic engine for the digital power plant," General Electric, Boston, MA, USA, Tech. Rep., Erlangen, Germany 2018. [Online]. Available: https://www.ge.com/digital/lp/ge-digital-twin-digital-power-plant
11. P. Glass and G. Di Marzo Serugendo, "Plateforme de coordination et collaboration pour échanger l'énergie, réguler et prédire la production/consommation dans le cadre d'un réseau électrique intelligent," University of Geneva, Geneva, Switzerland, Tech. Rep., 2021. [Online]. Available: https://archive-ouverte.unige.ch/unige:155369
12. F. Biesinger and M. Weyrich, "The facets of digital twins in production and the automotive industry," in *Proc. 2019 23rd Int. Conf. Mechatron. Technol. (ICMT)*, pp. 1–6, doi: 10.1109/ICMECT.2019.8932101.
13. A. Barthelmey, E. Lee, R. Hana, and J. Deuse, "Dynamic digital twin for predictive maintenance in flexible production systems," in *Proc. 45th Annu. Conf. IEEE Ind. Electron. Soc. (IECON 2019)*, 2019, vol. 1, pp. 4209–4214, doi: 10.1109/IECON.2019.8927397.
14. G. Weiss, L. Braubach, and P. Giorgini, "Intelligent agents," in *The Handbook of Technology Management*, vol. 3, H. Bidgoli, Ed. Hoboken, NJ, USA: Wiley, 2010, pp. 360–372.
15. K. Hadeli, P. Valckenaers, M. Kollingbaum, and H. Van Brussel, "Multi-agent coordination and control using stigmergy," *Comput. Ind.*, vol. 53, no. 1, pp. 75–96, 2014, doi: 10.1016/S0166-3615(03)00123-4.
16. R. Frei and G. Di Marzo Serugendo, "Self-organizing assembly systems," *IEEE Trans. Syst., Man, Cybern. C, Appl. Rev.* (1995–2012)*, vol. 41, no. 6, pp. 885–897, Nov. 2011, doi: 10.1109/TSMCC.2010.2098027.
17. A. Ferscha, P. Lukowicz, and F. Zambonelli, "The superorganism of massive collective wearables," in *Proc. 2014 ACM Int. Joint Conf. Pervasive Ubiquitous Comput.*, pp. 1077–1084, doi: 10.1145/2638728.2659396.
18. H. Ben Mahfoudh, A. Caselli, and G. Di Marzo Serugendo, "Learning-based coordination model for on-the-fly self-composing services using semantic matching," *J. Sensor Actuator Netw.*, vol. 10, no. 1, p. 5, 2021, doi: 10.3390/jsan10010005.
19. T. R. Grüber, "A translation approach to portable ontology specifications," *Knowl. Acquisition*, vol. 5, no. 2, pp. 199–200, 1993, doi: 10.1006/knac.1993.1008.
20. S. Törsleff, C. Hildebrandt, and A. Fay, "Development of ontologies for reasoning and communication in multi-agent systems," in *Proc. 11th Int. Joint Conf. Knowl. Discovery, Knowl. Eng. Knowl. Management (IC3K 2019), 2019*, pp. 450–457, doi: 10.5220/0008355804500457.

Authorized licensed use limited to: Carnegie Mellon Libraries. Downloaded on October 06,2022 at 14:24:14 UTC from IEEE Xplore. Restrictions apply.