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Digital twins, which replicate physical assets, are perceived as enablers of digital transformation. But implementations of digital twins are still rare, and there is little advice on how to successfully develop them. We describe how a Norwegian power grid company and its technology partners designed and implemented a digital twin of its grid network, and show that a digital twin's unique characteristics are a crucial source of organizational learning that require innovative co-creation efforts and effective data governance. We also provide recommendations for designing and implementing digital twins.[1,2]

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Digital Twins Represent a New Breed of Technology

"We are building a road here. We're not just driving up the road—we're building it along the way" Respondent 1, GridCo

Digital twins represent a special class of smart technologies that integrate the physical and digital realms through coupling physical objects to virtual counterparts, and thus leverage the benefits of both the physical and virtual environments.[3] Given that over two thirds of companies have implemented or are planning to implement Internet of Things (IoT) initiatives, digital twins are expected to gain broad interest among businesses.[4]

The concept of a "twin" is not new to industry. As long ago as the 1960s, NASA built two identical space vehicles for the Apollo program, one of which went to the moon and the other one remained on earth. The idea behind a twin is that an object *outside* the reach of engineers can be controlled and managed by having an exact replica available *within* their reach. The term "digital twin" was first coined by Michael Grieves in 2003 in a lecture on Product Lifecycle Management.[5] He proposed creating a digital replica of a physical product to compare what was

1 Federico Pigni is the accepting senior editor for this article.
2 The authors thank Federico Pigni and members of the review team for their thoughtful feedback and guidance throughout the review process.
3 Jones, D., Snider, C., Nassehi, A., Yon, J. and Hicks, B. "Characterising the Digital Twin: A Systematic Literature Review," *CIRP Journal of Manufacturing Science and Technology* (29), March 2020, pp. 36-52.
4 *Gartner Survey Reveals Digital Twins Are Entering Mainstream Use*, Gartner press release, February 20, 2019, available at https://www.gartner.com/en/newsroom/press-releases/2019-02-20-gartner-survey-reveals-digital-twins-are-entering-mai.
5 Grieves, M. *Digital Twin: Manufacturing Excellence through Virtual Factory Replication*, March 2015, available at https://www.researchgate.net/publication/275211047_Digital_Twin_Manufacturing_Excellence_through_Virtual_Factory_Replication.

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physically produced with what was virtually designed, thus closing the gap between design and execution.

Today, a digital twin is commonly understood as a digital replica of an organizational asset that enables companies to digitally manage that asset along its complete lifecycle.[6] A virtual counterpart is created that mirrors the physical asset, including its characteristics and behaviors, to the best extent possible. As a result, a digital twin allows the physical asset to be monitored in *real time* and can analyze its *historical data* points; more importantly, it also allows those data points to be used for *predicting the future* workings of the asset.

A digital twin is not merely a digital clone of a physical object. Rather, it is an enhanced replication of the physical object that is continuously updated with data from the physical object's performance throughout its lifecycle. Moreover, a digital twin can perform functions that cannot be performed by the physical object, such as calculating its current condition (e.g., age, activity levels) or predicting its impending failure (due to overdue maintenance), which is particularly valuable for changing environmental conditions.[7] Real-time monitoring of a digital twin provides the organization with a rich, in-depth understanding of the physical asset and reduces downtime, which is acutely important for volatile environments and infrastructures. Furthermore, digital twins play a key role in harnessing and unearthing new business opportunities, particularly for asset-centric firms where data is scattered across separate organizational silos.

Though substantial benefits can be gained from using a digital twin to monitor the performance of a real asset, designing and implementing a digital twin requires significant effort. The technical complexity of mimicking a physical asset makes digital twin projects different from traditional IT projects. In particular, these projects require an approach that emphasizes organizational learning gained from delving deep into the intersection between the virtual and the physical realms. For example, if the link between the physical asset and its digital twin is neither well understood nor defined as part of the project, the digital twin immediately loses its intrinsic value. To successfully implement a digital twin, an organization not only has to harness various competencies but must also be open to critically reflecting on existing processes, data structures and, most importantly, the possibility of constructive disruption. Even though many researchers and practitioners see digital twins as key components and enablers of digital transformations,[8] implementations are still rare, and the key factors for their successful development remain uncertain. Only a few successful examples exist where the design and implementation of a digital twin opened up unprecedented business opportunities.

In this article, we describe the successful implementation of a digital twin in the energy sector. We describe how "GridCo," a Norwegian power grid company, together with its technology partners "DigitalCo" undertook an $8 million digital twin initiative that we have termed "DigitalGrid,"[9] which GridCo regards as its single most important initiative in responding to the changes occurring in the energy sector. Our analysis of this case shows that organizational learning, innovative co-creation and effective data governance were key elements not only for the successful development of the digital twin but also for enabling both GridCo and DigitalCo to mature along several dimensions. (Our data collection methodology for this case study is described in the Appendix.)

Components, Capabilities and Characteristics of a Digital Twin

In essence, a digital twin consists of three major components: 1) a physical object, the original, that is to be mirrored; 2) a digital representation of that real-world object in the virtual space (e.g., in the cloud); and 3) connections, digital or otherwise, between the

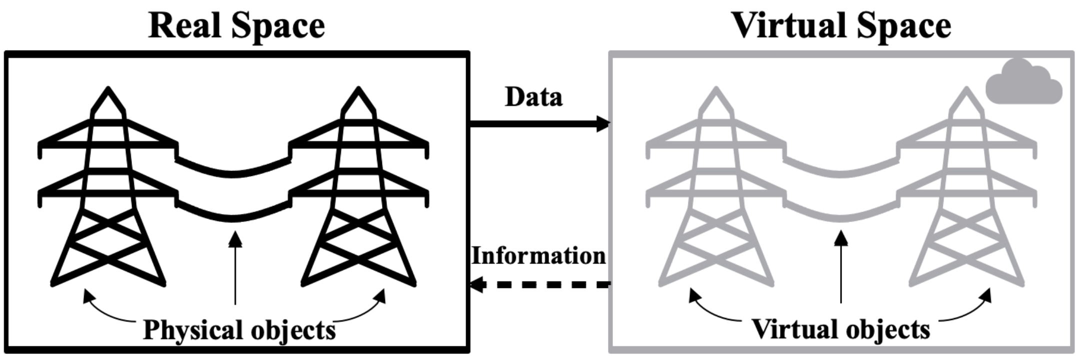
6 Dietz, M. and Pernul, G. "Digital Twin: Empowering Enterprises Towards a System-of-Systems Approach," *Business & Information Systems Engineering* (62:2), April 2020, pp. 179-184.

7 Enders, M. R. and Hoßbach, N. "Dimensions of Digital Twin Applications: A Literature Review," *Proceedings of 25th Americas Conference on Information Systems, AMCIS 2019: Cancun, Mexico, August 15-17*, 2019.

8 Saracco, R. "Digital Twins: Bridging Physical Space and Cyberspace," *Computer* (52:12), December 2019, pp. 58-64.

9 All companies mentioned in this article and the initiative are referred to anonymously.

Figure 1: A Digital Twin Model of a Utility Grid Network



Adapted from Grieves, 2015

real and the virtual spaces, that tie the physical and digital assets together.[10] Figure 1 illustrates the digital twin model of a utility power grid. The physical object, a network tower, is equipped with sensors that capture a continuous data stream of its capacity and load. These data streams form the core of the digital twin; they create a digital replica of the tower. Over time, the digital twin accumulates a data repository and uses that data for a variety of analytical purposes. Tasks the digital twin can perform include monitoring the grid's status quo, balancing its load, predicting faulty situations before they become reality and running simulations. The ultimate goal of a digital twin is to send information to its physical twin with specific recommendations for adjustments.[11]

However, variations of digital twins exist,[12] determined by the level of integration between the real and the virtual objects. In a "real" digital twin, both physical and virtual objects are fully integrated and exchange data and information on an ongoing basis in a bidirectional fashion and without manual intervention. In contrast, the data flow in a "digital shadow twin" is unidirectional (i.e., from the physical object to the digital twin). Another alternative is a "digital model," where data is only exchanged manually and its representation is often shorter and simpler. In this sense, a "real" digital twin is unique in several ways when compared to other IT artifacts. Unlike a "digital model," for example, a "real" digital twin represents a much closer approximation of the physical asset's characteristics and behaviors. Understanding the various facets of its physical counterpart and how the asset is embedded within the organizational structures—including its added value to the business model—is therefore vital and requires advanced analysis and design skills.

Moreover, and unlike traditional simulations where scenarios and conditions have to be specified selectively and upfront, digital twins enable real-time monitoring and analysis; by analyzing current and past data streams, they can switch between present, past and possible future scenarios. Analyzing risks in real time, scheduling predictive maintenance, planning for future upgrades and optimizing operations are just some of the tasks that digital twins can simulate and suggest, which is particularly valuable in rapidly changing environmental conditions.[13] However, these capabilities depend on digital twins being continuously coupled with their physical counterparts. In fact, if the coupling, which is predominantly based on a steady stream of accurate real-time data, is interrupted, the digital twin loses its lifeline.

It is therefore not surprising that organizations often perceive the high level of complexity involved in designing and implementing digital

10 Grieves, M., op. cit., March 2015.

11 Madni, A. M., Madni, C. C. and Lucero, S. D. "Leveraging Digital Twin Technology in Model-Based Systems Engineering," *Systems* (7:7), January 2019.

12 Kritzinger, W., Karner, M., Traar, G., Henjes, J. and Sihn, W. "Digital Twin in Manufacturing: A Categorical Literature Review and Classification," IFAC-*PapersOnLine* (51:11), 2018, pp. 1016-1022.

13 Enders, M. R. and Hoßbach, N., op. cit., 2019.

twins as prohibitive. While they understand that digital twins can open up unprecedented business opportunities, they also understand that creating digital replicas of all their products and associated business processes would require substantial resources and effort that could endanger the future of their business. Designing and implementing a successful digital twin requires continuously intertwining the real and virtual worlds, a full understanding of the physical object and its possibilities, and a steady stream of accurate and real-time data. It also requires a variety of competencies and an openness to critically reflect on existing ways of doing business.

Asset-centric companies, operating in a volatile environment where real-time monitoring is essential for their operations but data is scattered across the organization, are actively deploying or considering adopting digital twins. At present, industrial manufacturing companies are the most prominent players and are using digital twin technology to track their machines and the manufactured products they produce. Other industries are slowly following suit.

GridCo's Digital Twin Initiative

The energy sector is facing many external pressures. Renewable energies and their associated distributed production patterns, climate change and extreme weather situations all present challenges to the established, load-balanced and aging grid infrastructures of electricity utilities. Grid companies in Norway have implemented automated meter reading (AMR), which allows them to collect real-time data on energy consumption. Over time, AMR has been combined with other sensor technologies that can provide grid companies with a richer and more accurate informational base for monitoring and balancing their grids.

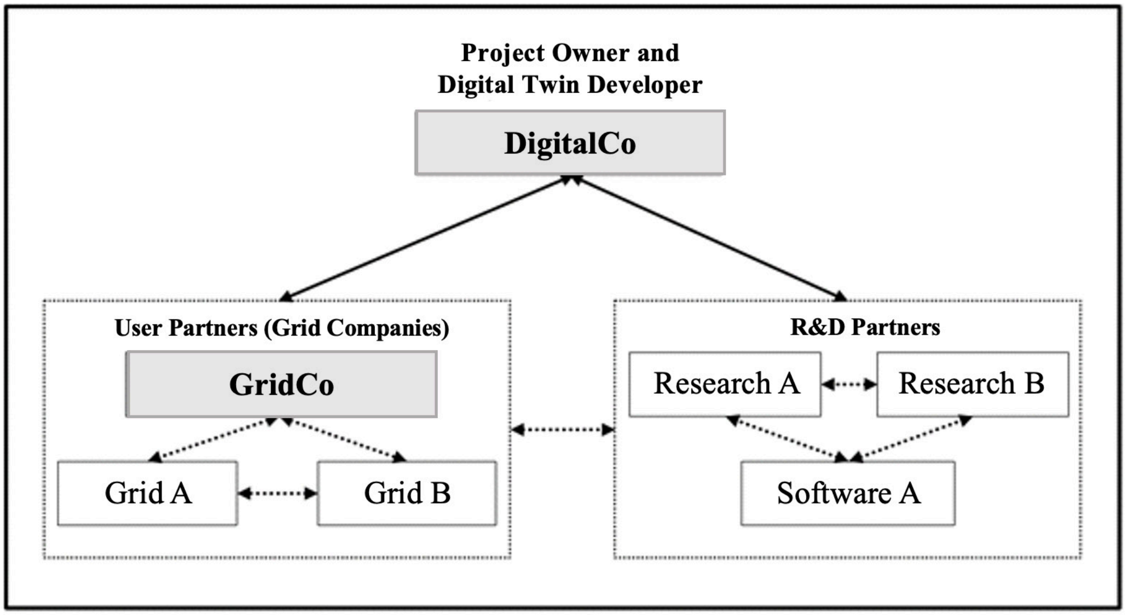
The GridCo case described below shows that the unique characteristics of digital twins required certain elements and approaches to be in place for the successful design and implementation of a digital twin. Specifically, organizational learning across hierarchies and departments, innovative co-creation and effective data governance were vital ingredients in the development of GridCo's digital twin.

Founded in the early 1900s with approximately 500 employees, GridCo is a large player in the Norwegian energy sector, managing more than 20,000 km of aerial power lines and underground power cables. It is responsible for building, operating and maintaining the regional and local grid network for distributing electricity to customers in a specific geographic area. GridCo has ambitious strategic goals and is undertaking a large digital transformation program, which implies major changes to the entire organization, ways of working, and increased use of data and digital technology. The overarching goal of the digital transformation is to optimize all resources for the benefit of its customers—businesses or private households within GridCo's concession area that consume (or produce) electricity. The digital transformation program aims to optimize both internal resources (e.g., human resources, data, technology) and energy sources within the grid network area (e.g., hydroelectric, wind turbines, solar panels, batteries).

Grid Co's digital twin initiative, which we refer to as DigitalGrid, is an important part of the digital transformation program. This initiative has its origins in 2017, when one visionary employee at GridCo was seated next to a representative from "DigitalCo," a software and digital solutions provider, at a conference dinner. The two talked about the possibility of developing a digital twin of the grid network in Norway, inspired by recent developments of digital twins in other industries. This led to DigitalCo presenting the DigitalGrid project to GridCo's very receptive management, which agreed to participate. Two other Norwegian grid companies joined the effort ("Grid A" and "Grid B"), along with two research institutes ("Research A" and "Research B") and a software provider ("Software A"). The DigitalGrid project structure and participants are depicted in Figure 2. Because GridCo played the biggest role of the three grid companies involved in the project, this article focuses on the relationship between GridCo and DigitalCo.

Driven by the increased digitalization in the offshore industry, DigitalCo was spun off in 2016 as a subsidiary of a long-established Norwegian company originally founded in 1814. This heritage means that, unlike GridCo, DigitalCo had a long history of technological innovations. Since 2016, DigitalCo has built expertise in developing

Figure 2: DigitalGrid Project Structure and Participants



digital twins, particularly in the oil and gas and maritime sectors. As shown in Figure 2, DigitalCo was the owner of the DigitalGrid project, responsible for developing the digital twin and leading the project. With its proven development environment and established position amongst industry partners, DigitalCo was able to exploit and more importantly transfer its experience of leading complex projects to the digital twin development for the energy sector.

DigitalCo had limited experience of the energy grid sector, so had to rely on GridCo (and the other grid companies) to provide insights and grid expertise for analyses and verification purposes, and to provide input on grid sector standards. The grid partners also contributed to the design of the digital twin. GridCo employees assigned to the project mainly came from operations (responsible for operating and maintaining the grid network in the short term) and development (responsible for maintaining and developing the grid network over the long term), though there were also some from the IT and the innovation department. Thus, most of the project participants were potential end users of the digital twin and, in addition to testing the usability of the solution, were able to provide feedback on features and graphical interfaces.

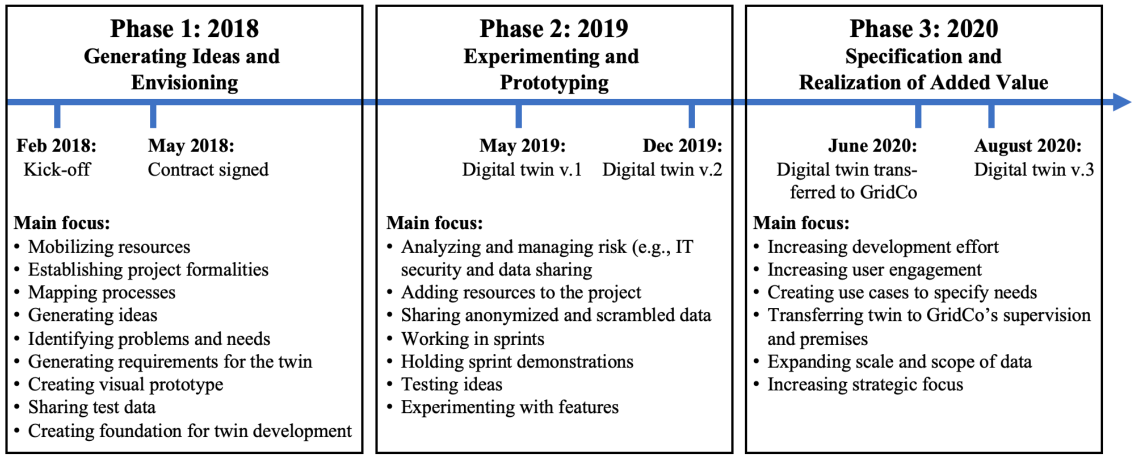
Research A and Research B (two of the R&D partners in the project) provided insights from ongoing research activities, in particular relating to smart grid concepts and optimization algorithms used in different industries. For instance, to ensure that the digital twin replicated the grid network, the underlying algorithms had to be adjusted to obey all electrical laws. The third R&D partner was a software provider, whose main contribution was related to the data architecture underlying the digital twin. The budget for the DigitalGrid project was 70 million NOK ($8 million)[14] and was financed by contributions from the Research Council of Norway, Innovation Norway, GridCo (and the other grid companies) and DigitalCo.

Three Phases of the DigitalGrid Project

The DigitalGrid project started in 2018 and was scheduled to take three years. As shown in Figure 3, the project proceeded in three phases: 1) generating ideas and envisioning,

14 Currency conversion rate as of late July 2021.

Figure 3: Three Project Phases



2) experimenting and prototyping, and 3) specification and realization of added value.

Phase 1: Generating Ideas and Envisioning

Considerable effort had been expended prior to the start of Phase 1 in February 2018, especially by DigitalCo. Having limited experience of the energy grid sector, DigitalCo put a lot of effort into understanding the details of the sector, including its wide-ranging legal landscape. The first tasks were to mobilize resources, establish project formalities and negotiate contract terms. GridCo officially signed the contract in May 2018, which included statements regarding GridCo's financial and human resource obligations for the duration of the project.

Once formalities and project details were in place, DigitalCo engaged an agency to facilitate workshops for mapping processes, generating ideas, and identifying problems and GridCo's needs. Four workshops were conducted, which were viewed as a means to include GridCo users in DigitalCo's thought process. As one participant observed:

> *"The people who initiated the project had a lot of good ideas beforehand. So, I think arranging those workshops was more to get the participants on board with those ideas, than necessarily getting the ideas out of them … But that's also an important process."* Respondent 21,[15] DigitalCo

The workshops generated a broad list of requirements for the digital twin, including must-haves such as "be flexible, available and customer friendly" and "be advantageous in both daily operations and fault situations." By thinking through requirements, participants were forced to consider the set of overarching goals for implementing a digital twin. Apart from generic goals such as "maintaining continuous distribution of electricity to customers," "giving employees opportunities to work in new ways" and "gathering all relevant information in one system," participants settled on the following goals for the digital twin:

- Contribute to an increased task efficiency through analytical support and automation
- Automate decision support
- Contribute to an increased up-time (i.e., reduce number and consequences of power outages)
- Contribute to faster repair of faults in the grid infrastructure
- Enable the simulation of grid changes before implementation.

Another output from the workshops was a visual prototype of the digital twin, which envisioned what the digital twin eventually could

15 As explained in the Appendix, we conducted interviews with 22 respondents, 20 of whom worked for GridCo and two for DigitalCo.

look like and provided suggestions for its design and features based on workshop discussions. During Phase 1, GridCo provided DigitalCo with an initial set of fictitious test data reflecting the grid network; the data represented the structure of the grid network, but not how it was laid out in reality, and was intended to provide a foundation for DigitalCo to start developing the digital twin.

Phase 2: Experimenting and Prototyping

Phase 2 commenced in May 2019. Before starting to develop prototypes of the Digital Twin, GridCo conducted a thorough risk assessment of IT security and data sharing. Data security is particularly important because the Norwegian energy sector is governed by the Norwegian Energy Act and The Regulation on Security and Preparedness in the Energy Supply. According to the act, data about the grid network is regarded as power-sensitive information and there are strict rules on sharing this data with outsiders. Accordingly, GridCo had information security agreements signed, established a secure file transfer protocol solution for data extraction and continuously evaluated risks. DigitalCo also assigned designated cybersecurity resources to the project. Once data and security measures were in place, development of the digital twin began, with DigitalCo assigning two full-time developers in Norway and a large team of developers from DigitalCo in India.

DigitalCo's developers worked in two-week sprints and arranged monthly virtual sprint demonstrations for GridCo users to update them on the development of DigitalGrid. Every third month, when the sprint demonstrations were a bit larger in scope, the team met face-to-face. The sprint demonstrations enabled DigitalCo to visualize the digital twin and show the development progress. In turn, these demonstrations generated discussions about the next steps in the development, with tasks being assigned to all parties, including GridCo users, DigitalCo developers and other project partners. The sprint approach continued throughout Phase 2, with DigitalCo expending considerable development efforts. A first version of the digital twin was launched in May 2019, and a second in December 2019.

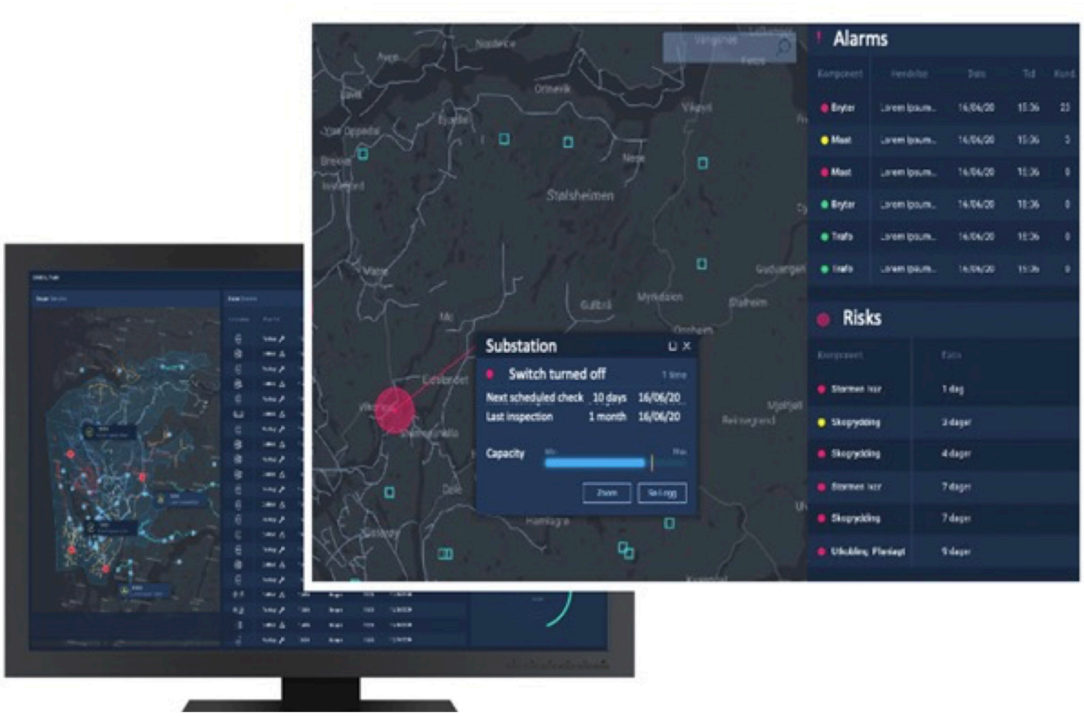
Overall, Phase 2 was characterized by exploring, experimenting and idea testing. DigitalCo developed proof-of-concepts and continually added features to the digital twin. The main focus during this phase was to develop features and tools for identifying and handling bottlenecks in the grid network. This involved implementing electrical calculations to identify voltage issues in the grid based on data from AMRs, as well as machine learning algorithms to suggest reconnections or changes in the grid network to accommodate these issues.

Because DigitalCo was responsible for developing DigitalGrid and carried out the work at its own premises, the data underlying the initial versions of the digital twin was not comprehensive. For example, the data was anonymized (because it is classified as sensitive power system information), did not contain any customer information and only represented approximately 3% of GridCo's network. Despite these restrictions, the first prototype of the digital twin had sufficient data to reflect the real grid network. The prototype was also continuously updated with new features. The second prototype, launched in December 2019, still included anonymized grid network data, but allowed informational updates on an hourly basis, including hourly consumption data at an aggregated level, as well as hourly switch position data (i.e., data on the configuration of the grid network). To comply with the Norwegian Energy Act, the data had to be scrambled (i.e., identifiable properties were removed) and shared through a common information model using a standardized XML format.

Phase 3: Specification and the Realization of Added Value

During Phase 3, which commenced in June 2020, DigitalCo assigned more developers, which not only speeded up the development but also increased the need to interact with GridCo users on a regular basis. As a result, GridCo was putting in more time as well. The two-week sprints and monthly sprint demonstrations were maintained in Phase 3, but the project was now more user driven. Concerned that it could end up with a digital twin that provided no value, GridCo decided to take a more active role during this phase to ensure that the digital twin

Figure 4: Digital Twin Screenshot



would meet its needs. Accordingly, GridCo users created specific use cases to guide the further development of the digital twin. These use cases represented specific needs that GridCo users had identified as part of their daily operations and as part of a long-term grid plan and were presented to DigitalCo as the areas on which to focus further development. DigitalCo agreed with the directions that GridCo users had suggested and linked features of the digital twin to GridCo's business processes.

Later in Phase 3, supervision of the digital twin was transferred to GridCo and the project was relocated to GridCo's premises. These changes allowed GridCo to expand the scale and scope of data used for the digital twin without risking the exposure of sensitive power system information. For example, GridCo widened the scope of structural data to include its entire grid network. The developers also implemented routines to increase the rate of extracting consumption and switch position data, moving from an hourly interval to real time. These features were included in the third version of the digital twin, which was launched in August 2020. There was also an aspiration to further increase the amount of real-time data from a variety of other data sources. Housing the third version at GridCo premises also enabled GridCo users to more actively test and use the digital twin and evaluate its ability to serve their needs.

During Phase 3, GridCo began to realize the strategic value of the digital twin, in particular, and the value of the DigitalGrid project, in general. As indicated in internal project documents, GridCo's management perceived DigitalGrid as valuable for preparing the company for tomorrow's challenges in a profitable and efficient manner because the digital twin enabled it to initiate future-oriented changes in the grid and to exploit and share data more efficiently. In summary, the digital twin had become an essential part of GridCo's digital transformation effort.

GridCo's Digital Twin Today

From the third quarter of 2020, the digital twin has been available as an application that presents users with a map of GridCo's network. The map shows all identifiable components of the grid network, such as house branch lines, distribution cabinets, feeder cables, grid substations, cable lines, substation departures and substations, in their exact locations. For each component, the digital twin provides accompanying information, such as voltage level, type of cable, length of cable, electrical properties, alarms and warnings.

The graphical presentation of the grid network components complies with predefined rules, based on grid sector standards. For instance, solid lines in the map represent underground power cables and dotted lines represent aerial power lines. If a power line is colored grey, no electricity is flowing through that line (i.e., the power switch in the substation feeding this cable is turned to "off"). A component highlighted in yellow indicates that it is reaching its load capacity (i.e., 80% of nominal current), and a component highlighted in red indicates that it is overloaded (i.e., over 100 % of nominal current). Figure 4 shows a screenshot from the digital twin. Note, in compliance with the Norwegian Energy Act, this image does not reflect real data.

Conceptually, the digital twin is built on an open information model, enabling GridCo to feed it with data from several sources. At present, the digital twin consumes the following data:

- *Grid network structural data:* Data about the topology and setup of the grid network, drawn from the network information system. It includes data about a variety of features for all grid network components, from metering points to substations
- *Consumption data:* Data about consumers' energy consumption, drawn from AMRs
- *Switch position data:* Data about the grid network configuration, showing from which substation and through which power lines electricity is flowing (i.e., how the grid is connected), drawn from the distribution management system.

GridCo anticipates that future versions of the digital twin will be able to consume more types of data, such as data from other internal information systems and grid sensors, as well as data from external sources, such as weather data. According to Respondent 1 from GridCo, "Everything that can be monitored in the grid in some way is very interesting." Transferring more and more high-quality data in real time from the physical grid to the digital twin will increase the power of the twin as a tool for running simulations, and providing support for decisions about operating, maintaining and developing the grid network. The features of GridCo's digital twin have proven valuable for operating and maintaining the grid network in the short term, as well as for planning and developing the grid in the long term. As summarized in Table 1, the digital twin is providing benefits in accommodating grid network challenges in three areas.

First, the digital twin provides *real-time* and *historical insights* of the network and all its components. GridCo users are able to monitor the overall electricity flow, the grid's capacity and the status of each component (ranging from larger substations to individual metering points

Table 1: Benefits of the Digital Twin in Accommodating Grid Sector Challenges

Beneficial Applications of the Digital Twin	Accommodating ...
(1) Providing real-time and historical insights	● Extreme weather conditions ● Aging grid network components ● Overloaded grid network components
(2) Running simulations	● Compliance with EU targets and Norwegian mandates ● New consumption patterns of increased electrification ● New production patterns
(3) Exploiting new technologies	● Overloaded grid network components ● Increased electrification ● New consumption and production patterns

in private households) as of now and at any point back in time. This allows GridCo users to identify bottlenecks in the grid and make adjustments to the configuration by, for instance, rerouting electricity from one substation to another and thus alleviating a supply problem in a specific area. As a result, GridCo users can address grid issues more proactively and, hence, prevent power outages from occurring. GridCo is also able to repair faults more efficiently based on information provided by the digital twin. This is highly beneficial because extreme weather situations associated with climate change, along with an aging grid infrastructure and several grid components close to peaking in capacity, have increased the complexity of fixing faults. Though existing information systems at GridCo's operation center were able to provide real-time insights of the network at a substation-level, the digital twin is the first tool to provide insights about lower-level components in the network and offer the ability to move backward in time to get an adequate view of the grid network's performance over time.

Second, the digital twin provides a *powerful simulation tool*, both for daily operations (e.g., suggesting solutions for bottlenecks by showing different scenarios) and for long-term scenarios. For example, in response to the European Union's 2030 Climate Target Plan,[16] the Norwegian government has set the objective of converting the entire Norwegian passenger ferry fleet to electric power by 2025. On average, ferries return to dock every two hours and will require electricity to recharge. With the help of the digital twin, GridCo users are able to simulate how recharging the ferry fleet will not only affect the load and capacity of the grid, but also how the flow of electricity for other customers is affected. Based on the recommendations from the digital twin simulations, GridCo users can make appropriate adjustments to reconfigure the network before the electric ferries become operational. Thus, the digital twin is helping GridCo to meet new demands for electrification and electricity consumption.

Third, the digital twin provided GridCo with the ability to envision new opportunities and exploit *new technologies* in the grid. Specifically, by installing additional sensor technology into the network and integrating these with the existing digital twin, GridCo is better positioned to explore greater flexibility. For instance, GridCo, together with DigitalCo, is experimenting with smart devices, such as adding (with the owners' permission) smart devices to conventional water heaters. Given that a 10-minute shower requires a water heater to be running for at least two to three hours after the shower has ended, and given that most people take showers during the same time period in the morning, causing a spike in electricity consumption, the use of smart water heaters opens up new possibilities for turning water heaters off and on based on the overall load and capacity of the grid. As one DigitalCo respondent explained:

> *"The water heater is kind of like a thermal battery, and it's very easy to move [when it's on or off]. It doesn't matter for you or your household. As long as the water is hot when you wake up or get home from work. And it's really very easy to move the load without it bothering anyone."* Respondent 20, DigitalCo

Recommendations for Designing and Implementing Digital Twins

Based on the input from our interviews, we have identified three generic themes that were highlighted by the respondents: 1) the digital twin project, almost inevitably, triggered organizational learning, 2) innovative co-creation played a key role in the development of the digital twin, and 3) initially, data governance hindered the development of the digital twin, but advanced during the project. Below, we describe each of these themes and, for each one, provide three recommendations for business and IT managers in organizations seeking to design and implement digital twins.

1. Digital Twins Are a Source of Organizational Learning

The DigitalGrid project involved several organizations working together toward the goal of developing a digital twin. The project evolved incrementally over time. GridCo was well

16 *2030 Climate Target Plan*, European Commission, available at https://ec.europa.eu/clima/policies/eu-climate-action/2030_ctp_en.

aware that the project constituted an ongoing learning process. This understanding was also one of GridCo's main reasons for participating in the digital twin project, as noted by a GridCo respondent: "The digital knowledge in the company has evolved. And that was one of the motivational sources for doing this in the first place: to mature the organization" (Respondent 8, GridCo).

Recommendation 1.1: Be Open to Tackling Challenges Together. By taking part in the digital twin project, GridCo was challenged to think differently, and the company developed a new understanding of the challenges and purpose of a digital twin. What started out as a broad idea was channeled by workshops with users in Phase 1, and then narrowed down by prototyping an initial digital twin with concrete, yet limited, features in Phase 2. Data security issues were addressed and viable solutions found for sharing data with the digital twin. Phase 3 was characterized by even closer cooperation and increased levels of specificity as GridCo users became more and more specific in expressing their needs and requirements, which DigitalCo accommodated. As one GridCo respondent admitted: "[over time], we probably have become a bit more [of a] 'demanding customer' … we have started to understand more, and started to become more specific" (Respondent 8, GridCo). Another GridCo respondent emphasized that challenges were viewed as important milestones of maturing:

> *"Through the project, we are challenged to think more thoroughly of what our problems are and what our needs are. They challenge us. The project challenges us. And that again results in competence building, and us paying a lot more attention to the market."* Respondent 7, GridCo

As learning matured, GridCo users were able to more actively specify their needs and demands for the digital twin, which, in turn, helped the digital twin mature. They acknowledged that learning was an active ingredient in the project, as was communication among project members:

> *"The benefit is that I can sit here and tell you what I'm telling you. I would've never been able to tell you this if I hadn't been part of this project. And it's not just me, that goes for the entire project. Being part of the project has developed our knowledge and matured us as a company."* Respondent 1, GridCo

Recommendation 1.2: To Think Outside the Box, You Need Outside-the-Box Competencies. Developing GridCo's successful digital twin required a mix of competencies. GridCo users' domain knowledge about electricity grid networks complemented DigitalCo's knowledge about process technology, data, modeling and simulation that it had accumulated over time by working in other industries. This complementary knowledge allowed developers from DigitalCo and the potential end users from GridCo to work together and adjust the underlying simulation algorithms to obey the electrical laws governing the grid network. GridCo also had a valuable learning experience from seeing what DigitalCo had accomplished by successfully implementing digital twins in other industries. Throughout the project, GridCo emphasized how DigitalCo, a newcomer to the energy grid sector, challenged it to think differently, introduced new technology and engaged with players unfamiliar to GridCo. This, in turn, enabled GridCo users to gain new insights into their own sector and invent new ways of working.

Recommendation 1.3: Create Use Cases for the Digital Twin that Go Beyond the Capabilities of the Physical Asset. Though the digital transformation aims were present throughout the project, it was not until later that GridCo fully understood the potential of the digital twin and how it would impact its entire operational and grid development practices. Both GridCo and DigitalCo were well aware that simply creating a digital clone of a physical product would not realize the full benefits of a digital twin. They understood that organizations have to sit down and contemplate which additional features are possible in the digital realm. In other words, digital twins of physical entities should be given additional attributes.

For example, while the physical grid provides readings about electricity consumption, its digital twin, because it is interlinked and exchanges data, is able to run simulations on predicted changes in consumption patterns. As an analogy, consider a chair. To mirror the physical aspects of a chair, one can easily envision a digital system that captures data about the chair's size and form, its shape and its fabric. But a digital chair might also hold information about when it was created, by whom, and how often it was sat on based on a sensor embedded in its cushion. This means the digital twin of a chair is not simply a twin but an enhanced twin. It has more characteristics than its physical counterpart.

In a business context, exploiting the additional characteristics of a digital twin can create new opportunities. For example, GridCo might consider integrating into its grid network sensor technology from electric vehicle chargers in customers' garages, solar panels installed on their roofs and other smart devices. Such integration would enable GridCo to build a truly self-controlling grid and lay the foundation for the grid to self-adjust to environmental and contextual circumstances. It might also provide the basis for fully replicating the grid network in detail in a digital twin (down to the smallest components). Organizations should therefore evaluate what additional characteristics a digital twin needs to have, as emphasized by a GridCo respondent:

> *"[We need to] study our processes: 'Where do we find that the digital twin can be the most useful or valuable?' And to do that we first need to understand what the digital twin is, and then we need to look more closely at our processes: 'Where can we get something out of this digital twin?'"* Respondent 6, GridCo

2. Successful Digital Twin Development Requires Innovative Co-Creation

Particularly during the initial idea-generation workshops and the subsequent sprint demonstrations, DigitalCo relied on the continuous exchange of views with and feedback from GridCo users. Both parties highlighted that the innovative co-creation approach to design was a vital ingredient in the success of the digital twin. For GridCo, the user-centric design approach was important to ensure that it was not just acquiring "yet another piece of software" and that the digital twin would serve its needs and accommodate its problems, both for daily operations and for future development of the grid network. For DigitalCo, a user-centric design was important to ensure that it developed a digital twin that is of value and utility for users. In the words of a DigitalCo respondent:

> *"It's really co-creation. The idea is to make the software together. That's the whole concept. To sit in the office and think you can come up with something genius without actually involving those who actually have a need, is hopeless."* Respondent 20, DigitalCo

Recommendation 2.1: Use Adaptive Storytelling to Engage Stakeholders with Challenges and Solutions. DigitalCo used various approaches to bridge the gap between its extensive experience of digital twin development and its limited knowledge about the energy grid sector, while also getting GridCo users involved. For example, DigitalCo used the idea of *storytelling*. The DigitalCo interview respondents used the Norwegian term "*historiefortelling*," which can best be understood as something in between fairytales and the descriptions of various scenarios. In the absence of a better translation, we use the term "storytelling" here. Specifically, DigitalCo engaged GridCo users (and management) in stories of grid sector challenges as a form of role play and to contemplate different scenarios. By doing so, it was able to demonstrate and often resolve how a digital twin could accommodate any or all of these challenges. The scenarios mostly related to GridCo as a company and the grid sector as an industry and accounted for relevant standards, rules and regulations.

GridCo very much appreciated how DigitalCo was able to illustrate the consequences and severity of grid sector challenges with the help of scenarios (the respondents even mentioned the term "horror-scenarios") and, eventually, with the help of a prototype. The storytelling approach enabled GridCo to envision a solution that promised to address many of its challenges, as confirmed by a DigitalCo respondent:

> *"It's all about telling a story about flexibility, problems and solutions. And then use our own tools to illustrate that it is actually possible to solve. Because people don't think it's possible, but it really is."* Respondent 20, DigitalCo

The storytelling approach not only provided DigitalCo with a better understanding, but—more importantly—also gained GridCo's buy-in to the project. By engaging GridCo users through storytelling, DigitalCo was able to learn about grid requirements while also creating a productive working relationship.

Recommendation 2.2: Foster Open Discourses Between the Parties and Carry Out Detailed Analysis, Especially in the Requirements Phase. Close collaboration also requires a commitment to communicate. Creating a digital twin is not just about replicating a physical entity, it also requires the developers and users to conceptualize it, which in turn requires exchanges and discourse among all players to ensure they truly understand the properties of the digital conceptualization. The need for this understanding was highlighted by a DigitalCo respondent:

> *"You really need to talk through all the details … and my understanding and respect for these things has just increased during the project. Because I can be quite pragmatic, kind of like 'Ok, now we have understood it, let's just get going!' But you can't just do that. And these differences, they're not just small nuances … they can be big differences. So, you need to talk your way through the processes."* Respondent 21, DigitalCo

In the GridCo case, the requirements phase received a lot, if not the most, attention, which was a key factor for the success of the resulting digital twin.

Recommendation 2.3: Encourage Continuous Stakeholder Feedback Throughout the Project, Not Just at the End. In developing the digital twin for GridCo's energy grid, DigitalCo not only modified its methodologies and frameworks but also adjusted its coding approach. As successive versions of the digital twin were illustrated during sprint demonstrations, GridCo users had the opportunity to provide feedback to influence the content and graphical interface of the twin. Moreover, as different versions were released, GridCo users had the opportunity to test drive the digital twin solution themselves and report back to DigitalCo on, for example, ease-of-use issues. DigitalCo learned early on that GridCo needed an intuitive design and thus relied on regular feedback from GridCo users to ensure that the digital twin and its features were consistent with familiar tools and had logical graphical interfaces. Such involvement from GridCo users also required that management was comfortable with experimentation, as explained by a GridCo respondent:

> *"I believe management has faith in us. I am allowed to test and fail a bit. So, I feel there is a proactive mentality in GridCo now, allowing us to put some speed to things. And that is a strength we need to get where we want to be. So, a culture where 'we can do this' and we are to be proactive, take some risks and see where it will take us. We are allowed to fail, and 'fail fast,' within certain limits of course."* Respondent 1, GridCo

3. Data Governance Evolves During Digital Twin Development

Though the origin of the digital twin project was a chance encounter between an energy executive and an IT executive, both parties were convinced of its value early on. Both GridCo and DigitalCo, realized that even a failed project would be beneficial for future IT projects, as emphasized by a GridCo respondent: "I believe that the great benefit of being part of this project is the learning and experience we get to take part in regarding both data security, and data exchange between internal and external systems" (Respondent 3, GridCo).

GridCo understood that it had to face data governance and associated security issues sooner or later—if not as part of the digital twin project with DigitalCo then with others later on. In that sense, GridCo took a calculated risk regarding data security when it embarked on the project. Nevertheless, and as GridCo experienced early on, data security was a tremendous and almost impenetrable barrier for getting the digital twin up and running. It certainly slowed down the initial phase of the digital twin project considerably. During the project, however, both parties' understanding of and competence in managing data security evolved tremendously.

Recommendation 3.1: Create Clear Guidelines for Managing and Exchanging

Sensitive Data Used in the Digital Twin. Because of the sensitivity of the grid network data, a significant challenge for GridCo was how grid network data could be shared with DigitalCo, given that the data was (and still is) classified as power-sensitive information. Moreover, GridCo lacked clear data exchange guidelines from management at the beginning of the project, and DigitalCo did not provide adequate documentation on data storage and management. However, as explained by a GridCo respondent: "The DigitalGrid project has contributed to opening our eyes to the complexity of IT security" (Respondent 6, GridCo).

Working together with DigitalCo, GridCo managed to eventually find viable solutions for exchanging data. The knowledge and experience gained about IT security and data governance were, according to GridCo, one of the greatest benefits of being part of the DigitalGrid project and would be valuable for other future settings as well. Though the Norwegian energy sector and the regulator's classification of data sensitivity may be peculiar for that country and sector, companies in other business sectors will likely face similar issues in their digital twin projects—particularly in Europe, where businesses are subject to the strict regulations and guidelines set out in the European Union's General Data Protection Regulation (GDPR).

Recommendation 3.2: Integrate External Stakeholders into Your Organizational Data Map. The DigitalGrid project clearly shows that a digital twin forces user organizations to rethink all of their data structures and sources. Even if not implemented, having discussions about what data would be necessary to create a digital twin can be extremely fruitful. Companies will have to rethink their data flows, and particularly their existing data silos, and in doing this they may discover that even the simplest form of a digital twin might not be feasible. They may also realize that some of the data depends on successful interchanges with other providers. In that case, they should consider including those providers as part of their organizational data map. The usefulness and performance of a digital twin, and its functionality, are directly related to the quality of data that feeds it, so it is vital that organizations analyze and possibly redesign their data structures and sources.

Recommendation 3.3: Expand and Contribute to Industry-Wide Data Standards. GridCo, along with DigitalCo, started off by conceptualizing a digital twin but quickly had to rethink its internal data structures, which led both companies to contribute to an industry-wide standardization effort. For example, to implement the digital twin, GridCo's entire grid network had to be converted to a digital format, along with all of the grid components and their properties. To achieve that, however, the map layout needed to be standardized. As a result, the grid network structure and configuration of the digital twin were revised to conform with standards in the energy grid sector.

Rethinking standards and data structures may also trigger further opportunities for industry players to collaborate and redefine conceptualizations and standards at the industry level. In the context of the Norwegian grid sector, for instance, GridCo's digital twin was the first to make use of the common information model that was established by DIGIN (*DIGitaliseringsINitiativ for energibransjen*), the digitalization initiative for the energy sector in Norway and a collaboration between Norwegian grid companies to ease data exchanges between them.

Finally, because of the challenges regarding data security and governance experienced in the digital twin project and the lessons learned, GridCo and its partners have embarked on a new project to develop a framework that grid companies can use to manage IT security and understand the regulations. The aim of this project is to establish a framework that will serve as an energy grid sector standard and help other grid companies with similar data-related issues in future projects.

Concluding Comments

As the DigitalGrid case has shown, developing a digital twin is not solely about creating a digital version of a physical asset—just as important are the mindset changes that the development of the digital twin will bring about. Building the digital twin to increase grid performance was important—but we argue that even more important was using it as a conceptualizing vehicle for organizational learning, co-creation and data governance. Put another way, the digital twin was a vital vehicle for reinventing how business is done. Though not appreciated at the start of the project, the reflections on the design of the digital twin and the subsequent implementation turned out to be important ingredients of GridCo's overarching strategy and digital transformation. We believe our recommendations derived from the GridCo digital twin case will be of value to other organizations as they embark on their digital twin journeys.

Appendix: Data Collection

The main data source over the three phases of the DigitalGrid project was interviews, which were supplemented by observations and archival documents. Overall, we conducted 27 semistructured interviews with 22 respondents during the three phases of the project (seven in Phase 1, 11 in Phase 2 and nine in Phase 3). Twenty of the respondents worked at GridCo, and two (interviewed during Phase 3) worked at DigitalCo and performed important roles in the DigitalGrid project. Seven of the GridCo respondents participated in the DigitalGrid project directly (mostly as potential users of the digital twin, but also as project manager, project owner and other project roles), three were managers not directly involved in the project, and ten were employees not part of the digital twin project but worked with processes where the digital twin could potentially be used. The data sources are summarized in the table below.

In the first two phases (2018 and 2019), interviews were conducted with respondents across a variety of positions and departments at GridCo, some of whom were more directly involved in the DigitalGrid project than others. In the third phase (2020), the interviews focused more on the DigitalGrid project. Each interview lasted between 40 and 90 minutes and was transcribed and translated from Norwegian to English to enable all authors to engage in data analysis.

In addition to conducting interviews, one of the authors spent one to three days a week with GridCo for the almost two years of the DigitalGrid project duration. As a result, we were able to complement our interview data with rich observations and documents relevant to the DigitalGrid project and the twin itself. These observations and documents were gained and obtained by participating in relevant meetings and sprint demonstrations, accessing formal and internal project documentation, and receiving demonstrations of the different versions of the digital twin.

To analyze the data (interview transcripts, observational field notes and archival documents), we used an open-coding approach with the objectives of capturing the specific characteristics of digital twins, understanding the relationship between the developer (DigitalCo) and user company (GridCo), and identifying themes that significantly contributed to the overall successful development of the digital twin. We then used the themes identified in the data to distill the recommendations for other companies seeking to design and implement digital twins.

Summary of Data Sources

	2018 (Phase 1)	2018 (Phase 1)	2020 (Phase 3)
Interviews	7	11	9
Observations	• One author spent 1-3 days per week with GridCo (September 2018 to July 2020) • Participation in meetings, seminars and workshops • Informal conversations with project members • Demonstration of the digital twin versions • Participation in sprint demonstrations • Field notes		
Documents	• Formal project documentation • Internal project documentation (GridCo) • Strategic documents (GridCo) • Other relevant documents		

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