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DIGITAL TWIN BARRIERS

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1.0	23.02.2021	Final	

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EXECUTIVE SUMMARY

The introduction of digital twins in SME companies is challenged by technological and organizational barriers. In this deliverable, we identify those obstacles that hinder accelerated adoption and implementation of Digital Twins.

Furthermore, we identify key barriers that could be solved by Digital Innovation Hub (DIH) and Change2Twin participants, and others not prioritized in Change2Twin but instead solved by others.

To this end, a series of mitigation techniques are suggested, aimed at addressing the barriers, classified by stakeholder type.

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1 DOCUMENT SCOPE

This report describes barriers [2] that hinder the uptake of Digital Twin technology by SMEs. The target audience of this report are SME companies in the smart manufacturing and production industry domain.

The justification for this document is – as it is for the project Change2Twin as a whole – the slow uptake of Digital Twin solutions by SMEs.

The audience for this report is Digital Innovation Hubs (DIHs), Change2Twin participants and other SME companies who stand to benefit from enabling digitization, specifically through the application of a Digital Twin solution.

To build a common ground for understanding, Chapter 2 provides definitions and discusses aspects and challenges of digitization, in general.

The analysis used to identify the barriers started from the following three sources:

1) The project use cases, with input from specifically Task 3.1;
2) Experiences of the project team, especially use case owners and solution providers, from their daily operations;
3) Existing studies and literature (see Chapter 6).

Chapter 3 distinguishes organizational and technological barriers. They are assigned unique identifiers for reference within this, and in subsequent, reports.

This report has the objective to help overcome the barriers. Chapter 4 introduces a high-level methodology that applies consulting tools to establish appropriate actions.

It is beyond the scope of this report to identify enabling technologies that help mitigate the barriers. These will be elaborated in Deliverable 1.3.

[2] The definition of the word *barrier* is meant as *that which keeps apart or makes progress difficult*. In other words, we use it interchangeable with either *challenge* or *obstacle*.

2 COMMON UNDERSTANDING

SUMMARY— We need to start from a basic common understanding and terminology of the Digital Twin *to be able to discuss the identified barriers hindering the adoption of Digital Twins. We provide a conceptual frame supported by the definitions:* A Digital Twin is a digital representation of an artefact, process or service that is sufficiently accurate that it can be the basis for decisions. The digital replica and physical world are often connected by streams of data.

Change2Twin will address Digital Twins of artefacts, processes and services associated with manufacturing. *In more complex cases, the solution is itself dynamic and involves combining different models, information sources and business processes and purposes, making it a cross-disciplinary challenge. Complexity increases when the Digital Twin becomes a part of the system it supports and, subsequently, has its own lifecycle management needs concurrent to that of the Physical Twin. The foundation for having an effective and efficient Digital Twin solution that SME companies can adopt, relies on a clear and agreed understanding of what the Digital Twin is understood to be, what value it is capable of bringing, and how to be able to manage it in the context of an operational system and business process in the Smart Industry setting.*

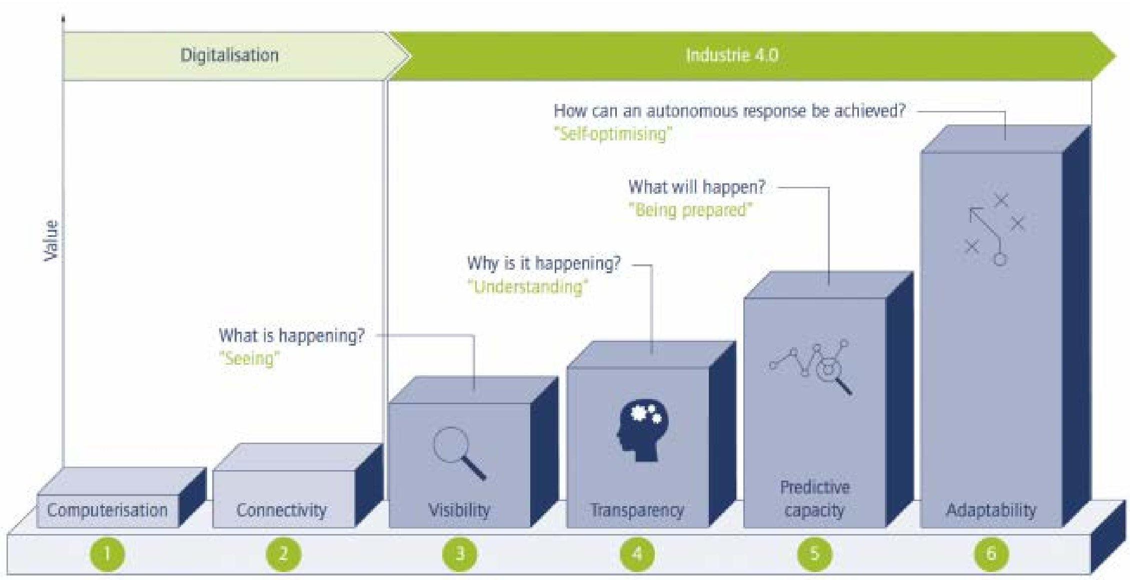
2.1 SMART INDUSTRY

Smart Industry (SI) stands for three main transitions:

1) Radical digitalization
2) Connecting products, machines, and people
3) Use of new production technology

The Dutch SI program, for example, has eight focus areas surrounding these transitions, namely smart products, servitization, Digital Factory, connected factories, sustainable factory, smart working, advanced manufacturing, and flexible manufacturing, shown in the following figure.

The SI initiative involves a major transition in a very diverse landscape. Most companies are still figuring out challenges relating to connectivity, while the end-goal is to engineer, operate and maintain an adaptive autonomous, and in the extreme case, self-aware, solution. These are represented by Levels 2 and 6, respectively, in the stages in the Industry4.0 development path, shown in the figure below.



Digitalization happens across all 6 stages, while the Digital Twin, an advanced form of Digitalization, happens when we start addressing the challenges in Stages 4 through 6.

2.2 SHARED DIGITAL TWIN DEFINITION

A Digital Twin is a digital replica of an artefact, process, or service sufficient to be the basis for making decisions. The digital replica and physical world are often connected by streams of data. Change2Twin will address Digital Twins of artefacts, processes and services associated with manufacturing with a goal being the devise and promotion of active use of a suitable ecosystem and marketplace that will accelerate affordable availability and give clarity to the market.

Grieves is recognized as coining the term Digital Twin, first using it to describe digital Product Lifecycle Management "information as a *twin* of information embedded" in "the physical system throughout its lifecycle" (Grieves & Vickers, Digital Twin: Mitigating Unpredictable, Undesirable Emergent Behavior in Complex Systems., 2017). Increased popularity of the term and availability of modern computing, engineering and management paradigms and practices, have promoted the Digital Twin as a key enabler of advanced digitalization.

The concept of the Digital Twin is by no means new. Cutting-edge and emerging technologies have made it possible to realise a Digital Twin solution capable of much more than previously possible. However, before the term was coined, the concept might have been referred to as an advanced version of a computational mega-model, a synchronized virtual prototype[3], or a device shadow. More generally, it may have been defined as an adaptive model used in an operating stage of a physical system for some specific purpose (Rasheed, San, & Kvamsdal, 2019).

In general, a key challenge hindering the widespread adoption of the Digital Twin is having an accepted shared definition and common language amongst experts and users. This is echoed by the current industry-led initiative, like the Digital Twin Consortium (Object Management Group, 2020), whose aim it is to have consistent vocabulary, architecture, security, and interoperability of Digital Twin technologies.

[3] A virtual prototype typically misses key aspects of a Digital Twin that mirrors an existing physical system with a data link. Synchronizing the virtual prototype is an earlier form of what we could consider a Digital Twin.

A survey of different solutions shows that different complexities and solutions make it possible to define the Digital Twin differently (Kritzinger, et al., 2018). However, in its simplest form and at its core, the definition provided herein underpins the more domain-specific and elaborate definitions.

A simulation makes it possible to combine physics-based and data-driven modelling to mirror the fusion of the real with virtual worlds (Rosen, Boschert, & Sohr, 2018). Simulation is considered essential and intrinsic to advanced digitalization. Digital Twin as an enabler of advanced digitalization is expected to harness the synergy between modern technologies of computing and engineering paradigms like High Performance Computing, Internet of Things (IoT), 5G technology, and Virtual Reality (Gunal, 2019). Current trends of AI and Machine Learning, and in particular Federated Learning, introduced the concept of online twinning, i.e., where the model improves itself (Bellavista & Mora, 2019).

Moreover, the Digital Twin is considered revolutionary because it reaches across different Industry domains. The underlying simulation models are increasingly complex, mirroring physical process complexity they represent (Boschert & Rosen, 2016), while new techniques in managing model complexities are necessary to operationalize the solution for the business process – a further complication to delivering an efficient and effective solution.

The complexity of the Digital Twin increases as the nature of the physical system, the purpose for which the twin is used, and the number and kinds of participants involved in developing, using and maintaining the solution, increase. Dealing with the complex dynamics of the system requires an adaptive, autonomous, and evolutionary solution. Recognizing the concurrency of having a continuously fit-for-purpose Digital Twin is essential to having an affordable, accessible, and appropriate solution. Maintaining unbroken cradle-to-grave digitalization is a real advanced challenge (Pileggi, Lazovik, Broekhuijsen, Borth, & Verriet, 2020) but is essential to avoid having to redesign and redevelop an expensive custom Digital Twin solution.

2.3 DIGITIZATION CHALLENGES AND OPPORTUNITIES

A key objective of the Industrial IoT (IIoT) is to embody IoT technology in the industrial decision-making process. IoT is considered an enabler of the Industry 4.0 vision, able to generate a myriad of data, multiplied by networking effects, usually aggregated, and stored on edge or cloud platforms (Xu, He, & Li, 2014).

In particular, in manufacturing, the efficient integration and management of IoT devices can open the door to new services and opportunities including, but not limited to, predictive maintenance, continuous monitoring, scheduling and remote running of maintenance interventions, process reconfiguration, and so forth, while achieving desired KPIs, process– and product-wise. All these capabilities could be evaluated and made possible through a Digital Twin implementation.

2.3.1 Digitization needs

The overall goal of IIoT technology and platforms is to enable and facilitate decision-making under the quality constraints imposed by the application domain and deployment environment, bringing gains in efficiency, safety, and stability of the IIoT system. In order to implement and deploy a Digital Twin, some key technological aspects need to be considered that are crucial to its success:

Connectivity: It is the basic building block enabling the interactions with and among connected things, feeding data from and to the Digital Twin and the physical process(es) spanning their full lifecycle. In this context, different options are available, differentiating from one another depending on cost and flexibility.

Industrial wired data acquisition and control networks, e.g., Fieldbus profiles standardized under IEC 61784/61158 or the more recent Time Sensitive Networking for Industrial Automation standardized under IEC/IEEE 60802, have been the cornerstone of industrial automation, guaranteeing high reliability and real time communication among things. While capable of fulfilling (strict) reliability and latency constraints, wired networks are expensive to deploy and maintain, making them unviable for many potential adopters. Fortunately, recent advances in wireless technologies, like 6TiSCH, Wireless HARD, Private 5G and the upcoming industrial WiFi7, will allow IoT technology to realize the Industry 4.0 vision, and currently more wireless networks are being deployed (Emerson, 2020).

Moreover, industrial and low-power wireless communications are converging, boosting the capabilities of IIoT. First, low-power wireless technology has shown capable of fulfilling reliability and power consumption requirements of industrial applications. Second, different standards have emerged factually enabling the convergence of low-power wireless and the Internet Protocol, greatly simplifying their integration into existing networks qualifying the technology as the true *eyes and ears* of the industrial Internet.

Data: A Digital Twin needs data collected from and about its real-world asset over its full lifecycle. In a standalone Digital Twin solution these data include:

- design data pertaining to the real-world asset, which include, e.g., design specifications, process and engineering data;
- manufacturing data including, e.g., production equipment, material, method, process, quality assurance and operators;
- operational data including configurations both hardware and software, telemetry and real time and historic usage data, and maintenance records) of the real-world counterpart (Boss, et al., 2020).

Depending on the scale and scope of the manufacturing domain, potentially different and heterogeneous communication standards, protocols and technologies could be employed to save and transfer data. These conditions further exacerbate the problem of understanding, finding, accessing and extracting relevant data needed for use case-dependent applications. In this context, the use of semantic frameworks and modeling approaches, such as the one proposed by RAMI 4.0 (DIN Spec 91345), coupled with data pipelining approaches, helps alleviate the data chaos. This constitutes the basis for a structured data extraction and filtering feeding the twin.

Modelling: The Digital Twin may contain different and heterogeneous computational and presentational models pertaining to its real-world counterpart. This may range from first-principle models adhering to natural laws, data-driven ones, e.g., statistical, machine learning, etc., geometrical and material, e.g., CAx models, like Computer-Aided Design/Engineering (CAD, CAE), or visualization-oriented ones, like mixed-reality. Hybrid approaches are also possible, e.g., the use of virtual-augmented reality complementing the physics/data-oriented ones or the use of physics simulation or modelling and AI-based approaches that alleviate problems, like those related to training data scarcity.

Considering the fast pace adoption of AI-based techniques in the manufacturing domain, the following technical issues arise which pose a significant burden for SMEs:

- **Data Labeling Effort**: Data-driven approach used for training the AI components usually require much cleaned and labelled data. The effort to create this trained data is considerable and should be optimized. The quality of data or labels is also important and of paramount importance.
- **Concept Drift**: It refers to the phenomena of deterioration in prediction accuracy, and usually occurs due to unforeseen changes on the learned statistical properties of the target variables being predicted.

- **Quality of Training data**: No model is better than the data upon which it is built. If the training data does not accurately represent the underlying task distribution, the model will not be able to learn the true phenomena. It is therefore important that industries have robust procedures for training data extraction and preparation.

Deployment: A Digital Twin can be deployed on the cloud-to-thing continuum, starting from the thing (lightweight/IoT Digital Twin), the edge and/or the cloud.
The specific deployment criteria depend on the scenario requirements and is typically based on:

- latency requirements, e.g., measured in terms of response time;
- security/privacy considerations of information flows;
- scope of the Digital Twin, e.g., whether we are dealing with a standalone solution or part(s) of a bigger system.

Without loss of generality, different deployment possibilities arise depending on device/IoT capabilities, objective and scope of the Digital Twin:

- **IoT Twin**: Lightweight Digital Twin deployed on premise or onboard the CPS machine performing utility tasks for quality management operations (low latency and high reliability). This twin gathers data from the physical twin forwarding them to a higher control entity, like an Edge Twin. Considering the constrained nature of this device, no training takes place and this process is often delegated.
- **Edge Twin**: Higher order control entity running on premise of the production site, i.e., plant gateway, tasked with the lifecycle management, i.e., deployment, instantiation, control and tear down, of locally deployed IoT twins. The entity performs computationally expensive tasks, controlling and gathering data from locality IoT twins, providing control knobs allowing local optimizations and interoperability.
- **Cloud Twin**: This resource rich environment, if employed, has a global scope, acting as a logically centralized repository of data. It is tasked with performing time-consuming and typically off-line simulation and training of models. The models are then successively feed to the edge twin consisting of, e.g., pre-elaborated predictive models that can be efficiently executed on premises of the production plant.

APIs: Digital Twins by nature need to interact with other components, e.g., other Digital Twins in a composite system or an operator consulting the system. To facilitate these interactions, various APIs must be in place allowing for information collection and control between the twin and real-world counterpart. Depending on the use case, different mechanisms are available:

- bulk or offline data access, e.g., through databases or any other form of repository containing relevant data to the twin;
- online data access, e.g., through RESTful APIs or any streaming technology available;
- management and interaction APIs enabling information exchange among cloud-to-thing continuum twin components (such as cloud-to-x, device-to-x);
- interoperable APIs facilitating information exchange among twins from different vendors.

Security: Considering the role and scope of the Digital Twin, its interactions among the physical and digital world require the implementation and deployment of security mechanisms aimed at:

- providing secure access to the Digital Twin contents;
- securing and attesting the information flow among the twin and the real-world counterpart and among twins in a composable system;
- securing the cloud to thing continuum, hence deployment environment and software updates.

2.3.2 Regulation and the law

Although it may be thought that the law changes relatively infrequently, changes typically have significant impact. Regulatory changes could have significant impact. Considering the effects digitization has on society, there are important considerations to be made early on when devising or selecting new or advanced digitization technologies, methodologies, and strategies.

The legal status of production, use and sharing of data, ML models and other smart properties is essential to enable legal accountability and traceability throughout the supply chain that make possible complementary regulation instruments as a means of self-regulation. The certification approach for non-deterministic processes makes the legal evolution of the servitization of manufacturing products a complicated task.

Ultimately, we should safeguard human self-determination and foster human empowerment. To achieve this, we need to be mindful of the various challenges related to law and regulation.

2.3.3 Innovation and business models

The lack of clear vision of a strategic holistic approach makes it hard to access the growth potential of Industry 4.0. Understanding the possibilities and benefits that can be achieved, will help with leadership. Even if manufacturing companies understand technological enables of opportunity, like Digital Twin, robotics, and AI, they require diverse human talent in many areas, like data and industrial IoT, and the profound roles required to support the vision.

Then there is the challenges of data and the speed to access, manipulate and manage it in a more complex connected supply chain with different stakeholders using it for different purposes and with different measures of success. This leads to a changing customer or partner, who has an increasing need to be more than what that have been before. This leads to a highly competitive landscape where those who move faster stand to benefit more, perhaps even becoming disruptive.

Leveraging new ecosystems and data to survive or thrive, companies need to diversify and access new revenue sources. Strategic choices are determined by servitization, but they are not always comprehensive. Uneven comprehension threatens the digitization effort as it opposes progress, cancelling it.

The lack of trust among parties, the concern of confidentiality and Intellectual Property (IP) protection, and the uncertainty about safety, security and liability conditions are some of the challenges to B2B data sharing. Analysis of enabling factors that promote the sustainability, replicability and scalability of data-driven Industry 4.0 models proves particularly hard.

2.3.4 Digital Skills and competences

In Data Science alone, job titles include the data engineer, scientist, and architect. Combining the knowledge of these roles is essential to a holistic solution but the care and skills required to develop, deploy, operate, and maintain their solutions successfully are grossly underestimated.

Development and recognition of digital competencies are essential to having skilled people who can have the ability to engineer a solution that brings the desired benefits. However, the systems we support are becoming more complex, harder for a single individual to handle. Separating concerns for those involved is becoming more important. While being a specialist in their own role, they need to be aware of the complementary roles to not complicate or hinder the system of experts working together to achieve the holistic solution.

Education and training of both IT and subject matter experts in the various sectors of the industry are essential to maintaining a manageable solution. An increase in the demand for high-skilled workers will result in more potential for job opportunities, like data scientists, in the next years.

3 DIGITAL TWIN BARRIERS

The uptake of Digital Twin by SMEs is hindered by obstacles. We classify these as being either technological or organizational. Where a barrier could be classified as both, we classify it as that which we find most appropriate. Moreover, we consider cultural aspects to be organizational.

Each barrier is identified using a corresponding label for reference later on.

3.1 ORGANIZATIONAL BARRIERS

3.1.1 [BAR-O1] Lack of visionary leadership

Having a clear vision of what leadership wants to achieve is crucial. Apart from knowing what the Digital Twin is, leadership should be clear on which business goals it should help to achieve.

Understanding the very diverse range of applications and knowing about which performance indices are typically affected helps align the future business ambition with the technical and operational aspects of what the company does.

Forming an ecosystem, and knowing which partners need to be involved, and how each contributes to a healthy competitive environment with shared R&D costs and affordable commercial offerings for large companies and SMEs alike would be beneficial in long term.

3.1.2 [BAR-O2] Unprepared for change in working practices

Working practices are changing. Digital transformation of the SME and their partners lead to new ways of working and business models. Being unprepared or resisting change can be detrimental to accessing the benefits that Digital Twin brings or can in the worst scenario lead to issues with the business.

As an integrated solution, Digital Twin unites different departments and disciplines to achieve business goals more effectively and efficiently. Workplace silos may need to collapse to achieve this. This may lead to changing workplace practices if there are tangible and measurable benefits or should the solution scope cross current silo borders.

Different participants in the same or co-operating organizations may:

- use different tools of the same, overlapping or disjoint domains, all of which contribute to the same Digital Twin data set;
- apply different data quality and release processes;
- have different measures of success.

The participants need to be convinced that the system gives benefits and is safe and useable. This poses a significant challenge when different people have different ways of understanding the same process. This is exacerbated by the fact that their working habits and understanding of the business may be fundamentally different.

3.1.3 [BAR-O3] Many open questions

As an enabler of digitization, Digital Twin enables new means and mechanisms that lead to innovation not only in technology, but also in new and alternative business models. This means that there is much more choice as to what to do and what to prioritize.

E.g., an operator is incentivized to have a comprehensive monitoring and optimization twin, while vendors can benefit from obtaining data during operation of the product twins. Sharing and collaboration for simulation and analytics can be favorable.

We need mechanisms that ensure fair rewards, pertaining to:

- **sharing responsibility**, where the creation and maintenance of a Digital Twin requires a dedicated organizational unit to manage the computational and network resources to operate the twin and the repository with its data connectors.
- **ensuring secure access**, where a Digital Twin is an extraordinary precious asset as the value of individual data sets from CAD, CAE, CAT, product lifecycle management, etc. is increased by combining them. The Digital Twin owner needs to have the capability to provide appropriately secure access methods.
- **protecting IPR**, where many organizational units contribute to a Digital Twin; not all of them will belong to the same organization. Agreements and technical solutions need to be put in place to ensure data ownership.

Monetizing through the use, re-use, repurposing, and servitization of Digital Twins or parts thereof are often unconsidered additional benefits for the Digital Twin owner.

3.1.4 [BAR-O4] Unclear ecosystem support

There is still much market confusion: Digital Twin purposes are many and varied. Moreover, the technical solutions support different ways of achieving the business goal. This means that solutions can become pricey and quickly complex.

The business landscape of the Digital Twin business is not entirely clear. Project-based consultancy firms are acquiring different solution provider companies, creating Digital Twin offerings that do not fit their current operating model well. Moreover, suppliers of models, data, and even Digital Twin integrators are neither clearly nor well-established yet.

The generic IT technology currently constitutes a small fraction of the entire cost of the Digital Twin solution, mostly a customized siloed solution. This market confusion hampers the progress of making Digital Twins a viable option, especially for SMEs, not only regarding its development, but also its operation and maintenance.

Although many standards and best practices exist for different technologies and methods used in digitization, there is a lack thereof for integrated Digital Twin solutions.

Standards and best practices are necessary to foster the development and agreement of a common language that can relieve quite some uncertainty in the intra- and inter-organizational and business relations. Moreover, a marketplace that supports a Digital Twin community for the models and reasoning tools would help companies monetize on Digital Twins that they spend money to develop and maintain.

A lack of an accepted basic definition and common language, standards, and best practices, also results in a technological challenge, in that, requirements are hard to identify and address when different terms and ambiguous solution definitions are plentiful. By addressing this organizational challenge, we enable more focussed technology.

3.2 TECHNOLOGICAL BARRIERS

3.2.1 [BAR-T1] Keeping it fit-for-purpose

The Digital Twin is a combination of

- data, giving insight into past, present, and future status of the system,
- system (model) knowledge, giving a view of aspects of the system as best we know it to be, and
- purpose-related models or algorithms that use the data and system knowledge (model) to calculate some fact about the system.

These cater specifically for some technical purpose that forms a part of a business process and supports a business goal. Depending then on the purpose, all of the data, system model and purpose model, need to be such that the Digital Twin is fit-for-purpose. And more than merely being fit-for-purpose, we need to be able to evaluate the fitness of the Digital Twin to continuously be sure it is working correctly to be able to update it and once the updates are in effect.

Complicating matters even further, system knowledge is often incomplete, inconsistent, or incorrect. ML and AI offer some support but introduce other challenges, having their own limitations and challenges like low interpretability and explainability, or requiring infeasibly long time to learn patterns. Still often valid they can either constitute a part of the system model, or the purpose-related model. The key challenge is making it operational, which requires expert skill.

3.2.1.1 Access to Quality Data

A sufficiently comprehensive Digital Twin has multiple concerns. It can produce substantial volumes of different data types, at a significantly high rate. A specialized user must be able to find the necessary useful information quickly, easily and without confusion.

Moreover, since a Digital Twin can also benefit from the large data repositories and live streams from the environment in which the physical twin operates, data federation involves combining different potentially enormous data sets with streams of potentially real-time information. The organization of this infrastructure can assist in effectively identifying and accessing quality data.

More challenging part is the consideration of sensitive data. Certain data is protected by privacy laws, others are business secrets. Not only is this a challenge of data locality, but it may require controlled, and result in limited, analysis. If the data can be discovered from the results of some analysis, the solution will not be used.

Different stakeholders who would use certain information for different purposes, will consider the quality of said data differently. This may also bias the solution to provide better access to different data, depending on how requirements are identified and integrated into the system.

Even though there is quite often much data available, it is often the case that there are too few events to train data-driven models, since they require a significant number of relevant samples that can then be used to classify or predict future events. Specifically, in industry, relatively large safety margins are in place resulting low failures, especially given the zero-defect engineered systems already in place.

Quality data is then data that is suited to the purpose. Collecting and making data available in time is relatively easy. Federating and processing that data is a consideration with expert knowledge of the system and the models (especially ML models) used for a specific purpose.

3.2.1.2 Having the right model fidelity

The Digital Twin solution needs to be fit-for-purpose. For the modelling exercise, this means that the abstraction level of the models must be suitable to be able to capture the salient features of the system that contribute to system's performance. The principle of parsimony helps avoid having an unnecessarily high level of fidelity, which in turn, could lead to a higher demand for computational resources and greater complexity, resulting in a challenge to understand and formally validate models for the sake of trusting them.

However, it is not always clear which features are salient. The same argument is made for the information available – or not. A strength of the Digital Twin is that the synchronization with real currently relevant data of the physical system, enables more appropriate evaluation and results. The challenge lies in understanding which are the information currently relevant, and how to make them Findable, Accessible, Interoperable, and Reusable (FAIR) (Wilkinson, Dumontier, Aalbersberg, & Appleton, 2016). These qualities are key to deriving most business value from the data.

The purpose also needs attention to be able to make sure the model and data infrastructure and applications can be evaluated as being fit-for purpose. Management criteria, like SMART (Doran, 1981), i.e., Specific, Measurable, Achievable, Realistic and Timely, can help focus efforts and increase chances of achieving the goal and can be used to relate the fidelity of the purpose to that of the model and data qualities.

Finding the right fidelity, or granularity configuration, of the Digital Twin solution is a crucial task for an effective and efficient solution. It requires realizing the complicated juxtaposition of these considerations; too much detail may become very expensive or infeasible, time-consuming to develop, implement, and maintain, and too complicated for SMEs to understand, manage, and eventually trust with a necessary level of confidence. The opposite also proves an obstacle, namely having a solution that does not bring value, yet will come at a high cost. Dealing with the unknown and uncertainty is yet an even further complication.

3.2.2 [BAR-T2] Maintaining reliable operation

One of the benefits of the Digital Twin is that it can be used throughout the lifecycle of the real-world twin. It can either be used in the same or a different way in each stage of the system, depending on the purpose or the user.

Lifecycle management of a Digital Twin is an important challenge to address because it is a complicated software and hardware system to manage. It combines lifecycle information, measurements of the asset state and simulations. They must be maintained by lifecycle management technology to reflect the actual state of a system. This includes new processes, like cognition, which naturally leads to self-awareness to support efficiency and validity.

The Digital Twin must be designed, built, tested, deployed, operated, maintained, and disposed of. Exacerbating these tasks, as a complex Digital Twin involves different stakeholders from different organizations, concurrent development and operation quickly becomes tricky. IT systems are necessary to be able to debug and understand what happens to the Digital Twin to use and improve it effectively.

Maintenance includes both upgrading the software system, hardware components, and the digital replicas (models) in the system. When they change, managing the ownership and control, as well as the effects these changes may have, are crucial to a Digital Twin that continues to bring value effectively, efficiently, and especially in an affordable way.

In all, without lifecycle management technology for the Digital Twin to ensure reliable operation that brings continued value, the Digital Twin solution will only be relevant for a limited context and eventually become obsolete, requiring expensive and time-consuming reparation turning this activity into a nightmarish endeavor.

3.2.3 [BAR-T3] Ensuring effective execution

A sufficiently comprehensive Digital Twin will require substantial computational resources likely to be distributed over a cloud that combines private and public clouds with vendor platforms and HPC resources. This design will need to carefully define what needs to be done on the edge of the system, and what is done in the cloud edge computing environment to deal with computational overload especially.

Distributed co-simulation of different kinds of models, synchronized with the actual system state, require design patterns to be effective. Current HPC and cloud native solutions are not generic enough. They require expert architecting of continuous development and deployment of the Digital Twin solution, pertaining to efficiency of shared computation, communication, and storage resources.

Scaling-up with a more powerful machine is not always the scalable way to ensure continued operation. Distributed architectures that ensure the growth and evolution of your system requires careful consideration.

Beyond the issue of scale, security is not always consistent, which means a secured-by-design solution is needed for a generic approach as IP and safety are typically critical for the industry domain.

3.2.4 [BAR-T4] Accounting for uncertainty

A Digital Twin is only as good as the data, and simulation and reasoning models used in the solution. Data must be cleaned, reconciled, and become understood by those who wish to inspect them to increase trustworthiness of the system. Models (even *first principles* ones) must be validated and tuned to ensure they follow the state of the facility.

System engineering and operating methodology, like that of Model-Based System Engineering, are to be adapted to be able to maintain continued confidence and trust that the Digital Twin is performing well, as expected and will continue to do so in the system context it finds itself operating.

Trusting the results of models and algorithms used are not in place or operational, especially at scale. Moreover, the data used by models and algorithms need to be trusted. Trust is related to the ownership of the data, models and system itself. Being able to identify who did what, when it was done, and why, gives the user of the results a means of accountability and allows potential level of confidence to be decided. Wrong decisions, or their repetition, can be avoided.

3.2.5 [BAR-T5] Bringing it all together

Development of a Digital Twin requires understanding the dynamics of the system. These are presented in the form of requirements that the Digital Twin software must support. Developing a Digital Twin is not only more challenging because of the heterogenous and highly granular compositional nature of the distributed co-simulating model that must integrate efficiently with reasoning logic to address a specific purpose, but it requires careful design to allow for the integration of multiple stakeholders and probably different kinds of unexpected purposes.

Data from such heterogeneous sources need to be converted into the homogeneous data format of the comprehensive and consistent Digital Twin. Such data conversion may result in loss of information. A Digital Twin data model may, for example, support only explicit geometry, whereas the source application stores parametric geometry. Also, converters will usually be provided by the source application vendor. The correction of errors and delivery of converter scope extensions may take time.

To integrate data from different sources requires a good understanding of the Digital Twin data model; integration is usually not supported by source application vendors as it is outside of their data domain. It may happen on low levels of granularity when, for example, the nodes of an analysis mesh need to be linked to the underlying CAD-shape and to sensor locations on a test rig.

Versioning of input data or models, or human interaction, to the static parts of a Digital Twin, that is, to its configuration, requires special attention. An update of its CAD shape may make simulation and testing models invalid, as well as, input that is streamed from sensors. Change control and history tracking are challenging topics of a Digital Twin data integration.

Many already have some form of digitalization efforts underway; others have existing solutions that may require significant modification. Not all participants are technically able or can afford to redesign their entire plant. Therefore, the existing digitization technologies and processes that are already in place need to be considered carefully as well. Existing processes and technologies need to be uninterrupted, otherwise your Digital Twin success could be at the detriment of another part of your business.

Engineering the holistic Digital Twin means that you need a solution that is:

- **Low code**, since not every model developer or user is a programmer;
- **Highly (semi-)automated**, since your solution can be, or become, quite large and quickly unmanageable;
- **Interoperable**, since interdependencies and complexity are increasing, with a larger volume and variety of data, models and system components.

4 MITIGATING ACTIONS

This section introduces methodological steps to establish appropriate actions to help mitigate the barriers we highlighted in the previous section. We introduce the high-level methodology and point to concrete available consulting tools that are provided by Change2Twin.

4.1 IDENTIFY CHALLENGES TO BE SOLVED BY DIGITAL TWINS

Preparation starts with assessing and documenting the current situation. For this reason, the problem statement must be described clearly and concisely such that requirements are retrieved appropriately. Non-experts in the domain must be aware of the situation. For this reason, it is reasonable to introduce the concept of *solution-patterns*. Such patterns, presented on a marketplace in the form of market-ready or innovative offerings, should include a variety of technologies or methodologies, and are characterised by specific manifestations that are applicable across different domains.

Guidelines for assessments or innovations are provided to support the analysis of the business case, potential influence on an organisation, and selection of the appropriate technologies. The first step is to translate business goals into technical capabilities that have the potential for gaining a competitive advantage.

The role of DIHs is to act as a key contact point for companies. In general, DIHs[4] should support those companies in their Digital Twinning process by generating a Digital Twin roadmap. Here the focus is on manufacturing content.

A consultant guides the company through an assessment introducing skills and experience, i.e., interview experience, familiarity with business topics and change management, ability to speak to management level, general knowledge on digital transformation and the Digital Twin, and having a clear understanding of KPIs related to finance, market, and operation.

A top-down approach starts from the business needs and inspects the application scenario, approaching concrete technical details. First a business understanding specifies or clarifies business needs. Second, a technical understanding considers the identified technical barriers, required data and appropriate technical services. Third, organisational understanding links actual business needs with the technical capabilities appropriately for the organisation itself, enabling a smooth transformation from idea to the operational solution.

Change2Twin offers a set of consulting tools, like the:

- ***Compass* assessment tool**, used before elaborating finer technical details of the Digital Twin;
- ***Scene2Model* tool**, used to define business models;
- ***OMiLAB Innovation Corner* environment** that provides support for the transformation.

The Compass tool supports the identification of the stage and proposes three major levels of maturity. A low assessment result, representing levels one and two of the Industry4.0 maturity model, indicates that digitalization is unlikely to be mature enough to use a Digital Twin. A medium assessment result, representing levels three and four, prompts further analysis of readiness. A high result represents levels five and six, making it a prime candidate for a Digital Twin.

[4] Within the context of the EU Project Change2Twin, DIHs need to be registered in the European DIH catalogue4.

The Scene2Model tool supports the innovative co-creation of new or improved business models by applying design-thinking approaches, where users are co-creatively working on a common idea, using creativity techniques, like SAP Scenes. The model-based ADOxx approach suggests Digital Twin offerings from the marketplace during a workshop using this tool, in order to trigger and guide it.

The OMiLAB Innovation Corner is an environment with three abstraction layers:

- **Business layer**: is concerned with the creation of business scenarios and models.
- **Organisation layer:** provides modelling infrastructure to model the appropriate use of Digital Twin technology for an organisation.
- **Technical layer**: establishes proof-of-concept realisation for requirement analysis and decision support.

Key pillars of DIHs are testing, investment identification, training, and networking within an innovation ecosystem. Holistic assessments, transparent problem descriptions as well as sophisticated data preparations can help minimise barriers in the relationship between DIHs and companies.

By applying such tools, we aim to address organization barriers BAR-O1, BAR-O2, and BAR-O3 by helping to shape and communicate business vision and leadership intention, give insight into the potential working practices that may need to change, and focus the scope on the more urgent and impactful business aspect pertaining to the Digital Twin consideration.

4.2 CO-CREATE OR INNOVATE DIGITAL TWIN SCENARIO

A joint systems and software engineering approach to develop, operate, and maintain Digital Twin, helps the solution to meet the requirements identified by the stakeholders.

The transformation of a physical real-world problem into a Digital Twin requires thorough consideration of potential barriers starting with the transition from real-world to conceptual (digital) model. This can either be performed by directly transforming the real-world into a conceptual model, or alternatively use supportive steps like the generation of a physical model. Such a physical model can reduce complexity, simplify real-world issues, and allow association of similar characteristics to ease the contribution of non-experts of the domain.

Production processes in the form of business process modelling notation (BPMN) models, high-level data models in form of KPI models, or simulation capabilities in form of Petri Nets, can be used to conceptualise the real-world scenario. However, the direct transition from the real-world and its physical objects to a conceptual model seems to neglect some key issues that emerge by digitising the real-world – such as network, security, or hardware issues. It seems reasonable to introduce the concepts of abstraction and association. The overall challenge of DIHs is to reduce the barriers in building such a digital model and, furthermore, a Digital Twin, in the industry to accelerate and support the real-world transformation by the usage of digital technology.

The introduction of a physical model allows to support requirements engineering, the design of a methodology, as well as the assessment of the readiness, supported by abstraction and associations. The concept of abstraction is applied at the beginning to formalise the specific real-world scenario, while there is a focus on the concept of associations required for training and consultancy workshops. Abstraction in form of formal models – so called requirement vectors – enable a transparent documentation by following a generic approach, so that it can be applied to various production or material handling scenarios with similar characteristics.

By applying abstraction, a high-level roadmap, based on recurring patterns from the marketplace, can be defined for numerous real-world processes. This is the foundation for going into further detail. Training and consultancy workshops between DIHs and companies help formulate a targeted plan aligned with the business needs that are based on the identified formal models and test the applicability within the frame of a physical model. Furthermore, such a physical model can promote more effective exchange of knowledge between different participants within a testing environment, as outlined in the following section.

Further guidance in the context of assessments is provided for DIHs by Change2Twin. As mentioned above, the assessment tool consists of two major stages. In the first stage, a focus is set on business needs and general digitalization aspects, while the second stage assesses technical readiness for the different Digital Twin purposes with respect to the current state of digitalization. TNOs Seven-Step Digital Twinning approach is translated into a technology readiness assessment by Change2Twin to guide the development of a Digital Twin for a specific purpose.

These mitigation technologies address both organizational and technological challenges, connecting leadership and business process with technical experts (BAR-O1, BAR-O2), and also helping technical experts identify and communicate their more specific technical focus points with the rest of the teams, including management (BAR-T5). It also promotes a healthy high-level way of tracking and ensuring progress in division of work and way of working to ensure the resulting Digital Twin remains fit-for-purpose and executes effectively (BAR-T1, BAR-T3).

4.3 SELECT DIGITAL TWIN OFFERINGS

The marketplace provides a set of offerings that support the transformation towards a Digital Twin. Currently, we distinguish between the following offering types:

- **Consulting offering**: A consulting offering manifests as a consulting workshop, teaching or training events.
- **Information offering**: Reference data sets, references processes, success stories, and studies and analysis, are possible information offerings that require information access credentials on the marketplace.
- **Software application offering**: For software application offerings, both software-as-a-service (service access credentials required) as well as bundle (Docker Container registration) offerings, for example, include simulation services, database services or data analytics, are available.
- **Digital infrastructure offering**: IoT infrastructure, RFID tags or edge computing environments could be potential digital infrastructure offerings.

There is a relationship between a so-called *innovation shop* and a *marketplace*. Innovation shops collect any input enabled by research or technology organizations independent of the technological readiness level. Rudimentary ideas, prototypes and services are available from such innovation shops as a collection of ideas, approaches and solutions.

The marketplace allows only purchasable offerings. All items on the marketplace have a technology readiness level that enables market entrance. Innovation shops are a foundation for marketplaces, enabling the outcome of research to be exploited. Some examples for EU-project innovation shops are

Caxman[5], GO0D MAN[6] or CloudSocket[7]. Some examples for marketplaces would be the EU funding and tender platform[8], IBM[9] or Microsoft[10].

The idea is to provide a flexible marketplace ecosystem consisting of

1. a technology that can be extended, exchanged, and operated,
2. a model that abstracts the technology of the marketplaces and defines a common understanding across offerings and marketplaces, and
3. a methodology that enables access to offerings from several marketplaces and provide them to the interested user.

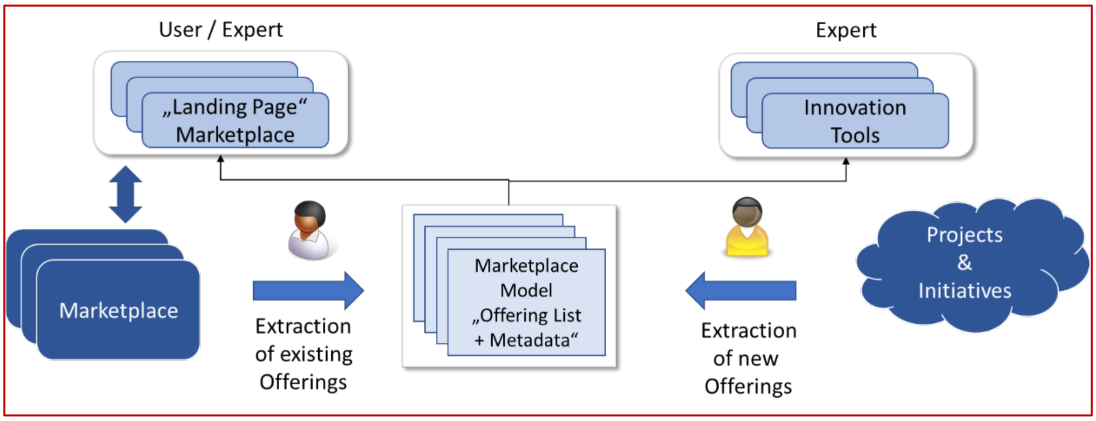
This ecosystem has a landing page in form of a website, but also – and we believe this is much more important – a conceptual harmonisation of different offerings that can be used by any assessment, documentation, or innovation tool to link offerings to concrete user requests.

Within the project, we implement two approaches in the marketplace, namely

1. search for offering on online platform, and
2. assess, innovate, and select offering in expert tools.

While the first approach focuses on browsing and searching for Digital Twin solutions at the landing page of marketplaces, the second approach concentrates on designing, assessing, and selecting Digital Twin solutions, built into the consulting tools.

The figure shows the relationship of the technical features of the marketplace and the conceptual harmonisation using a marketplace model.



The marketplace is further detailed as the landing page, the middleware, and the infrastructure. To ensure sustainability of the marketplace, the architecture builds on standards and open technologies, like ADOxx, mark-down representations, microservices, GitLab, and Docker Containers.

Starting with the landing page of a marketplace anyone interested can filter item lists, find item details, and trigger the deployment of offerings. Business needs are expressed as requirements and the

[5] https://caxman.boc-group.eu/innovation-shop
[6] https://go0dman.boc-group.eu/innovationshop/
[7] https://site.cloudsocket.eu/cloudsocket-innovation-shop
[8] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/horizon-results-platform/search
[9] https://www.ibm.com/marketplace/workbench/
[10] https://appsource.microsoft.com/en-us/marketplace/apps?product=teams

corresponding capabilities of digital solutions offered on the marketplace can be aligned using smart algorithms in consulting tools, or on the landing page of the marketplace.

The requirements of the business cases, as well as the capabilities offered by a marketplace, must be matched by applying smart alignment processes, enabled by either human experts or artificial intelligence algorithms. The resulting semantic network has the capability to describe the users' needs so that offerings in form of ideas, approaches or solutions can be proposed.

This marketplace addresses the organizational barrier of clarifying and promoting ecosystem and market support for viable business (BAR-O4). Moreover, it naturally promotes availability and advancement of technology solutions that help alleviate problems of technological barriers, like providing access to quality data, making appropriate fidelity models available, making reliable operation maintainable and ensuring effective execution. In fact, all technological barriers are potentially addressable by marketplace participant, since solutions that help account for uncertainty and integrate the different technology components of the Digital Twin can be delivered via the marketplace. Depending on the urgent need and the degree of complexity, appropriate solutions should arise.

4.4 INTRODUCE DIGITAL TWIN TECHNOLOGY

Knowledge transfer must be enabled in such a way that different technology providers can demonstrate their potential solutions to the end-user. Therefore, we include the possibility for experimentation in form of a physical models.

Those physical models are provided in innovation laboratories like the OMiLAB Innovation Corners, to demonstrate solutions for a real-world challenge within a simplified, abstracted, and associated form. This allows the interactive co-creation between users, DIHs and technology providers in order to find an appropriate Digital Twinning solution targeted to a specific real-world case. The physical experiment allows the demonstration of several – partly distinguishing or complementing – approaches in a flexible and heterogeneous way.

This enables:

- **reduction** of barriers during the transformation from real-world problem to a conceptual model;
- **reusability** of patterns and technologies;
- **exploitation** of the potential of digital technologies;
- **enlargement** of the contribution environment facilitating potential collaborations.

The mentioned advantages pave the way for enlarging the contribution opportunities by means of a *sandbox* model. In particular, the sandbox allows to integrate external infrastructure. Technology or service providers can then extend and further develop the physical model by integrating their own technologies. On the one hand, this allows companies to find the optimal combination of technologies for their real-world problem and, on the other hand, technology and service providers can minimise potential barriers, like hardware, network or security issues, before actually implementing their concepts in a real-world production process.

Once the end-user and the set of solution providers successfully agree on approaches, formats, and solutions within the sandbox environment of the physical model, the end-user can decide if the findings are used as a requirement specification and purchase the required solutions accordingly on the market, or if each part of the model is iteratively exchanged in a professional and reliable form at the end-user's site.

In both ways the training of the workers can be started with the physical model and seamlessly be continued while the real-world solutions are being built.

This aspect addresses the organizational barriers BAR-O2 and BAR-O3, since it allows a flexible yet focussed way that different participants can collaborate, accepting that working practices are different for different participants and can also evolve for the user. Moreover, this sandbox approach addresses BAR-T5, helping to investigate and realise an integrated technology solution in a safe space for the user and the other necessary ecosystem participants.

4.5 ENSURE SUSTAINABLE END-USERS SITE USING FRAMEWORKS

To implement and operate a Digital Twin in a sustainable and proficient way, it is necessary to draw awareness to the fact that enabling sub-disciplines like, but not limited to, knowledge representation, formal methods, scalable computing, or data science need to be managed either with the support of consultants or by skilled end-users at the end-user's site. These technologies consider the domain knowledge embedded in the Digital Twins' models, and are owned by the facility's engineers, e.g., chemical, petroleum, mechanical, electrical and control, and managers.

There are some challenges related to uncertainty, validation, and data science. The Digital Twin is built on models. A Digital Twin of a large or complex system will inevitably contain many and potentially heterogeneous models. Some are based on physical principles, like structural, geometrical and process simulations, while other will be purely empirical, e.g., models based on machine learning. These models should be validated against observed behaviour and aligned so that they reflect normally observed behaviour. Aligning models to the observed data is difficult and remains quite challenging.

A maintainable Digital Twin will contain structured tools that allow validation and tuning of all the models in the system. Hybrid analytics, i.e., the combination of data science with physical and engineering simulations, is a valuable and fruitful area of research. The marketplace encourages the development of technologies and solutions that help address technology barrier BAR-T4, in that it creates a viable space and clear mechanism for the developers to bring their products to market.

Good statistical practice is needed in the engineering communities and engineering knowledge is needed among data scientists.

Recognizing the intrinsic challenges embodied by Digital Twin technology, several standardization bodies and interest groups have started to take on some of the issues discussed herein.

The IEC 62832 ("Digital Factory Framework") is a well-established standard, which defines a representation model for digital factory assets and relationships among assets. The ISO/IEC JTC1 group published a technology trend report identifying *Digital Twin* technology as the number one area needing an in-depth analysis, also stressing the importance of cooperation with the open-source community and to ways on how this cooperation could effectively materialise.

Building on this front, a notable example is the Eclipse BaSyx project, providing a software development kit aimed at developing Digital Twins conforming to the specification of Asset Administration Shell. As part of Eclipse IoT7, Eclipse Ditto combined with Eclipse Vorto offer a generic and flexible Digital Twin framework. Recently, Microsoft announced its Azure Digital Twin solution consisting of a documented relational model, a set of APIs through which components interact along with a kit to develop the twin.

The *Automation Systems and Integration* committee of ISO/TC 184 formed a group to formalise Digital Twins defining appropriate data architecture models. In 2019, the IEEE Standards Association also launched IEEE P2806 to define a system architecture for digital representation of physical objects in the factory. Interoperability of different Digital Twins are addressed with a *plug and play* approach of the *Digital Twin Manufacturing Framework* (ISO/AWI 23247).

Other consortia, like the W3C, propose the *Web of Things*. It consists of a set of specifications aimed at digitally representing things. The Object Management Group recently established the Digital Twin Consortium with key industry players with currently over 250 international members with the main goal of promoting market clarity and focusing on key industries who stand to benefit significantly from the Digital Twin trend. One of their designated industries is manufacturing.

Identifying then the key standardization efforts and best practice helps reduce many open questions as to how to realize effective and efficient Digital Twins. In Change2Twin, we include a catalogue of relevant standards that, depending on a specific domain and application, can help achieve the Digital Twin.

5 CONCLUSION

This report contains the important technological and organizational barriers we identified that hinder the uptake of Digital Twin in SME companies in the smart manufacturing production industry domain.

We feature participant solutions, suggesting how to support DIHs, Change2Twin participants and other SME companies who stand to benefit from enabling digitization through the application of Digital Twin.

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