Position Paper

Overcoming 9 Digital Twin barriers for manufacturing SMEs

Paolo Pileggi, TNO

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Authors
Paolo Pileggi, TNO
Armir Bujari, University of Bologna
Oliver Barrowclough, SINTEF
Jochen Haenisch, Jotne
Robert Woitsch, BOC-EU

Editors
Oliver Barrowclough, SINTEF
Marcela Alzin, TTTech
Peter Laloli, TNO

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TABLE OF CONTENTS

INTRODUCTION

Digital Twin is an advanced digitisation trend that promises to deliver great value in and across many application domains. However, organisations must overcome many organisational and technological barriers to achieve a feasible solution that brings that value they seek. This represents a challenge for Small and Medium Enterprises (SMEs), as Digital Twin solutions can be quite costly and time-consuming to develop, use and maintain.

In this position paper, we give our perspective based on our practical experience, expertise and offerings, with the aim to accelerate the adoption and implementation of reliable Digital Twins for manufacturing SMEs. We highlight nine barriers that focus on key organisational and technological aspects, which we identified and elaborated in the H2020 project Change2Twin. Furthermore, we suggest concrete tools and techniques for manufacturing SMEs to overcome these barriers. Although there is no single solution that solves all challenges or addresses a barrier completely, together with Change2Twin partners, and in collaboration with Digital Innovation Hubs (DIHs) all over Europe that support SMEs in digitisation, we provide solutions covering the entire list.

This document is of most interest to DIHs and SMEs that have identified Digital Twin as a suitable solution to deliver value and create the desired business impact. Together with the marketplace offered by the Change2Twin consortium, which makes technological solutions readily available and accessible, the barriers can be used to guide organisations in the implementation of their Digital Twin.

About Change2Twin: *Change2Twin* is an EU-funded project (part of I4MS), which promotes a broader acceptance of Digital Twins among manufacturing SMEs and mid-caps through a unique support scheme, cooperating with local DIHs, technology providers and related European projects.

The scheme reaches from analysing a company's digitisation potential and individual mentoring plan, to a *ready-to-use* recipe for Digital Twin deployment. The project provides companies with funding that covers the assessment of their readiness and fitness for digital twinning, as well as the actual deployment of the Digital Twin, including application experiments.

The project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No. 951956. The project runs from June 2020 until May 2024. The project consortium consists of 18 partners based throughout Europe.

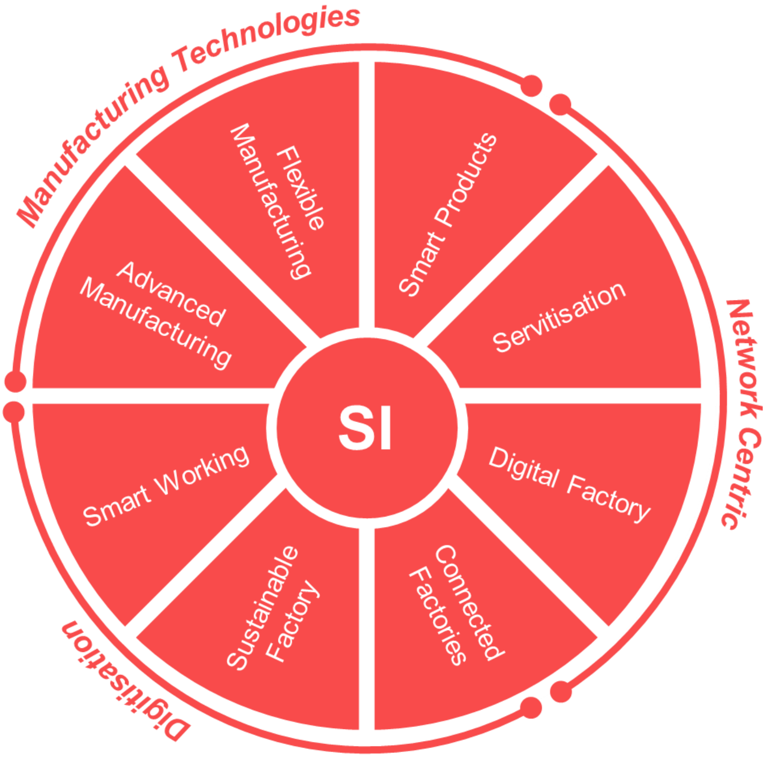
For further details, visit the project website: www.change2twin.eu and the website of I4MS initiative www.i4ms.eu.

DIGITAL TWIN IN SMART INDUSTRY

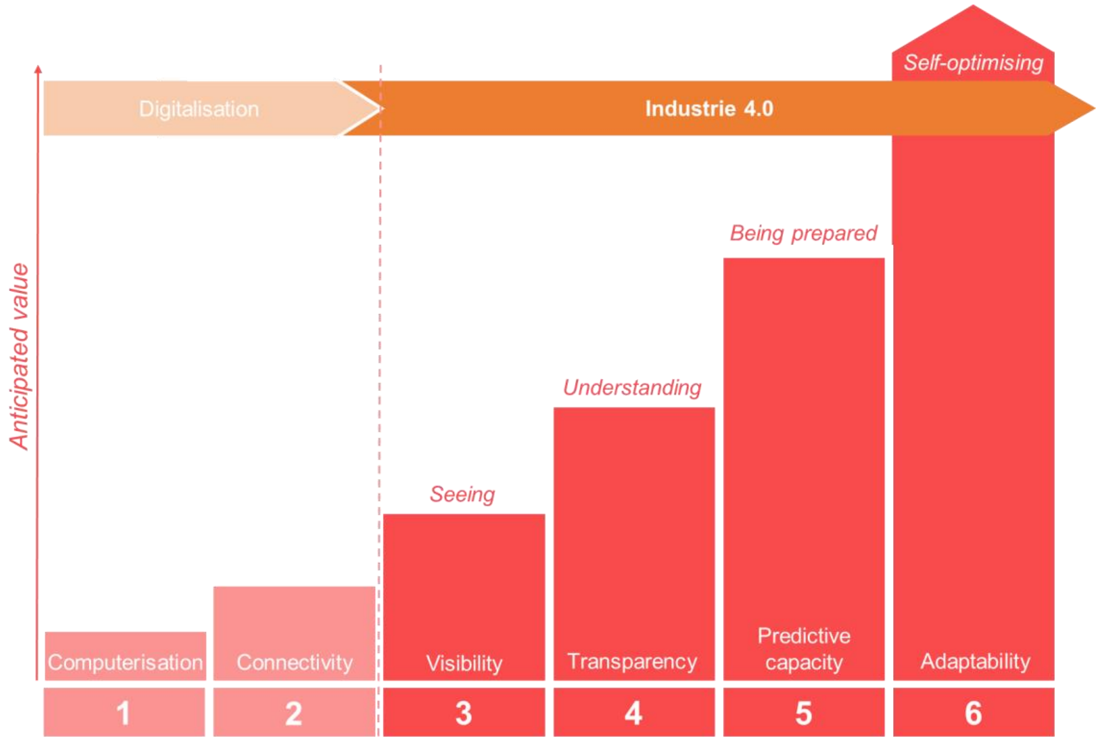
Smart Industry (SI) stands for three main transitions:

1) Radical digitisation
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, Servitisation, Digital Factory, Connected Factories, Sustainable Factory, Smart Working, Advanced Manufacturing, and Flexible Manufacturing.



This SI initiative involves a major transition in a very diverse landscape. Most companies are still in the process of addressing the challenges relating to connectivity, while the end-goal is to engineer, operate and maintain an adaptive autonomous, and in some cases, a self-aware solution. These qualities are represented by Stages 2 through 6 of the stages in the *Industry4.0* development path. Digitisation happens across all 6 stages, while the Digital Twin, an advanced form of Digitisation, happens when we start to address the challenges in Stages 4 through 6.



A COMMON UNDERSTANDING

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 to promote of active use of a suitable ecosystem and marketplace that will accelerate affordable availability and give clarity to the market.

Grieves is recognised 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 digitisation.

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 synchronised virtual prototype[1], 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

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

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.

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 and virtual worlds (Rosen, Boschert, & Sohr, 2018). Simulation is considered essential and intrinsic to advanced digitisation. Digital Twin as an enabler of advanced digitisation 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 artificial intelligence (AI) and Machine Learning (ML), 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 becoming increasingly complex with time, mirroring the complexity of the physical processes they represent (Boschert & Rosen, 2016). This generates the need for new techniques in managing model complexities to operationalise the solution for the business process – a further complication to delivering an efficient and effective solution.

The complexity of Digital Twinning increases in line with 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. Dealing with the complex dynamics of the system requires an adaptive, autonomous, and evolutionary solution. Recognising 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 digitisation is an advanced challenge (Pileggi, Lazovik, Broekhuijsen, Borth, & Verriet, 2020) but is essential to avoid having to redesign and redevelop an expensive custom Digital Twin solution.

DIGITISATION CHALLENGES AND OPPORTUNITIES

A key objective of the Industrial IoT (IIoT) is to embody IoT technology in the industrial decision-making process. IIoT, as an enabler of the Industry4.0 vision, is able to generate a plethora of data, compounded by usually aggregated networking effects, and stored on edge or cloud platforms (Xu, He, & Li, 2014).

In particular in manufacturing, the efficient integration and management of IIoT devices can bring new services and opportunities including predictive maintenance, continuous monitoring, scheduling and remote running of maintenance interventions, process reconfiguration, etc., all the while achieving desired KPIs – process– and product-wise. All these capabilities could be evaluated and made possible by a Digital Twin implementation.

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. To implement and deploy a Digital Twin, some key technological aspects need to be considered that are crucial to its success:

Connectivity: This is the basic building block enabling the interactions with and between connected things, receiving data from and transporting them to the Digital Twin and the physical process(es). This spans their full lifecycle. In this context, options are available, differentiated on the basis of cost and flexibility.

Industrial wired data acquisition and control networks, like Fieldbus profiles or the more recent Time Sensitive Networking for Industrial Automation standards, have been foundational to industrial automation. They guarantee high reliability and real-time communication between things. While capable of fulfilling strict reliability and latency constraints, wired networks are expensive to deploy and maintain, making them unfeasible for many potential adopters. Fortunately, recent advances in wireless technologies, like *6TiSCH*, *Wireless HARD*, *Private 5G* and the upcoming industrial *WiFi7*, will help IIoT technology realise the Industry4.0 vision. 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 been shown to be capable of fulfilling reliability and power consumption requirements of industrial applications. Second, various standards enabling the convergence of low-power wireless and the Internet Protocol have emerged. These standards greatly simplify 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 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 that include design specifications, process, engineering data;
- *manufacturing data* including production equipment, material, method, process, quality assurance and operators;
- *operational data* including configurations of 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*, coupled with data pipelining approaches, helps alleviate the data chaos. This constitutes the basis for a structured data extraction and filtering, synchronising the twin.

Modelling: The Digital Twin may contain different and heterogeneous computational and representational models pertaining to its real-world counterpart. This may range from first-principle models adhering to physical laws; data-driven, like statistical and ML models; geometrical and material, like CAx, Computer-Aided Design/Engineering (CAD, CAE); or visualisation-oriented ones, like mixed-reality.

Hybrid approaches are also possible, e.g., the use of virtual-augmented reality complementing the physics/data-oriented models, or the use of physics simulation or modelling with AI-based approaches that alleviate problems like those related to training data scarcity.

Considering the fast-paced 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 approaches used for training the AI components usually require a large amount of cleaned and labelled data. The effort to create this trained data is considerable and should be optimised. The quality of data or labels is also of paramount importance.
- *Concept Drift*: Concept drift 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 be unable 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 (also the lightweight Digital Twin), the *edge* or the *cloud*. The specific deployment criteria depend on the scenario requirements and are typically based on:

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

In general, different deployment possibilities apply that depend on the device or IIoT capabilities, objective and scope of the Digital Twin:

- *IIoT Twin*: A lightweight Digital Twin deployed on premises or onboard the machine performing utility tasks for quality management operations; namely, low latency and high reliability. This twin gathers data from the physical twin, transmitting them to a higher control entity, like an Edge Twin. Considering the constrained nature of this device, no training occurs and this process is often delegated.
- *Edge Twin*: A higher order control entity, running on the premises of the production site (i.e., plant gateway) is tasked with the lifecycle management (i.e., the deployment, instantiation, control and disposal) of locally deployed IoT twins. The entity performs the more computationally expensive tasks, controlling the flow of, and collecting data from local IoT twins. This provides the control knobs that enable local optimisations and interoperability.
- *Cloud Twin*: If employed, this environment rich in resources has a global scope and acts as a logically centralised repository for data. It is tasked with performing time-consuming and typically off-line simulation and training of models. The models are then subsequently provided to the edge twin consisting of, e.g., predictive models elaborated in advance that are more efficiently executed on the plant premises.

APIs: Digital Twins need to interact with other components, e.g., Digital Twins in a composite system or an operator consulting the system. To facilitate these interactions, various APIs must be available to allow for information collection and control between the twin and its 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 for the twin;
- *online data access*, e.g., through RESTful APIs or some streaming technology like Apache Kafka;
- *management* and *interaction APIs*, enabling information exchange among *cloud-to-thing* continuum twin components, like *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, physical-to-digital (and *vice versa*) interactions require security mechanisms aimed at:

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

Regulation and the law: Although one may think that the law changes relatively infrequently, changes typically have significant impact. Considering the effects digitisation has on society, there are important considerations to be made early on when devising or selecting new or advanced digitisation technologies, methodologies, and strategies.

Knowledge of 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. The certification approach for non-deterministic processes makes the legal evolution of the servitisation of manufacturing products a complicated and challenging 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.

Innovation and business models: The lack of clear vision of a strategic holistic approach makes it hard to access the growth potential of Industry4.0. Understanding the possibilities and benefits that can be achieved will help with leadership. Even if manufacturing companies understand technological enablers of opportunity, like Digital Twin, robotics, and AI, they require diverse human talent in many areas, like data science and industrial IoT, and the profound roles required to support the vision.

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

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 Industry4.0 models proves to be particularly hard.

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 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 and 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 highly skilled workers will result in more potential for job opportunities, like data scientists, in the next years.

NINE DIGITAL TWIN BARRIERS

The nine Digital Twin barriers can be classified as being either of organisational or technological nature. However, by no means are these exclusive designations. Classifying them under what we consider to be their *primary* designation, we elaborate them as follows.

Organisational	Technological
1. Lack of visionary leadership	5. Keeping it fit-for-purpose
2. Being unprepared for change	6. Maintaining reliable operation
3. Many open questions	7. Ensuring effective execution
4. Unclear ecosystem support	8. Accounting for uncertainty
	9. Bringing it all together

BARRIER 1: LACK OF VISIONARY LEADERSHIP

Having a clear vision of what the organisation's 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 research and development costs, and affordable commercial offerings for large companies and SMEs alike, are beneficial in the long term.

BARRIER 2: BEING UNPREPARED FOR CHANGE

Working practices are changing. Digital transformation of the SME and their partners leads to new ways of working and new business models. Being unprepared or resisting change can be detrimental to accessing the benefits that the 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 organisations may:

- use different tools of the same, overlapping or disjoint domains, all of which contribute to the same Digital Twin dataset;
- 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, useable, and reliable. 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.

BARRIER 3: MANY OPEN QUESTIONS

As an enabler of digitisation, 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 prioritise.

For example, an operator is incentivised to have a comprehensive monitoring and optimisation 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 organisational 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 extraordinarily valuable asset as the value of individual datasets from CAD & CAE, 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 organisational units contribute to a Digital Twin; not all of them will belong to the same organisation. Agreements and technical solutions need to be put in place to ensure clear data ownership.

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

BARRIER 4: 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 costly 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 clear nor well-established yet.

The generic IT technology currently constitutes a small fraction of the entire cost of the Digital Twin solution, mostly involving a custom 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.

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

A marketplace that supports a Digital Twin community for the models and reasoning tools would help companies monetise on Digital Twins. Their Digital Twin is an asset they can monetise too.

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

BARRIER 5: 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 to 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 be sure it continues to work correctly, to be able to update it, and to know when the updates are correctly completed.

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.

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 specialised user must be able to find the necessary useful information quickly, easily and without confusion.

Moreover, 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 datasets with streams of potentially real-time information. The organisation of this infrastructure can assist in effectively identifying and accessing quality data.

A more challenging issue is the consideration of sensitive data. Certain data is protected by privacy laws, while others include business secrets. Not only is this a challenge of data locality, but it may also require controlled analysis. If the insights into the data can be discovered from the results of some analysis, the use of the solution will be limited.

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 often much data available, it is also often the case that there are too few events of significance to train data-driven models. This is because such models require a large 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 requiring expert knowledge of the system and the models (especially ML models) used for a specific purpose.

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 (or Level of Detail, LoD), 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 unavailable. A strength of the Digital Twin is that the synchronisation 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 the 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, of the Digital Twin solution is a crucial task for an effective and efficient solution. It requires realising 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 individuals 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 comes at a higher cost. Dealing with the unknown and uncertainty is yet an even further complication.

BARRIER 6: 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 organisations, 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, is 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.

BARRIER 7: 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 computing environment to deal with computational overload especially.

Distributed co-simulation of different kinds of models, synchronised 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 most effective way to ensure continued operation. Distributed architectures that ensure the growth and evolution of a system require careful consideration.

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

BARRIER 8: 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 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.

BARRIER 9: 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 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. It also 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 the 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 companies already have some form of digitisation 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 digitisation technologies and processes that are already in place need to be considered carefully as well. Existing processes and technologies need to be uninterrupted, otherwise Digital Twin success could come at the detriment of another part of the business.

Engineering a holistic Digital Twin requires 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.

MITIGATING ACTIONS

Mitigating these barriers is a hard challenge. It is furthermore compounded by the wide diversity of uses, needs and applications for Digital Twins. We elaborate the enabling technologies offered by Change2Twin project partners and indicate which of the barriers they address.

IDENTIFY THE CHALLENGES TO BE SOLVED

Preparation starts with assessing and documenting the current situation. For this reason, the problem 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 advisable 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 should support 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, before moving towards concrete technical details.

- First, a business assessment 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, including:

- *Compass* assessment tool, used before elaborating technical details of the Digital Twin,
- *Scene2Model* tool, used to define business models, and
- *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 digitisation 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 Stages 5 and 6, making it a prime candidate for a Digital Twin.

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 and using creativity techniques, like SAP Scenes. The model-based ADOxx approach suggests Digital Twin offerings from the marketplace during a workshop using this tool.

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

- *Business* layer: 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 activities 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 organisation Barriers 1, 2 and 3 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.

CO-CREATE OR INNOVATE YOUR 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 and digital model. This can either be performed by directly transforming the real-world into a conceptual model, or alternatively, by using 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* models, high-level data models in form of KPI models, or simulation capabilities in the 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 the support of 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 also a focus on the concept of associations required for training and consultancy workshops. Abstraction in the form of formal models – so called requirement vectors – enables 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.

Change2Twin provides further guidance to DIHs in the context of assessments. As mentioned, the assessment tool consists of two major stages. In the first stage, focus is set on business needs and general digitisation aspects, while the second stage assesses technical readiness for the different Digital Twin purposes with respect to the current state of digitisation. TNO's *Seven-Step Digital Twinning* approach (Borth & Broekhuijsen, 2021) 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 organisational and technological challenges, connecting leadership and business process with technical experts (Barriers 1 and 2), and also helping technical experts identify and communicate their more specific technical focus points with the rest of their teams, including management (Barrier 9). It promotes a guided 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 (Barriers 5 and 7).

SELECT YOUR 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 datasets, 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) and *bundle* (Docker Container registration) offerings including, e.g., simulation services, database services or data analytics.
- *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 organisations 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*[2], *GO0D MAN*[3] or *CloudSocket*[4]. Some examples for marketplaces would be the *EU funding and tender platform*[5], *IBM*[6] or *Microsoft*[7].

The idea is to provide a flexible marketplace ecosystem consisting of:

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

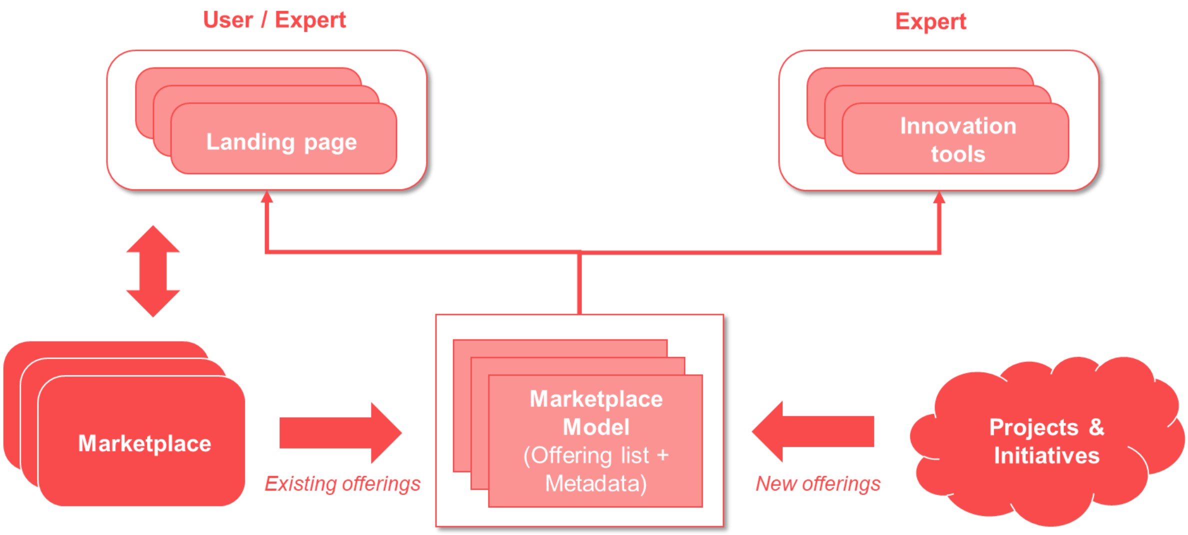
This ecosystem has a landing page in the form of a website, but also – and we believe this is much more important – a conceptual harmonisation of different offerings that can be used by any assessment, documentation, or innovation tool to link offerings to concrete user requests.

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

1. search for offerings on an online platform, and
2. assess, innovate, and select offerings 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 following figure depicts the relationship of the technical features of the marketplace and the conceptual harmonisation using a marketplace model.



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

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

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

This marketplace addresses the organisational barrier of clarifying and promoting ecosystem and market support for viable business (Barrier 4). 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 items, 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.

INTRODUCE 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 Twin solution targeting a specific real-world case. The physical experiment allows the demonstration of several partly-distinguishable or complementary approaches in a flexible and heterogeneous way.

This enables the reduction of barriers during the transformation from real-world problem to a conceptual model, the reusability of patterns and technologies, the exploitation of the potential of digital technologies, and the 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 for the integration of 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. On the other hand, technology and service providers can minimise potential challenges, 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 organisational Barriers 2 and 3, since it allows a flexible yet focussed way for different participants to collaborate, accepting that working practices are different for different participants and can also evolve for the user. Moreover, this sandbox approach addresses Barrier 9, helping to investigate and realise an integrated technology solution in a safe space for the user and the other necessary ecosystem participants.

ENSURE SUSTAINABLE END-USER 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 models of the Digital Twins, 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 others will be purely empirical, e.g., models based on ML. 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 8, 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. Recognising the intrinsic challenges embodied by Digital Twin technology, several standardisation 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 highlighting the importance of cooperation with the open-source community and ways this cooperation could effectively materialise.

Building on this, a notable example is the Eclipse BaSyx project, providing a software development kit for developing Digital Twins that conform to the specification of Asset Administration Shell. As a 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 is 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. Their main goal is 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 standardisation efforts and best practice helps reduce many open questions as to how to realise effective and efficient Digital Twins. In Change2Twin, we include a catalogue of relevant standards that, depending on a specific domain and application, can help give clarity about the Digital Twin solution and promote interoperability and maturity.

CONCLUSION

This position paper contains important technological and organisational considerations that we present as nine barriers. We identified these barriers by combining the knowledge and expertise of Change2Twin project partners, as well as part of pilot experiments being conducted with SMEs and partners.

These barriers hinder the uptake of Digital Twin in Smart Industry in SME and mid-cap companies. As a reference to real solutions that start to help overcome these barriers, we feature enabling technologies made available by the Change2Twin partners.

This paper serves to inform DIHs, Change2Twin partners, and other SMEs and mid-cap companies as how they can prepare themselves for the perhaps less obvious and often extraordinary challenges the Digital Twin trend brings.

Although the mitigating actions we present do not necessarily cover all possible uses, needs and applications pertaining to the Digital Twin, they form a part of a catalogue of enabling technologies we aim to make accessible via our Digital Twin technology marketplace. The Change2Twin marketplace is an ongoing development and promotes high access, availability, and interaction between technology providers and end-users, able to grow over time to suit the actual needs of a Digital Twin development and user ecosystem.

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ABOUT THE AUTHOR

Paolo Pileggi (PhD) is an ICT business consultant for the Dutch national applied research organisation TNO. With a background in Computer Science (Computer Engineering specialisation), he has a doctorate in telecommunication engineering and has participated in *Marie-Sklodowska-Curie Innovative Training Networks* in the area of mobility, location and radar tracking applications.

His primary interests cover a broad range of topics, with the at-scale performance modelling of concurrent complex systems theme recurring. His interest in the Digital Twin has as focus the digital lifecycle management and engineering of the Digital Twin itself, particularly for application contexts that are large, complex or dynamic.

He is responsible for TNO ICT's *Reliable Digital Twin* program with this focus, underpinned by three main research pillars, namely (1) *distributed co-simulation architectures*, (2) *multi-purpose orchestration*, and (3) *operationalising AI*. Adaptability and accountability are essential to deliver Digital Twins that bring value consistently well, especially in and across different application domains and organisations.

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Author	Paolo Pileggi, TNO
Co-Authors	Armir Bujari, University of Bologna Oliver Barrowclough, SINTEF Jochen Haenisch, Jotne Robert Woitsch, BOC-EU
Date of publication	April 2021
Contact	TNO Anna van Buerenplein 1 PO Box 96800 NL-2509 JE The Hague The Netherlands paolo.pileggi@tno.nl +31 6 1548 7209 www.tno.nl
Copyright holder	Change2Twin project Represented by coordinator: Tor Dokken SINTEF Digital Forskningsveien 1 P.O. Box 124 0314 Oslo, Norway hello@change2twin.eu
WWW	www.change2twin.eu