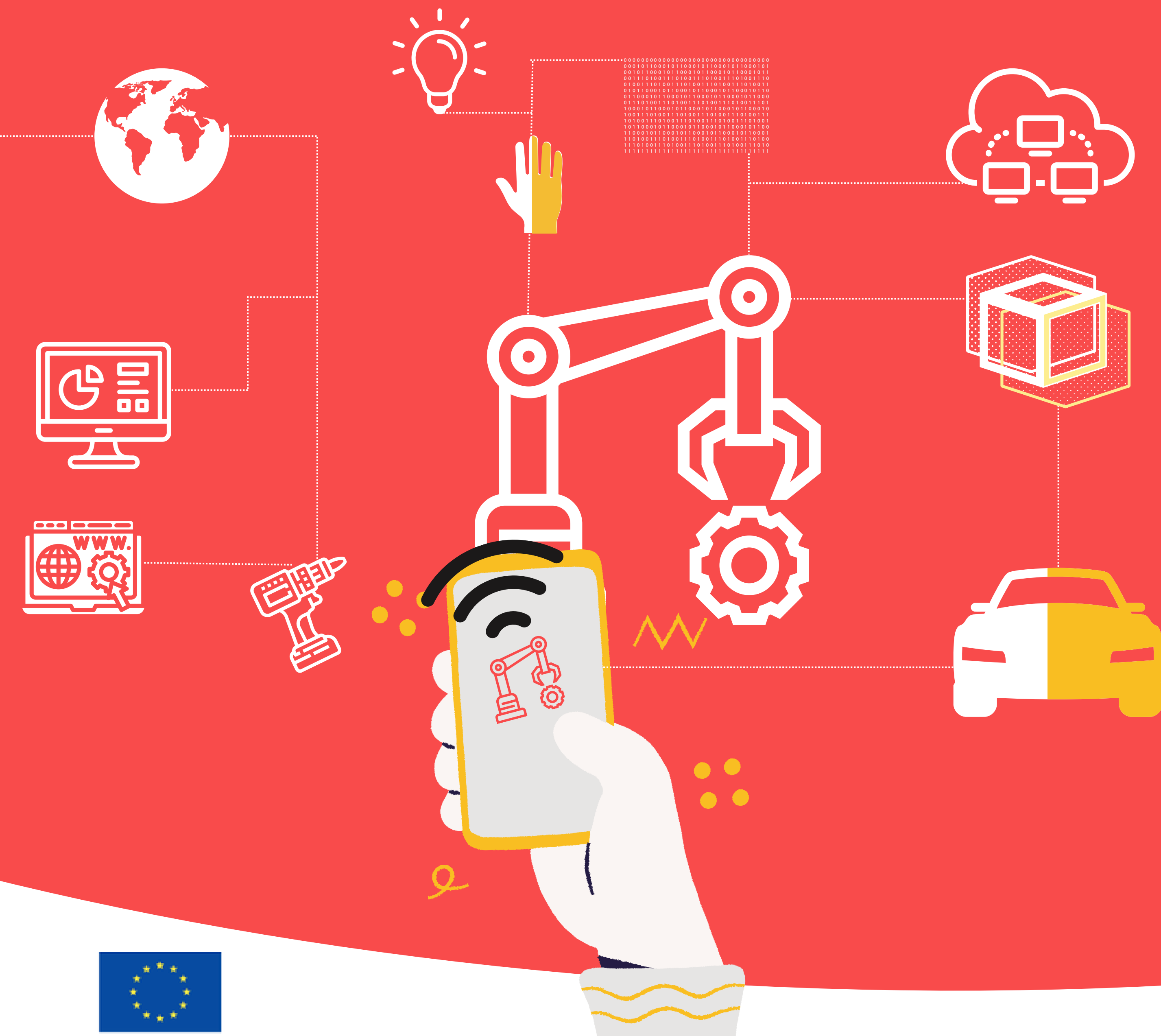
CHANGE2TWIN

Position Paper

Enabling technologies for digital twins in manufacturing

Oliver Barrowclough



Horizon 2020

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Released

September 2022

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1 INTRODUCTION

Digital twins are by nature broad in scope, and thus encompass a wide range of technologies, from the **traditional computer aided technologies (CAx)** to **advanced computational hardware** and also more **emerging technologies** such as the (industrial) internet of things and deep learning. In order for SMEs to get the most out of their digital twin implementations, it is important that these technologies are made available and are presented to them in a way that is understandable and relevant to their business.

One of the main barriers to the adoption of digital twins in industry is the lack of understanding of the opportunities that recent technological developments provide. The **aim of this position paper** is to provide a simple and **concise introduction** to a wide variety **of technologies that are important for digital twin implementations**. We also discuss how taxonomies of the technologies will assist in making the technologies accessible and findable to Digital Innovation Hubs (DIHs) and SMEs. We point to the initial version of the Change2Twin marketplace as a platform for users to search and discover technologies and how the marketplace is growing to meet the evolving needs more comprehensively.

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.

2 A COMMON UNDERSTANDING OF DIGITAL TWIN

The term "digital twin" has become common in Industry 4.0, but it is often misunderstood or misrepresented. It is therefore important to review existing definitions of the term that leads to a common understanding of the term. Though the formal definition varies depending on the context, the following definitions give a broad view of what can be considered a digital twin.

The **definition of digital twin used in Change2Twin** is as follows:

> *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. This digital replica and the real world are often connected by streams of data.*

Since Change2Twin began, **two more definitions have been developed**. The concise definition provided by the **Digital Twin Consortium**, part of the Object Management Group, is as follows[1]:

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

Another more detailed definition provided by the **American Institute of Aeronautics and Astronautics**, is as follows (AIAA Digital Engineering Integration Committee, 2020):

> *[A digital twin is] a set of virtual information constructs that mimics the structure, context and behaviour of an individual / unique physical asset, or a group of physical assets, is dynamically updated with data from its physical twin throughout its life cycle and informs decisions that realize value.*

Despite the slight differences in phraseology, these definitions are sufficiently similar to give a consistent view of what we mean by a digital twin. The **actual manifestation of the digital twin**

[1] https://www.digitaltwinconsortium.org/hot-topics/the-definition-of-a-digital-twin.htm

is, of course, entirely **dependent on the specific use case**, meaning that they can be very **different in practice**, **but all share the properties of being a virtual representation of a physical asset that is kept synchronized as changes to the physical twin occur.** The solution itself is often dynamic and involves combining different models, information sources, business processes and purposes, making it a cross-disciplinary challenge, but the result always targets creating value for the relevant stakeholders. Change2Twin specifically addresses digital twins associated with the manufacturing sector.

3 DIGITAL TWIN ENABLING TECHNOLOGIES

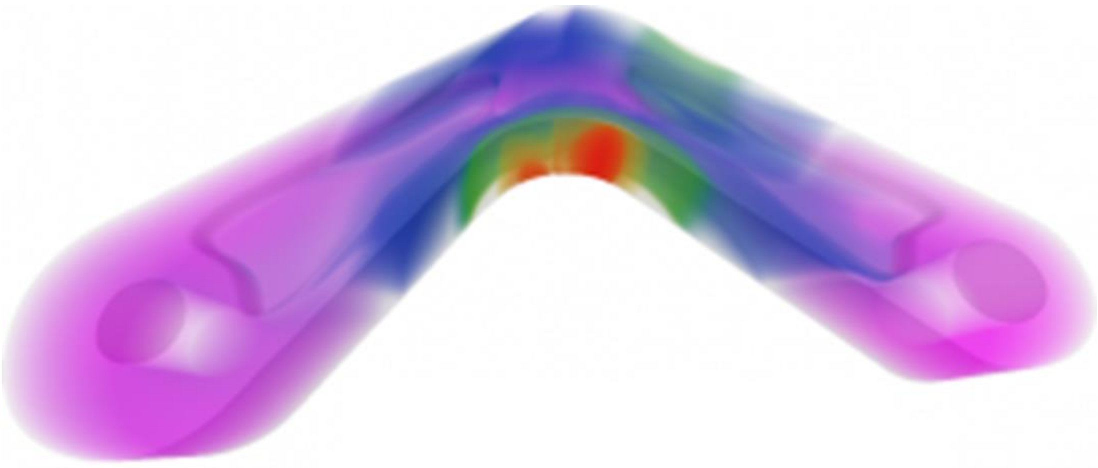
In this section we review the current literature detailing some of the types of technologies that are commonly required for digital twin implementations. This is intended as a **high-level categorization of the technologies**, as opposed to a more complete taxonomy which breaks down the technologies into their constituent parts, as introduced later in the document. It is also more geared towards **digital twins in the manufacturing sector**, than to digital twins in other domains.

There exist several different review articles detailing the types of enabling technologies that are encountered in digital twin implementations (Fuller, 2020), (Rasheed, San, & Kvamsdal, 2020), (Kritzinger, et al., 2018). In this section we will briefly mention some of the most relevant. The following categorization is inspired by (Rasheed, San, & Kvamsdal, 2020), however, in our summary we also include one additional category on data management and merge the categories on data-driven modelling and big data cybernetics. In the subsequent subsections **we address the following categories**:

- **Geometric and physics-based modelling**
- **Data-driven modelling & big data cybernetics**
- **Infrastructure and platforms**
- **Human-machine interface**
- **Data management**

It should be noted that **digital twin implementations are continually evolving** and could in the future come to include other technologies, especially as new ones mature and become commercially available. The following subsections are thus a non-exhaustive list of technologies. However, they can be considered a **collection that covers some of the most important aspects of current digital twin implementations**.

3.1 GEOMETRIC AND PHYSICS-BASED MODELLING



3.1.1 Computer aided design and image processing

Digital twinning often begins with a **geometric modelling** activity. Indeed, many SMEs already have models of their products available in one form or another, which can be an ideal starting point for their digital twins. **3D models** used in digital twins are often created during the design stage in a product development process and are created using **computer aided design (CAD) software**. Depending on the specific use case, it may or **may not be sufficient** to use the design model as the basis for a digital twin. For example, if the digital twin is to be used as a basis for decisions that are dependent on the material characteristics of the physical asset, a more detailed model might be required.

In cases where design models are not available, **reverse engineering (RE)** can be a useful tool. RE involves converting scans of a physical object (e.g., laser scans, photogrammetry, CT-scans) back to a geometric model. This can involve full volumetric information about the asset (e.g., when CT-scans are used), or just recovering the outer surfaces of the geometry as is the case when laser scan or photogrammetric data is available. In many cases both CAD software and image processing tools are used in combination in order to successfully reverse engineer a physical asset.

3.1.2 Computer aided engineering

Often the interesting aspects of a digital twin need to model **how the object relates to its environment**, for example, modelling how temperatures or stresses vary throughout the object under different conditions. This requires methods for **physics-based modelling** which involves solving known mathematical equations related to the physical properties of the model. Standard CAD-type models are, in many cases, not suitable for this as they typically only represent the boundary of an object and do not explicitly represent its interior. The most common approach for making a model suitable for physical simulations is to discretize the geometry or the computational domain. The type of discretization is very dependent on the type of simulation and the methods they use, whether it be elasticity computations, fluid dynamics or heat transfer. Functionality for discretization of models and solving the equations is available in standard **computer aided engineering (CAE)** software, however it can be a laborious process. A more recent approach emerging from scientific literature aims at reducing the amount of manual labour required in product design-simulation workflows is known as **isogeometric analysis (IGA)** (Cottrell, 2009). IGA attempts to unify the design and engineering representations and can be of particular interest in the digital twin context as a single representation can be used for multiple purposes, including design, simulation and representing material properties of the object.

3.1.3 Computer aided manufacturing

In the case of twinning manufacturing processes, **computer aided manufacturing (CAM)** tools are also of interest. CAM software can be used to define and communicate information such as computer numerical control (CNC) data and machine parameters for subtractive manufacturing processes. In the case of additive processes, slice information and scan vectors may also be relevant. Although such data is mostly of interest when **twinning manufacturing processes**, it can, in some cases, be useful to preserve this information in the digital twin of the actual manufactured product. For example, if the failure rate of a product is dependent on the material and manufacturing technique used, having that information available in the product digital twin is **critical for applications such as predictive maintenance**. However, in some cases such information can consist of very large amounts of data, some of which may be restricted by intellectual property rights, so considerations regarding what manufacturing information should be preserved in a product digital twin must be taken on a case-by-case basis.

3.2 DATA-DRIVEN MODELLING AND BIG DATA CYBERNETICS

3.2.1 Industrial internet of things

An alternative to the physics-based approach of modelling processes via known mathematical models is to make measurements of actual conditions on the physical twin and apply **data-driven modelling** methods. One advantage of data-driven modelling is that the data can encompass both known and unknown physics, thus providing a more complete account of the physical processes. However, in order to model physical processes in this way, **large amounts of data are typically required**. Another limitation on data-driven approaches is that the ability to measure certain conditions can be difficult in some circumstances (e.g., measuring the temperature on the interior of an object).

In order to obtain the data required for data-driven modelling, there is a **need to install sensors** that can make measurements and stream the data back to computer systems for further processing. Such setups comprise the **internet of things (IoT)**, which consists of a web of interconnected sensors, instruments and other devices that can gather and continuously stream large amounts of data. In the manufacturing context the **industrial internet of things (IIoT)** is often more pertinent, where requirements with respect to accuracy and quality of the sensor readings as well as the security of the transferred data are typically much stricter than in the consumer market.

While the sensor readings from IIoT devices can be interesting in and of themselves, in the digital twin context they typically produce too much data to be analysed manually. Recent advances in **artificial intelligence** have opened new possibilities for generating deeper insights into large amounts of data. While artificial intelligence encompasses a wide variety of computational methods, most of the recent advances have been in machine learning, and particularly the field of deep learning. It is now computationally feasible to model high dimensional and highly non-linear phenomena using **deep neural networks (DNNs)**, as is often required in data-driven approaches.

3.2.2 Artificial intelligence and machine learning

Artificial intelligence is a broad term that covers modern approaches to **machine learning**, in addition to more traditional algorithms. In practice, many uses of artificial intelligence contain software components of both these types. In digital twinning, the main aims behind artificial intelligence are to **embed expert knowledge in the digital twin, and to extract knowledge from the sensor data collected at the physical twin**.

Many of the recent advances in AI have come from developments in machine learning, and in particular deep learning. Machine learning is often categorized into three classes:

- **Supervised learning** is particularly useful when wanting to embed existing human knowledge in the digital twin, as it is based on modelling pairs of input data and labels. The labelling can either be done manually, representing human knowledge, or computationally, as for example in the case of approximating simulation results with DNNs. The result of training a supervised learning model is that the model can then infer labels for new input data, entirely automatically. By training the network on data based on labels generated by multiple experts, supervised learning algorithms can in some cases perform better than human operators, with fewer inconsistencies. In other cases, they can be used to speed up laborious manual labelling processes by providing an initial label that an expert can quality control, and edit, if necessary, without having to be involved in the entire labelling process.

- **Unsupervised learning**, on the other hand, does not require labelled data. Unsupervised approaches such as clustering can be used to gain new insights on the nature of the data, or to detect anomalies in large bodies of data. Such algorithms are often used in tandem with human experts who can use the results to make better interpretations of the data.

- **Reinforcement learning (RL)** is yet another approach where a machine learning model (which we call the agent) learns to take actions based on observations of its environment. The environment may, for example, correspond to the readings from IIoT devices, relevant simulators or a combination of both. The agent is then rewarded according to some desired behaviour and learns by trial and error over time to maximise its reward. RL is particularly useful in the context of planning and controlling digital twins.

AI technologies that are dominantly data-driven often generate questions with regards to the **privacy of the data**. In some cases, this is related to the ability to extract raw data about individuals from AI models. In recent years, techniques such as **differential privacy** (Abadi, et al., 2016), which ensure the effect of single samples on the AI model is limited to a certain degree, have been developed to address this. In other cases, the question is more related to how to gain insight into datasets that are decentralized and should not be shared with a central server. **Federated learning** is an approach to machine learning that sends the AI model to the nodes of the network and updates it, before sending it back to the central server to be pooled with the results from other nodes (Yang, et al., 2019). This approach of sending the algorithm to the data, rather than the converse, ensures that multiple actors can gain common insights without sharing raw data.

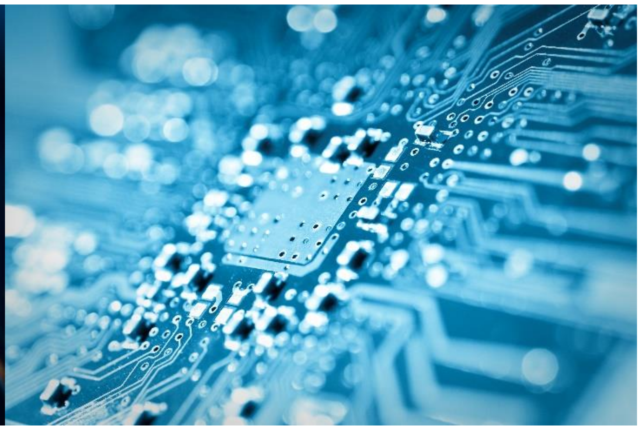
3.2.3 Hybrid analytics

Hybrid modelling approaches aim to combine physic-based and data-driven modelling approaches. Hybrid analytics often provides a more flexible and robust approach and has the advantage of preserving the known physics of the model while also dealing with the low quality or quantity of data that plagues data-driven approaches. Nevertheless, the combination is often more complex and requires a more tailored approach (Karniadakis, et al., 2021).

Big data cybernetics is a term used to describe the application of the above approaches in a cybernetics context (Rasheed, San, & Kvamsdal, 2020). Cybernetics is a cross-disciplinary field where the aim is to steer an arbitrary system towards a certain reference point, by exploiting feedback from chosen actions in order to determine further actions. Some aspects that can be considered **enablers for big data cybernetics** include:

- **Data assimilation**, where data is processed and filtered, and
- **Reduced order modelling (ROM),** where complex high-dimensional problems are approximated by lower dimensional problems.

3.3 INFRASTRUCTURE AND PLATFORMS

There exist several services that aim to ease the implementation of (I)IoT technologies and digital twinning as a whole, by **offering complete solutions**. Such offerings often include aspects of **Software-as-a-Service (SaaS)** and **Platform-as-a-Service (PaaS)**, covering multiple elements of cloud and edge computing, and relevant communication protocols. The recent explosion of interest in AI is also driven by advances that make computations with neural networks much faster and more efficient than previously.

3.3.1 Cloud computing

Many of the models and data involved in a digital twin require significant computational resources when they are to be processed. One of the major technologies that enables processing in a big data context is cloud computing. Cloud computing offers computational resources from a remote location over a network. One of the key benefits of cloud computing is that it offers **flexible scalability of compute resources** without SMEs having to invest in their own infrastructure, which can be useful considering the different computational requirements at different stages of digital twin implementations. For example, training DNNs is often a very computationally heavy exercise, but inferring results from pretrained networks is much less intensive. In some cases, DNNs that have been trained for many days on high-end graphics processing units (GPUs) can actually perform reasonably well on standard CPU hardware, when it comes to inference. Thus, exploiting cloud computing resources to periodically train a model without having to invest in high-end computational hardware, can result in **significant cost savings**. Another benefit of cloud computing is that users can get access to the latest updates, both to hardware and software, without the risk of depreciation. The benefits of cloud computing are sometimes contrasted with the **risks of proprietary data leaving the premises of the data owner**. While state-of-the-art security is often employed to offset these risks, there can also be legal aspects of transferring data for remote processing, especially if the data will cross national boarders.

3.3.2 Edge computing

Cloud computing can be contrasted with edge computing which aims to bring computational resources closer to the source of the data. A major benefit of edge computing is that the **data can be processed without ever having to leave the local network**, solving issues with latency by avoiding transferring huge amounts of data. An additional benefit of edge computing is that it is easier to ensure the data remains private and secure. However, it often requires a **significant investment in local computer hardware**. A hybrid approach to computation known as **fog computing** which aims to automatically **combine edge and cloud resources** to optimize the processing of the data, can also be valuable in some cases.

3.3.3 High performance computing

Similarly, to cloud computing, high performance computing (HPC) is also typically offered from a remote location but in contrast to cloud computing, it targets **solving hugely complex problems** that cannot typically be solved by a single consumer-grade computer. HPC jobs are normally subject to a queuing system, where jobs are submitted and await the availability of the computational resources. HPC is particularly useful when highly parallel computations are required such as for complex simulations, or for processing vast amounts of sensor data in batches. In this way it can support the use of the digital twin as a replacement for physical testing to some extent.

3.3.4 Networks

The IIoT devices that have been discussed previously need to be connected to a sufficiently fast and reliable infrastructure to pass the data from the physical twin to the digital twin. Availability of high-speed wireless networks has resulted in it being much easier to integrate IIoT devices that can monitor manufacturing processes than previously. While **wired networks** have advantages in terms of reliability, they are often more expensive to maintain and less flexible for subsequent augmentation with new devices, making updating the digital twin more cumbersome. The **emerging technology of 5G**, which brings ultra-low latency together with higher speeds, increased reliability and increased availability will also be a driver for digital twin implementations. 5G also addresses issues with the limited number of devices that can share the radio frequency by using a wider bandwidth, enabling more and more sensors to be added in the future.

3.4 HUMAN MACHINE INTERFACE

3.4.1 Augmented, virtual and mixed reality

Digital twinning brings excellent possibilities to exploit advanced visualization methods such as **augmented reality (AR), virtual reality (VR)** and **mixed reality (MR).** If a digital twin of a physical asset is available, it makes sense, in many settings, to superimpose data extracted from the digital twin onto the physical twin. This can be done in a variety of ways, from using VR/AR headsets or other screens to directly projecting the information onto the physical twin. MR is a hybrid of AR, VR & MR technologies provide visual feedback to the user, but there is also the need for passing information from the user to the twin, (e.g., for control). They are therefore often combined with technologies such as **natural language processing (NLP)** or **gesture recognition** to provide effective environments in which the twin can be controlled either through voice control, or via physical movements.

3.4.2 Low-code development platforms

Much of the interest in digital twins is driven by the ability to extract sufficiently comprehensive knowledge from them that they can be used to make decisions. In many cases, the exact questions one wants to ask of a digital twin are not clearly formulated at the implementation stage. Often users are aware of what data is of interest to certain processes and the relevant sensors are installed accordingly, but the specific queries are not well defined. One way to interrogate the digital twin is to programmatically request information and to present that information in a certain format. However, digital twin users often have no background in computer coding, meaning simplified interfaces are needed for them to create their queries. Low-code development platforms (LCDPs) provide an environment where **non-expert programmers can use graphical user interfaces to make custom queries in a simplified manner**. This means that a wider range of stakeholders can make use of the digital twin and it can be used a wider range of purposes than initially envisioned.

3.5 DATA MANAGEMENT

As we see from the plethora of enabling technologies, digital twin implementations can involve a complex array of software and hardware components as well as data types and formats. In order to bring the contribution of all the technologies together into something that can be described as a digital twin, sophisticated approaches to data management are required.

3.5.1 Product lifecycle management

Digital twinning involves many different model versions that can represent different aspects throughout the lifetime of the twin, from design and simulation to manufacturing and actual use. Product lifecycle management (PLM) provides a **platform for integrating, storing, and accessing data throughout the lifetime of a product**. Key benefits of PLM are that it provides configuration control and traceability. PLM can be used for many different types of data, from product structure data and CAD drawings to documentation and related e-learning information. PLM is also an important driver for the use of standards, which is vital in digital twin implementations for ensuring that there is interoperability between the different components, and also interoperability between the digital twin and the outside world.

3.5.2 Blockchain

Blockchain is a technology that has in the past few years been popularized through its use in various cryptocurrencies. However, blockchain does have a wider use that can be of interest in digital twinning. Blockchains provide a **permanent decentralized historical record of**

information that is secure, traceable, and transparent; all of which are important in the digital twin context. Alternatives to blockchain technologies, such as directed acyclical graphs (DAGs), that address some of the issues with scalability are also emerging in some contexts.

4 ACCESSING DIGITAL TWIN TECHNOLOGIES THROUGH THE CHANGE2TWIN MARKETPLACE

The **Change2Twin Marketplace** is an online platform presenting solutions of European technology providers that facilitate the creation and deployment of digital twins. The Marketplace has been developed as a tool for European Digital Innovation Hubs which help manufacturers in their digitalization efforts. Today, it is mainly used by those which are part of the Change2Twin network, however in the future, this tool should be available to a much broader DIH network.

A core feature of the **Change2Twin** approach is making enabling technologies for digital twinning available in an **online marketplace**. The marketplace includes items that differ in nature, including:

- **consulting services,**
- **information,**
- **software,**
- **hardware, or**
- **complete digital twin solutions**.

The following figure shows the original concept of the end-to-end service provided by the **Digital Innovation Hub (DIH)** to the SME using the marketplace that provides enabling technologies. It is extended to show how the technology provider is involved in making enabling technologies available and accessible through the marketplace. Moreover, the figure depicts the simple steps of engagement for successfully supporting the SME.

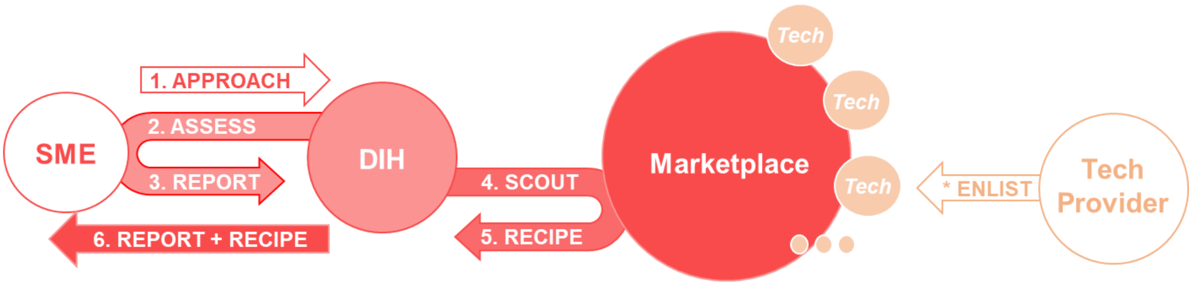


FIGURE 1: HOW SMES, DIHS, AND TECH PROVIDERS INTERACT WITH THE MARKETPLACE

The participants in this scenario are the SME, the DIH, the marketplace and technology provider. **The main entry point into this scenario is where the SME approaches the DIH for support.** From the perspective of the DIH, the steps are as follows:

1. The DIH is approached by the SME for support.
2. The DIH assesses the situation of the SME, with the SME. This can be done, for example, by completing the Change2Twin COMPASS assessment and readiness tools.

3. The DIH and SME complete the report as to which digital twinning purposes are most suitable for the SMEs, with an instruction and agreement as to which should be pursued.
4. The DIH assists the SME by scouting the marketplace in search of enabling technologies suitable for the selected purposes.
5. The enabling technologies are provided as a recipe to the DIH by the marketplace.
6. The DIH provides the matching recipe to the report with recommendations of enabling technologies, the associated technology providers, and information about developing and implementing a workable digital twin for their designated purpose.

In parallel to these steps**, technology providers can register their enabling technologies in the marketplace**, to make them findable by the DIH, and to make them accessible to the SME. It is crucial that the information about the technologies is up-to-date, especially with regards to revisions or fixes, and changes to contact and operating details.

The Change2Twin marketplace originated as an arena for sharing the technologies of the Change2Twin consortium, but it now contains several listings from external parties and is growing day-by-day.

4.1 TIPS FOR TECHNOLOGY PROVIDERS: HOW TO ENROLL IN THE MARKETPLACE

If your company provides solutions for the creation and deployment of **digital twins targeting the manufacturing sector**, you are welcome to enrol in the Change2Twin Marketplace – the service is completely free of charge! To join the Change2Twin Marketplace and catch the attention of **Digital Innovation Hubs** and **end-users** in their search for appropriate digital services and products, simply follow four easy steps:

1. Send your enquiry to marketplace@change2twin.eu
2. In return, you will be given a form to be filled in, and a guide on how to proceed. Make sure that your description is precise and relevant to digital twinning.
3. When you submit your description, our Onboarding task force will take care of it. They will assess your item against technical and non-technical quality criteria. If necessary, they will contact you directly to complete the validation of your listing.
4. When your listing is validated, it will be published on the Marketplace, and you will be notified per e-mail.

4.1.1 How to prepare a great listing

The Change2Twin Marketplace offers solutions for the creation and deployment of digital twins. Therefore, each item needs to provide precise information about its relation to digital twinning to be recognisable for end-users. Additionally, it has to specify effort required for installation, which type of process/manufacturing is involved, how the item can be acquired, website and contact details for more information etc.

4.1.2 Review procedure before publication

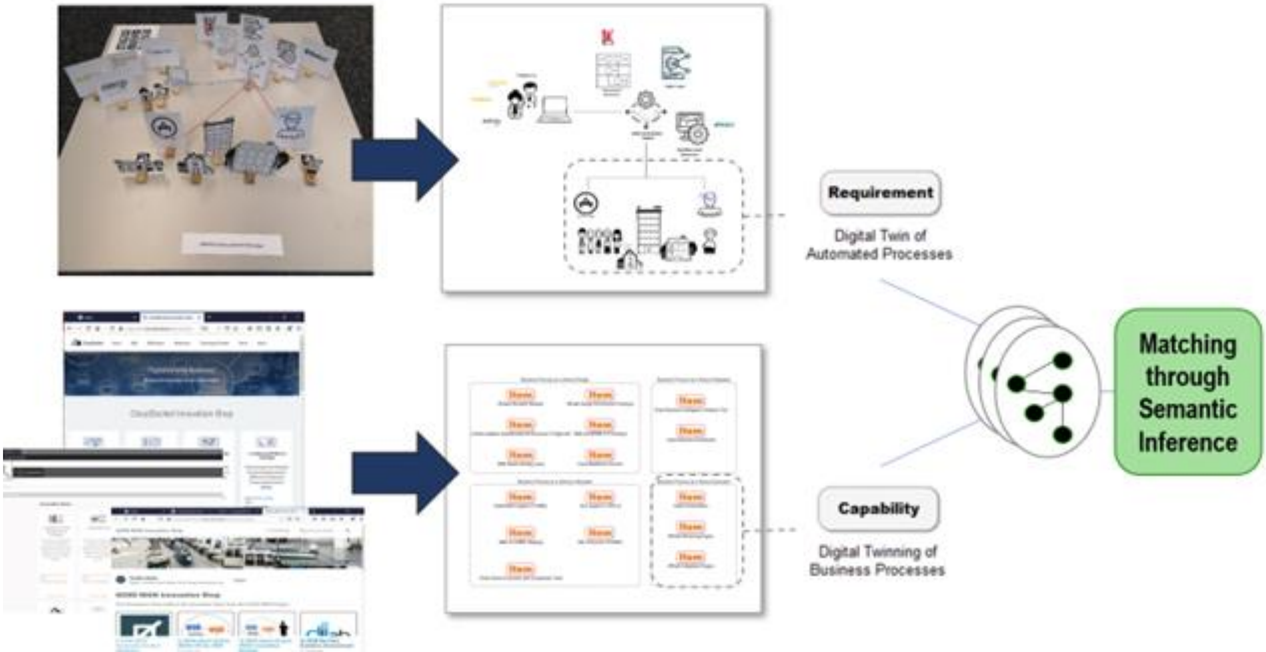
Accepting a new offer into the Marketplace is based on an onboarding process which guarantees the quality and relevance of the listed solutions. As mentioned above, the Onboarding task force will review each listing and contact their owners when necessary. In case of non-compliance to the requirements or non-responsiveness of the provider, the offer may be rejected.

A technical review is required in case there is a need for an item to be deployed or technical requirements need to be discussed. In addition to the technical review, a non-technical (administrative) review has to be done with all submitted solutions. After the offer is accepted, the Marketplace is updated accordingly, and item owner is notified.

4.2 TIPS FOR END-USERS: HOW TO SEARCH FOR SUITABLE SOLUTIONS ON THE MARKETPLACE?

The Change2Twin Marketplace is growing, making it more and more necessary to make the items accessible via search functionality. The basic search functionality now available in the Marketplace enables searching for keywords, offering types, companies, technology readiness levels (TRLs) and solution descriptions.

Even more advanced search is possible with the recently introduced semantic search offering. It allows to find the most fitting items in one or more marketplaces starting from your use case needs, using semantic matches.



A specific model type is introduced for this scope in order to define the capabilities of the marketplace item and the user requirements. The requirements can be defined manually or extracted and associated to scenes representing the use case. A semantic matching is then performed in order to infer which item best fits the needed requirements. The matching returns a matrix view where for each marketplace model available, all the items matching each requirement are visualized.

5 CONCLUSION

This position paper provides an overview of many of the important technologies that are typically involved in creating manufacturing digital twins. The technologies were presented based on a review of current literature and based on the experiences of the Change2Twin project partners who have been involved in a wide range of digital twin implementations. The technology descriptions are aimed at providing SMEs and mid-caps with a starting point when trying to understand what technologies are available and how these can be combined to make digital twins. The domain of digital twinning is very dynamic with new technologies emerging all the time. The Change2Twin marketplace aims to reflect this by providing a foundation of technologies that is continually updated and complemented as and when new technologies become available.

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Since completing his PhD at University of Oslo in 2013 as part of the Marie Curie Initial Training Network (ITN) SAGA, he has been involved in many EU projects covering aspects as diverse as air traffic management, additive manufacturing and medical imaging. The common thread in his work has been the need for creating and maintaining geometric representations, something that is a cornerstone in many digital twin applications today.

In Change2Twin he is leading the work package on Enabling Technologies for Digital Twins, where technology providers are enhancing their solutions to be more relevant to the needs of digital twinning in the manufacturing domain.

IMPRINT

Title	Enabling Technologies for Digital Twins in Manufacturing
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Date of publication	September 2022
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