1. Module 1: The Theory of the "Digital Twin"

1.1. Intro

When we talk about the link between digital systems and the physical world, we often hear the term "digital twins." Like many other modern concepts, such as artificial intelligence or the metaverse, the meaning of "digital twins" can vary.

For some people, a digital twin is connected to the Internet of Things (IoT). Here, the digital twin acts as a digital version of a sensor or a physical object, such as an engine. This digital version makes it possible to test and experiment in ways that would not be possible with the real object. For example, a digital engine can be exposed to stress levels far beyond what the actual engine could handle in real life.

For others, a digital twin is similar to an avatar in the metaverse. In this case, the digital twin is a virtual version of a real person or a fictional figure. These avatars can interact with each other in virtual spaces, such as games, online events, or digital social platforms.

A third view is that a digital twin can represent a virtual human actor. This digital actor makes decisions in the virtual space, and these decisions can help guide actions in the physical world.

To gain a clearer understanding of digital twins, this module will explore what a digital twin is, how the idea developed, the different types that exist, and the main advantages and disadvantages.

1.2. What is a Digital Twin?

A digital twin can be described as a digital or virtual model of a physical product, system, or process. It acts as a counterpart to the real object and is used for simulation, testing, monitoring, integration, and maintenance.

It is helpful to look at what a digital twin actually is, since a definition alone does not always give a clear understanding. Figure 1 gives an overview of the basic idea.

The Theory of the “Digital Twin”

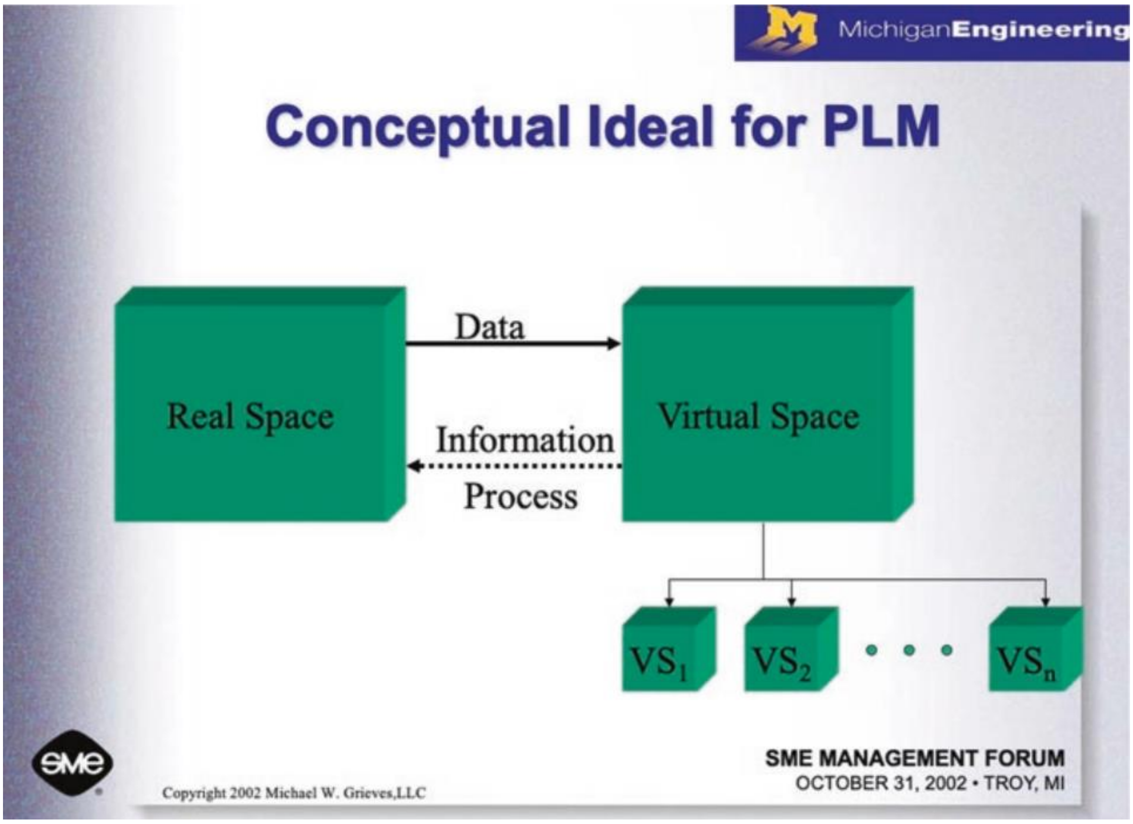

Figure 1: Image from the first presentation on Digital Twin as part of the conceptual idea for Product Lifecycle Management (PLM)

- Digital Twins: Past, Present, and Future (2023) - Michael W. Grieves

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The Digital Twin model, as shown in Figure 1, is built around three main elements:

1. **The physical twin** – the real or intended physical object that exists, or will exist, in the physical world. ("the physical twin" / "Real Space").
2. **The digital twin** – the virtual version of the physical object, located in a digital space. ("the digital twin" / "Virtual Space").
3. **The digital thread** – the connection that transfers data and information between the physical and digital versions. ("the digital thread" / "Data and Information Process").

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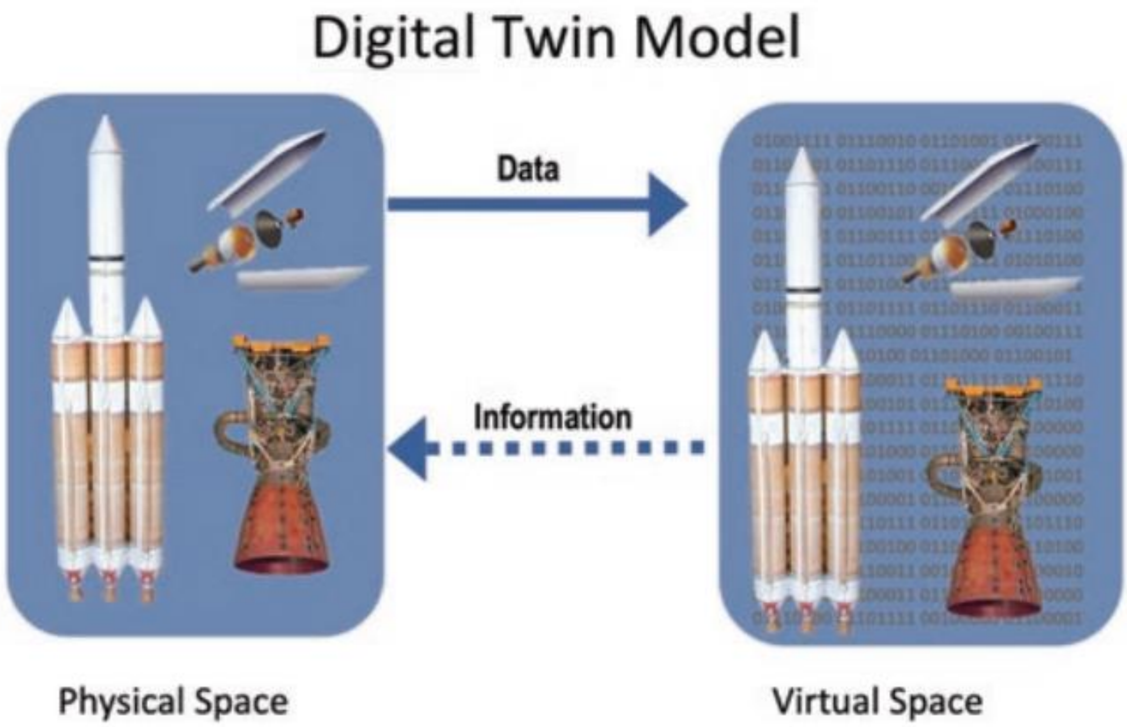


Figure 2: The model of the digital twin as practiced today, showing the correspondence between the virtual and physical spaces.
- Digital Twins: Past, Present, and Future (2023) - Michael W. Grieves

Figure 2 shows a more recent version of the same model. The graphic is from NASA, but the core idea is still the same as in the original version from 2002.

On the left side of the model is the physical space, with the physical products we use in the real world. We will always need physical products to carry out work in the physical environment.

On the right side is the virtual space. Here, we find the digital representations of the physical products, along with all the information about them.

The third part of the model is the connection between the two spaces. The goal of this connection is to bring data from the physical world into the digital world, so the digital twin stays updated. At the same time, information created in the digital world can be used to improve decisions or actions in the physical world. This connection is often called "the digital thread."

Digital twins can represent many types of real-world entities. This can include sensors, machines, people, and even entire organizations. A digital twin can also represent a process, such as flying a drone or running an autonomous vehicle.

A key point is that the digital and physical versions are synchronized. This means each version reflects the state of the other, making them true "twins."

Sometimes the term "digital twin" is confused with "digital model" or "digital shadow."

- A **digital model** is a virtual copy of a physical object. Information mainly moves from the digital world to the physical world.
- A **digital shadow** is created when real-time data from the physical object updates the digital version. Here, information only moves from the physical to the digital world.
- A **digital twin** includes data flow **in both directions**.

This two-way synchronization allows the virtual system to mirror the physical system and vice versa. The purpose of this setup is to reduce wasted physical resources by replacing them with information. This is why digital twins are becoming important in product development, manufacturing, and maintenance.

Even though the digital twin model has not changed much since its introduction in 2002, modern information technology now makes it possible to implement the concept in ways that were not feasible earlier.

In the next section, we will look at where the idea of the digital twin originally came from.

1.3. Where have Digital Twins been Used? – A Historical Overview

When searching for the term "digital twin," NASA's Apollo space program in the 1960s is often one of the first results. During the Apollo 13 mission, simulations were used to study the failure in the oxygen tank. NASA also used a full physical model of the spacecraft on Earth. In this case, the approach was not truly digital, and it was not a digital twin as we define it today, but the core idea was already present.

If we look more broadly at the concepts that came before the digital twin, the main idea is the simulation of the real world through a digital model. Agent-based models and computer simulations form the foundation for modern digital twins. Since the early days of artificial intelligence, starting with Alan Turing, the goal has been to mimic the behavior of humans or other intelligent physical systems.

The term "intelligent agent" refers to any entity placed in an environment that can sense what happens, make decisions, and act through some form of output. This concept dates back to the 1990s and is central to artificial intelligence research. One early example is Shakey the Robot, built by SRI International. Shakey moved in physical spaces by first creating a digital model of those spaces and then planning a route through them. This showed early forms of synchronization between the digital and physical worlds, something digital twins rely on today. Even simple devices like thermostats were described as intelligent agents, much like basic digital twins used in IoT systems.

The Theory of the “Digital Twin”

The history of computer simulation stretches back to World War II. Mathematicians John Von Neumann and Stanislaw Ulam used early computers to simulate neutron behavior. At first, simulations were mainly used in the military and aerospace sectors. Later, as computers became more accessible, simulation was adopted across science, engineering, and business. Agent-based simulations combined digital models of intelligent agents with models of the physical environment. This made it possible to test the behavior of these agents safely and effectively in the digital world.

The idea of a “digital twin,” known under several names over time, was first used in 1997. A clearer definition appeared in 2002, as described earlier. In 2018, organizations such as the U.S. Department of Defense refined the definition to something close to what we use today. Since then, the concept has evolved rapidly, including new types of digital twins and broader applications. The next section will explore these developments in more detail.

1.4. Where are Digital Twins Used Today? – Types of Digital Twins

To understand where digital twins are used, it is helpful to look at the product lifecycle. One way to divide this lifecycle is into four phases:

1. The product is created.

2. The product is built or manufactured.

3. The product is operated and maintained.

4. The product is phased out. This last phase is rarely discussed in relation to digital twins and will not be covered in detail here.

These four phases repeat in a cycle. Even though they overlap in practice, they are useful when explaining the different types of digital twins.

In the field of digital twins, we often talk about three main types. Each type relates to a specific stage in the product's lifecycle: the Digital Twin Prototype (DTP), the Digital Twin Instance (DTI), and the Digital Twin Aggregate (DTA). Figure 3 below shows these three types. This way of categorizing digital twins is helpful, as the purpose and value of digital representation depend on whether the product is still an idea or already in active use.

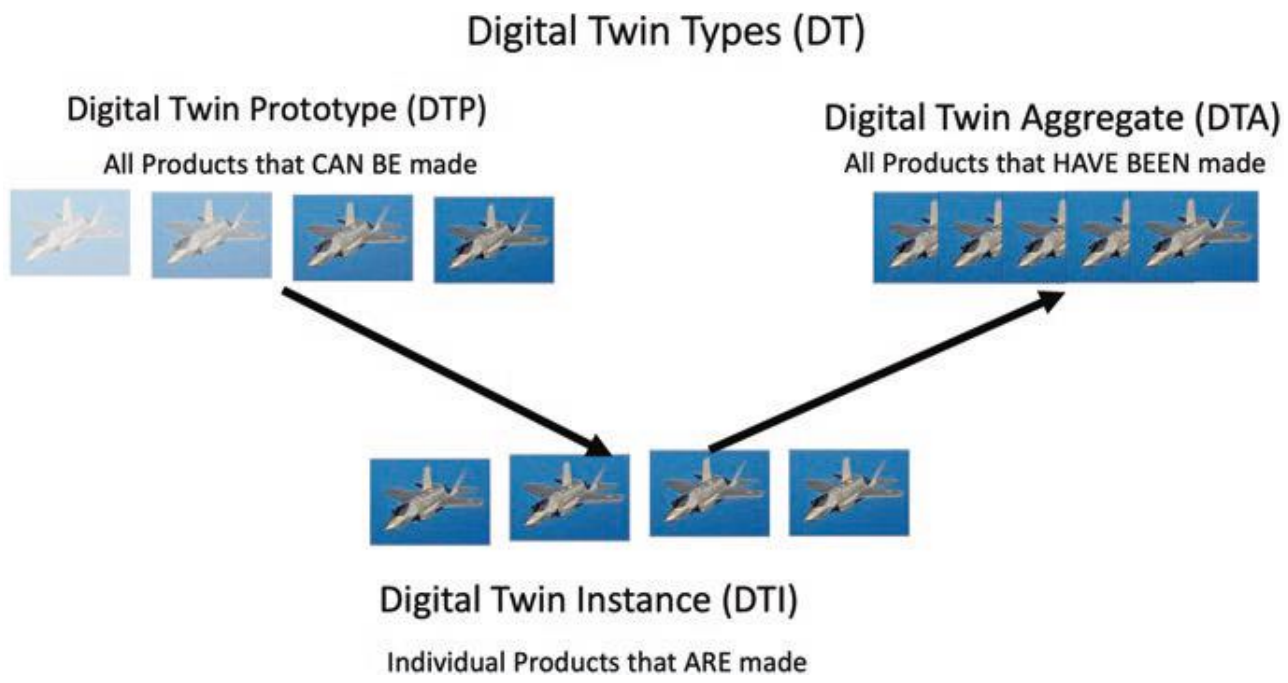


Figure 3: Types of digital twins in relation to a product's lifecycle

– Digital Twins: Past, Present, and Future (2023) – Michael W. Grieves

1.4.1. Digital Twin Prototype (DTP)

The Digital Twin Prototype (DTP) is the digital twin that exists before the physical product is built. It works as a virtual prototype and is used to design, simulate, test, and improve the product in a digital environment.

The main benefit of the DTP is that errors and design changes can be explored digitally, where the cost and effort are much lower than in the real world. This reduces the need for physical prototypes and makes it possible to test many different design options efficiently.

In this phase, Virtual Reality (VR) is especially useful. VR allows users to see and interact with the product in a realistic way, which improves understanding and helps avoid misunderstandings.

1.4.2. Digital Twin Instance (DTI)

When the physical product has been manufactured, a Digital Twin Instance (DTI) is created. Unlike the DTP, which is based on ideal specifications, the DTI contains exact measurements, serial numbers, and production data for that specific unit.

DTIs are used to follow the product through its entire lifecycle. They support maintenance, updates, and performance monitoring. For complex products such as aircraft like the F-35, the DTI is essential. For simple items, such as a paperclip, a DTI has no real value.

In this phase, Augmented Reality (AR) becomes more important. AR makes it possible to show the digital twin directly on top of the physical product. This gives technicians live information while they work, improving accuracy and efficiency.

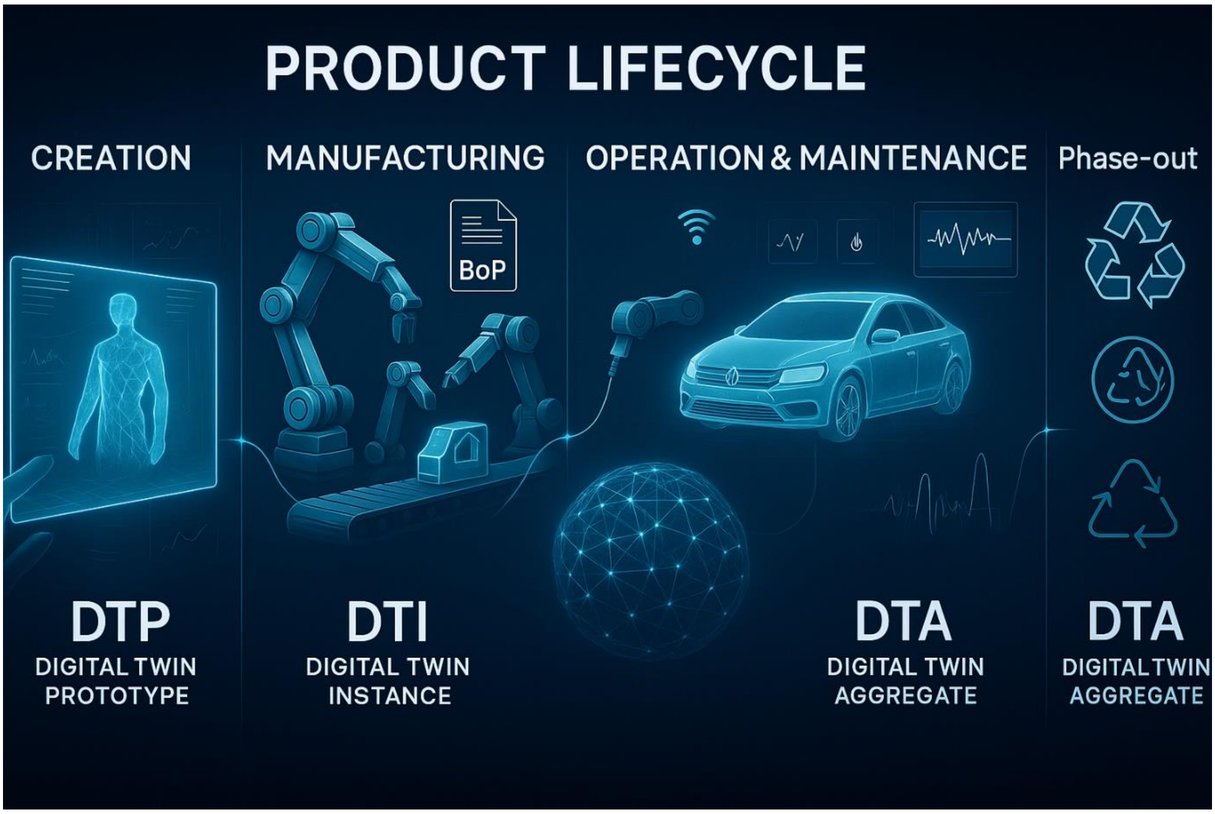
1.4.3. Digital Twin Aggregate (DTA)

The Digital Twin Aggregate (DTA) is the combined collection of all DTIs. By bringing data from many individual products together, it becomes possible to identify patterns, predict failures, optimize maintenance, and detect potential issues early.

This type of digital twin is especially important in condition-based maintenance and machine learning. Here, historical data from older products is used to improve the performance of new ones. DTAs create value both over time (longitudinal analysis) and across many units at once (latitudinal learning).

1.4.4. Digital twins throughout the product lifecycle

As mentioned earlier, a product's lifecycle can be divided into four phases: creation, manufacturing, operation and maintenance, and phase-out. The digital twin model is designed to support all phases, from the first idea to real use. To understand how the three types of digital twins – DTP, DTI, and DTA – work in practice, it is helpful to look at how they are used in each phase.



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In the creation phase, the Digital Twin Prototype (DTP) plays the main role. At this point, no physical product exists yet. The product is therefore developed first as a virtual model. The goal is to move as much work as possible into the digital space. This makes it possible to design, test, and improve the product before anything is built physically. Ideally, design errors and inefficiencies are found and corrected digitally, so the physical product can be manufactured correctly the first time. Many companies now reduce the number of physical prototypes for this reason.

When the product enters manufacturing, the digital design must become a real physical product. This requires detailed production plans and an understanding of how the product will actually be built. A common misunderstanding is that manufacturing is simply a step after engineering. In reality, manufacturing shapes how the design is realized. The DTP helps create a digital version of the production plan, known as the Bill of Process (BoP). This BoP is then passed on to the digital twins of the production equipment.

As the physical units are produced, Digital Twin Instances (DTIs) are created. Each product receives its own DTI, which shows exactly how that specific unit was built. The DTI includes measurements, tolerances, serial numbers, process data, and quality control information. Much of the DTI is based on the DTP, but the DTI documents what was actually produced—not just what was intended.

During the operation and maintenance phase, the DTIs continue to be updated. Products change over time, and it is important to record their condition, performance, and any repairs or changes. A major benefit of the DTI is the ability to store historical data. In the physical world, such information is often lost, but the DTI keeps a complete record of the product's behavior across its lifetime.

When many DTIs have been collected, they can be combined into a Digital Twin Aggregate (DTA). The DTA shows how an entire series of products performs. This allows for powerful analysis: by finding connections between sensor readings and failures, it becomes possible to predict issues before they happen. This supports a shift from scheduled maintenance to predictive, condition-based maintenance. Machine learning also plays a role by learning from earlier products and helping improve future versions.

This creates a closed feedback loop. Data from the DTA can be brought back into the creation phase. This makes it possible to design new products based on how the previous ones actually behaved—not how they were expected to behave. Many design flaws are repeated simply because no one challenged the original assumptions. The digital twin helps close this gap and connects theory with real-world performance across the entire lifecycle.

Although the phase-out stage is often overlooked, digital twins also offer value here. Both the DTI and DTA can support sustainable disposal and recycling. With detailed knowledge about materials and components, it becomes easier to reuse or recycle parts and comply with environmental requirements.

1.5. Which Hardware and Software Can Be Used?

Working with digital twins requires the right hardware and software. The exact requirements depend on what the digital twin will be used for—modeling, simulation, monitoring, or analysis. In education, the needs are usually lower, but it is still important to choose a suitable setup.

On the hardware side, a modern computer with good processing power, a dedicated graphics card (GPU), enough RAM, and a fast SSD will cover most needs for 3D modeling and basic simulation. If the goal is to view or interact with the digital twin through virtual or augmented reality, devices such as Oculus Quest, HTC Vive, or Microsoft HoloLens can be useful. These tools can enhance understanding in teaching environments by making complex concepts easier to visualize.

In industrial environments, more equipment is often required. This can include sensors, IoT devices, and edge computers that collect data from machines or systems. The data is then sent to local servers or cloud platforms such as Microsoft Azure, AWS, or Siemens MindSphere. This setup is more advanced but makes it possible to build and maintain digital twins that are updated in real time.

On the software side, CAD tools like Autodesk Inventor, Fusion 360, or SolidWorks are typically used to create the initial 3D model. Many of these programs offer built-in simulation features, while more advanced simulations can be handled by specialized software such as Ansys or COMSOL. For data analysis and visualization, tools such as Power BI, Python (with libraries like Pandas or Scikit-learn), or MATLAB are commonly used. If immersive or interactive experiences are needed, Unity or Unreal Engine can be added to the workflow.

In an educational context, it is important to choose tools that balance realism with ease of use. The goal is not always to use the most advanced technology, but to give students a clear understanding of how digital twins work and allow them to experiment in a safe learning environment. In this way, the technology becomes a link between theory and practical application.

1.6. What Can the Future Bring for Digital Twins? – Development and the Road Ahead

Digital twins have quickly moved from being a theoretical idea to becoming an important technology in both industry and education. But where is the technology heading? And what opportunities and challenges can we expect in the future?

One way to create an overview is shown in Figure 4. On the x-axis, we see the development of information—how much we can process, how we process it, and how fast it can be done. The y-axis represents time. In the figure, the x-axis is shown as linear, but this is not entirely accurate. In reality, the development is much closer to exponential growth. Today, new technologies appear so quickly that it can be difficult to keep up.

Moore's Law states that computers roughly double in power every two years without becoming more expensive. Even though we are reaching physical limits for how small transistors can be made (for example 3-nanometer chips), the exponential trend continues. This is possible through new hardware designs, better software, and specialized processors. The future of digital twins and intelligent simulation relies on this continuing exponential growth. In addition, the rapid development of artificial intelligence (AI) has further accelerated technological progress.

In this material, the simple model with four phases is used because it helps illustrate how digital twins may develop in the coming years. It provides a clear way to understand the direction of the technology, even though the real development is more complex.

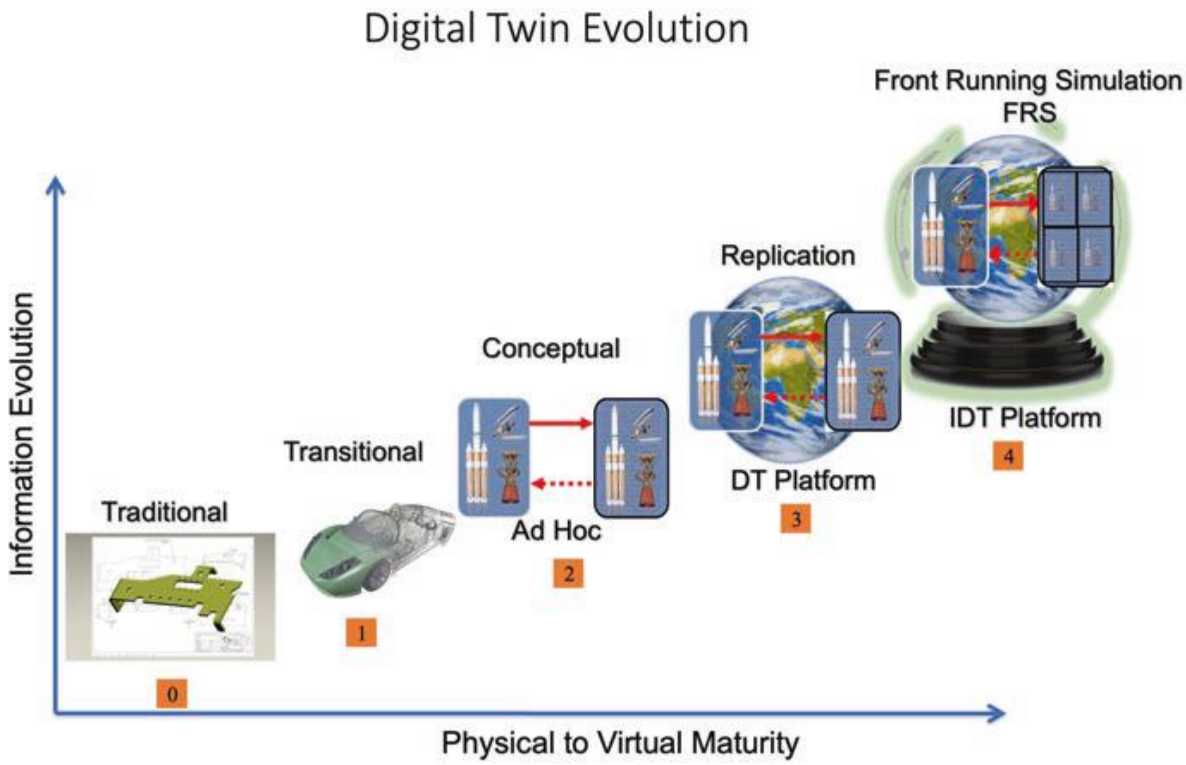


Figure 4: The different phases in the evolution of Digital Twins.

– Digital Twins: Past, Present, and Future (2023) – Michael W. Grieves

1.6.1. Phase 0 – Traditional (The Historical Approach)

In this phase—which describes most of human history until the late 20th century—ideas were always turned into physical form right away. People drew sketches on paper, built simple models, and later created technical drawings. Even when CAD software became common in the 1980s, it was mostly a digital copy of a physical drawing and not a functional model. There was still no true digital representation that could develop and exist alongside the physical product.

1.6.2. Phase 1 – Transitional (The Beginning of Digital Models)

This phase marks the start of what we now call the digital twin era. In the 2000s, companies began using digital 3D models actively in product development. It was a major step forward to be able to view a product from many angles and assemble it digitally. Even more important was the ability to simulate how the product would behave. Physical mockups were gradually replaced by Digital Mockup Units (DMUs), and the need for physical prototypes was greatly reduced.

1.6.3 Phase 2 – Conceptual and Experimental

As computing power grew, companies began combining data from different sources to create early versions of digital twins. Much of this work was done manually and without fully integrated systems. This phase focused on asking "what if" questions and exploring whether existing data could be used for prediction, analysis, and new insights. It was still an early stage, aimed more at testing ideas than building complete, operational platforms.

1.6.4 Phase 3 – Replicative Platforms

Today, we are in this phase. Digital twins are no longer experiments but established technologies offered as complete platforms. Companies now use systems that can collect data from many different sources and present it as an active digital twin. The information does not have to be stored in one place—the platform can retrieve and combine data intelligently across systems. All three types of digital twins—DTP, DTI, and DTA—are supported at this level.

It is now possible to simulate a product’s function and behavior directly during development and to follow the product throughout its entire lifecycle. This phase creates the foundation for the next, more advanced stage of digital twin development.

1.6.5 Phase 4 – Predictive and Intelligent Twins

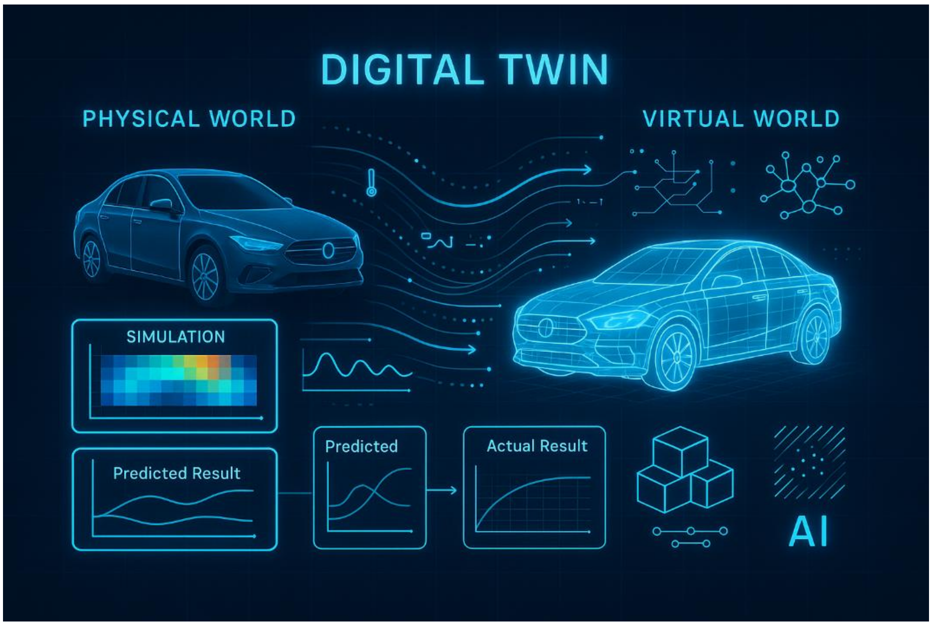
The future of digital twins is linked to what we call Front Running Simulations (FRS) and Intelligent Digital Twins (IDT). In this stage, the digital twin becomes an active and intelligent system that constantly monitors and analyzes the condition of the product. With artificial intelligence and machine learning, these twins will not only react to events—they will also predict future scenarios and give proactive advice. This means that intelligent digital twins must always be online.

An intelligent digital twin can detect issues before they happen and warn the user. For example, it may identify a component that has a 60% risk of failing within the next month. During the design phase, the twin can also suggest suitable components and simulate how they fit into the system—in real time.

This level of capability requires very high computing power, but with today's rapid technological development, it is becoming realistic. We are moving toward a future where the digital twin not only mirrors the product but also helps control, improve, and optimize it continuously.

1.6.6 Digital Twins as a Testing Tool – The Next Step in Development

Throughout their development, digital twins have shown that they can bridge the gap between reality and simulation. As the technology matures and computing power increases, digital twins are becoming more important for testing, evaluation, and prediction. The next step is not only to create virtual models, but to use them actively to support decisions and prevent errors before they occur.



Simulation plays a key role in this process. A model is a static digital representation of a product, while simulation adds time as a factor. This makes it possible to predict how a product will react under different conditions and over time. Whether it is crash-testing a car or predicting how a complex system behaves in operation, simulation can show deformation, stress responses, and performance trends—without touching the physical product. To achieve this, we need a strong understanding of physical laws and enough computing power to apply them digitally. Both areas are advancing quickly. A few decades ago, only simple products could be simulated, but today even complex systems can be handled on standard computers. This progress is again supported by Moore's Law.

However, we must also ask whether our simulations are accurate. This question led to the idea of "Tests of Virtuality," inspired by the Turing Test. These tests measure how closely a simulation matches reality. The newest method, Grieves' Test of Prediction, takes this further. Here, the digital system predicts a future state. When that moment arrives in the real world, the prediction is compared with what actually happened. The closer the match, the more reliable the digital twin is.

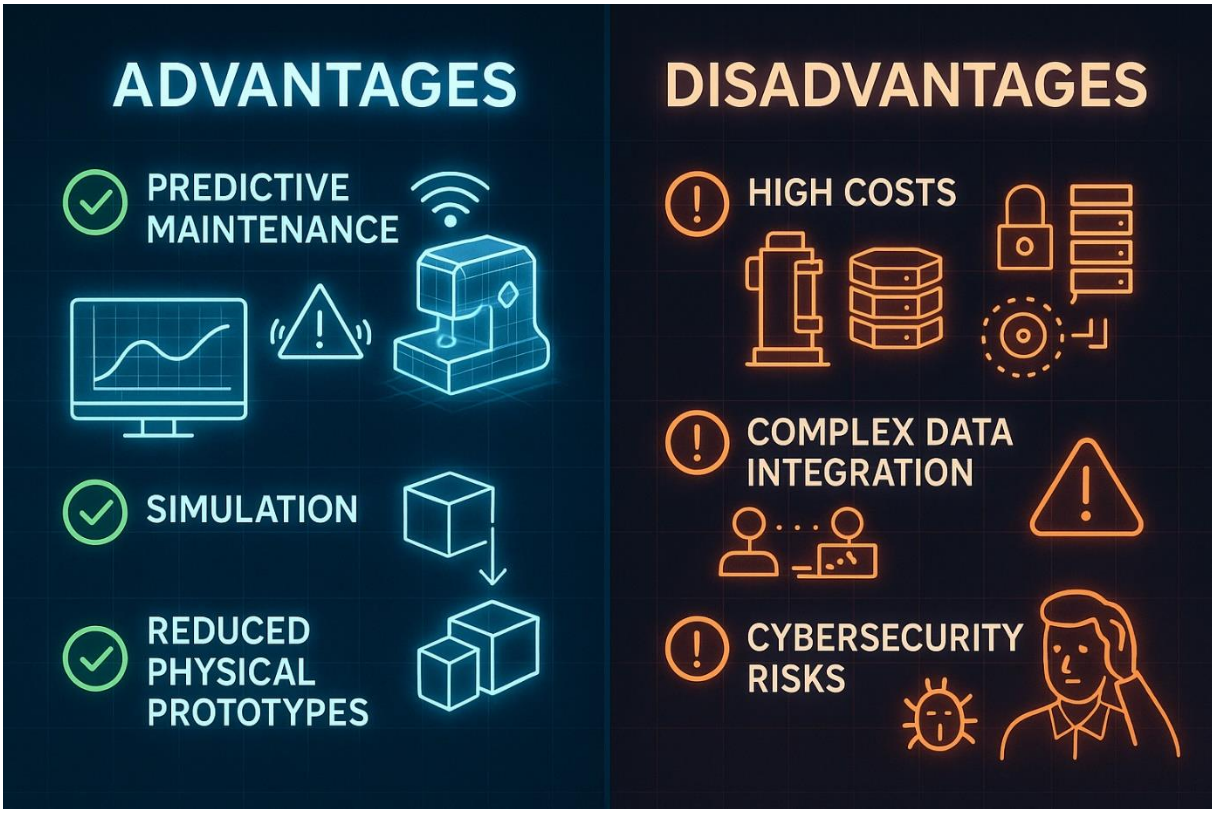
This type of testing is technically demanding, but very valuable. If we can predict component failures or warn about human errors, digital twins can save significant resources. In the most critical situations, they can even prevent accidents and save lives.

Intelligent digital twins—IDTs—are moving toward this vision. They combine real-time data, historical information, and behavioral models to make constant predictions. The most advanced IDTs will use large datasets and artificial intelligence to identify patterns and support decisions in complex environments. Achieving this requires continuous work, both technically and organizationally. Users must experience clear value, since maintaining these systems requires time and resources. But when they work as intended, the benefits are large: lower costs, higher safety, and faster responses.

This marks a shift from reflection to proactivity. The digital twin is no longer just a model—it becomes a dynamic partner in product development and operations, where simulation, testing, and prediction merge into a single intelligent system.

1.7 Advantages and Disadvantages of Using Digital Twins

Digital twins have become increasingly popular in industry because they offer many ways to improve development, operation, and maintenance. However, like all technologies, digital twins also come with challenges that must be considered before they are implemented. Below is an overview of some of the most important advantages and disadvantages of using digital twins.



1.7.1 Advantages

monitoring and analysis of production. By using sensors and integrating data, it becomes possible to track the condition of machines and systems. This supports predictive maintenance, where potential failures are detected before they happen. For example, if a motor begins to vibrate abnormally, the digital twin can identify the issue before physical damage occurs. This helps avoid costly, unplanned downtime.

Another major benefit is the possibility to simulate changes digitally before making them in physical production. Companies can test new workflows, production speeds, or layout adjustments without interrupting daily operations. This makes it easier and more cost-effective to optimize processes and make informed decisions.

Digital twins also reduce the need for physical prototypes. During development, products can be modeled and tested in a virtual environment. Physical production only begins once the digital design has been validated. This saves time, materials, and money—and helps products reach the market faster.

A further advantage is improved documentation and traceability, especially through the Digital Twin Instance (DTI). When each manufactured unit has its own digital twin with measurements, serial numbers, and process data, it creates a strong foundation for quality assurance and maintenance. This is especially important in sectors with strict documentation rules, such as food production, pharmaceuticals, and aerospace.

1.7.2 Disadvantages

Even though digital twins offer many opportunities, there are also several challenges when implementing them. The first challenge is cost. The technology requires investment in sensors, IT infrastructure, software platforms, and often upgrades to existing machines. For small and medium-sized companies, these initial costs can be a barrier.

Another challenge is the technical complexity. It can be difficult to ensure a smooth flow of data between different systems—for example from PLCs to cloud-based analytics tools. Integrations must be set up, data structures defined, and questions about data quality and data ownership must be handled. A digital twin is only useful if the underlying data is reliable and up to date.

Cybersecurity is also an important issue. As production becomes more digital and connected, the risk of hacking, data breaches, or manipulation increases. Systems that are connected to the internet or external providers must be protected from the start. A security breach can have serious consequences—not only for operations, but also for the company's reputation.

Finally, digital twins place demands on the organization. Employees need to understand and use the systems correctly, which often requires new skills. Without proper training, there is a risk that the technology will not be used as intended. A digital twin is only as valuable as the knowledge and decisions that come from it.

1.8 Considerations for Using Digital Twins in Education

The advantages and disadvantages of digital twins apply not only to industry but also to education—especially in vocational training. When digital twins are integrated into teaching, educators can bring real production environments closer to students while maintaining a safe, controlled, and repeatable learning space.

Just as in industry, the technology makes it possible to simulate complex processes before students encounter them in real life. This helps them understand how systems are built and how they function, and it strengthens their ability to analyze and solve problems. For example, a digital twin can show how a production line reacts to sequencing errors or how a hydraulic system responds to changes in pressure and flow. This gives students a visual and hands-on understanding that is difficult to achieve through theory alone.

Digital twins can also act as training tools. Students can practice operating, troubleshooting, and maintaining systems without risk. Because these digital environments can be repeated exactly, they also support independent learning, where students can work at their own pace and receive feedback. This fits well with modern teaching methods such as flipped classroom and blended learning.

However, using digital twins in education also presents challenges. Developing and maintaining digital learning environments requires time and resources. Equipment, licenses, and software can be costly, and teachers must have the necessary skills to create and use relevant scenarios. If teachers or students are not familiar with the technology, it can lead to frustration and reduce the quality of learning.

It is therefore important to see digital twins as pedagogical tools that must be used with care. When applied correctly, they can support engaging, practice-oriented teaching that improves students' understanding and better prepares them for the technologies and tasks they will meet in their future careers.

1.9 What's Next for You in Module 2?

In the next module, we move from theory to practice. You will be introduced to Autodesk Inventor and learn how to create a simple 3D model. The purpose is to give you a basic understanding of how digital twins begin with digital models, and how these models can later be used for simulation and analysis.

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