The evolution of the digital twin

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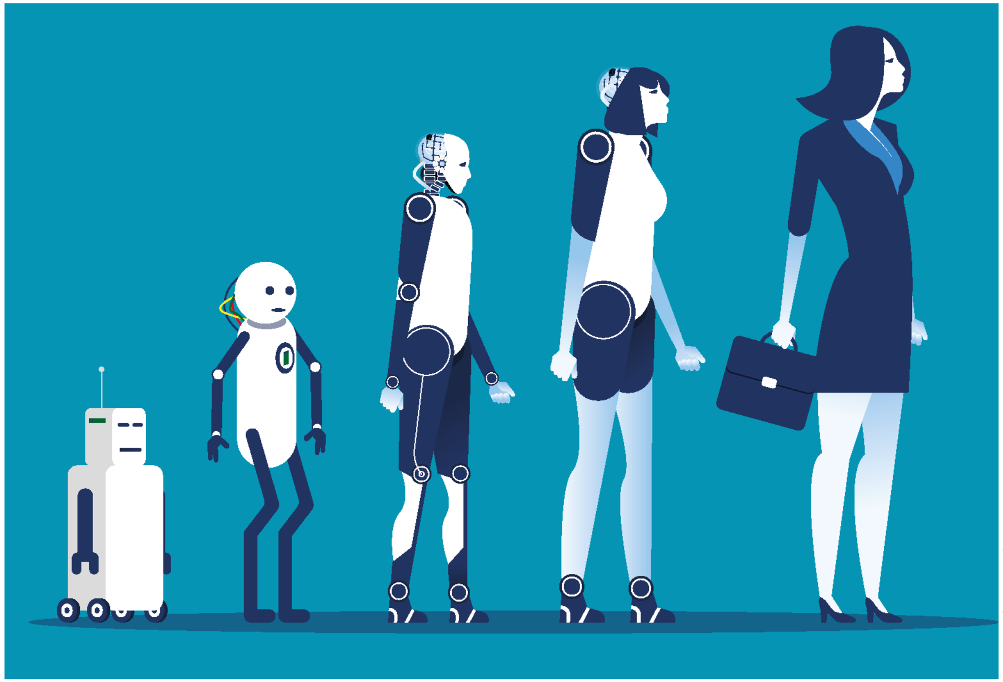

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The Evolution of the Digital Twin

A visionary product concept brings big changes for the future

Michael Grieves, Florida Institute of Technology Center for Advanced Manufacturing and Innovative Design (CAMID)

The Digital Twin is a product manufacturing concept that is receiving much current attention. While the concept originated over a decade ago, the advances in information technology have now made the Digital Twin feasible to implement. The attractiveness of the Digital Twin is that it promises to provide value for both manufacturers and customers throughout a product's creation and life. There are several types of the Digital Twin. Digital Twins will increase in intelligence, which will be critical as Artificial Intelligence (AI) moves into products.

The Digital Twin model made its public debut in December 2002 at the University of Michigan. It was part of a presentation at the formation meeting of the proposed Product Lifecycle Management Center. The attendees included executives from the Big Three Detroit automotive companies (General Motors, Ford, and Chrysler), Tier 1 automotive suppliers, and Product Lifecycle Management (PLM) software providers. The model did not have a name at that time. The slide was simply entitled, „Conceptual Ideal for PLM". However, the label was meant to convey that PLM was all about capturing, maintaining, and using information about a product. It was the idea that all the information about a product could be mirrored with information in PLM.

The idea that there is an informational "twin" of physical products, had been an area that was explored during a doctoral program at Case Western Reserve University. Informational Twins have existed as long as humans have had things that they made or what we call "products." Informational twins first existed as ephemeral thoughts in people's minds and then progressed to a tangible permanence as people began to capture their thoughts on paper and physical scale models. The rise of computers in the last half of the 20th century and their exponential advancement as described by Moore's Law meant that we were rapidly reaching the point where a Digital Twin that could fully mirror a physical product was not too far off.

The value of the Digital Twin (and informational twins) is that information is a replacement for wasted physical resources: time, energy, and material. While physical resources have to be expended in activities in order to accomplish desired results in our physical world, knowing exactly what activities will produce those results can dramatically reduce physical resource usage. Using digital bits that get cheaper every day is usually far more efficient and effective than using physical atoms that get more expensive every day.

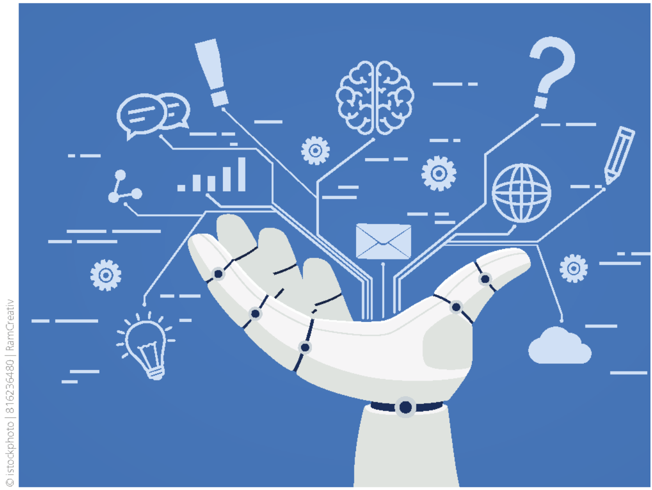
Admittedly the Digital Twin was ahead of its time when it was introduced. The Digital Twin's real usefulness also required that PLM move from the create phase in engineering into the build phase of manufacturing and the usage/support phase when the product is placed into service. By around 2015 both the technology of modeling and simulation, and the usage of the digital tools throughout the product lifecycle made the Digital Twin a reality.

In the past year, there has been acceleration of the usage of the Digital Twin as both manufacturers and users have recognized its value in mirroring a product's creation, manufacturing, and performance. Gartner, Inc. a leading information technology research firm, named the Digital Twin as one of the Top 10 Strategic Technology Trends for 2018.

> Information is a replacement for wasted physical resources.

The Digital Twin and Its Types

The Digital Twin model is made up of three parts, the physical product (which can also be thought of as the Physical Twin), the Digital Twin, and the communications of data and information between the two. The Digital Twin model requires all three of these components in order to be useful. What would be helpful are some definitions to rely on when referring to the Digital Twin itself and its different manifestations in different phases of the product's lifecycle. The following definitions are proposed:



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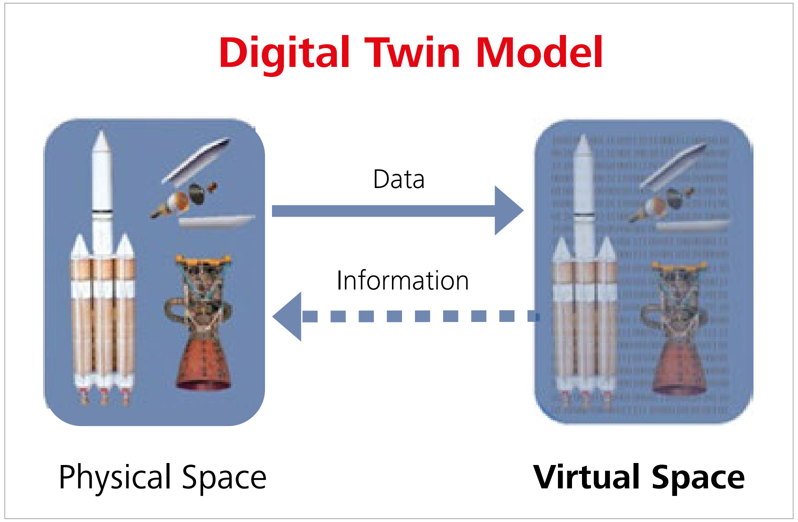

Figure 1:
Picture of the Digital Twin.

Digital Twins are of three types: Digital Twin Prototype (DTP), Digital Twin Instance (DTI), and Digital Twin Aggregate (DTA).

Digital Twin (DT): the Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the micro atomic level to the macro geometrical level. At its optimum, any information that could be obtained from inspecting a physical manufactured product can be obtained from its Digital Twin. Digital Twins are of three types: Digital Twin Prototype (DTP), Digital Twin Instance (DTI), and Digital Twin Aggregate (DTA).

Digital Twin Prototype (DTP): this type of Digital Twin describes the prototypical physical product. It contains the informational sets necessary to describe and produce a physical version that duplicates or twins the virtual version. While the Digital Twin is thought to be the "twin" of an existing product, the reality is that the Digital Twin is created before there is a physical product. The ideal is that we would like to develop the Digital Twin, test it to ensure that it produces the behaviors we desire, manufacture it digitally to make it as lean as possible, then use and support it digitally, simulating it throughout its life cycle. Only when we are convinced that the product design meets all our requirements, we would then make the physical product. Again, if we are seeking the ideal, we would print it using Additive or 3D Manufacturing! Clearly the complexity of the product drives the amount and types of data and information needed. A paper clip doesn't need a DTP. A 21st century fighter jet needs a substantial and complex DTP.

Digital Twin Instance (DTI): this type of Digital Twin describes a specific corresponding physical product that an individual Digital Twin remains linked to throughout the life of that physical product. Depending on the use cases required for it, this type of Digital Twin may contain many different types of information: geometrical information, service information, part changes, etc.

Digital Twin Aggregate (DTA): this type of Digital Twin is the aggregation of all the DTIs. Unlike the DTI, the DTA may not be an independent data structure. It may be a computing construct that has access to all DTIs and queries them either ad-hoc or proactively.

The idea of an active or intelligent Digital Twin was always a part of the concept from the beginning.

What are the major uses of Digital Twins?

The two major uses are predictive and interrogative. Predictive - the Digital Twin would be used for predicting future behavior and performance of the physical product. At the Prototype phase, the prediction would be of the behavior of the designed product. In the Instance phase, the prediction would be of potential component failures of an individual product: an airplane, pacemaker, turbine.

Interrogative - Digital Twin Instances could be interrogated for the current and past histories. Irrespective of where their physical counterpart reside in the world, individual instances could be interrogated for their current system state: turbine blade speed, geographical location, structure stress, or any other characteristic that was instrumented. Multiple instances of products would provide data that would be correlated for predicting future states. For example, correlating component sensor readings with subsequent failures of that component in a population of products would result in an alert of possible component failure being generated when that sensor pattern was reported.

Intelligent Digital Twin (IDT)

The initial discussions of the Digital Twin focused on it as being a passive repository of the physical product information that was able to be interrogated. However, the idea of an active or intelligent Digital Twin was always a part of the concept from the beginning. One of the key characteristics of PLM that was articulated initially was called "cued availability." While not a particularly elegant term, cued availability meant that the Digital Twin would present appropriate information based on the contextual cues of the product status in the environment that it was operating in. With the current rapid advancements in Artificial Intelligence (AI), combining the Digital Twin with AI leads to the Intelligent Digital Twin.

One of the major opportunities for an IDT is to do Front Running Simulation (FRS). What FRS does is to take the current state of the product and, based on its modeling and simulation of behavior, predict the product's state into the future, in minutes, hours, or days. This would be useful in predicting product degradation or failure, bottlenecks in factories that would occur, or actions with the operation of equipment that could lead to unsafe or catastrophic conditions. With the rise of IoT, there is much discussion about putting AI in the equipment itself to modify equipment behavior and responses, i.e., "learn", as time goes on. This sounds reasonable until one realizes that there is a real possibility of unintended behavior cascading out of control in a disastrous fashion. Having an IDT to provide overwatch and FRS capabilities, intervening and bringing a product back under control needs to be a precondition before putting AI in products. ■

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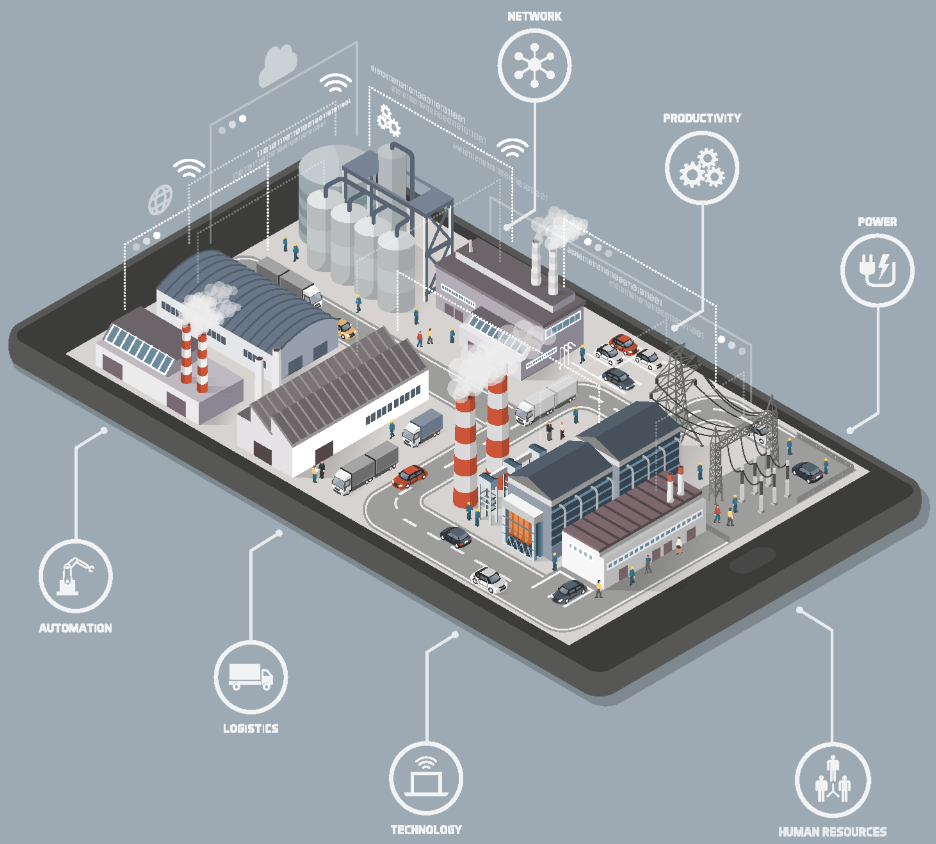
Kurz und bündig

Obwohl das Konzept des Digitalen Zwillings schon seit über einer Dekade bekannt ist, kann es erst durch moderne Informationstechnologien realisiert werden. Der Digitale Zwilling hat die Möglichkeit das Produktdesign zu optimieren und damit neue Ansprüche zu erfüllen. Die Entwicklung zu einem Intelligenten Digitalen Zwilling, ermöglicht es Aussagen über den Lebenszyklus von Produkten, welche mit KI ausgestattet sind, zu treffen, deren Kosten zu reduzieren, ihre Verlässlichkeit zu steigern und ihre Kontrolle zu erleichtern.

Twin Planning: Virtual and Real Factory Planning

Lai Xu, Giacomo Cabri, Marco Aiello, Massimo Mecella & Paul de Vrieze, EU-Project FIRST



The manufacturing industry is entering on a new era in which information and communication technologies (ICT) and collaboration applications are integrated with traditional manufacturing practices and processes to increase flexibility of production, mass customization, speed, quality and time to failure. To cope with the rapidity of change in today's markets, frequent updates of the planning are needed. As such the planning needs to be adaptive, dynamic and resilient to failures. Building a virtual model of the factory and applying explicit planning to it can help in achieving a more effective planning in the actual factory.

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Two main forces are driving major changes in modern factories. The first one being the high degree of globalization. Factories have an increasing need to efficiently collaborate with their suppliers and their customers, possibly all over the world. The second is the fact that the degree of automation and digitalization has reached unprecedented levels. Factory production equipment is not only producing data at high frequency, but it is also driven in an automated and integrated way. This calls for an accurate and comprehensive planning of modern factory production processes. Planning entails the precise enactment of all the processes, procedures or applications which concur to the overall production of goods. To cope with the rapidity of change in today's markets frequent updates of the planning is needed. As such the planning needs to be adaptive, dynamic and resilient to failures. Building a virtual model of the factory and applying explicit planning to it can help in achieving a more effective planning in the actual factory.

Virtual Factories

The manufacturing industry is entering a new era in which information and communication technologies (ICT) and collaboration applications are integrated with traditional manufacturing practices and processes to increase flexibility of production, mass customization, speed, quality and time to failure. Virtual factory models can be created before the real factory is implemented to better explore design options, evaluate their performance and commit the automation systems, thus saving time-to-production [1]. This foundational concept to future manufacturing allows the flexible amalgamation of manufacturing resources in multiple organizations to model, simulate, test factory layouts and processes in a virtual environment. As a result, the actual factory can be created in a shorter time with demand-driven product lines or to simulate the desired factory be generated before committing to investment. Moreover, the virtual factory approach can be exploited when the real factory has already been implemented, in order to better manage it by means of a virtual model that represents it; this is particularly useful in manufacturing factories, where modifications in the field require careful evaluations.

As pointed out in the "Factories of the Future 2020 Roadmap" [1], pre-requisites for proper manufacturing integration include the need for agreements on industrial communication interfaces and protocols, common data models and the semantic interoperability of data, and thus on a larger scale, platform inter-communication and inter-operability. The achievement of these objectives will allow a boundary-less information flow among the single product lifecycle phases in turn enabling an effective, whole-of-life Product Lifecycle Management (PLM). Indeed, the most significant obstacle is that valuable information is not readily shared with other interested parties across the Beginning-of-Life (BoL), Middle-of-Life (MoL), and End-of-Life (EoL) lifecycle phases but it is mainly locked into vertical applications, the so-called silos.

Technological challenges

Kuhn [2] argues that the digital factory concept, where all aspects of the production line are digitized, requires the integration of tools for the design, engineering, planning, simulation, communication, and control at all levels. He suggests that openness and interoperability are the key factors in implementing a digital factory concept. Gregor and Stefan [3] state that a very important property of a digital factory is the ability to integrate process planning and product development using common data. They further suggest that it is important to gain all the required data once and manage it with uniform data control to allow all software systems to utilize it effectively. Overall, they imply that the digital factory is a link between the 'what', product development, and the 'when and who', process planning, with the use of common data to provide the 'how' within the product lifecycle. In the following sections, we point out three key factors to enable the synchronization between virtual and real planning.

Interoperability

The synchronization between virtual and real planning, the "twin-planning", must be supported by interoperability among the equipment and the software applications of the factory. Too often, on the very same production line, data of one stage is not used by the following stages, in turn increasing the chances of defects and failure in the production.

The systems should be able to communicate, to recognize the context respectively state of production and to make decisions based on the implementation details.

In order to create the digital twin planning and to manage the interoperability of heterogeneous systems throughout the product lifecycle, several approaches could be used [4]:

- A straightforward but limited approach is where a single overall schema is created that is used by data sources [4]. In this tightly coupled approach any change of an individual system needs to be reflected by an update of the entire overall schema.
- Object-oriented interoperability approaches are closely related to tightly coupled ones. Different types of these approaches are described in Pitoura, Bukhres, Elmagarmid [5]. Object-oriented interoperability approaches use common data models which have similar problems when dealing with modification of individual systems.
- Loosely coupled interoperability approaches are more suitable to achieve scalable architectures, modular complexity, robust design, and integration of third party components. Using Web services as communication method is one of such loosely coupled interoperability approaches. A notable extension to Web services are Semantic Web services [6], in which a machine usable meaning allows automation of service use.
- Service-Oriented Architecture (SOA) has emerged as the main approach for dealing with the challenge of interoperability of systems in heterogeneous environment [7], [8]. SOA offers mechanisms of flexibility and interoperability that allow different technologies to be dynamically integrated, independently of the system's Product Lifecycle Management (PLM) platform in use [9]. Several standards for Product Lifecycle Management (PLM) use SOA, such as OMG PLM Services [10], [11].

EUROPEAN UNION SUPPORTS THE IT-CONCEPTS FOR VIRTUAL FACTORIES

The project "virtual Factories Interoperation suppoRting buSiness innovaTion" (FIRST) provides the new technology and methodology to describe manufacturing assets; to compose and integrate the existing services into collaborative virtual manufacturing processes; and to deal with evolution of changes. From the overarching objective to enhance manufacturing integration through the application of advanced IT solutions, the innovative project brings together an experienced researcher with expertise in the designing an interoperability framework for facilitating interoperability on data/information, services and process levels respectively. These outcomes lead to significant business innovations for virtual factories, made possible by an internationally recognized group expertise in (manufacturing) services/assets description languages, semantic services discover methods, and automated interoperability. The FIRST project will take advantage of this complementary experience as well as the academic and industrial relationships in Europe and China respectively, taking advantage of the unique opportunity to address the concept from both perspectives.

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Service composition

In connection with the interoperability aspect, in a factory "ecosystem" there are many services that support the Product Lifecycle Management. State-of-the-art equipment typically does not only provide data about its own functioning, but also exposes services by which the machines can be programmed and driven. The trend towards programmatically accessible equipment is expected to increase in the near future.

Services can be provided at various levels, from very simple ones to very complex ones; the former are more robust and can be exploited in a wide range of situations; the latter are very specific and do not require a relevant effort to be exploited.

For the planning of manufacturing the available services, in particular the simplest ones, must be composable in order to provide higher-level building blocks to the planners. A number of new challenges need to be addressed: (i) services can be heterogeneous (two teams designing the same service will come up with a different service interface), (ii) the correct service(s) must be discovered, requiring a way to describe services and tools that enable searching for the needed one(s), and (iii) in complex factories the composition should be autonomous and adaptive to actual production context, in order to limit costly and slow human intervention. As an example of an approach addressing these issues, the project "Self-aware Pervasive Service Ecosystems" (SAPERE) is representative [12].

Business and IT alignment

In addition to interoperability, the effectiveness of the virtual planning depends on the alignment between business strategy and IT strategy [13], taking into consideration also social aspects [14]. With the rising importance of innovative digital technologies for performance and competitiveness, the concept of digital business strategies (DBS) emerged [15]. "The fusion of business and IT strategies is presumed to account for the inevitable transformations that digital technologies triggered. This paradigmatic shift poses new challenges to practitioners and researchers, as current assumptions regarding strategizing processes need to be questioned" [15]. Some means are available to enact the alignment between business and IT strategies. For instance, COBIT 5 is a comprehensive framework of globally accepted principles, practices, analytical tools and models that can help any enterprise effectively address critical business issues related to the governance and management of information and technology [16].

Conclusions

Twin planning refers to having two levels of planning in factories: the virtual planning, which is applied to a virtual model of the factory, and the real planning, which is applied to real resources of the factory. The virtual planning enables to apply modifications to the model in order to understand the effects on the real factory without disrupting production. We have pointed out three key factors for successfully implementing twin planning. First, the interoperability among the factory equipment and software applications is needed to synchronize the virtual and the real planning, in particular to allow for the virtual planning to be based on accurate models of the factory. Second, the IT infrastructure must enable the composition of the various components in the factory – enabling planning on a high level; and thirdly the business strategy must be aligned with the IT strategy, in order to drive the planning in a consistent way. The "FIRST", Horizon 2020-RISE-EU-project, already started developing concrete and valid approaches to twin planning and will be investigating the above-mentioned points in the near future. ■

Kurz und bündig

Wie kann die Planung eines digitalen Zwillings erfolgreich sein? Die Autoren sehen hier drei essentielle Faktoren, welche der Artikel näher erörtert. Zunächst müssen Fabrik Equipment und Software Applikationen kompatibel sein. Des Weiteren muss die IT-Infrastruktur die Zusammenführung von fabrikinternen Komponenten ermöglichen und schließlich muss die Business-Strategie nach der IT-Strategie ausgerichtet werden.

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