DIGITAL TWIN

Its Role and Structure within a Modern Systems Engineering Approach

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The complexity of systems is rapidly increasing across all industries. Embedded systems and interactive environments account for an increasing share of the product features and the total product cost . At the same time, the need to develop and maintain innovate new products and "products as a service" is critical for corporate success and, in some cases, even for enterprise survival. Companies must ensure a cost effective and reliable product is introduced to the market in a timely manner while also addressing the challenges relating to in-service product updates and on-going maintenance. The Digital Twin is becoming a critical player in such highly innovative and competitive environment.

Market Trends and Challenges

Before considering some of the main engineering trends that are closely associated with the Digital Twin, it is important to understand the main market trends and challenges businesses are facing in today's environment that are driving these engineering trends.

A Global Economy with Increasing Dynamic and Diversity

In today's rapidly changing digital world, many regions and industries are not only interconnected, but in many cases, also interdependent upon each other. In addition, the immense variety of cultures across many geographical regions makes it difficult to define and create common denominators satisfying the huge amount of various and constantly changing requirements. For the markets, a major challenge is the change toward an "experience-driven" economy / society where consumers demand much more flexibility and choices. The time where "one size fits all" is rapidly diminishing. Consumers are also much more conditioned to expect instant gratification. "Time to market" reaches new levels of understanding and expectations.

Technologies are Changing and Evolving Ever More Rapidly

Global competition combined with the digitalization of every aspect of our lives dramatically increases the pressure on all companies to sustain their business competitiveness. Companies constantly need to ensure that the latest technology and business approaches are applied to ensure their business model is capable of effectively making use of the current technology and engineering capabilities. Simultaneously, the latest high-end technology is now becoming available to almost all sizes of business. This enables upcoming businesses, as well as start-up companies in well-established economies, to compete with the larger, established market leaders across all industries. This is changing the market dynamics – it is truly a game changer.

The Age of Data, Information and Knowledge

Data and information and the way it is transformed into knowledge are some of the most essential assets in the 21st Century business environment. The way businesses and societies use data and convert it into knowledge is and will be a major market differentiator and determines who will be a leader or a laggard. This includes how we capture data and knowledge and make it available for further use. Furthermore, it is important that data and information is not just blindly used, but proper intelligence is applied to ensure the quality of the data and its source as verified and guaranteed.

Digitalization, Visualization and Collaboration

With the digitalization of business and its related ecosystems, virtual realities are becoming more relevant within our daily life. The major challenge is to transplant the openness towards and the usage of the modern technology that we use daily in our lives into the business environment. Thus, create a business culture and infrastructure that allows closed-loop connections between the physical (real) and the virtual worlds. Many modern engineering processes and applications are requiring such a connection to be real-time (or close to it). In so many ways, the

business environment is lagging behind our modern social and interactive environment that is present in many societies already.

Virtual realities leverage a large amount of virtual simulation at various fidelity levels. In addition, collaboration at all stages of the product lifecycle is a key enabler for increased competitiveness. Rapid visualization of simulation results, data, and models are paramount. The challenge is to achieve this with the right balance of information between the various stages and domains without sacrificing content.

The Complexity Challenge

Digitalization has led to the rapid growth of electronics and embedded software in almost all products drastically increasing the system complexity. To stay competitive, businesses need to adjust for this increasing complexity. At the same time, the consumer is expecting new product releases to the market find their way more often and in shorter time but also that existing products can be upgraded seamlessly.

Some industries have already adapted to this great challenge while others still need to react and adapt to find their way. For instance, the integrated circuit industry was able to continuously apply the latest technologies without increasing time-to-market, while the automotive industry managed to drastically reduce time-to-market over the years. On the other hand, autonomous driving technology is throwing a 'wrench' into this trend threatening to reverse it. Despite being pioneers and longtime practitioners of the systems engineering approach, the established aerospace and defense industry is still struggling with this complexity issue. (Figure 1)

Available technology and tools are not usually the greatest issues. More complex technologies are challenging the ability for middle and upper management to understand the emerging needs of the business and adjust to those needs. Without disruptive changes to the business, this is an almost impossible equation to solve.
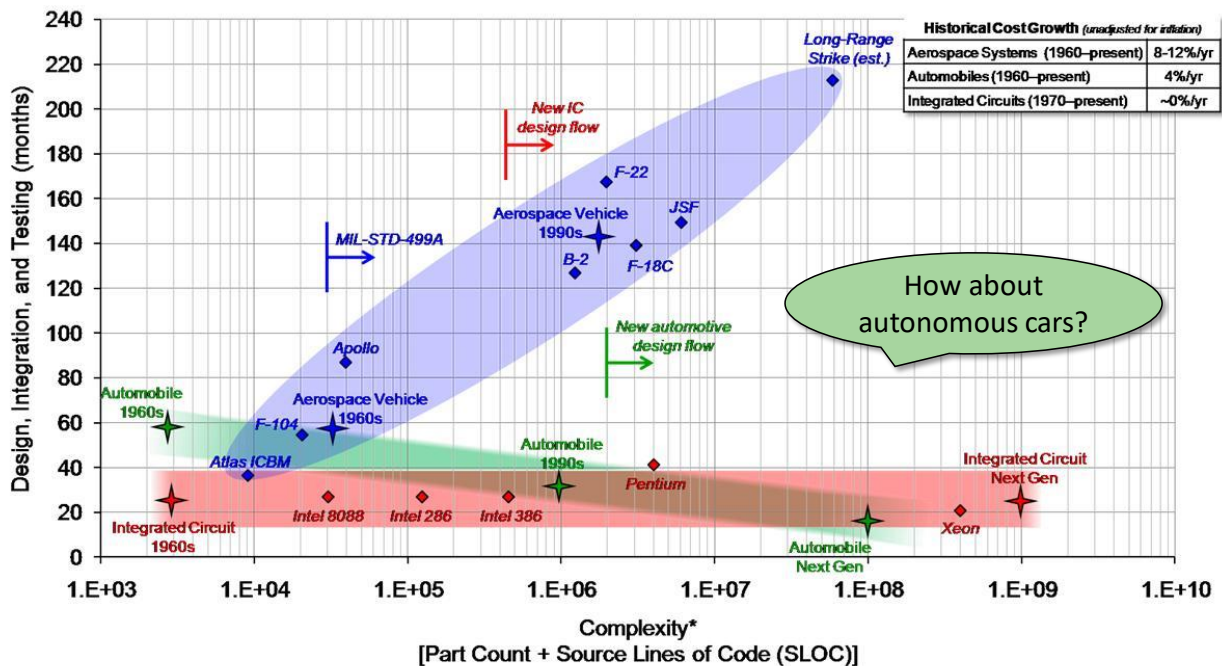

Figure 1: The Complexity Challenge [1]

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[1] Source: DARPA AVM pres. (adapted)

Engineering Trends

There are many trends associated with virtual engineering capabilities, its usage and impact on product and processes development, and its impact on business performance.

Increased Complexity and Demand for Flexibility

Complexity can be associated with products, processes and the organization associated with those surrounding ecosystems.

Product complexity is not only the increase in the number of mechanical assemblies but the overriding demand for electronics, software, and embedded systems that have become an essential part of today's customer solutions. Furthermore, products now need to connect and interact with one another (i.e., smart connected products). Customized materials utilized for many products are becoming an accelerant of this complexity due to new manufacturing technologies. As was mentioned earlier, the thinking of "one size fits all" is going away. End users expect that products and services can be customized to meet their needs and desires. They want them to be a personal experience.

Process complexity increases hand-in-hand with product complexity. Traditional "lean" manufacturing approaches need to be enhanced incorporating agile thinking that spans across the entire supply chain of a product. Manufacturing becomes a connected, interactive and a collaborative ecosystem on its own.

Consumer ecosystem complexity is another level each business must address. Environmental impact thinking and awareness (*sustainability)* in our societies increasingly dominate. Companies need to understand that they design and manufacture products and provide services that are increasingly *connected and interactive while meeting individual needs* within all the varieties of our societies*.*

Continuously Improved Product Quality and Robustness

Consumers expect that their products will be much more reliable than ever before. New flexibility in materials and manufacturing methods (i.e. additive manufacturing) provide more cost effective and timely solutions. At the same time, it is expected that a product has successfully passed rigorous design and testing processes that utilize the latest development technologies and processes before being placed into service. Smart preventive maintenance service and performance updates, even while products are in operation, are becoming a common expectation for many types of products.

Digitalization

To be able to meet the consumer's needs and wants as well as provide the desired "personal experience", companies must be able to bring products and services to the market more quickly and respond even faster to changes in the market. This requires virtual capabilities at many stages of engineering, from inception, through product development, manufacturing, to in-service. Modern digital/virtual *data and process management, visualization, and collaboration,* as well as the required *predictive capabilities* are required fundamental enablers.

But just having everything in digital form within a company doesn't mean that it has achieved "digitalization". Digitalization means a company is able to capture all relevant data (be it from the real or virtual worlds), create new data and information virtually, transform it into knowledge, and make this data, information and knowledge available for re-use and decision making, thereby creating a virtual engineering environment. The way a company manages its data and information is an indicator of its engineering maturity. The speed it takes to make use of data and information in order to make decisions drives the performance of products and services and allows for interaction between domains, products, and systems. This defines a company's business maturity in terms of both organizational behavior and relative market position. (Figure 2)
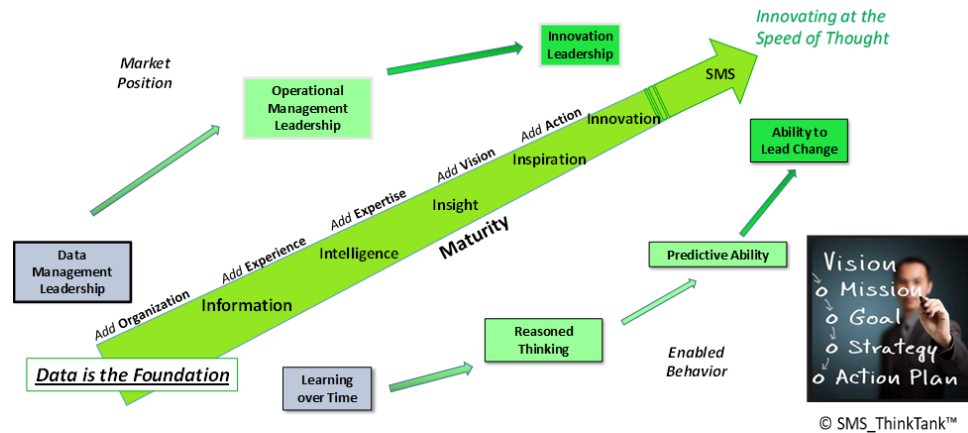
Figure 2: Innovating at the Speed of Thought

Market leading companies enable the capability to *Lead Change* while also be an *Innovation Leader* in the market. Achieving this maturity means, that data, information and knowledge is readily available and almost real-time accessible. This is what we call "*Innovating at the Speed of Thought".* (Figure 2)

In addition, there are various levels of innovation maturity within a business which can have an impact on competitiveness and profitability of the enterprise. The level of digital transformation defines the level of innovation maturity companies have achieved. Leading companies strive to create a virtual environment which allows them to enable **sustainable innovation. T**hose leaders are in enviable positions to **disrupt** the market. (Figure 3)
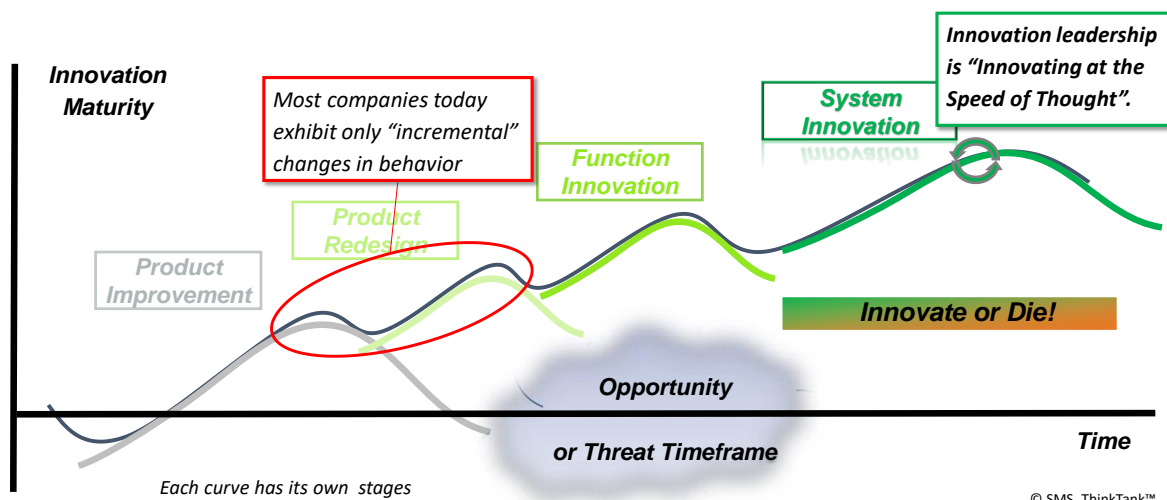
Figure 3: Innovation Maturity

To become or maintain leadership in their respective industries, companies need to define, deploy and live best practices utilizing virtual engineering that can support the goal of **Innovation Leadership** enabling **Sustainable Innovation.** Some of the major enablers for that are:

➤ Systems modeling and simulation

➤ IIoT (Industrial Internet of Things) and Industry 4.0

➤ Big data and IoT (Internet of Things)

➤ Agile, iterative, and collaborative approaches

➤ Cognitive Engineering

Systems Modeling and Simulation (SMS)

SMS is the use of interdisciplinary functional, architectural, and behavioral models (with physical, mathematical, and logical representations) in performing *MBSE (Model-Based Systems Engineering)* to specify, conceptualize, design, analyze, verify and validate an organized set of components, subsystems, systems, and processes. [2]

IIoT and Industry 4.0

Achieving higher levels of innovation maturity requires new thinking in the area of manufacturing and in-service operations. Digital transformation in manufacturing with the enabling of IIoT introduces a new area wave of thinking and activities which is often referred to as "Industry 4.0".

"Industry 4.0" is a name given to the current trend of automation and data exchange in manufacturing technologies. It includes cyber-physical systems, IoT (Internet of Things), cloud computing and cognitive computing. Industry 4.0 is commonly referred to as the fourth industrial revolution. "Industry 4.0" fosters what has been called a "smart factory". Within modular structured smart factories, cyber-physical systems monitor physical processes, create a virtual copy of the physical world and make decentralized decisions. [3]

IIoT is a subset of the larger scope of IoT focused on manufacturing and in-service operations. It has been revolutionizing manufacturing by enabling the acquisition and accessibility of far greater amounts of data, at far greater speeds, and far more efficiently than ever before. A number of innovative companies have started to implement IIoT by leveraging intelligent, connected devices in their factories.[4]

Big Data and IoT

The way we collect and distribute data is changing rapidly. To support the goal of achieving higher levels of innovation maturity, a new better equipped infrastructure is needed. IoT and Big Data play a central role.

IoT is a network of intelligent computers, devices, and objects that collect and share huge amounts of data. The collected data is sent to a central cloud-based service where it is aggregated with other data and then shared with end users in a way that meets their unique needs and objectives. IoT will increase automation in homes, schools, stores, and in many industries.[4]

Big data refers to data sets that are too large or complex for traditional data-processing application software to adequately digest. Current usage of the term *big data* tends to refer to the use of predictive analytics, user behavior analytics, or certain other advanced data analytics methods that extract value from data, and seldom to a particular size of data set.[5]

Over the IoT network, cyber-physical systems communicate and cooperate with each other and with humans in real-time both internally and across organizational services offered and used by participants of the value chain. [3]

Agile, Iterative, and Collaborative Approaches

The time for very rigid, sequential, stage-gate engineering strategies is rapidly disappearing. To be able to optimize products and processes quickly and effectively while in development and improve and optimize performance while in operation, each stage of the product's lifecycle needs to be agile, iterative, and *closed-loop.* Only such modern approaches and practices can allow collaboration within teams and between teams and domains, and even across companies, and not only within the global supply chain.

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[2] SMSWG – Terms & Definitions: https://www.nafems.org/about/technical-working-groups/systems_modeling/smstermsdefinitions/s-u/

[3] Source: https://en.wikipedia.org/wiki/Industry_4.0

[4] Source: https://inductiveautomation.com/what-is-iiot

[5] Source: https://en.wikipedia.org/wiki/Big_data

Cognitive Engineering

This enables the use of **predictive analytics** in conjunction with simulation models, data, and information gathered utilizing IoT, to improve the predictive behavior of a system. This can be applied to products as well as processes while in development or already in operation. Cognitive behavior implies the utilization of **deep learning** (see also machine learning and AI) capabilities. Furthermore, the **Digital Twin** capability is adherent to the level of cognitive engineering maturity. The details for this capability are being discussed further in this publication.

The level of deployment and utilization of any of the previously mentioned trends and capabilities along with the way data and knowledge is used are strong indicators of the competitiveness and eventually the market position of companies (see Figure 2). Companies that have processes in place that allow real-time (or close to real-time) access to data and information are, and will continue to be, the **innovation Leaders across various industries.** This is what is referred to as **"Innovating at the Speed of Thought".**

2. Digital Twin Definition and Basic Architecture

Before embarking on a journey on how and where the Digital Twin can be used and its meaning throughout the product lifecycle, the definition needs to be established.

Digital Twin refers to a digital surrogate that *is a dynamic physic-based description* of physical assets (physical twin), processes, people, places, systems and devices that can be used for various purposes. The digital representation provides both the elements and the dynamics of how an Internet of things device operates and lives throughout its life cycle. [6]

Various definitions of digital twin technology used in prior research emphasize two important characteristics. First, each definition emphasizes the connection between the physical model and the corresponding virtual model or virtual counterpart. Second, this connection is established by generating real time (or close to it) data using sensors, often referred to as IoT devices. (Figure 4)
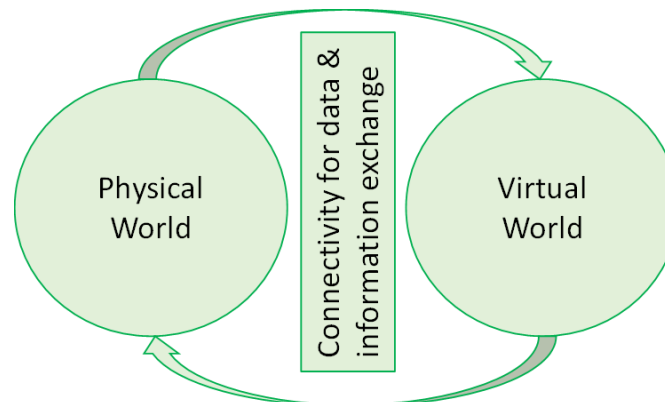

Figure 4: Basic Architecture of Digital Twins

The digital twin accompanies its real-world companion throughout its lifecycle, being changed in tandem with the physical twin. It integrates internet of things, artificial intelligence, machine learning and software analytics with spatial network graphs to create living digital simulation models that update and change as their physical counterparts change. A digital twin continuously learns and updates itself from multiple sources to represent its near real-time status, working condition or position. This learning system, learns from itself, using sensor data that conveys various aspects of its operating condition; from human experts, such as engineers

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[6] Adapted from: https://en.wikipedia.org/wiki/Digital_twin

with deep and relevant industry domain knowledge; from other similar machines; from other similar fleets of machines; and from the larger systems and environment in which it may be a part of. [6]

In various industrial sectors, twins are being used to optimize the operation and maintenance of physical assets, systems and manufacturing processes. They are a formative technology for the Industrial Internet of things (IIoT), where physical objects can live and interact with other machines and people virtually. In the context of the Internet of Things, they are also referred to as "cyberobjects", or "digital avatars". The digital twin is also a component of the Cyber-physical system concept.[6]

A digital twin also integrates historical machine usage data to factor into its digital model, thus, providing the basis for refined models that enable component and system-level prognostics. Archive digital descriptions of new systems would greatly facilitate any subsequent re-engineering/optimization required in the future. [7]

3. Digital Twin – The engineering "V" and Lifecycle

To position the Digital Twin, the traditional understanding of the lifecycle of a product or process needs to change from a sequential to an iterative view at every stage based on a closed loop process. At the same time, the traditional understanding of the **Systems Engineering** "V" needs to be expanded. Figure 5 is used to explain the model-based systems engineering process (MBSE) and expansion towards the Digital Twin in a simpler way.

We defined SMS earlier and identified MBSE as a subset of it. For better clarity, the definition for MBSE is provided: "MBSE is the formalized application of modeling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later life cycle phases." [8]
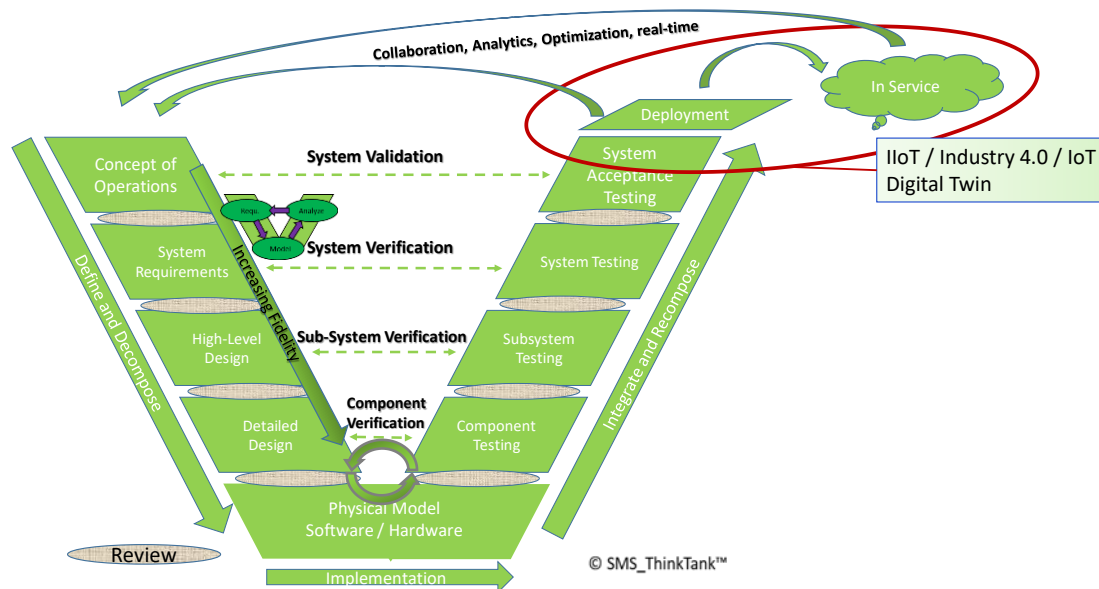
Figure 5: The Digital Twin in Relation to the Systems Engineering "V" [9]

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[7] Adapted from: https://www.dodmantech.com/ManTechPrograms/Files/AirForce/Cleared_DT_for_Website.pdf

[8] Source: https://www.nafems.org/about/technical-working-groups/systems_modeling/smstermsdefinitions/m-o/

[9] Source: Frank Popielas, Ed Ladzinski – SMS_ThinkTank™: "Achieving Sustainable Innovation – *Business Challenges in the Age of Digitalization and the Path forward*"; COE 2017 Annual Experience & TechniFair; April 23-27, 2018; Orlando, FL, USA

Digital Twin
Its Role and Structure within a Modern Systems Engineering Approach

From Figure 5 it becomes clear that IIoT/Industry 4.0 and IoT are changing the way we need to think about the traditional sequential and stage gate product development lifecycle approach. Subsequentially, the Digital Twin is going beyond the traditional thinking and scope of the systems engineering "V".

But before we go deeper into that discussion, let's use the traditional fundamental lifecycle stages (Figure 6) which describe with its coloring the typical "S-curve" behavior for a product or process. We will use this graphic combined with the adapted "V" from Figure 5 to understand at what point it makes sense to talk about the existence of a Digital Twin. While developing that understanding, we will soon realize the limitations of the traditional fundamental lifecycle stages from a modern (digital transformation) business perspective.

Innovation	Pioneering	Growth	Maturation	Decline	Retirement

Figure 6: Traditional fundamental Lifecycle Stages

Per definition, the Digital Twin as associated with a physical asset – the Physical Twin. Following that thinking, we can logically conclude that at the point when a product or process is released into the real (physical) world <u>and</u> becomes associated with its "as released" virtual model, this virtual model becomes the **Digital Twin** of the real-world asset. Only at that point is the Digital Twin "born". Without this association, a virtual model just remains what it is – a virtual model.

Let's use an example to help explain the understanding of the Digital Twin. A virtual model is typically associated with a real-world asset, such as a product series (i.e. vehicle Series A Model Year 2019) or a general process (i.e. vehicle body forming operations for vehicle Series A Model Year 2019). The Digital Twin, on the other hand is only associated with <u>one specific</u> vehicle (vehicle XYZ from the Series A Model Year 2019) or specific process (vehicle body forming process for Series A Model Year 2019 in the plant ABC). The word "specific" highlights the fact that <u>each</u> vehicle from Series A Model Year 2019 rolling off the production line with all its associated datasets has its own Digital Twin.

It is important to know at what point the Digital Twin starts to exist. Like every other model of the product and its processes, the Digital Twin is moving together with the real-world physical model and its associated virtual model through the lifecycle. Following the understanding that the lifecycle is a closed-looped process at every stage, thus, the Digital Twin can and should help improve the actual product even before it's ready for production and eventually released into service.

Following the understanding that when a product or process is released into the real (physical) world <u>and</u> becomes associated with its "as released" virtual model, this virtual model becomes the Digital Twin of the real-world asset. It therefore needs to be concluded that the Digital Twin can exist at every stage of the lifecycle, even at the concept stage. This is under the assumption that a physical real-world model of the virtual concept model has been previously created. At that point, the Digital Twin starts to move through the various stage of the lifecycle together with the associated physical assets (Figure 7).
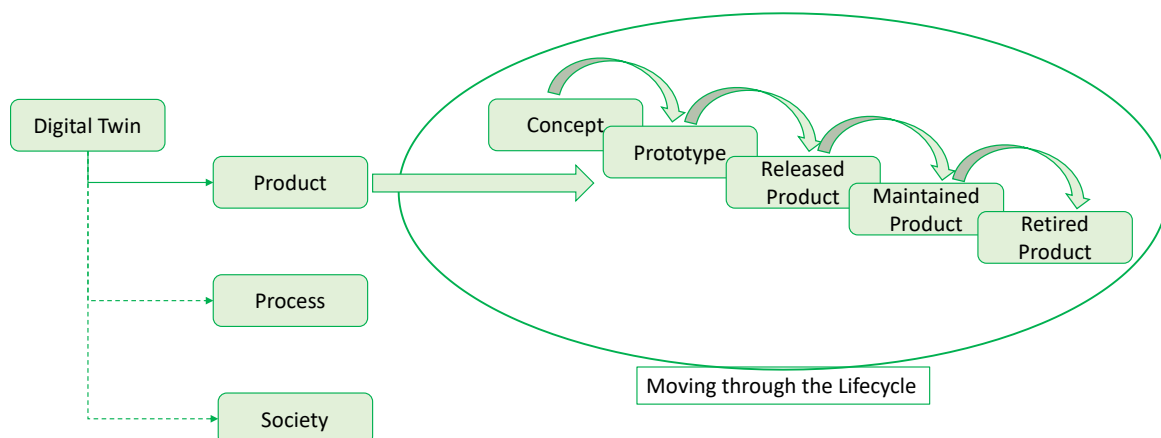

Figure 7: Moving through the Lifecycle
(Courtesy of CIMdata & SMS_ThinkTank™)

For example, while the Digital Twin of a prototype is specific for that physical prototype, it will be associated with many "released into service products" when moving further along the lifecycle.

4. Application Streams of the Digital Twin

Based on the specifics of the role and purpose within the ecosystem, a Digital Twin can be created for a variety of different purposes and domains. Per definition, elements for those domains can come from products, processes, people, places, systems and devices. They find their way into various applications segments. We call those segments the application streams of the Digital Twin within the ecosystem.

The complexity seems almost endless (Figure 8). The focus of this figure is on the engineering/industrial side of the Digital Twin (product and process). Since human behaviour and society can be modeled and predicted as well, we mention this possible portion of a Digital Twin for completeness. For simplicity, it is captured for the purposes of this paper under the "Society" application stream. Future publications on the Digital Twin topic will go into greater detail.
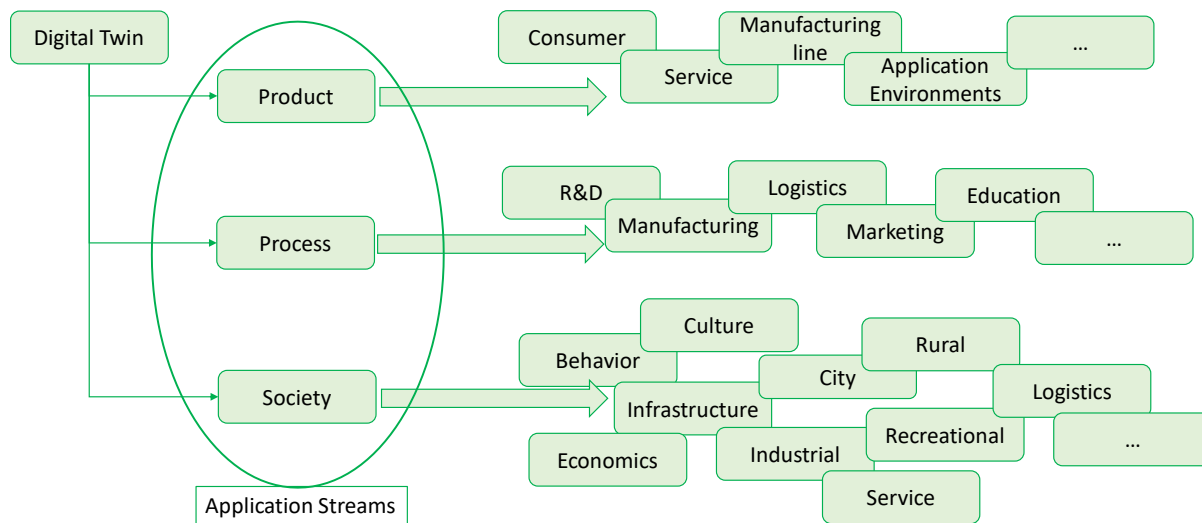

Figure 8: Application Streams of the Digital Twin
(Courtesy of CIMdata & SMS_ThinkTank™)

The application streams require several aspects/elements to be considered for each stream. Some of those elements represent stages in the lifecycle of the product or process, such as R&D, manufacturing and service. Others represent supporting activities, such as marketing and education. Others, on the other hand, can be attributed to the usage view point, such as the consumer, developer and designer. This can quickly become very complicated, since the latter viewpoints can also be associated with stages in the lifecycle.

When linking it back with the fundamentals of the engineering "V" and the understanding of the closed-loop nature, we can recognize that each of the viewpoints and stages have different input and outputs that eventually influence the overall behaviour/performance of a system.

Bottom line, if a virtual model can be created to simulate real-world behaviour as well as have the required associated links established, then a Digital Twin can be created.

Digital Twins exist to:

➢ Optimize the design during the verification and validation phase

➢ Optimize the performance and life of a specific product while in operation

➢ Optimize operational performance of processes in operation

➢ Provide real-world input for future design improvements (duty cycles, operating loads, stresses and fatigue life, vibration levels, sound levels, etc.)

➢ …

5. The Role of Platforms and the Digital Thread

The Digital Twin thrives based on more and better operational data. That data can come from the physical product or process operating in the real world, from the virtual world as well as associated intelligence from other Twins and operations. Remember, "Innovating at the Speed of Thought" (Figure 2) keeps in mind that a proper data backbone is paramount. In today's enterprise application environments, the **Product Innovation Platform** not only takes on the role of such a backbone but connects all users and their information in a single environment to continuously cultivate creativity. This yields improvements in products and processes and inspires new and better innovations throughout full lifecycles and across generations of products.

A Product Innovation Platform spans the enterprise to support users across all functions and disciplines. The platform provides a comprehensive set of heterogeneous process-enabling capabilities including platform-native applications which can be packaged and configured to establish and support standardized **end-to-end business processes** and related data access. (Figure 9)

Figure 9: CIMdata's Product Innovation Platform
(Courtesy of CIMdata)

Such platforms are the prerequisites to enable the **Digital Thread.** The digital thread is the foundational requirement to enable the Digital Twin. The Digital Twin needs to have access to the entire history and the current state of a product (or process) to help improve future designs (or processes) and optimize the performance while in operation. It also enables the proper association to other models, twins and real-world operations to help optimize its performance/behavior.
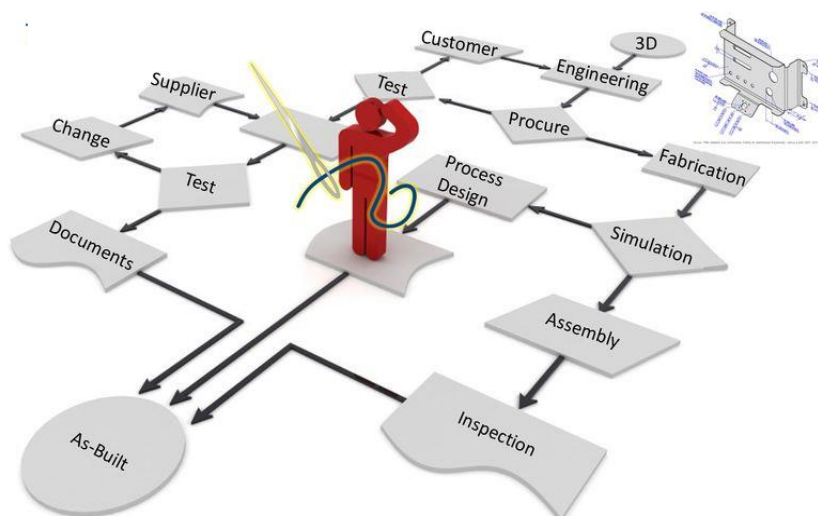
Figure 10: The Digital Thread [10]

This discussion highlights the importance of an **iterative, agile, and closed-loop end-to-end approach.** These are essential elements for any modern systems engineering approach, especially since the Digital Twin plays a vital role in the systems modeling and simulation lifecycle strategy and approach.

6. Going beyond the "V"

Earlier, the Digital Twin's relationship to the engineering "V" (Figure 5) and the foundational role of data/information (Figure 2) was presented. That discussion revealed the complexity surrounding the Digital Twin. Typically, there are several platforms involved to realize all the benefits of having a Digital Twin available. The underlying Product Innovation Platform needs to be able to bring the threads of all those platforms together to ensure that data and information is consistent and not duplicated. Figure 11 reflects the higher-level architecture of how the Digital Twin needs to connect to the various sources of data/information.
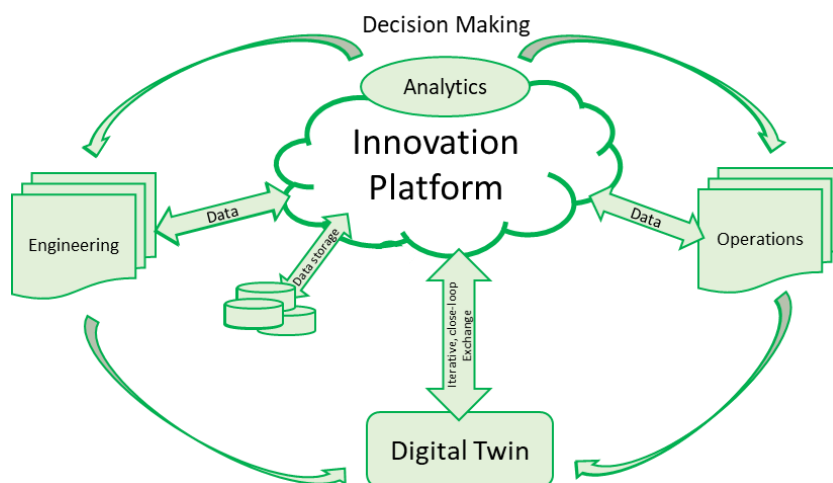

Figure 11: Higher Level Architecture for the Digital Twin
(Courtesy of CIMdata & SMS_ThinkTank™)

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[10] http://www.manufacturing-operations-management.com/manufacturing/2016/04/what-is-the-digital-thread-and-digital-twin-definition.html

Due to the complexity of associated platforms and data/information sources, **emerging standards**, which enable vendor-neutral collaboration, model exchange, and co-simulation (i.e. FMI/FMU, QIF, OSLC to name a few) are vital to any business to ensure an agile and efficient approach for establishing the required Digital Thread that in turn enables the Digital Twin. Depending on the application stream for the Digital Twin, different platforms will be called upon to provide data, for instance: MES, ERP, and IIoT for manufacturing.

The commonality between all the platforms is the need for **predictive analytics**. Without enabling advanced predictive analytics capabilities, the Digital Twin will be challenged to optimize the behavior/performance of a real-world physical asset real-time. There are four elements important to achieving advanced analytical capabilities[11], thus enabling proper use of the Digital Twin:

➢ *Intent*: Resolving to be data-driven - creating structures, processes, and incentives to support analytical decision making

➢ *People*: Mix of data science, business acumen, and technical expertise

➢ *Data*: Quality, consistent data stored in a manner that is easy to access

➢ *Tools*: State-of-the-art tools like unstructured databases, scale out compute clusters, and heuristic instrumentation

Note, that those four elements, not only strongly tie back to the product innovation platform approach described earlier, but highlight the need for a proper balancing of the three major categories in the following order:[9]

➢ Organization / Culture / People

➢ Processes

➢ Technology

Those are foundational categories for next generation **systems engineering of complex cyber-physical systems** where a **model-based** approach plays a vital role. Figure 11 depicts only the technology aspect of the "analytics" capability and its relationship/linkage to the other sources of data/information.

Such high-level architecture for the Digital Twin (Figure 11) doesn't provide enough detailed information to gain a basic understanding of the ecosystem infrastructure needed to enable the Digital Twin. We need to recall the extension of the engineering "V" to effectively position the Digital Twin (Figure 5). In general, the following sequence should be considered (Figure 12):

➢ To make effective use of the Digital Twin requires enabling the flow of information from the real-world physical asset to the virtual model. For the manufacturing operational environment this would be IIoT, while for service environment this would IoT.

➢ Only at that point can one take advantage of "deep learning" algorithms. Traditionally, "deep learning" is associated with "machine learning". For the overall understanding of Digital Twin enablement this thinking needs to be broader. It needs to extend to the service field as well.

➢ The final level will enable "predictive analytics".

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[11] Source: 2013; Bain Research: "Bain Brief—The Value of Big Data"

➢IoT

➢**<u>Digital twin</u>**

➢Deep learning

➢Predictive analytics

5G

Figure 12: Digital Twin - Cognitive Engineering - Ecosystem Infrastructure

All those steps need to take place and the proper infrastructure has to be established for the "Analytics" bubble in Figure 11 to function smoothly. Enabling those levels are a pre-requisite for a cognitive engineering capability, which will be discussed later more in detail.

There is currently a lot of discussion regarding connectivity between devices and databases/compute systems. The emerging high speed "5G" network infrastructure will be a major enabler for higher-level Digital Twin maturity. Countries investing into this IoT infrastructure technology will very likely have a clear "first mover" advantage.

Let's have a look at some examples as they are being discussed in the media and how they relate to the topic "Digital Twin".

General Electric (GE) is probably one of the better-known initial players when it comes to Digital Twin technology (Figure 13). They had the visionary thinking to bring such technology forward as it relates to their products focusing on IoT devices in the industrial sector, might it be wind turbines or aircraft engines. Based on a recent forecast, there will be more than 64 billion IoT devices by 2025, up from about 10 billion in 2018, and 9 billion in 2017.[12]

The initial vision was (as depicted in Figure 13) to have the digital prototype followed by the real-world physical prototype. Through the enablement of the IoT devices those will be linked to create the specific Digital Twin. That vision still holds true. The execution is another question.

Figure 13: Billions of IoT Devices will be connected
(Courtesy of GE Digital (GE.com))

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[12] Source: https://www.businessinsider.com/internet-of-things-report

As was highlighted before, technology alone will not win the battle. Processes and, foremost, culture are part of making such digital transformation happen (or not). Like retired GE CEO Jeff Immelt said: "If you went to bed last night as an industrial company, you're going to wake up this morning as a software and analytics company." It was well said, but probably still too early to realize and address the full complexity associated with it. In the section "Digital Twin – Maturity" the hype and perception of the Digital Twin and related elements, like IoT will be discussed. One thing though is clear, it is a system challenge and needs to be approached as such. Such approach needs to follow a holistic approach built on three major pillars[13]:

- ➢ Organization / Culture / People
- ➢ Processes
- ➢ Technology

Another example rapidly coming into the forefront is the automotive industry with its focus on autonomous driving technology. Autonomous driving technology is presenting even greater engineering challenges. Not only are we talking about complex systems but "Systems of Systems". Vehicles communicate with each other and with their surroundings via a communication network. Such a network has to be able to accommodate the physical environment, a vehicle is operating in this environment (i.e. road network, traffic rules/signs, …), changes in nature (i.e. weather, …), human factors and other random behaviors that are not easily predictable (i.e. accidents, congestions, people/animals crossing the road, …). It also has to communicate the proper position of the vehicle while integrating and communicating all this information throughout the overall system. Some of that communication has to happen real-time to react immediately ensuring safe driving, optimize the performance of the system as well as to predict behavior. Such capabilities of a system and "system of systems" requires **cognitive** abilities.

This points to various activities that need to be invoked from a product, process and society perspective. This refers back to the application streams as highlighted in Figure 8. Moving from product to society, the complexity is drastically increasing.

Capturing data and information in order to be able to decide how the systems need to behave brings us back to IoT. Figure 14 describes some of the aspects of an IoT environment for automotive while Figure 15 depicts graphically how it can support the enablement of safer driving.
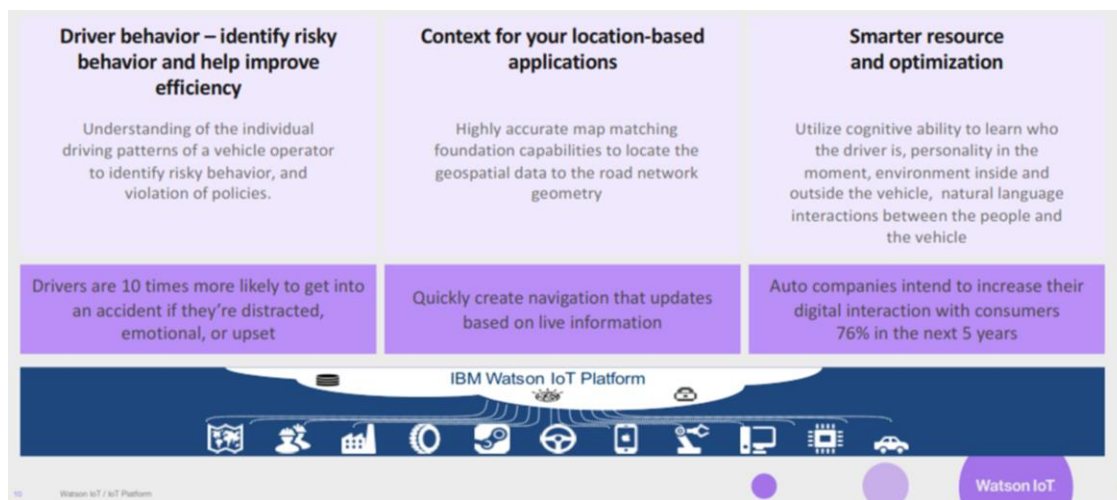

Driver behavior – identify risky behavior and help improve efficiency	Context for your location-based applications	Smarter resource and optimization
Understanding of the individual driving patterns of a vehicle operator to identify risky behavior, and violation of policies.	Highly accurate map matching foundation capabilities to locate the geospatial data to the road network geometry	Utilize cognitive ability to learn who the driver is, personality in the moment, environment inside and outside the vehicle, natural language interactions between the people and the vehicle
Drivers are 10 times more likely to get into an accident if they're distracted, emotional, or upset	Quickly create navigation that updates based on live information	Auto companies intend to increase their digital interaction with consumers 76% in the next 5 years

IBM Watson IoT Platform

Watson IoT / IoT Platform

Watson IoT

Figure 14: IBM Watson IoT for Automotive [14]

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[13] Sources: Frank Popielas, Edward A. Ladzinski – SMS_ThinkTank; "Systems Engineering – Challenges for Management"; COE 2018, San Diego, CA, USA – April 15-18; CAASE 2018, Cleveland, OH, USA – June 5-7

[14] Source: July 2017; IBM Watson IoT Connected_Products_Presentation

Figure 15: IoT for safer driving [14]

Most automotive OEMs are working on developing autonomous driving technology. But even if we are able to measure and capture all the various aspects that help enable autonomous driving, the question remains: "Are we capable of making use of that information and data to make the proper decisions?" This brings us back to the Digital Twin and its maturity.

7. Digital Twin – Maturity

The Hype

The term "Digital Twin" is a nice catch phrase. But few realize the complexity it entails to deploy this capability. We learned that a Digital Twin moves together with the product/process through the lifecycle (Figure 7). This needs to be highlighted again to recognize there are different maturity levels.

IoT plays a significant role in enabling Digital Twin at highest maturity levels, especially when it comes to systems that require real-time capability. Even for IoT it is currently difficult to accurately predict future adoption and penetration into the market. Too often predictions are driven by non-realistic perceptions. Figure 16 shows the current state of IoT adoption (2018). It shows that the predictions are still very fluid. One can only assume that the 2020/2022 outlook is likely too optimistic.
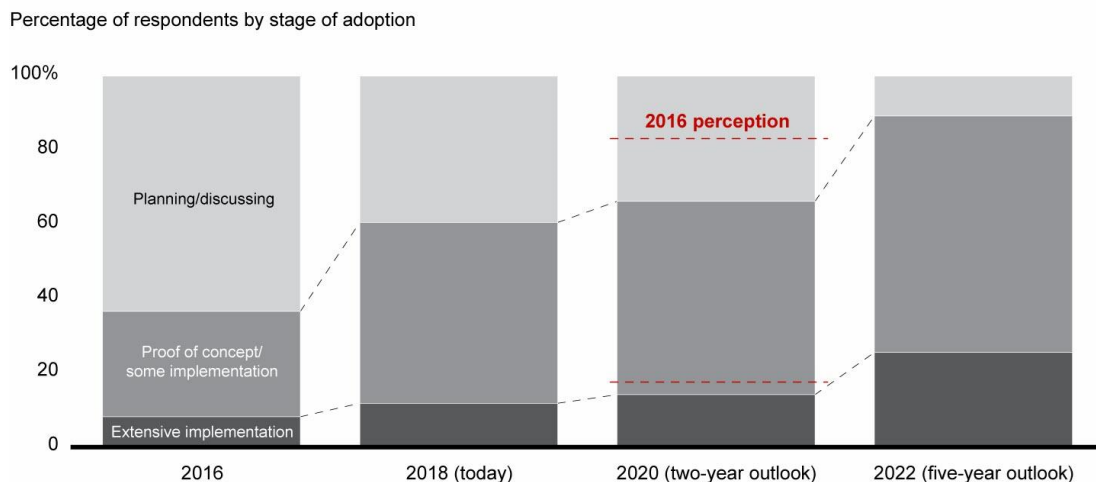

Figure 16: Current Stage of IoT Adoption[15]

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[15] Source: https://www.forbes.com/sites/louiscolumbus/2018/08/16/iot-market-predicted-to-double-by-2021-reaching-520b/#7f10e0fd1f94

Figure 17 shows that Systems integration and Data centers / analytics play a more leading role than before. It underlines, once again, the importance of a holistic approach that is built on three major pillars[13]:

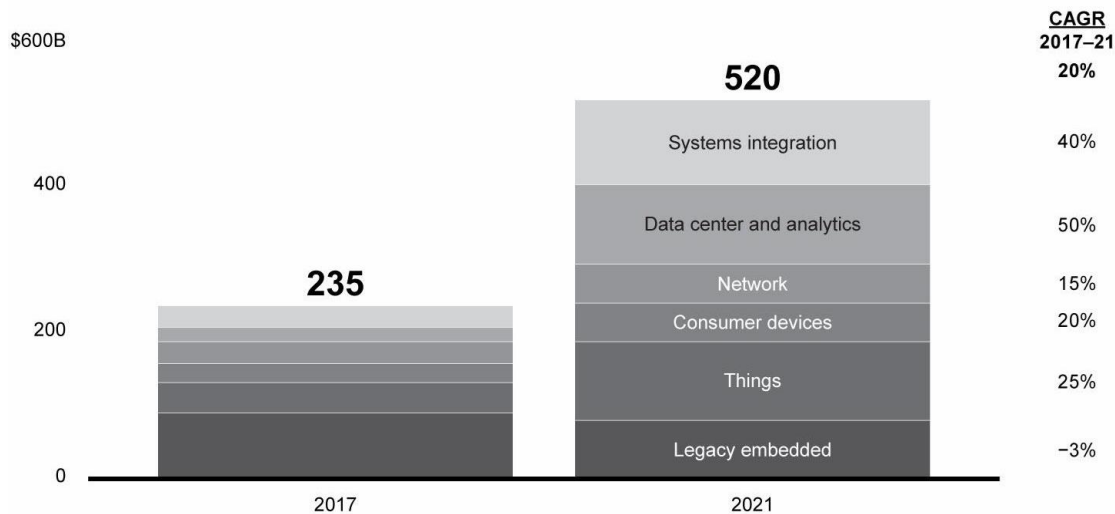➢ Organization / Culture / People

➢ Processes

➢ Technology

Figure 17: IoT and Analytics Revenues[15]

Even though the Digital Twin as an idea and practice has been around for a while, there is still quite a bit of hype associated with it.[16] Just because people are talking about the Digital Twin doesn't mean they have the proper understanding of what is involved to properly and fully implement such a concept. Similar to the **Hype** about IoT, there is a hype about the Digital Twin (realizing they are both closely linked). In addition, we must differentiate the maturity for the various application streams, which will vary by industry and even by company within various segments (i.e., automotive, aerospace, high-tech, medical equipment, heavy machinery, etc.).

For better illustration, let's use the Gartner Hype curve and see where various stages of the Digital Twin can be found. (Figure 18)

The majority of industries are still at the first up-slope (1). Even many of those industries with product focused Digital Twins utilizing some aspects of IoT functionality don't realize the complexity that comes with the integration of systems into systems. (Figure 18)

Only a few early adoption leaders have gone beyond the "Peak of Inflated Expectations." They are typically in the automotive, machinery and heavy equipment industries utilizing IIoT functionality and certain aspects of artificial intelligence (AI) capabilities used for deep learning (2). Those companies realize the complexity of the required architecture better than most of other companies. Examples of these early adopters are companies leading in developing autonomous or semi-autonomous driving technology as well as electrical vehicle systems. (Figure 18)

Still, to make the turning point through the "Trough of Disillusionment" (3) another important understanding needs to take hold. Areas where we see elements of this turning point are the thought leaders utilizing IIoT and focusing on Industry 4.0, as well as application of social media using the latest AI capabilities. (Figure 18)

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[16] Source: Dr. Grieves "Digital Twin: Manufacturing Excellence through Virtual Factory Replication", White Paper, 2014
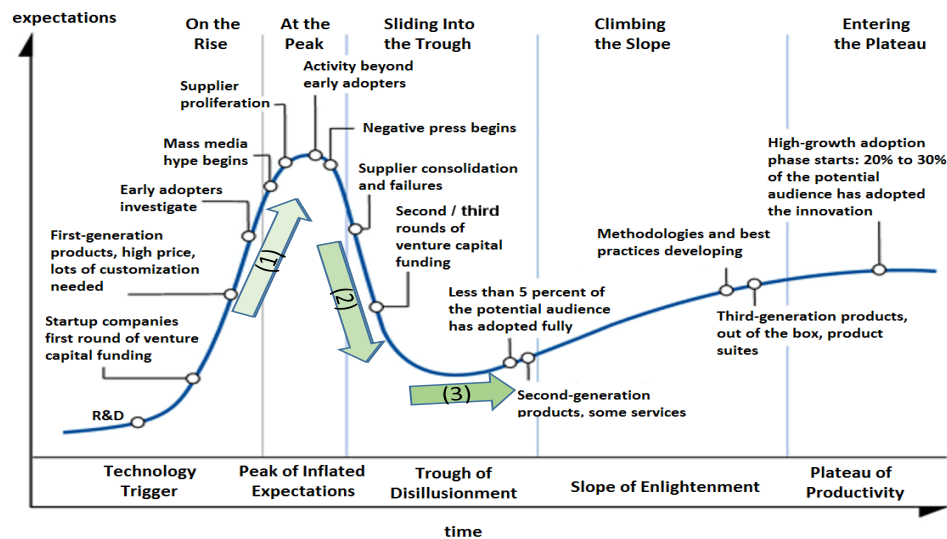
Figure 18: The Hype of the Digital Twin [17]

Even though we mentioned the importance of the holistic "Organization-Culture/Process/Technology" approach, studies performed concentrate mainly on the technology component. This raises the question: *Is the business or organization ready for the Digital Twin?*

The Centrality of the Digital Twin in Product Development

Among early adoption leaders, the Digital Twin is central to the digital transformation of their product development processes. However, they have come to realize that it is a gradual process and a business needs to have a long-term plan and Roadmap and commit the resources required to steadily mature over time in their Digital Twin applications capability. Those "Best-in-Class" companies have also recognized the transformational potential of the Digital Twin across all the major stages of product development lifecycle.

"Best-in-Class" companies are 1.8 times more likely than "All Others" to deploy the Digital Twin in designing products and in their manufacturing processes. In product production, the "Best-in-Class" edge jumps to 2.6 times more deployment of the Digital Twin compared to "All Others". [18]
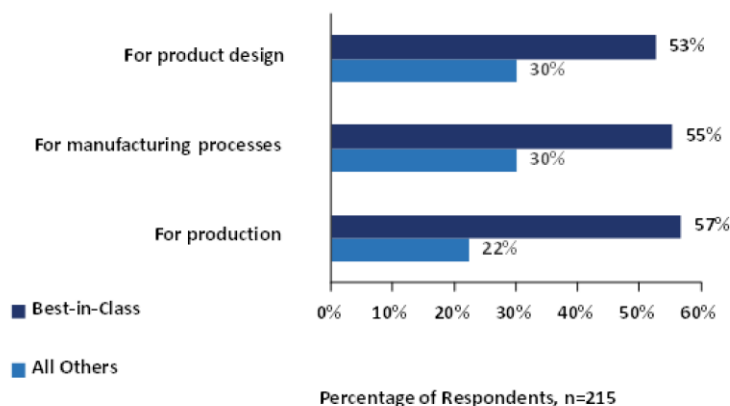
Figure 19: The Centrality of the Digital Twin in Product Development [18]

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[17] Source: Gartner Hype-Curve, adapted

[18] Source: Aberdeen Group "Product Development and the Centrality of the Digital Twin"; July 2017

Cognitive Digital Twin Maturity

The increasing complexity in terms of the Digital Twin becomes clear when looking at the various application streams as mentioned in Figure 8. In addition, the discussion regarding "Innovating at the Speed of Thought" (Figure 2), enabling real-time capability for the Digital Twin, requires a special understanding of this maturity level. In connection with the top-level of cognitive engineering maturity, the highest level for the Digital Twin is the **cognitive Digital Twin.**

Cognitive relates to "action or process of acquiring knowledge and understanding through thought, experience, and the senses. It encompasses many aspects of intellectual functions and processes such as attention, the formation of knowledge, memory and working memory, judgement and evaluation, reasoning and "computation", problem solving and decision making, comprehension and production of language. Cognitive processes use existing knowledge and generate new knowledge."[19]

Figure 20 describes in more detail how a Cognitive Digital Twin architecture should look. It contains all the building blocks of the high-level Digital Twin architecture mentioned in Figure 11.
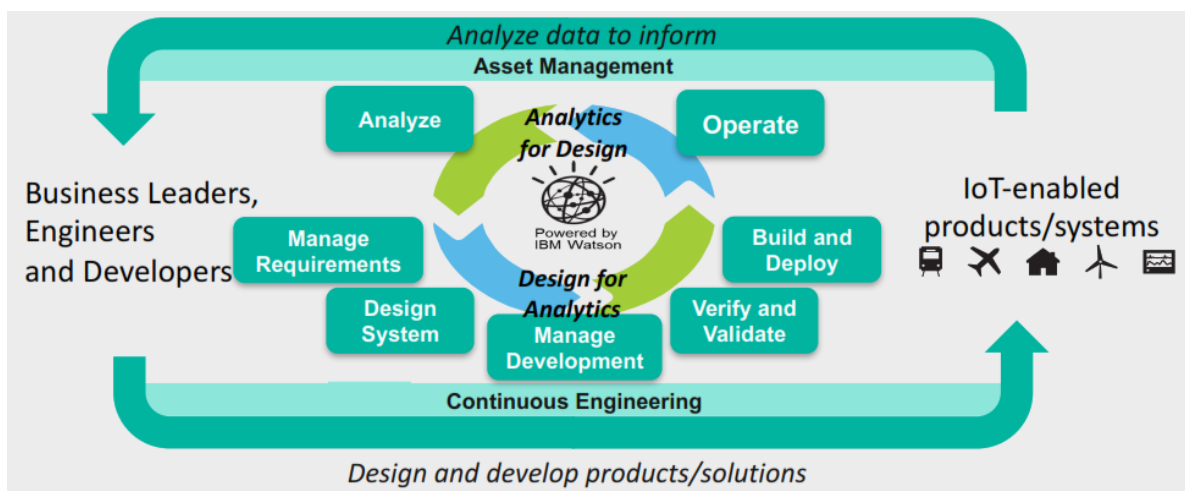

Figure 20: Cognitive Digital Twin Architecture [14]

With the understanding of the word "cognitive" in relation to the top innovation maturity, the major behaviors can be highlighted:

➢ Learn faster

➢ Adapt faster

➢ Innovate faster

Achieving Sustainable Innovation

When a company or organization enables Cognitive Digital Twin capabilities it grants a business the coveted ability to reach a new horizon of **System Innovation** and the enviable position to disrupt the market(Figure 21)

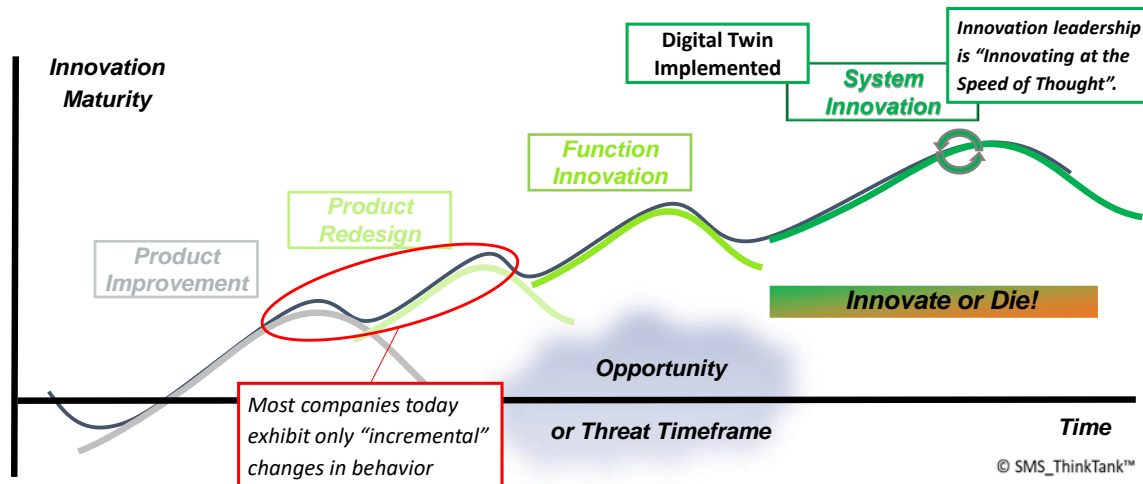[19] Source: https://en.wikipedia.org/wiki/Cognition

Figure 21: Digital Twin in Relation to Innovation Maturity

System Innovation is defined by the way a company uses the information that is available (see "Innovating at the Speed of Thought" in Figure 2). Predictive and analytic capabilities play a vital role in enabling the movement toward this top level of maturity.

Today, companies understand that they must go beyond the typical "S-curve" to stay competitive. This moves companies to the higher level of "Product Redesign". This is where most companies operate today. It also can be described as an "incrementality behavior". To go beyond this level, companies need to start the journey of digital transformation. During the first stages of that transformation companies can achieve "Functional Innovation" (Figure 21).

Maturing further requires applying new model-based principles within engineering and move beyond a company's four walls. It requires changes in the understanding of the lifecycle. With the enablement of IIoT, IoT and Digital Twin, there is additional untapped business potential for a product and its related IP while in service. Only mechanical life and user acceptance decide the remaining life of a product at that point. (Figure 22)

Figure 22: New Understanding of the Lifecycle

The main return on investment will happen once a product and process are released into service. This in turn is the point where businesses need to reach the level of **System Innovation. (**Figure 21)

8. Future Considerations

The Digital Twin is present in various application streams – Product, Process and Society. This highlights its complexity as well as **disruptive** potential when properly implemented. Additional deeper dives into various underlaying aspects for the Digital Twin need to happen.

As mentioned several times, the automotive industry has started to gain a greater appreciation of the need for the Virtual Twin to meet the challenging requirements and trends in the automotive market that very likely move towards a "new auto industry" [20]. This is particularly important when considering how the underlaying three megatrends: "autonomous vehicles, "Mobility-as-a-Service (MaaS)" and "electrification" interact and eventually converge. Each of those megatrends require their own Digital Twin strategy and a proper understanding how they need to converge into a new ecosystem that defines this "new auto industry". One can say, that without a Digital Twin strategy, none of these trends can be realized.

When looking at the mobility projection for the US and how autonomous driving technology is excepted to conquer the market, the need for the Digital Twin deployment not only becomes much clearer but also urgent further. (Figure 23)
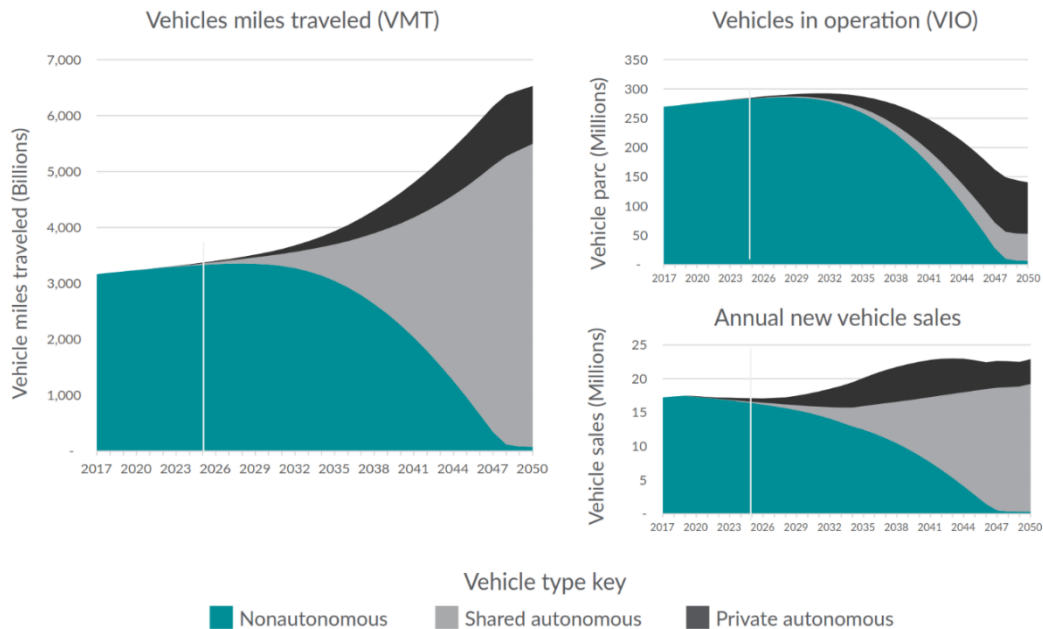

Figure 23: Mobility Projections (U.S.) [20]

As discussed, the topic of the Digital Twin is very complex and even though it has been around for a while, it is still foreign to many. The goal of this first paper was to provide an initial understanding. But a much deeper understanding is needed to further realize the great potential and proper applications.

Future publications will focus on the deeper understanding of the Digital Twin and address those topics in more detail. We are currently considering the following additional installments:

➢ Digital Twin: Its Maturity Levels and Impact on Business Maturity and Competitive Positioning – A Deep Dive

➢ Digital Twin: Foundational Elements that Enable the Necessary Infrastructure and Ecosystem

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[20] Source: Plante Moran; "The future of mobility: Reinventing the auto industry"; February 2019; www.plantemoran.com

9. References

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5. Donald Tolle – CIMdata white paper: "Evolving from Digital Prototypes to Physics-Based Digital Twins: *The Key Role of Modeling & Simulation in Enabling Closed-Loop Lifecycle Performance Engineering".* December 2018 - Developed in partnership with SMS_ThinkTank™