BOSCH
Invented for life

Digital Twin

WHITE PAPER

INDEX

ABBREVIATIONS USED IN THIS WHITE PAPER

A/D Converters	Analog to Digital Converters
AI	Artificial Intelligence
API	Application Programming Interface
APMIC	Asset Performance Management and Intelligence Center
ANN	Artificial Neural Network
AR	Augmented Reality
C-suite	Executive-level managers within a company - CEO, CFO, COO, etc.
CAD	Computer Aided Design
CAGR	Compound Annual Growth Rate
Capex	Capital Expenditure
CHT	Conjugate Heat Transfer
CIM	Common Information Model
CMMS	Computerized Maintenance Management Systems
CNC	Computer Numerical Control
CPS	Cyber Physical System
CUF	Capacity Utilization Factor
DAQ	Data Acquisition
DCS	Distributed Control Systems
DX	Digital Transformation
EAM	Enterprise Asset Management
ERP	Enterprise Resource Planning
HFS	High Fidelity Simulations
HIL	Hardware In Loop
HTML	Hyper Text Markup Language
I4.0	Industry 4.0
IaaS	Infrastructure as a Service
IAPM	Integrated Asset Performance Management
ICT	Information and Communications Technology
IoT	Internet of Things
IIoT	Industrial Internet of Things
IT	Information Technology
KPI	Key Performance Indicators
LAN	Local Area Network
ML	Machine Learning
MPLS	Multiprotocol Label Switching
MR	Mixed Reality
MRO	Maintenance, Repair and Overhaul
MSCB	Multi-Stage Centrifugal Blower

MTBF	Mean Time Between Failure
MTBR	Mean Time Before Replacements
NASA	National Aeronautics and Space Administration
O&M	Operations and Maintenance
OEE	Overall Equipment Effectiveness
OEM	Original Equipment Manufacturer
OLE	Object Linking and Embedding
OPC	Open Platform Communications
Opex	Operational Expenditure
OT	Operations Technology
PaaS	Platform as a Service
PCA	Principle Component Analysis
PCB	Printed Circuit Board
P&L	Profit and Loss Statement
PLC	Programmable Logic Controller
PLM	Product Lifecycle Management
RPK	Revenue Passenger Kilometers
RUL	Remaining Useful Life
SaaS	Software as a Service
SCADA	Supervisory Control and Data Acquisition
SOP	Standard Operating Procedure
SSA	Singular Spectrum Analysis
TBC	Thermal Barrier Coating
TCO	Total Cost of Ownership
UX	User Experience
VPLS	Virtual Private LAN Service
VPN	Virtual Private Network
VPRN	Virtual Private Routed Network
VR	Virtual Reality
VUCA	Volatility, Uncertainty, Complexity and Ambiguity
XML	eXtensible Markup Language

INTRODUCTION

The Foundation of Industrial Digital Transformation

It all starts with a focused mindset that envisions the entire value chain about a future digital enterprise; it begins to explore comprehensively integrated digital transformation solutions built using intelligent software systems, connected products, and robust industrial security infrastructure and this helps turn data into knowledge, and knowledge into wisdom.

Can you imagine...

- A chief engineer at a power plant receiving a priority alert that calls for immediate inspection of high furnace exit temperature which indicates a possible excess heat pickup in the super-heater and pre-heater sections of the power plant boiler.
- An O&M engineer in the iron and steel industry receiving instructions on his hand-held device to perform a static stress analysis of the industrial system conveyor structure at a particular location during the next planned shutdown.
- An OEM of a windmill receiving actual field performance inputs from thousands of machines operating across a wide geographic area directly connected with the PLM, which could direct them to upgrade their designs and also provide insights on possible cost-reduction options.
- The C-suite of a process industry being provided with persona-based information to tackle invisible inefficiencies of capex and opex intensive assets and their KPIs such as field complaints, MTBR, MTBF, TCO, OEE, RUL, O&M expenses, etc., which directly impact the bottom-line of the company.

What do the above narratives have in common?

These personnel are being augmented with physics, engineering, and business insights, enabling them to drive business outcomes. These insights are emerging out of digital or virtual replicas of assets or processes called **DIGITAL TWIN.**

In this digital era, things change faster than they used to. For enterprises, time is extremely valuable; each day, organizations aspiring to embrace digital transformation as a lever for growth, strive to fill every second with meaningful data and consciously channelize all their efforts towards this transformational journey that they are yearning for.

Today, industrial systems are designed, built, and operated based on diverse data sources, numerous operating environments, and specific business models. Gradual proliferation of IT into the industrial space has encouraged enterprises in multiple ways to work with enormous amounts of data. Subject matter experts tandem with specialized teams conducting independent analysis to accomplish tasks. In such an ecosystem, these specialized teams would typically concentrate on a specific area of the overall system involving their domain expertise thus conceptualizing distributed operating models. This often results in under-utilization of vast amounts of time and resources. Under these circumstances, the probability of non-availability of relevant and current information is high and hence the desired insights sought by the decision-makers in the organization may not be readily available for crucial decisions. This way of working in silos increases cost and creates inefficiencies and uncertainties. To give enterprises a competitive edge in a tough environment, organizations must look intensely at innovations that drive efficiency. **One such innovation is called Digital Twin.**

A Digital Twin is a super integrator; it can contextually ingest information stream from every idea, every process, every machine, every stakeholder, and eventually, the business objectives of the enterprise. Ultimately, this forms a unified digital enterprise that helps to improve companies of any size. What starts with a few small steps involving stochastic data clubbed with uncertainty will evolve into a holistic digital replica of assets operating in the field. A Digital Twin is more than virtual images of physical products; it has the potential to extend across the entire product and asset life-cycle by creating a digital feedback loop to review activities, interactions, and consequences of diverse planned decisions while the real system keeps operating in its core pervasive state. A Digital Twin built in its true sense can deliver value to multiple units of an enterprise, such as engineering, business, maintenance, service, operations, and so on.

This white paper explores the concept of a Digital Twin and its potential applications to offer data-driven insights based on first principles, natural intelligence, statistics, and model-based system engineering. The primary objective of such a solution is to enhance products, processes, and services, drive integrated asset performance management, and to play a key role in the digital transformation journey of organizations.

In the decade since the 2008-09 global economic crisis, the world has witnessed an accelerated adoption of digital technologies. This has impacted the business reality of many industries and enterprises and has also shaped the social and political landscapes of many nations, be it underdeveloped, developing or developed. Organizations have been implementing large-scale transformations to stay competitive and digital transformation is at the core of this growth.

Many reports suggest that as industries become ecosystems, they enable improbable combinations of attributes, making improbable business models a reality. The consumer space was the first to witness the disruptive influence of digitalization on fundamental business operations; the industrial marketplace is now poised to witness the same, but at a much faster pace. Additionally, this is happening in an increasingly volatile, uncertain, complex, and ambiguous (VUCA) world, which poses several distinct challenges. As incumbents are forced to digitally transform, they run the risk of self-cannibalizing their products and disrupting the status quo.

Organizations have to deal with the uncertainties and complexities for which they are unprepared. Moreover, it's difficult to tell if their digitalization efforts are resulting in true gains because of a lack of visibility of efficiencies. The modern business system demands more transparency than ever before to succeed in a VUCA environment, and this will only become more apparent as businesses continue to become more global. Today, digital transformation the world over is poised to drive the core of globalization. Companies like Apple, Google, and Amazon were the ones who raised the bar.

Experts in the digital world now believe that digital transformation is geared up to exert its influence on the industrial marketplace which traditionally has been nonchalant and currently has a risk of disruption. It is believed that the magnitude and pace of adoption of digital technologies in the industrial space will be superfast in contrast with the consumer space.

Digital transformation creates a winning ecosystem for the industrial houses; the actual economic value, technological, financial, and societal impacts will differ for the diverse industrial segments.

The future vision of globalization will be based on new age technologies like IIoT, AI, Digital Twins, Hyperconvergence, Machine Vision, Blockchain, Quantum Computing, etc. It is believed that with the advent of these new age technologies, what looked seemingly impossible, difficult to achieve, or what had been in the realm of imagination, can now be realized.

In this context, Digital Twin has been a forerunner and is likely to impact most of the enterprises worldwide. Digital Twin recreates living replicas of the physical model enabling remote monitoring, visualization, and controlling, involving human in loop based on the behavior and responses received from these digital replicas. This brings in a plethora of simulation options and what-if scenarios at your disposal while the actual asset remains operational in its core pervasive state.

In common parlance, the expectation from enterprises is that Digital Twins would enable humanization of assets. However, this process also evolves over time like the journey of a new-born, from toddler to adulthood. The comprehension capabilities of a Digital Twin will also evolve over a period. Due to the proliferation of AI in a multi-layered fashion, a Digital Twin can be viewed as a prediction machine which evolves capabilities to understand context, interact, network, learn, remember, and adapt to the changing conditions. Depending on the complexity of the problem statement, this could be achieved subjectively to a larger extent. However, one needs to be cognizant of the fact that to realize such an aspiration there is a need to create an ecosystem which enhances collaboration between man and machine. Digital Twin formulates such a conducive ecosystem resulting in the genesis of cognitive machines.

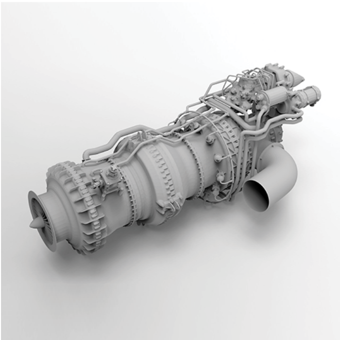
ML is one of the key technology enablers to realize the Digital Twin. It is interesting to note that when organizations deploy Digital Twin to address a specific business problem, they need not actually deploy a garrison of subject matter experts to code all the steps for solving the business problem in advance. Instead, the Digital Twin would be presented with a very large amount of diverse data based on which tell-tale signatures get generated, and now the Digital Twin automatically recognizes unique patterns based on telemetry richness, first principles, and natural intelligence of employees working to address the business problem. This entire process involves interaction with big data and an appropriate computing environment to process large data volumes. With time evolution, the Digital Twin could be trained to comprehend and process natural language, detect subtle abnormalities in machines, or identify the tiniest irregularities in processes, or even graduate to control industrial systems with human in loop. Once this acme is reached, organizations would metamorphose competency to deploy Digital Twin for similar applications based on effective ML which might involve only small data sets.

Data is the DNA of Digital Twin. People-centered digitalization is what Digital Twin aims to create. To comprehend the role of digital transformation, it is important to position it from a long-term perspective. Hence, organizations aiming to achieve digital transformation should have clear answers on questions that connect their innovation strategies with Digital Ubiquity. Stakeholders in such organizations should parade a transversal view of their organization, breaking the barriers of traditionally operating silos to accelerate transformation towards digitality. This journey is not as easy as it sounds. For some enterprises, this might represent a semantical shift from a conventional IT-based support system to a DX-enabled conducive ecosystem. In situations like this, Digital Twin helps organizations to analyze the very transformational nature of digital transformation, thus sprouting the culture of practitioner's approach. This fundamentally helps the organization to refine its aspired digital concepts with respect to their very nature, scope, and the possible business implication, cleansing their decision-making process.

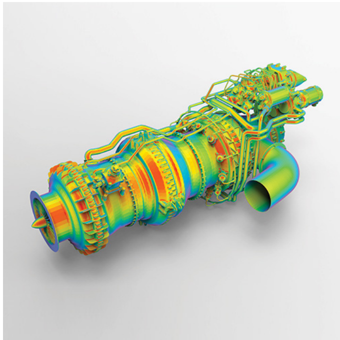
In this white paper, we take you through the journey from envisioning to how a Digital Twin solution can be constructed, deployed, scaled, and eventually driving the digital transformation for your organization. In addition, the white paper also deliberates how this solution, when deployed horizontally, removes organizational limitations, and helps realize the true purpose of Digital Transformation.

DEFINITION OF DIGITAL TWIN

A Digital Twin is a dynamic software model of a physical asset or process that relies on sensor and instrumentation data to understand its state, respond to changes, predict outcomes, improve operations, and aid judgments for business decisions.



PHYSICAL



DIGITAL

DIGITAL EXPERIENCE

It is a cyber-physical system that involves modeling industrial assets with all their geometrical data, kinematic functionality, and logical behavior, permitting business operations to be simulated, controlled, and improved.

A Digital Twin brings all the experts together on a collaborative platform, enabling helpful analyses, diagnostics, and prognostics. This facilitates a seamless interconnect of everything and everyone by onboarding them on a comprehensive communication network called the Digital Highway. A Digital Twin creates an ecosystem for harvesting actionable information specifically tailored to drive identified competitive, operational, or business advantage.

Key traits of Digital Twin

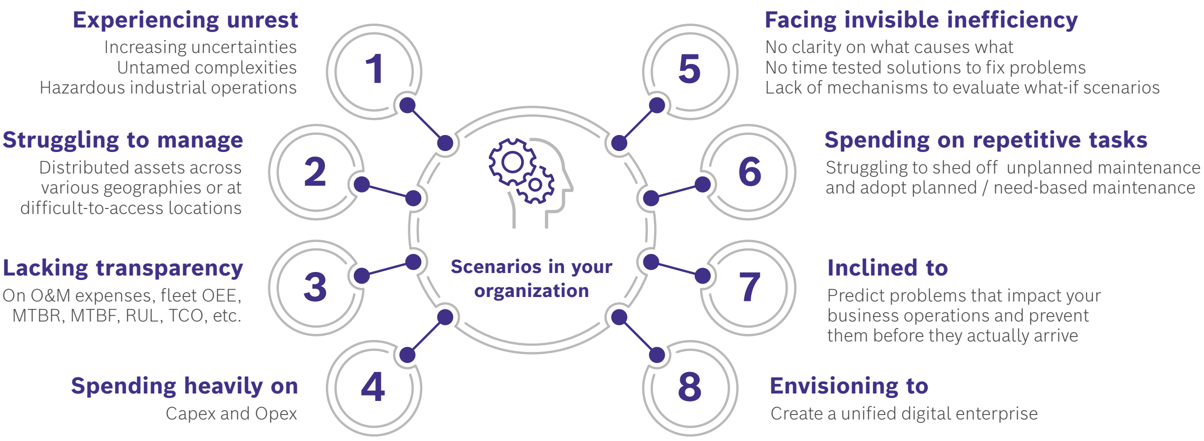
- Tailor-made, organization-driven, modular digital transformation solution
- Cyber-physical system built on sensors, software, and services framework
- Has four layers: Connect - Collect - Consume - Cognition
- AI-powered IAPM that relies on natural intelligence and first principles
- Digital prediction machine that generates physics, engineering, and business insights
- Enhanced by virtual sensors and 3D interactive, immersive environment
- Set of evolving digital engineering models built to address specific business problems
- Digital tool to transform traditional workforce into an interdisciplinary digital workforce
- Collaborative digital solution enabling the C-suite to drive business outcomes

INVESTMENT REASONING

Driving Business Outcomes

Rationale

The challenge in the field to invest and build a Digital Twin to drive targeted business outcomes rests entirely on the accuracy of the data across the spectrum of value, which bridges the physical and digital worlds at all points along the value chain. This opens the door to innovation and multiplies the possibilities of what can be achieved through collaboration. Enterprises can now establish perpetual connectivity with the industrial infrastructure, which would help them to cut costs and derive new business models for additional revenue generation. You need to invest in a Digital Twin if your organization is experiencing the following scenarios:



Unrest due to uncertainties and complexities

A business can face operational surprises if outcomes are not predicted accurately which may lead to dire consequences. The inability to predict what lies ahead or under-appreciating the complexities can impact the future readiness of a company and make the organization oblivious to the need for adapting to changing times. As a result, there is a very high probability of businesses facing difficulty in developing a clear line of sight to recognize cause and effect while making crucial decisions. **Issues that look small at one point could result in repercussions that go a long way in creating real damage.**

Lack of transparency

In the digital era, most companies have already adopted technology as the backbone of development. These technologies generate humongous amounts of data, which when looked at from the right viewpoints could reveal useful insights. These insights would add tremendous value when one can relate a particular situation with multiple units of an organization transparently. **A lack of confidence in the accuracy of data can create a major glitch in the judgment process.** In the face of a lack of transparency, decision-makers may end up either underestimating or overestimating risk, which can make their decisions flawed.

Invisible inefficiency

While companies invest in a big way on systems and solutions, it can be difficult to identify which solutions actually drive efficiency and which don't. Efficiency demands judicious utilization of organizational resources but many companies do not have the required visibility built within them and are thus unable to identify the drivers of efficiencies.

Heavy capital expenditure

A popular assumption is that if a company needs to produce state-of-the-art products and services with the aim of achieving excellence in deliveries, it will require a major infusion of capital – not just to invest in implementation but also to continue with operations. This belief hinders many companies from adopting modern technologies such as AI and IIoT, leaving them on the backseat when it comes to digitalization.

> A Digital Twin reduces the anxiety around digital transformation by employing full life-cycle data to drive real-time innovation. It can bring in transparency and real-time visibility into systems, assisting companies in critical decision-making.

The Digital Twin is a virtual representation of the physical product created to help executives and engineers glean insights and analyze data from in-use systems. Larger systems can have multiple Digital Twins linked to each other to visualize complex systems such as a power plant or a fleet of machines. Digital Twins were previously perceived as CAD representations of things. According to Gartner[1], the modern Digital Twin is different in four ways: **model robustness**, **connection to the real world**, **business applications**, and **ability to evaluate scenarios**.

How can a Digital Twin help tackle organizational challenges?

Digital transformation can instill efficiency and help offset increased costs of infrastructure, materials, and components, with predictive and preemptive maintenance scheduling, and agile production processes causing less wastage. This would also help reduce production downtime and lead times, giving enterprises a competitive edge.

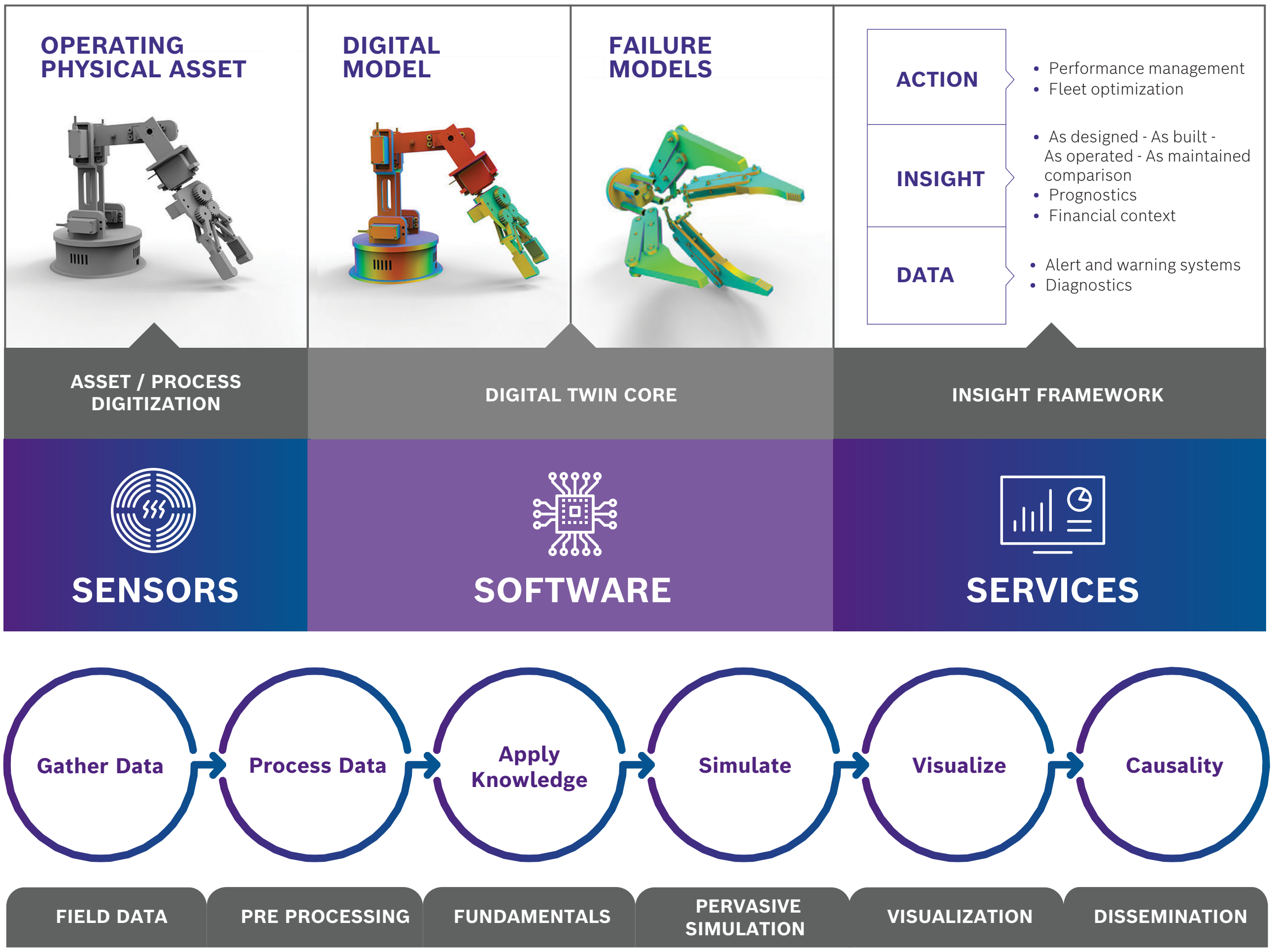
A Digital Twin can handle business challenges that are predictable and avoidable, which helps garner useful insights. Engineering insights can help improve OEE, reduce unplanned downtime, reduce maintenance costs, and improve quality. Business insights can help understand asset criticality, plant efficiency, and reduce failure mitigation cost by enabling predictive maintenance. With this progression, organizations experience impetus resulting in the evolution of reliability centered maintenance.

For instance, a Digital Twin could help fleet managers employ sensor data remotely to monitor the locations of hundreds of trucks and their real-time mechanical fitness, speeds, and fuel consumption levels. This can help them prepare for breakdowns even before they occur and rapidly innovate on processes across the network. It also enables prototyping innovations across geographies and product versions at scale.

[1]Gartner Top 10 Strategic Technology Trends for 2019. Available at: https://www.gartner.com/smarterwithgartner/gartner-top-10-strategic-technology-trends-for-2019/ (Accessed: May 21, 2020)

BUILDING THE DIGITAL TWIN

An Overview of the Solution



The modern Digital Twins are dynamic software models of assets or processes that enable real-time monitoring and improve process efficiencies. It improves enterprise decision-making by providing information on maintenance and reliability, insights into how an industrial asset, system or product could perform more effectively, data about new productions, and information on drivers of efficiency.

In this digital era, we are exposed to volumes of data generated from multiple sources that are flowing in as continuous streams. Gathering this data and understanding it to decipher an insight to support management decisions is a big challenge. A Digital Twin creates a digital highway that combines all the lanes of data, collating them into a single point of truth through a dashboard or as an immersive environment or as an APMIC which shows everything that is going on in an organization.

A Digital Twin dwells on the concept of attaining that moment when a decision-maker or user is equipped with a single source of truth derived from a river of information.

Pervasive engineering - a synchronized mechanism for asset performance management - connects the physical product, dynamic simulation, and software development, to harvest information streams from digitally tracked assets. It uses instrumentation clusters, sensors, and imaging systems, which connect to a data analytics hub that generates physics, engineering, operational, and business insights.

Also, the state of all assets can be developed continuously, iteratively, and pervasively, by building prototypes and selectively extracting components and attributes of the physical assets, while the operating field assets remain operational in their core pervasive state.

Pervasive engineering simulation augmented by Digital Twin and data analytics empowers the C-suite, as well as the engineering, operations, and service organizations with the right tools for their day-to-day activities. It encourages them to explore and enhance system design, product development, operations, and maintenance by understanding real-world conditions.

Building a successful Digital Twin

Access to apt historical data and acquiring relevant real-time data

This is a prerequisite for any solution that requires predicting outcomes based on current and past data. Rich historic fault data of industrial assets, high quality operational and process data of the ecosystem form the basis of building a robust prediction mechanism. Further to this, strong correlation to the present state of operations to that of its past state is achieved by building a comprehensive real-time data acquisition framework that ingests highly reliable real-time data into the systems. These aspects contribute significantly in determining the accuracy of predictions based on the combination of data analytics and data science.

IIoT communication grid

This is vital to establish ubiquitous data connectivity to enable computational intelligence powered by both wired and wireless technologies. A reliable system will essentially establish perpetual connectivity providing organizations unprecedented situational awareness on asset operation and industrial processes resulting in the evolution of intelligent automation.

Data integration

This is required to represent a real-world object by different subgraphs of nodes and edges. The integration of the different nodes results in creating a laminar data flow thus helping us to construct the visual abstract, which represents the anatomy of a Digital Twin.

Fidelity and allegiance

This is essential to mirror assets or processes from its physical form by creating High Fidelity Simulation (HFS) models thus enabling operators to train on virtual machines. This evolves as footing for increasing the awareness on the asset or the process incorporating diverse operating conditions. It is important to note that HFS models are building blocks that postulates closeness to the physical system.

Computational Intelligence

For a given circumstance, computational intelligence attempts to emulate learning, reasoning power, decision-making, and optimization techniques that human beings exhibit. This could be achieved through a series of techniques which mirror these adaptive evolutionary idiosyncrasies of nature's most evolved creatures. These kind of techniques could be deployed either as a standalone system or in combination with more complex hybrid methodologies, resulting in the creation of advanced systems with enhanced capabilities. For example, deploying fuzzy logic to drive decision-making under conditions of uncertainty augmented with learning and adaptation that ANN provides, or achieving optimization by arraying genetic algorithms.

The digital thread

Before you get started with Digital Twin, you should plan and architect a digital thread as this is required to improve the quality and accuracy of the Digital Twin through collaboration and transparency. A Digital Twin is no longer the sole construct of mechanical and electrical systems; it's now layered with new complexities of software engineering, pervasive simulation, high-performance computing, data analytics, iterative design, and multi-tiered supply chains managing dependencies created within the system of systems. All this can sound mind-boggling, but interestingly, they drive data through digital threads that in turn connects to a Digital Twin.

The networked Digital Twin

Engineers who ride on Digital Twins can transform themselves into a digital workforce and balance work-cost effectively. Through advanced digital devices like industrial tablets, AR/VR/MR systems, or APMIC, they now have access to early insights about potential problems even before they arise. This results in fewer errors, less rework, and hence, less chaos.

Digital Twins can be leveraged to boost multi-discipline collaboration on product innovation. Frankly, the Digital Twin is not a new concept, but until now it was operated as a standalone system powered by distributed intelligence. Things are now evolving at a faster pace and machines are creating content unlike anything ever seen before. Hence, in this growing digital industrial space, the Digital Twins must evolve to connect, interact, and communicate with each other on a higher value chain by creating a network. We call this the networked Digital Twin.

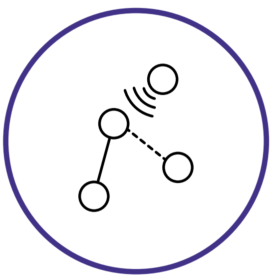
Digital Twin's relevance in Industry 4.0

What will customers want in the future? They will demand a wider range of variants and more personalized products. Thus, future production must be able to adapt quickly to changing market requirements. Industry 4.0 (I4.0) is the answer to this challenge.

Digital Twin is being deliberated as a significant enabler for I4.0 initiatives. While Digital Twin has made visible inroads into the industry as a standalone solution, the concept of it being pivoted as a critical element of I4.0 is sprouting and yet to reach its pinnacle. As we speak, it is already making its impact felt across diverse businesses worldwide. Forward-thinking companies representing automobile, healthcare, process industries like oil and gas, and other large industries have already started harvesting the economic value of Digital Twin. A Gartner survey[2] reveals Digital Twins are entering mainstream use. According to the survey, 75% of organizations implementing IoT already use Digital Twins or plan to within a year; only 13% of respondents claim to already use Digital Twins, and 62%, are either in the process of establishing the technology or plan to do so in the next year. Organizations that are increasingly adopting IoT backed by AI are in a way creating a fertile digital ecosystem and by deploying a Digital Twin they can now claim to have achieved the literal connotation of digital transformation. Digital Twin, in principle, not only helps in predicting the future performance of an organization's industrial assets or processes but also enables anatomization of the historical performance, ultimately driving efficient business operations. Bosch already has all the relevant enablers for I4.0 in its portfolio and offers a wide range of hardware and software solutions.

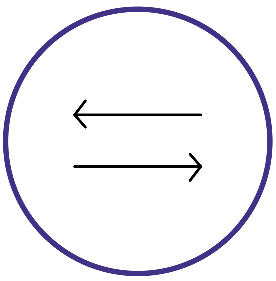
Under the umbrella of I4.0, some industrial end users, power plant companies, and those from process industries, will deploy Digital Twins to build a link between the physical product and the virtual product with an intention to achieve manufacturing or operations flexibility. Other companies, typically OEMs, would deploy Digital Twins to improve product design with an intention to map the product throughout its life-cycle thus improving quality in manufacturing or improve cost positions. The challenge currently is the fact that there are only few possibilities to facilitate synchronization between the physical world and the digital world, which makes it difficult to establish a seamless flow of information.

Drawing from our long experience, we found seven key features of I4.0 that serve as guidelines for all new components, software modules, and services offered by Bosch.



1. Distributed intelligence

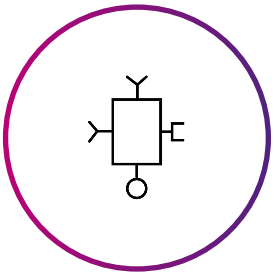
With distributed intelligence, modules know their technical skills and organize themselves decentrally.



2. Fast integration and flexible configuration

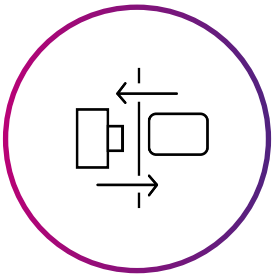
Fast integration and flexible configuration facilitate the adaptability of I4.0. People, machines, and processes are connected easily and fast and can be quickly adapted to ever-changing requirements.

[2] Gartner Survey Reveals Digital Twins Are Entering Mainstream Use. Available at:
https://www.gartner.com/en/newsroom/press-releases/2019-02-20-gartner-survey-reveals-digital-twins-are-entering-mai
(Accessed: April 14, 2020)



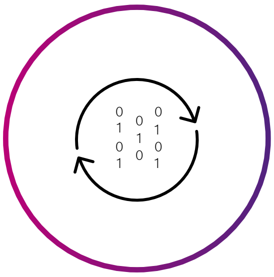
3. Open standards

Open standards are essential for integrating equipment and software from various suppliers into connected concepts. They form the basis for horizontal and vertical integration and thus the seamless exchange of information.



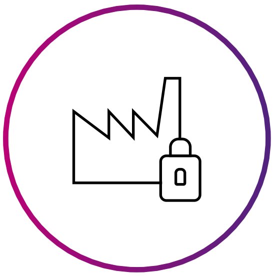
4. Virtual real-time representation

Virtual real-time representations of objects interact with each other and with software systems. They enable real-time analysis of assets, all manufacturing or process data, and the control of all physical objects.



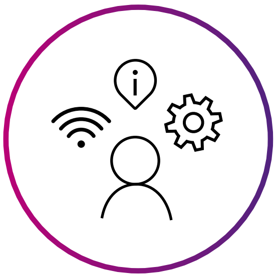
5. Digital life-cycle management

Aggregating and analyzing all the available data during the complete lifespan of a product helps to continuously improve the design and manufacturing processes.



6. Secure value-creation network

Safety and security for I4.0 includes the protection of people from machinery-related hazards and faults from the surrounding environment.



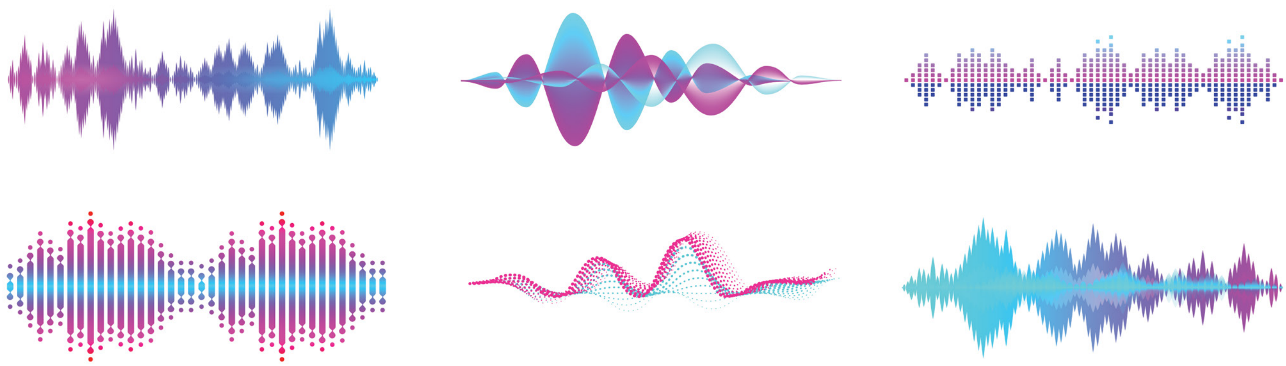
7. People as key players

In I4.0, people are the key players – work is getting easier, safer and more efficient – enabled through technology – and machines will continue to play the subordinate role.

CHALLENGES IN BUILDING THE DIGITAL TWIN

Understanding Complexities and Roadblocks

Field data sanctity



While building a Digital Twin of a product or a process, the primary focus will be on 1. Internal function relationships (defines structure of the system) and 2. External function relationships (narrates behavior of the system) with respect to the operating environment. This highlights the factors of distinction and helps understand causes and effects. Hence, one needs to collect the relevant data and not just different data streams of all sorts taking into cognizance the attributes of the telemetry.

COLLECTING THE RIGHT DATA

- Knowledge of sensor placement location
- Knowledge of DAQ operating environment
- Telemetry inconsistencies
- Sensor failures
- Deficiency in labelled and learning data
- Invisible critical data
- Sensory data from heterogeneous assets
- Scalable instrumentation
- Diverse data sources and formats
- Protocol use overlap
- Integrating data engineering
- Bandwidth definition for communication events

ATTRIBUTES OF TELEMETRY

COMPREHENSIVENESS

- Continuous-time Vs Discrete-time signals
- Continuous-valued Vs Discrete-valued signals
- Deterministic Vs Random signals
- Outliers and corner cases

STATE OF QUALITY AND RELEVANCE

- Clean and relevant data
- Diversity and quantized samples
- Causality and stability

TIMING, SAMPLING AND RECONSTRUCTION

- From t_0 to $t_{\text{end of life}}$
- Diagnostics and prognostics
- Recursive or non-recursive

Clear business problem narrative

Before one plans to drive digital transformation in their organization by deploying Digital Twins, it's very important to have a clear vision of the expected business benefits. It is also essential to perform a techno-commercial viability check based on realistic technology assessment and the associated costs involved. Therefore, the recipient organization is expected to possess sound knowledge of the application identified for twinning along with relevant information technology tools, application architecture, and germane system and statistical analysis that needs to be incorporated and scaled to meet a range of requirements a Digital Twin is expected to deliver. In situations where a clear business problem is missing, we often end up building solutions that don't fit the actual need. It is always advisable to prove with relevant historical data the necessity of deploying a Digital Twin to solve the business problem. With such an exercise it becomes possible to tune the solution in two modes – **Optimal Cost Mode** and **Optimal Productivity Mode** to address challenges of the changing times.

Missing or invisible data narrating an incomplete picture

Imagine a complex production line, for example, a hot strip mill in an iron and steel plant. This application is of an extremely complex nature involving energy transfer, thermodynamics, kinematics, and differential balances in three dimensional form. This production line will definitely exhibit several undocumented behaviors and associated interactions and responses between people, processes, and the production line in its subsystems involving the entire value chain. Now, the immediate focus is to reduce this complexity, but when an attempt is made to address this, the path may lead to other failure patterns, which might complicate it further. Therefore, it becomes essential for a Digital Twin to evolve over time and cope with these complexities. Or else, it will end up contributing to only an insignificant portion of a larger problem.

The point or the pretext that defines the business problem based on which a Digital Twin is created will actually dictate Digital Twin engineering efforts and associated cost of creation. The success and the life-cycle of a Digital Twin will entirely depend on the relevance of the business problem, the expected benefits, and possible use cases that a Digital Twin should cater to. Organizations keen on deploying Digital Twins will generally have incompatible data formats or models that might not even exist in a digital format. This condition will result in long Digital Twin road maps and enormous effort is required to normalize these aspects in a way that Digital Twins can comprehend.

Whenever we have data that cannot be leveraged at all, organizations make an attempt to create new sets of data, which is time-consuming. These delays can be extremely long (months even years) and the businesses will have to wait for a long time to work on an operational Digital Twin. Under such circumstances, for organizations that are not cognizant of the inherent data deficiencies, any efforts to build a Digital Twin based on incomplete dataset will only result in business disengagement.

In common parlance, organizations aspire to have Digital Twins that provide insights, correlations, and comparisons on as-designed, as-built, as-operated, and as-maintained conditions. Realizing this scenario in a practical time frame is extremely difficult when the organization has missing or invisible data. On the contrary, if the organization possesses systems that have the highest degree of sensor deployment with reliable telemetry, high-end automation, data centers, and command and control centers, they are likely to be more successful.

System update with consistent flow of relevant data

Imagine a high-temperature reactor operating in a chemical plant receiving process air through a Multi-Stage Centrifugal Blower (MSCB). To build a Digital Twin for a MSCB, data pertaining to 20 critical parameters needs to be continuously collected. This will ensure digital continuity, which should essentially guarantee timely updates of the Digital Twin templates.

At times, the available data could be constrained by pre-existing limited sensor population installed on the machine and sometimes by the limitations imposed by an OEM with an intention to ensure machine integrity. Under these conditions the Digital Twin template can only be built based purely on externally observable measurements. This represents a combination of black box, white box, and gray box views of the system/machine. Situations like these demand an additional set of external sensing mechanisms to be installed on the machine to ensure reception of relevant telemetry that will result in sensor integration.

Sensor integration is a complex process that needs to be meticulously architected. With the huge inflow of data streams in the form of multi-source, multi-format, labeled, partially labeled and unlabeled data, the immediate challenge is how to make sense out of them. The obvious choice is data correlation, but it's not as easy as it sounds.

Currently, to overcome this challenge, organizations deploy programmers to code the relationships based on a known logic. However, this is an interim solution as the programmers can only program a few instances where the direct correlations are obvious and there would be compromises that might overrule the complexity of reality. This clearly defeats the purpose of the Digital Twin.

To overcome this hurdle, we need to create a decision support system that can train the Digital Twin utilizing AI and ML tools, reduced order models, etc. With this we can solve only one aspect of the problem i.e. correlating causal events. For non-causal events, virtual sensing and pervasive simulation could be combined with data analytics. Together, this will help organizations to understand themselves, shape decision-making, and drive business outcomes.

Rare class faults

Many organizations that invest in Digital Twins are often under the assumption that a Digital Twin can address all the problems under the sun pertaining to the machine or system. Only a few are aware that **a Digital Twin is always built to address a particular business problem**. Imagine a combined cycle power plant; if the organization has a Digital Twin deployed to understand the thermal stress gradient in a gas turbine in correlation with the Thermal Barrier Coatings (TBCs) applied on the spinning blades, the same Digital Twin cannot be used to understand the transient thermal stresses that causes failure of steam turbine rotors which happens to be the most critical and highly stressed system.

A large integrated industrial system like this always has some rare class faults unlike anything ever seen before. These kinds of faults cannot be modeled in the Digital Twin in the initial stages as the plant has never witnessed such faults before. However, under these circumstances, if the Digital Twin cannot classify the evolving fault, it makes an attempt to flag the outlier based on cognition, but 100% assurance cannot be guaranteed as these are black swan events.

For example, imagine an oil and gas facility where the O&M team plans to work on axial force balancing on a multi-stage pump to change the suction sense of a few selected rotors by providing a balance chamber. Now, one needs to know that axial force compensation requires appropriate disc diameters and clearance dimensions matching the application demand. However, despite taking care of the same, if the balancing disc relieves the high-pressure sealing around the shaft causing surprise leakages, the Digital Twin might not detect this in the first instance.

Once a rare class event occurs, the Digital Twin needs to be updated and trained manually. The first step in this regard is sampling, during which we have to intentionally manipulate the distribution of samples based on permutation and combination so that this rare class fault could somehow be represented in the training set. Next, we have to apply boosting algorithms to improve the performance of weak base learners and gradually transform them into strong base learners. Once the interim outputs are available, we need to experiment with a series of basic classifiers. At the end of each iteration, the weight of each training sample needs to be adaptively changed based on the training error thrown out by the basic classifier, following which we can build specific classifiers based on the weighted distributions of the original training set. By doing this, appropriate classifiers will now be forced to emphasize more on learning samples that were earlier misclassified by basic classifiers.

The human factor

For now, if we hypothetically assume that we have solved all the above-mentioned technical challenges pertaining to a Digital Twin and the same has been deployed in the organization, it doesn't necessarily mean it will be successful in driving digital transformation. To make it successful, the organization has to deploy a workforce that has a holistic mindset and not a reductionist mindset to operate and manage a Digital Twin.

One has to remember that, to successfully build and operate Digital Twins, organizations have to graduate from being transactional to collaborative. The value that a Digital Twin delivers to the organization always increases incrementally and not exponentially. Therefore, the intelligence evolved will never be in the form of a series or steps or sequence. IAPM enabled by a Digital Twin is always data-centric and not process or review-centric. This could be viewed as change management or at times as a cultural issue, which needs to be addressed by the C-suite of the organization.

The technology factor

Barriers in sensing systems

Practical industrial scenarios demand comprehensive and flawless monitoring of several physical parameters like vibration, temperature, pressure, humidity, noise, speed, leakage, power system, etc. Even though advances in instrumentation technology have enabled us to monitor exhaustive metrics, there are impediments in real-world deployments owing to the complicated operational environments. This might prevent installation of standard physical sensors, affecting the quality of telemetry. To overcome the challenge we need to install customized sensing mechanisms. However, adding it to existing equipment will be expensive as these intrusive sensors may require hardware updates or even redesigns. If operating conditions present a pressing need to have a large number of measurement points to be monitored by deploying these dedicated/customized sensors, then it might render the Digital Twin project unaffordable. Also, these traditional physical sensors are mostly intrusive in nature and it is not recommended to retrofit these sensors onto an asset which is operational and hasn't already been equipped with such a sensor.

Attempting this might impact the integrity of the machine at times. Given these conditions, non-intrusive sensing methods or virtual sensing systems which could work based on transfer functions would be preferred as they could prove to be an easier alternative. One has to keep into consideration that even though virtual sensors get deployed, practically in the field, physical parameters keep changing very fast. The trade-off of commissioning these surrogate sensors comes in the form of fragmented or less accurate data as compared to the conventional sensor data. The key takeaway here is that there cannot be a single solution that would fit all requirements.

A conscious choice of the sensor instrumentation in accordance with the business problem being solved would be necessary to cushion the gap of inconsistent telemetry. Many a times, complex feature engineering techniques remain as the only options to overcome these telemetry challenges.

Barriers in operating systems

The successful implementation of a Digital Twin project principally depends on real-time, two-way communication between the physical asset and its Digital Twin which essentially has to ensure uncompromised physical realism coupled with pragmatism. This is not as easy as it sounds; once the Digital Twin is operational, there can be an inundation of field challenges disrupting the perpetual connectivity between the asset and its Digital Twin. For example, multiple aspects need to be considered such as: 1. Spatio-temporal resolution errors of sensor data 2. Outsized data generation rate 3. Occasional burst of large data volume 4. Data diversity 5. Data genuineness 6. Communication latency 7. Data archival and retrieval speeds 8. Fluctuating online and offline data processing speeds, etc.

One has to bear in mind that large industrial assets that are twinned will undergo maintenance, repair and overhauling multiple times throughout their lifetime, which results in the upgradation of the physical asset, and hence it evolves with time. This being the case, high fidelity models should also evolve correspondingly to ensure forward compatibility while still maintaining previous models to assure backward compatibility. Digital Twin for all practical purpose is a sophisticated CPS and hence necessitates high levels of safety and security to operate.

To ensure proliferation of Digital Twin projects, it is necessary to present the Digital Twin visualizations in a format which is simple and comprehensible such that the insights manifest with greater transparency and interpretability to facilitate decision-making. Finally, the Digital Twin needs to be presented to the end user in a way that it appears to be two-of-a-kind in comparison with the physical asset by being easier in nature and more intuitive to operate. To create this experience the models need to be interpretable and physically consistent. To address a majority of the above listed challenges, efforts boil down to system modeling involving mathematics, physics, thermal, 3D, data-driven, high fidelity, etc.

ESSENTIAL PILLARS OF THE DIGITAL TWIN

How Organizations Can Build and Operate Digital Twins to Drive Business Outcomes

A major chunk of data required to operate a Digital Twin is always analog in nature at the point of origin. Hence, to successfully build and operate a Digital Twin, organizations will need to first form a strategy on data management. Once the right data gets ingested, we need to then devise techniques to acquaint the insights generated by the Digital Twin in an intuitive manner based on different individuals operating it. A modular approach in positioning the required algorithms would help in horizontal provisioning at all levels. With this hypothesis, there are four pillars on which a Digital Twin is built:

Cluster 1: Connect

This is all about bringing together the relevant field data. This encompasses the Digital Twin's sensory layer funneled by sensors, actuators, PLCs, DCS, thermography, tribology, ultrasonic sensors, force measurements, noise measurements, laser-based measurements, power systems measurements, process controllers, SCADA, etc.

Cluster 2: Collect

This focuses on the assessment of subject vitals based on performance monitoring by utilizing process data, automation, and other information sources like EAM, CMMS, and ERP, which will finally collaborate with the Digital Twin sensory layer forming data fusion. Standards for information exchange to operate a Digital Twin are still evolving, for example, OLE for OPC is preferred by many organizations that are asset-intensive, XML is being used to overcome communication barriers and asset data integration while HTML is being used to manage document formats. The ingredients of this cluster are A/D converters, DAQs, multi-functional I/O, gateways, natural data repositories, historians, HIL simulators, wireless test systems, signal conditioners, distributed measurement and control devices, etc.

Cluster 3: Consume

Predictive analytics-based systems are data intensive by principle and design. Considering multiple functionalities brought about by the Digital Twin, consume layer has various portfolios to feed to. A layer that was customarily dedicated to creating digital user experience today plays a significant role in the Digital Twin solution construct.

This layer essentially embodies the necessary prerogatives of twin visualizations comprising of industrial dashboards, industrial apps, simulation engines, custom user interaction channels, alert and notification systems, trend indicators, HMI systems, and so on. In addition, a consume layer is responsible to a list of other components such as database repositories creation, hosting chatbot engines for user interaction, etc. This layer also manages the workflow creations, asset audit request handling, and defining of first level rules based on vital parameter checks.

In case of serious threats that need to be detected by a Digital Twin, there exists a necessity to have edge-based systems in place that can take quick actions based on the streaming analytics. These tightly coupled systems usually form a part of a consume layer. For example, if one wants to know how soon the journal bearings in a rolling ball mill at an alumina refinery can fail due to extensive oil whirl phenomenon, or in case of a large thermal power plant how one can dynamically balance the pressure of fuel transport air and forced draft fan to ensure that the power plant is always operated with a slightly negative draft (balanced draft) to address problems of air ingress, these kind of situations call for edge-based systems for rapid actions to be taken.

When edge computing is composed out of an HPC environment, latency in processing the field data is almost nil and as a concomitant factor, Digital Twin can now respond almost instantaneously eliminating lag time. Having an edge processing system at your disposal furthermore assists in hybrid architecture where the field data resides at customer premises and Digital Twin visualization, dashboards, industrial applications, etc. can be enabled through cloud connectivity in a secured environment (MPLS VPN - point-to-point, VPLS, VPRN). In addition, business-sensitive insights if required can also be managed using distributed ledger technology.

Cluster 4: Cognition

This cluster is all about creating digital prediction machines and building machine intelligence to power a Digital Twin that can comprehend, analyze, reason, and act in a way similar or superior to humans. This is achieved by deploying ML, neural networks and deep learning under a structured compute environment involving data center, cloud storage, etc. Edge computing load typically involves data preprocessing and scoped data analytics; For example, feature selection process from maintenance data, correlation-based feature extraction, acquiring context-specific information, parametric techniques, non-parametric techniques, problems with data set size, etc. The key ingredients of this cluster are:

- Data security, networking technologies and protocol definitions
- Models for filtering and state estimation, interpretation, prediction, diagnostics and prognostics
- Ensemble models to generalize predictions along with probability and confidence scores
- High fidelity models, pervasive simulation, entropy and relative entropy estimation
- Edge analytics core functionalities, APIs and microservices
- Model-based system engineering and data lake
- Fault tree analysis, non-destructive evaluation, failure mode effects, and criticality analysis
- Supervised and unsupervised anomaly detection (point, contextual, and collective)
- Prediction methods for rare fault classes and outlier detection
- Failure detection – supervised, unsupervised, semi-supervised, individual, contextual, and collective
- Knowledge networks for deriving complex relations for contextual decision-making
- Evolving decision support system
- Data bank to drive AR/VR/MR (3D immersive environment) enabling Digital Twin visualization

SECURITY ASPECTS OF DIGITAL TWIN

Digital Twin As CPS Aids IT and OT Integration to Realize the Vision of Digital Transformation

In recent years Digital Twin has shown evolutionary signs of driving next generation core infrastructure powering industrial digital transformation. With such transformational technologies picking up pace, they hinted at rudimentary gaps in the connect and collect layers of the existing systems. Following this, companies started focusing on comprehensive asset digitization strategies and realized the pressing need to inculcate the sensing capability of humans to fine tune the deployed algorithms. This was primarily to achieve positively influencing effects on manufacturing efficiency and improve accuracy levels of predictions.

Secondly, in an effort to accommodate required field data sanctity there originated a need to deploy a state-of-the-art communication system which could handle high volumes of data. This communication framework was also responsible for effectively managing the perpetual connectivity between the physical and digital space to ensure synchronization at all points of time. Lastly, from an end user or OEM's perspective, the communication network was also employed to transport data to the presentation layer of the Digital Twin where all critical alerts, insights, trends, diagnostics, prognostics, etc. are presented.

In all of the above cases it is evident that critical and sensitive information on asset performance or product manufacturing is exchanged between multiple subsystems including users of different personas. This is where the security vulnerability shows up. From a security frame of reference, data security breach on connected machines at a large industrial house or on a smart manufacturing facility of an OEM might cause devastating effects triggering damage to physical infrastructure, equipment, and even the operating environment. It is of prime importance to ensure when Digital Twins are getting deployed, security aspects are embedded into the project from the initial stages itself.

For instance, Common Information Model (CIM) infrastructure throws light on typical security requirements for a smart manufacturing facility; this includes security aspects at sensor-actuator levels on the assets, cell control, supervisory level, plant, and enterprise levels. This broadly covers meta schema, managed object formats, namespaces, mapping existing models into CIM, repository framework, etc. On similar lines, while architecting the security aspects of Digital Twin, the main focus should be on data at rest, data in motion, data under processing, and data in storage. It is important to note that security requirements differ from project to project and would vary depending on the methodologies of deployment – SaaS, PaaS, IaaS, on premise, hybrid, etc.

Companies investing in digital transformation projects are the most sought-after target by flagitious troupers who persevere to unethically defeat cyber security. In the last few years, IoT-related cyberattacks are on the rise and the intent behind these attacks is to exploit the digital systems and take control. As we speak, many enterprises have limited understanding on the security gaps between the physical asset and its Digital Twin. Let's consider the Connect and Collect layers of Digital Twin which essentially encompasses sensors, multi-function I/O devices, packaged controllers, board-level controllers, industrial communication buses, software defined radios, etc. These systems comprise sensing mechanisms, digital signal processors, micro-controllers, memory systems, etc. The Digital Twin operating system might not have the required degree of microscopic visibility on these systems. This is one such security vulnerability which needs to be carefully managed by deploying compliant security systems, and trusted and certified hardware and software systems.

Another weighty security concern is that the Digital Twin happens to be a virtual replica of the real system. Imagine if knavish personnel succeed in defeating the cyber security and gain unprincipled access, the blueprint to the real system gets exposed. From there on it's very easy to navigate and identify all components, systems, sub-systems, their interfaces, their behaviour, their networked Digital Twins, etc. With this information in hand, the knavish personnel will first try to identify the weak points. Once these vulnerabilities are identified, scripts can be created to run on the compromised Digital Twin. This might create invisible tunnels to the real system and their physical system interfaces thus permitting the scofflaw to meticulously plan attack mechanisms.

Enterprises planning to invest in Digital Twins are expected to have sound knowledge of cyber security, a reinforced cyber security planning guide in place, and security systems to guard against malicious software, spyware, and adware. Hence, it is highly recommended to deploy defense-in-depth mechanism for cyber security as against perimeter security. This will in a way enable organizations to lock software, hardware, and data to specific devices which are identified by the organization via hardened enterprise APIs or by deploying robust data protection technologies. With this, organizations can ensure that even though data or software is copied, the same is rendered inaccessible and non-operational on unidentified machines.

DIGITAL TWIN VISUALIZATIONS

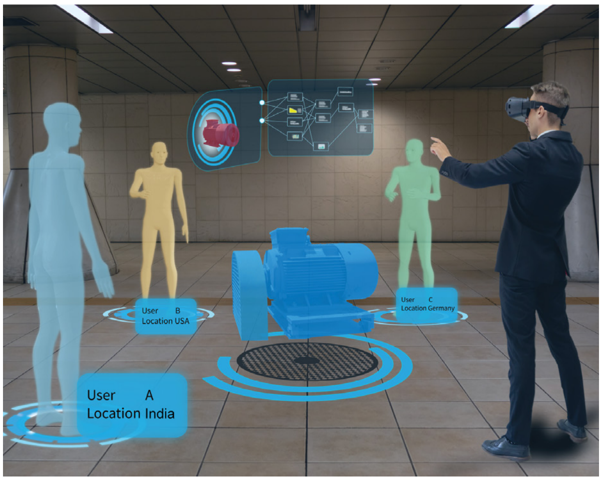
Converting Data Into Knowledge and Knowledge Into Wisdom

Transforming a river of information into a single source of truth

The best thing about the Digital Twin solution is its modularity. Be it in terms of high fidelity models, failure modes, or the immersive visualization experience it offers, all these aspects are highly modular in nature. This makes it easy to integrate or stitch a solution based on the business problem that one is trying to address. Persona-based visualization is the key differentiating factor that ensures the necessary information reaches the stakeholder in a format they can comprehend seamlessly.

Digital Twin dashboards that can run on smartphones or tablets give the required info-visual to field personnel on the go. More capabilities are built into the dashboards that run on the PCs or laptops that are usually used to configure or troubleshoot a situation with its help. Highly immersive AR/ VR/ MR visualizations powered by Digital Twins come into action during training and remote assistance from a distant geography. A 360^0 view in an APMIC brings to life the entire Digital Twin functionalities to form a command and control center like environment, from where the entire operation is monitored and controlled.

Simulation capabilities are made available on dedicated computing environments as they are compute-intensive and require high-performance computing infrastructure to fulfill runtime needs of the applications.



TACKLING THE REAL WORLD PROBLEMS

Why Organizations Need to Think of Digital Twin as a Key Enabler in their Digital Transformation Journey

IMAGINE...

Offshore and onshore wind power parks populated with hundreds of windmills

A paper machine all the way from forming section head box to winders

Reciprocating compressors operating in an oil and gas facility

Large conveyors and kilns in a cement plant

Carbon black reactor in a chemical industry

Centralized and decentralized compressor units operating in an aircraft manufacturing facility

A rolling ball mill in an alumina refinery

What do these assets/systems have in common?

- They are complicated and large
- They have high capex and opex
- When they break down, they can bring down entire plant operations
- They operate in difficult-to-access locations or hazardous environments
- They are distributed across large geographies
- They present increasing uncertainties
- They exhibit untamed complexities
- Their operations might lack transparency and have invisible inefficiencies
- Their operations directly impact a company's P&L
- To keep them up and running, 24x7 monitoring is required
- To keep them up and running, one needs to predict problems before they actually arrive

How do we address these business problems?

These business problems can be addressed by organizations through systematic deployment of Digital Twins. The Digital Twin offering from Bosch is a cyber-physical system, a modular digital transformation solution that is participative in nature. In other words, it's built by Bosch but operated by customers.

> Organizations can look at Digital Twin as AI-powered integrated asset performance management system built on the basis of natural intelligence and first principles.

Digital Twin holds a lot of opportunities but can also be perceived as a challenging add-on for manufacturers. This comes as no surprise as the machines powering manufacturing in industrial houses are becoming more complex and companies are looking to manufacture their products in a flexible way. As a matter of fact the solution to this equation lies in creating a sustained flexible production ecosystem built on modern digital technologies.

Generally, 70% of the cost of the product is already decided in the engineering phase and a Digital Twin can be deployed to influence these costs early. From PLM to manufacturing, operations and service, Digital Twins are always updated with current and historical data on a shared platform, feeding operational information to the design team as product performance feedback.

From an OEM perspective, once the machine is in the field, service technicians can create performance improvement requests through the Digital Twin. This would be a kind of feedback loop for the product feature innovation or upgrades. It creates the need for the networked Digital Twin, which can now have relationships and can communicate seamlessly with other Digital Twins. In addition, this will help you to accelerate and optimize the entire product life-cycle and improve products and services continuously, down to the last detail.

With ever-increasing and growing network streams of connected data, product life-cycle processes would shrink and get streamlined, dismantling silos and ensuring decision access for all disciplines.

“The best way to predict the future is to create it.” This quote is credited to both Abraham Lincoln and Peter Drucker. Organizations envisioning to achieve in-depth view of assets augmented with physics, engineering, operations and business insights have to fundamentally create Digital Twins to realize their vision as it is almost impossible to achieve this level of digital enablement in real-time by deploying any of the other mature technologies that are currently available in the market. By the very nature of Digital Twin, it aims to simplify complexity and strives to remove the limitations from a given business environment.

A unique feature which sets the Digital Twin apart is its ability to provide access to the subject of Digital Twin from anywhere. This enables monitoring of the asset and allows for the asset to be remotely controlled under human supervision by deploying appropriate feedback mechanisms. Availability of qualitative data, insights churned out of data analytics and improvement measures suggested by data science will succor in more informed and faster decision-making during normal, hardship and distress operating conditions. With its ability to generate and segregate persona-based recommendations, the Digital Twin’s automated reporting system will ensure availability of the right data to the right people at the right time; thus enhancing predictability and improving transparency.

USE CASE ILLUSTRATIONS

Cement plant

Critical operations in cement plants include transporting, heating, and grinding of raw materials. Hence, working with cement requires a mix of force and finesse. To drive these complex applications, cement plants deploy electro-mechanical direct drives. The biggest challenge in managing these giant complex machineries is to ensure the highest levels of OEE, resilience, and system interlocks, offering comprehensive protection, fine speed control, and unbeatable flexibility. In applications throughout a cement plant, a Digital Twin helps you safeguard uptime, productivity, and the service life of your equipment.

Below are a few identified applications and key metrics which when managed through Digital Twins drives business outcomes for cement plants.

Material conveying systems

- Protection of conveyor belts from overloads – regulating torque control
- Ensuring minimal belt stress levels – precise control points for soft starts and stops
- 24x7 monitoring irrespective of low, medium, and high speeds – digital inspection
- Planned torque management – for example, high starting torque for a limited period
- Digital planning enabling machine startup in any load condition

Apron feeders

- Torque regulation for an unlimited period
- 24x7 monitoring and built-in protection against shock loads
- Engineering insights guiding easy handling of frequent starts and stops
- Variable speed control – enabling process optimization

Ball mills

- Guidance for variable speed - optimized production process
- Intelligent torque control, be it low speed and high torque - enabling trouble-free inching

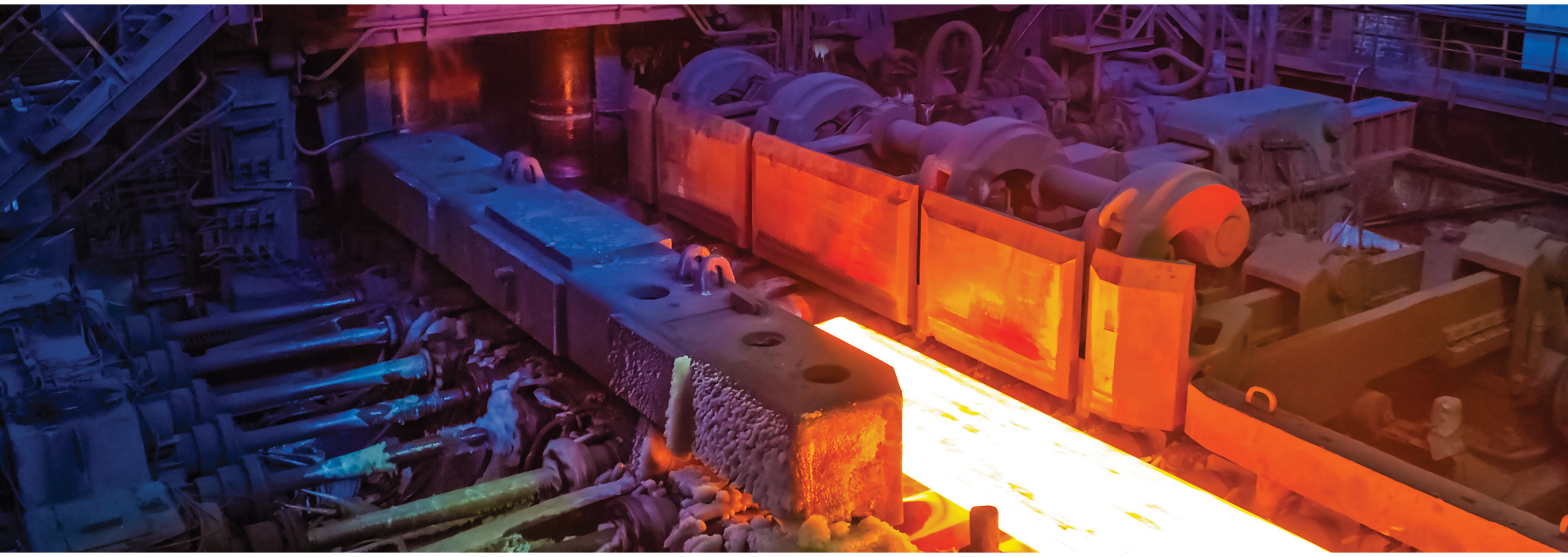
High-pressure grinding roll

- Digital management of low moment of inertia – accurate torque control
- Watchdog for limited force between the rolls – less unground material
- Guidance for minimal roll wear – optimized grinding + easy maintenance

Chemical plant

The chemical industry needs tough and reliable system solutions to meet the demanding needs of challenging operating conditions. A Digital Twin can help craft unique performance characteristics, low life-cycle costs, and maximized productivity. Deployment of Digital Twins could be done for both new and retrofit installations in chemical plants such as reactors, agitators, mixers, gear pumps and fermenters, Z-blade mixers, dryers, extruders, etc. Below are a few key metrics that Digital Twins can manage to drive business outcomes for chemical plants:

- Dynamic estimation for best power-to-weight ratio for compact motors
- Single control window for multiple motors operating independently
- Guidance mechanism to determine the right drive torque for the above listed applications, ensuring protection for the drive shafts
- Predicting values of set points enabling variable speed drives to regulate the flow from gear pumps



For industrial assets operating in harsh environments such as the one shown in the picture above, the highest PLF and CUF are of utmost importance to ensure continuous and smooth operation of metallurgical processes. Therefore, plant engineers and users need reliable automation partners. Digital Twins can augment existing automation solutions and components for the entire range of steelworks and rolling mill technology, including ladle turrets, continuous casting machines, vertical casting machines for aluminum slabs, and roll adjustment in cold and hot-rolling mills, to name a few.

In many countries, digital solutions such as Digital Twins are incorporated into new steelworks and rolling mill projects. These solutions are being retrofitted for existing facilities as part of their digital transformation journey. The productivity of these facilities can be increased most effectively with the help of a Digital Twin. Industrial houses in this segment need digital advisory services to create a blueprint for the entire project, from the initial planning to turnkey delivery.

The automation solutions operating in the metal segment need to guarantee precision and reliability throughout the entire lifespan of the facility. This is where a Digital Twin can integrate all your needs as a simple converged system.

Digital Twins can increase the productivity of steelworks significantly. For instance, they can generate predictions for highly precise gauge control systems with powerful hydraulic or electric drives to guarantee high quality and excellent surface finish. Similarly, for servo cylinders with control systems to ensure an optimized mold oscillation process.

Below are a few key metrics that Digital Twins can manage to drive business outcomes for metal and mining units:

- Set point recommendations to maximize equipment uptime in order to optimize productivity
- Reduce limitations and protect machines from damage
- Enable machines to withstand harsh environments and resist wear and tear
- Help machines to augment ruggedness and function without adding bulk and weight

Since the Wright Brothers' first powered flight in 1903, the aerospace industry has demonstrated a privileged record of achievement through a major source of innovation and technological advancements. Compared to other industrial businesses, aircraft manufacturing companies have a larger international footprint and are thus vulnerable to different set of direct and indirect challenges which are unique in nature. Typically, these challenges pertain to supply chain, engines, material science, certifications, export credit fairness, airline customers, aircraft leasing companies, business jets, MROs, maintaining skilled workforce, decarbonizing aviation, aircraft safety, employee safety, etc. Characteristically, the airline customers have thin operating margins, which translates into business pressure on aircraft manufacturing companies to build fuel efficient and reliable jets which could ensure the best in class RPK.

Quite often, aircraft manufacturers struggle to keep the deliveries on track due to unforeseen circumstances as one or the other operational issue impedes the speed of the aircraft assembly process. Despite having best-in-class digital transformation in place, aircraft manufacturing will always need large amounts of manual work content. Deploying the Digital Twin here will help augment the workforce with insights, ultimately leading to the evolution of a connected workforce which in turn can drive the desired business outcome.

From the manufacturing perspective, which exhibits a higher degree of variance, Digital Twin could renovate the production logic of aircraft manufacturing rendering it simple, flexible and adaptable. In this process, if the highest point of efficiency is achieved for a given operation then the process could be templatized. The Digital Twin templates could then be reused, modified or redeployed for similar operations. In addition to this, Digital Twin could be deployed on real assemblies as well under twin-in-a-box concept. In this manner, the functionality and operability of selected assembly processes can be tested during the project planning stage itself.

Below are a few use cases in aircraft manufacturing where Digital Twins can manage to drive business outcomes:

- Networked Digital Twins for smart tool clusters involving operations like tightening and drilling
- Digital Twin of production system design which evolves as a factory twin involving part fabrication systems, part inspection systems, and automated assembly systems

Ideal recipients for Digital Twin would include:

- Wing skin mills
- Long-bed, gantry-style milling machines
- CNC trimming and drilling system
- Ultrasonic cutting machine
- Automated fiber placement machine
- C-frame fastening machine
- Automated wing fastening system
- Ring riveter assembly system
- Electrical or hydraulic lifting devices at major component assembly and final assembly line
- Heavy duty mechanical gantries (process cranes)

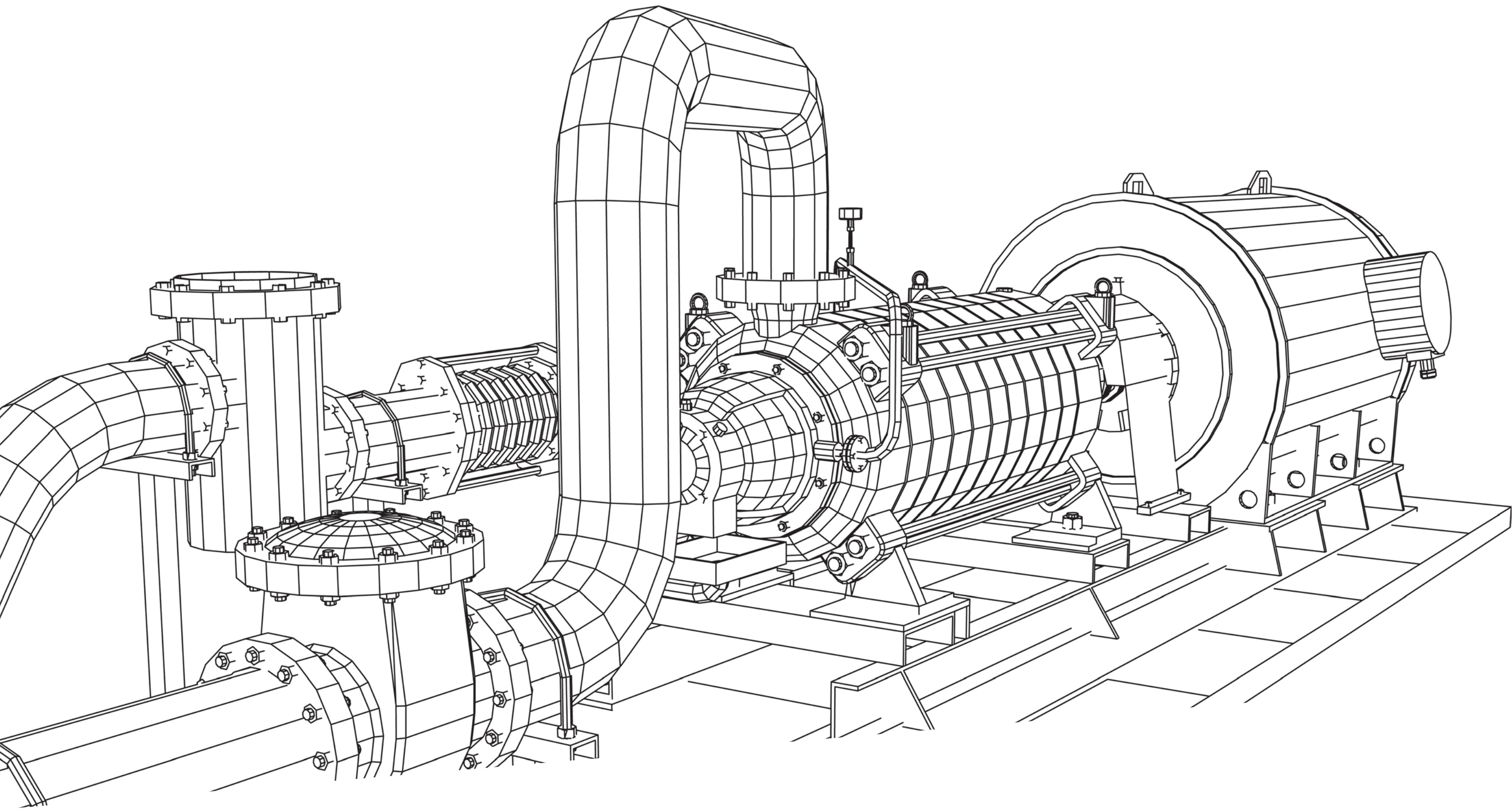
Below are a few key metrics that Digital Twins can manage to drive business outcomes for commercial aircraft manufacturing facility:

- Simplification of complicated automation
- Creation of collaborative automation
- Comparison of actual assembly processes and procedures with SOP
- Modelling and simulation of control programs for various operating conditions
- Pinpointing areas or procedures which needs immediate attention
- Enhancement of learning curve of employees while at work (knowledge network)
- Optimization and benchmarking of operations to realize best efficiency
- Fruition of employee centric production system aiding digital continuity
- Evolution of integrated asset performance management framework

CONSPECTUS OF INDUSTRIAL APPLICATIONS

How Organizations Can Deploy Digital Twins to Drive Business Outcomes

Large industrial centrifugal turbo machinery



Business problem

Turbo machinery like fans, pumps, blowers, compressors, etc. generally have certain limitations in their operational range. At low mass flow rate conditions, these turbo machines exhibit unstable working conditions resulting in severe machine damage. These peculiar behaviors cannot be sensed easily as they evolve over a period of time, therefore we need to create kinematic models with mathematical descriptions. Some dangerous failure reasons include surge, vaneless diffuser rotating stall, abrupt impeller rotating stall, inlet recirculation, etc. A Digital Twin has to identify these symptoms and generate insights to prevent machine breakage.

Basis of Digital Twin construct

The basis is asset portrait reconstruction based on kinematic models, torsional models, bending force, base excitation analysis, etc. in correlation with the pressure signal telemetry from different points close to the surge onset. The asset phase portrait reconstruction is done with the method known as the Principal Component Analysis (PCA). The idea is to ascertain the dynamical analysis of the telemetry feed as applied for PCA for instability detection and isolation recommendations. In addition to this, relevant statistical procedures are used to realize orthogonal transformation. This will enable the Digital Twin to convert a cluster of multivariate observations into a definitive cluster of linearly correlated variables. However, when a partially trained Digital Twin gets deployed purely based on PCA, the Digital Twin construct has to essentially have the relevant data components, which are diverse and independent. But if the analysis demands exclusive time series telemetry, the arriving values necessarily have to be non-independent, such that the extension of PCA called Singular Spectrum Analysis (SSA) can be made available as an alternative and SSA needs to be applied only for the lag versions of a single time-series variable.

Algorithm construct

The window technique will be applied to continuous and discrete-time, non-periodic, or periodic telemetry. If the telemetry to be processed happens to be non-periodic continuous-time signal, it will be subjected to three processes before it can be processed: sampling, windowing, and periodic continuation. Depending on the order of these operations, three options would be available to apply windowing to the continuous-time signal, to the discrete-time signal, or to the periodic discrete-time signal. This enables the Digital Twin to provide insights on system stability; this can be checked by finding the roots of polynomial or the eigenvalues of matrix in a state-space representation.

Expected business outcome

- Minimize unplanned shutdown from four per month to zero
- Avert catastrophic failure on a similar machine in close proximity

Rolling mills

Business problem

Milling and grinding solutions like horizontal mills, stirred mills, vertical roller mills, roller presses, etc. are key pieces of equipment for secondary grinding following crushing and are suitable for grinding all types of ores and other materials. They are used in the mining, cement, and chemical industries. These large machines exhibit unstable working conditions owing to invisible direct and indirect wear, resulting in severe machine damage. This can include mechanical/ thermo-mechanical/fretting fatigue, journal bearing failure, gearbox failure, etc. These peculiar behaviors cannot be sensed easily as they evolve over a period of time, so we need to create kinematic models with mathematical description. The Digital Twin has to identify these symptoms and generate insights to prevent machine breakage.

Basis of Digital Twin construct

The basis is asset portrait reconstruction based on kinematic models, torsional model, bending force, base excitation analysis, etc. in correlation with the structural, sub-structural, and tribological telemetry from different points on the machine. The asset phase portrait reconstruction is done with respect to the impact or compression experienced due to forces applied normally, oblique forces, parallel forces, and characterizing tumbling based on rolling balls that roll over.

To investigate the multi-body impact load behavior, a Digital Twin will be designed to perform a series of experiments in virtual space based on discrete element method simulations constructed to improve the grinding efficiency and prolong the life of machine components and subsystems. The baseline for the Digital Twin would be based on the assumption that optimum efficiency could be achieved when the CUF of the ball mill is around 60%-75%. The CUF for chemical plants, however, should be 35%-60% depending on the grinding media being used.

Algorithm construct

Most of the time, the ball mill behaves like a discrete time system. Hence, convolution summation in combination with cross-correlation and autocorrelation with appropriate filters over several layers will help derive engineering and physics-based insights. Also, feed from motion amplification, thermal imaging feed to CNNs will help to arrive at semantic segmentation, thus offering industrial inspection with immersive environment.

The system stability insights would be based on the nature of bounded excitation, which would be creating the appropriate bounded response. For specific operating conditions, the state-space method would be used as it offers the advantage of analyzing systems through the manipulation of matrices based on feature engineering, which can be carried out efficiently using array or vector processors. The inherent advantage of this method is that it also helps to characterize and analyze time-dependent systems.

Expected business outcome

- Provide operational insights to regulate performance of the machine with respect to operating loads
- Predict remaining useful life of various subsystems and ensure reduction of electro-mechanical stress levels on subsystems

Business problem

A reflow oven is used for reflow soldering surface-mount electronic components on Printed Circuit Boards (PCBs). The process is conducted in a nitrogen-rich environment to prevent oxidation of components in the high-temperature environment. The equipment is divided into various zones for performing the heating and cooling cycles for the soldering process.

Flux is used to facilitate the soldering process. At high temperatures, the flux melts and vaporizes. There is a cooling zone in the oven, where the flux vapor can leak. The flux vapor leaking in the cooler sections of the oven cause it to condense on the walls. After a certain threshold, this condensate collects and falls on the PCBs, resulting in the loss of the PCBs and triggering shutdown of the machine.

The mechanics of this process is not precisely known, making preventive maintenance time-bound; in spite of this, shutdowns have been necessitated due to flux leaks.

Basis of Digital Twin construct

- Thermodynamic and fluid flow models to understand the reasons behind flux condensation and build-up in reflow ovens
- Physics and material science-based models to understand sensitivity of condensate buildup based on several operating parameters
- A continuous monitoring system for flux buildup to enhance the OEE of the oven, reduce quality rejections, and migrate from planned to need-based maintenance

Algorithm construct

Heat transfer analysis based on two-dimensional steady state problem, heat transfer through walls, three-dimensional transient problem i.e. heat dissipation through ribbed surfaces, Conjugate Heat Transfer (CHT) which concerns the coupled heat transfer between fluids and solids. Finite element analyses for heat transfer processes and heat flow when phase changes take effect. Performance prediction is derived in terms of percentage overshoot, rise and settling time, while the stability margin of the system is indicated in terms of the gain and phase margin using the Bode plots. ANN models based on feedforward architecture and trained by backpropagation technique will represent system behavior more accurately as compared to the dimensional analysis approach. Now, based on the least error criterion, number of cycles required for the training can be ascertained so that the ANN models can rigorously be trained.

Expected business Outcome

- Predict operating conditions for different load profiles that could lead to flux leakage to overcome quality and batch rejections

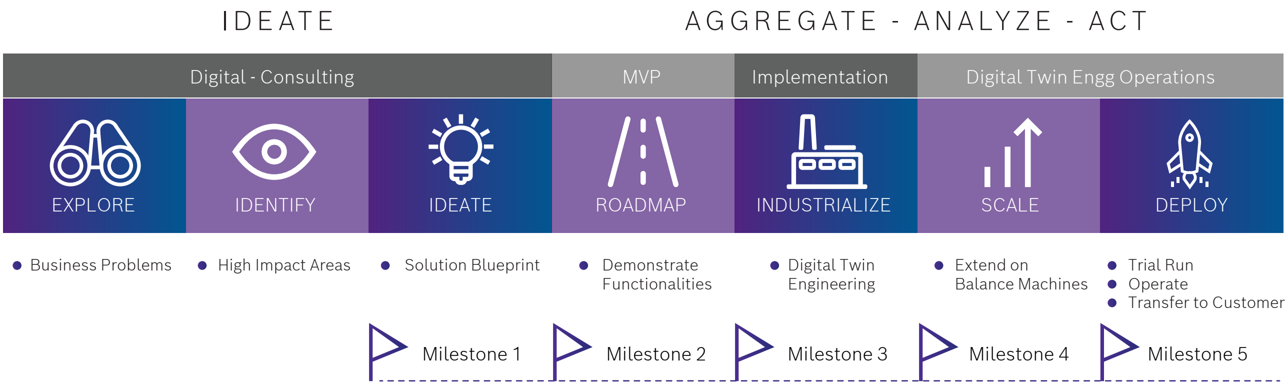
Required compute environment for the above applications

- VM-centric, hybrid cloud architecture with MPLS VPN connectivity
- Modular DAQ with high channel count
- 4x8 OR 4x16 server counts with 4x32 GB OR 4x64 GB server memory

PARTNERING WITH BOSCH TO BUILD THE DIGITAL TWIN

How Bosch Helps Customers Build Digital Twins

Bosch with its I4.0 expertise has tried-and-tested methodologies to help customers realize digital transformation for their organizations. We understand what our customers want in the future. Our team of IIoT consultants, software developers, solution architects, project managers, UX designers, business model innovators, trainers, etc. will work with you to bring your IIoT idea from strategy to implementation. When organizations plan to invest in Digital Twin for their brownfield or greenfield projects, it is business-critical to establish the vision, objectives, and operating strategy based on the shortlisted use cases followed by business case evaluation. Bosch offers Digital Twin advisory services for business case evaluation, which includes workshops, field studies, feasibility assessments, etc. to validate and customize the most appropriate and scalable architectural framework of the Digital Twin to be adopted.



DIGITAL ADVISORY

Ideate under specific themes, modernize and transform the identified business operations from analog to digital

IT–SERVICE BUSINESS ALIGNMENT

Transition IT infrastructure from enterprise services to business drivers

FIX THE CORE

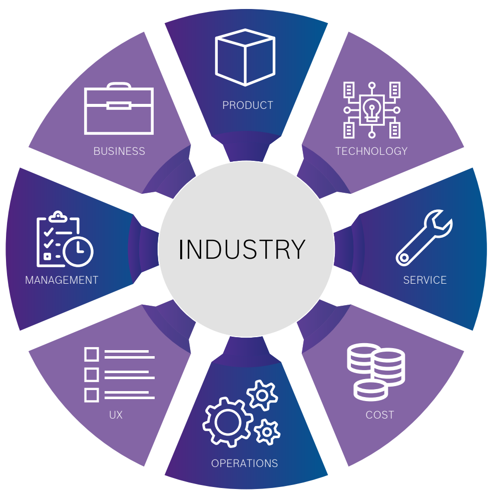
Identify pressure points, create strategy to address business problems that have far reaching business impact

GROW THE CORE

Ideate the DX channels and laminarize the analog to digital transition process

EXPAND INTO NEW OPPORTUNITIES

Power business analytics with a Digital Twin, create new digital offerings fueling growth and drive business outcomes



THE TAKEAWAY

Summary

A Digital Twin enables enterprises to see the unseeable, perform experiments to understand the what-if scenarios, simulate, execute, and control their business operations. It facilitates enterprises like yours to evolve rapidly and get much closer to the digital enterprise you envisioned!

Forward-thinking organizations who understand digital and have systems that help comprehend patterns or insights originating from data analytics and data science can formulate data-driven strategy to logically control their business operations. This could offer them points of advantage to achieve the desired business growth. The recent Markets & Markets report[3] advocates that the Digital Twins market is estimated to grow from USD 3.8 billion in 2019 to USD 35.8 billion by 2025, at a CAGR of 45.4%. Such growth rates will compel one to ponder about the propensities influencing a growth of this nature.

Digital Twin concept picked up momentum during the early 2000s, however, the root of this technology dates back to the 1960s when NASA devised this concept for the Apollo 13 mission control center to mirror the systems operating in space. As of today, only a few enterprising organizations have been bold enough to invest in Digital Twin on a conservative scale and have harvested the benefits out of them. Decades ago, even though people were aware of the benefits of Digital Twin, they were reluctant to invest in it due to technological limitations and exorbitant upfront investment of costs, resources, and time. Today, vertiginous technological advancement in ICT has paved the way for proliferation of IoT-related solutions such as the Digital Twin, rendering it economical and more gettable for organizations of every scale.

Digital Twin implementation at scale is likely to be witnessed in industrial segments such as oil and gas, power generation, iron and steel, railways, aviation, etc. which typically have capex and opex intensive assets, challenging operating conditions and complicated processes. Other segments will soon follow, comprehending the business outcomes achieved by the pioneers.

Digital Twin exists in many forms i.e. Product Twin, Application Twin, System Twin, Process Twin, and so on. This, over a period of time, evolves to fundamentally become the backbone of Industrial Digital Transformation. Companies who once deployed laborious methodologies to evaluate machine, plant or process performance and associated KPIs can now remotely evaluate and manage the same at a time, date and place of their choice. There has always been a trade-off between immediacy and depth leading to compromises on achieving business targets. Digital Twin helps organizations solve these mutually exclusive objectives.

In the long term, Digital Twins bring about the possibility of integrating systems and data across the entire ecosystem of an organization. Today, Digital Twins are built mainly for

[3][Updated 22 Jan 2020], Digital Twin Market by Technology, Type (Product, Process, and System), Industry (Aerospace & Defense, Automotive & Transportation, Home & Commercial, Healthcare, Energy & Utilities, Oil & Gas), and Geography - Global Forecast to 2025, Markets and Markets, Accessed: April 14, 2020, https://www.marketsandmarkets.com/Market-Reports/digital-twin-market-225269522.html

intra-organizational consumption, however, in the future, Digital Twins would be built for inter-organizational consumption as well. Digital Twins can drive companies, industries, and societies, to become safer, smarter, and greener.

Sensor data, remote monitoring, and industrial analytics, made possible by a Digital Twin enable more profitable, safe, and sustainable operations. Digital Twins can be connected to the manufacturing processes or OEMs, creating a digital collaborative ecosystem accelerating innovation and design for smarter and better products. This will naturally result in new business models and never-before imagined outcomes, which can address the needs of new markets.

Digital Twins can transform your organization into a digital enterprise that assures a smart future, eventually improving your business results. Are you ready for this journey?

Conclusion

Ultimately, we are limited only by our imagination. Technology is just an enabler to what a human mind can envision. It is that focused mindset of creating a unified digital enterprise which leads to leveraging all potentials brought about by a Digital Twin.

To quote a McKinsey Global survey[4], "Transformations are hard and digital ones are harder". What is even harder is to sustain these transformations long enough to reap their benefit. The key would, however, be to always ideate under specific business themes to be able to demonstrate value on an industrial scale. With Digital Twin, every obstacle faced by an organization can be looked at as an opportunity to advance oneself. It is just a matter of time that digital transformation solutions such as Digital Twin become a necessity rather than a luxury to keep pace with the ever-changing market requirements and competitive business models.

A systematic approach of clear definition of the business problem to address distinct pain points will help in winning this digital transformation marathon with a lot less inertia.

Knowing what is vital to put together a perfect Digital Twin orchestration through the layers of connect, collect, consume, and cognition would help achieve the best possible efficiencies and tackle the most complex industrial problems. With a robust ecosystem, proven engineering expertise, meticulous business processes, and a vast IT landscape, Bosch has every ingredient that is necessary to build a successful Digital Twin. With a strong Digital Twin foundation built on natural intelligence and first principles, the Bosch Digital Twin solution always relies on human intelligence more than anything else. We strongly believe that building a comprehensive solution is one side of the coin; a collaborative mindset of people who use this as a medium to solve an existing problem is what completes the other side of it. A Digital Twin is always better when it is "**Invented for Life**".

[4]McKinsey Global, Available at:
https://www.mckinsey.com/business-functions/organization/our-insights/unlocking-success-in-digital-transformations
(Accessed: April 14, 2020)

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