Digital Twin for manufacturing industry

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- Director of the Innovation and Product Realisation(IPR) research environment
- Head of the Network and the Networked and Embedded Systems division, MälardalenUniversity, Feb. 2014-2018.
- Doctor of Philosophy in Computer Science and Engineering, MälardalenUniversity, Nov. 2010.
- Co-authored 182 scienticpublished articles/papers and one book chapter
- Has long time experience in conducting research in close collaboration with many industrial partners through several research projects.

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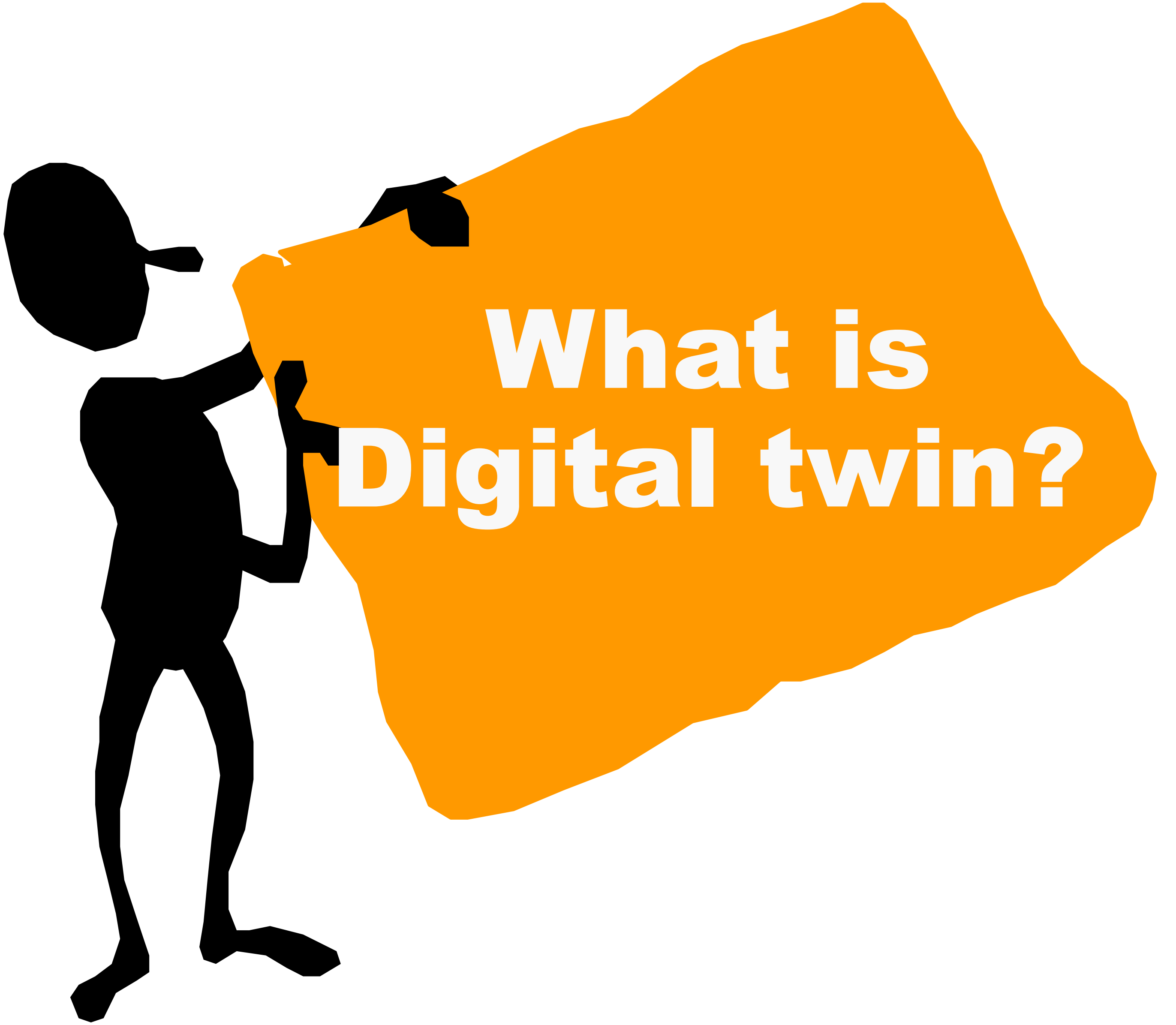
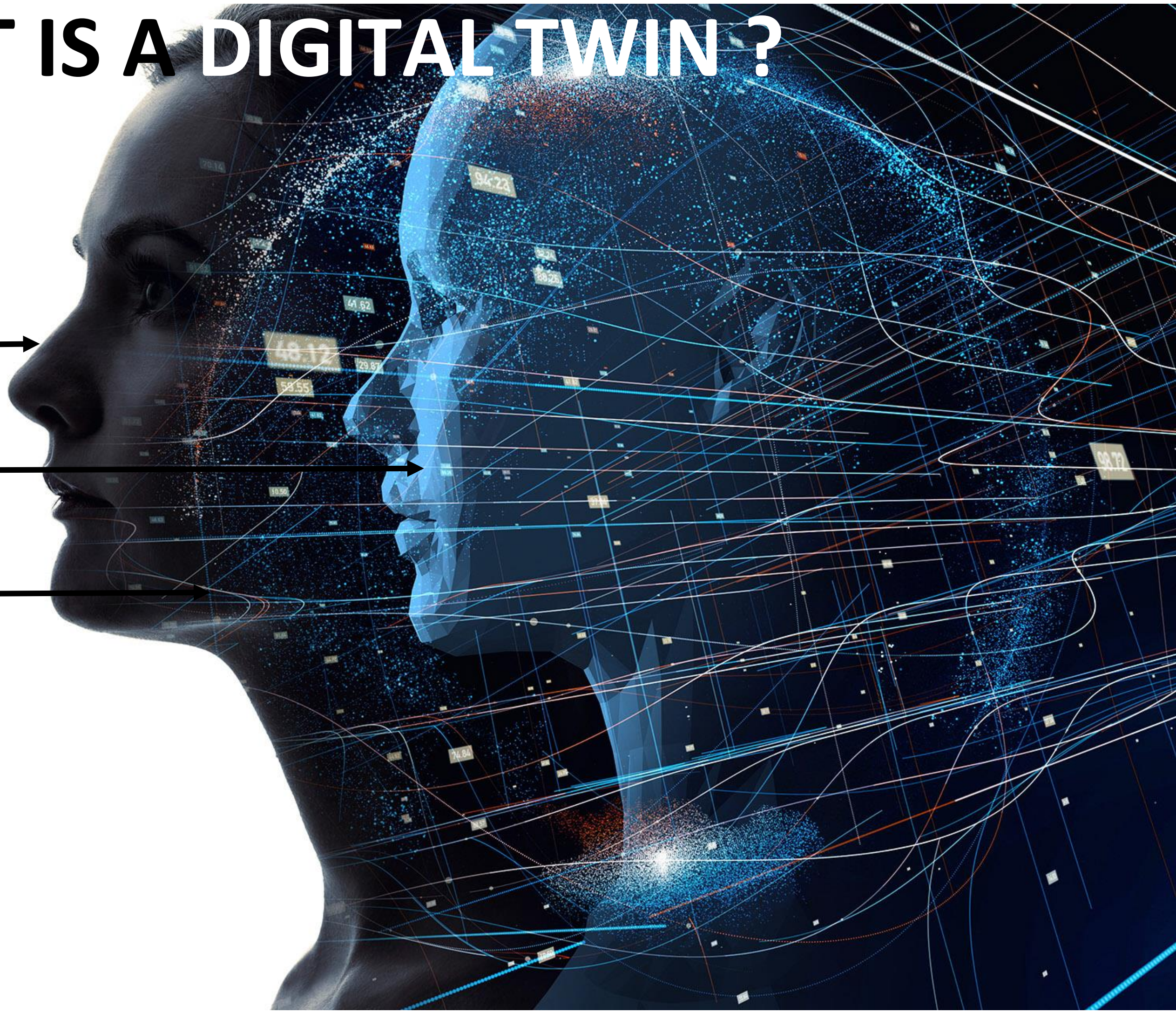


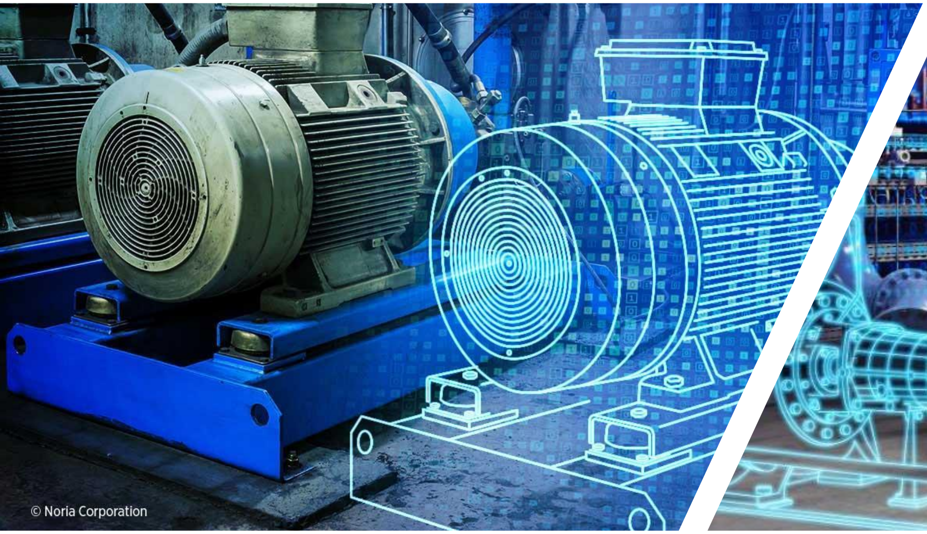
WHAT IS A DIGITAL TWIN ?

Physical entity

Virtual entity

Connections

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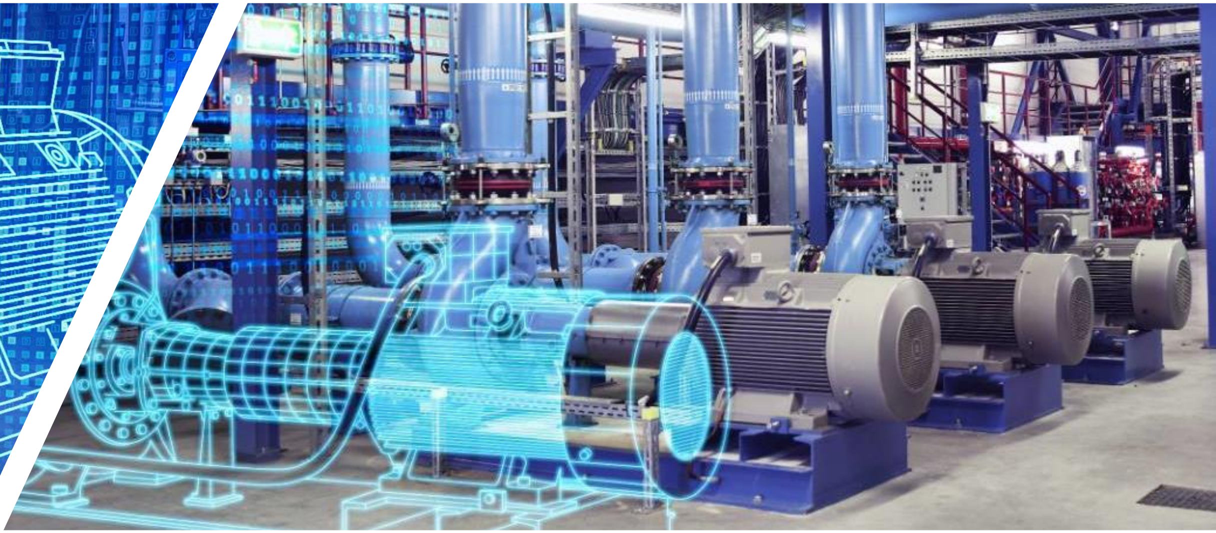
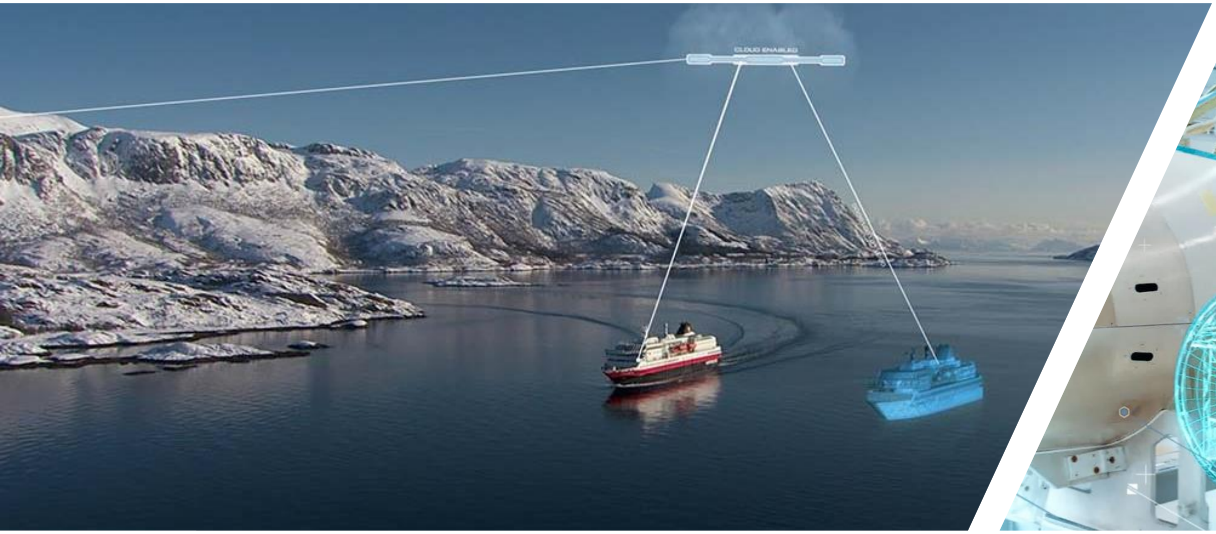




DIGITAL TWIN ADVANTAGES

Increased monitoring

Reducing Time to Market

Keeping Optimal Operation

Reducing Energy Consumption

Reducing Maintenanc e Cost

Increasing User Engagement

History of DT

1970
NASA builds twins of its shuttles since Apollo

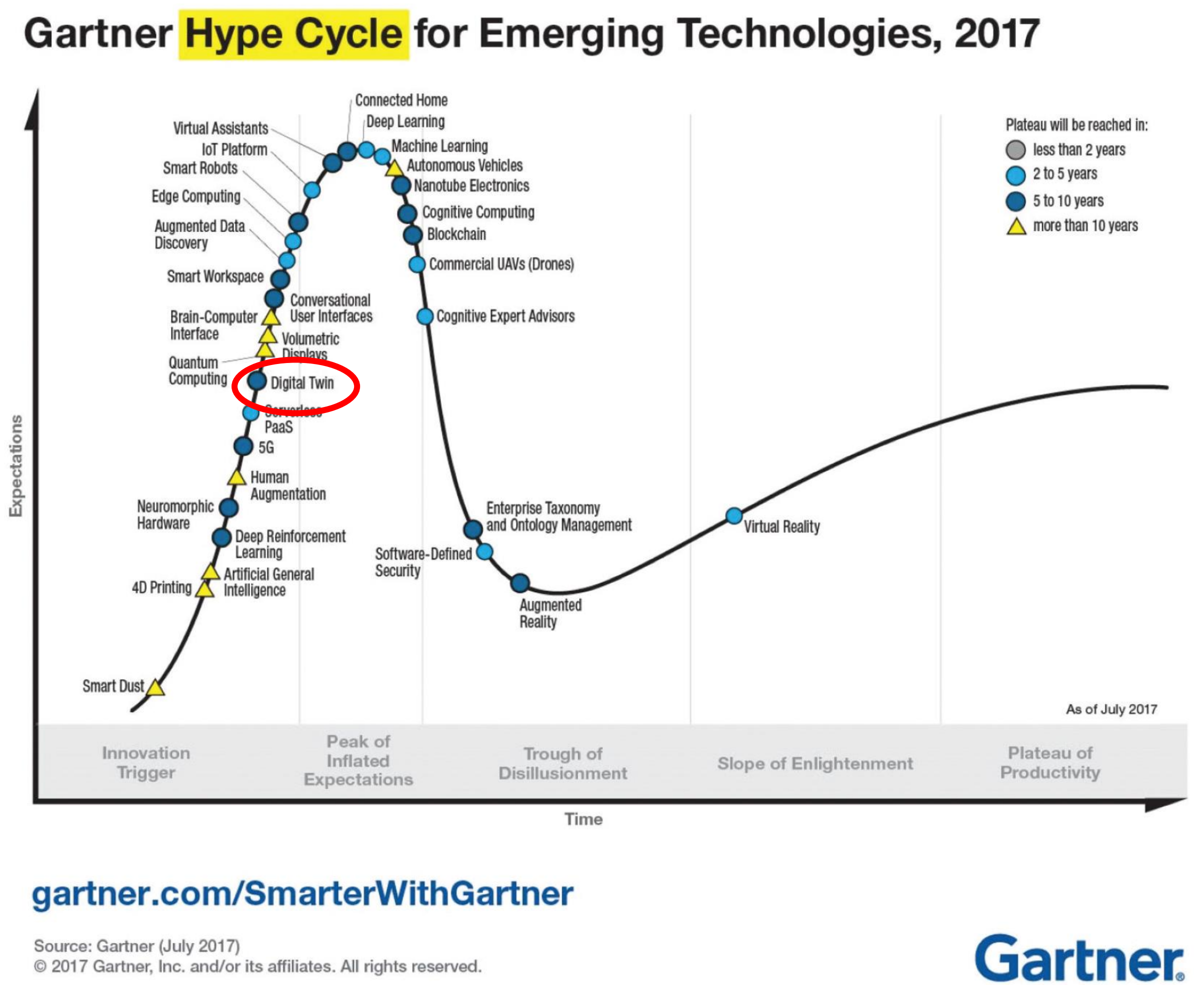
2003
Dr. Grieves from University of Michigan

NASA illustrates DT for space vehicles
2010

2014
White paper

A WHOLE NEW WORLD

History of DT



A WHOLE NEW WORLD

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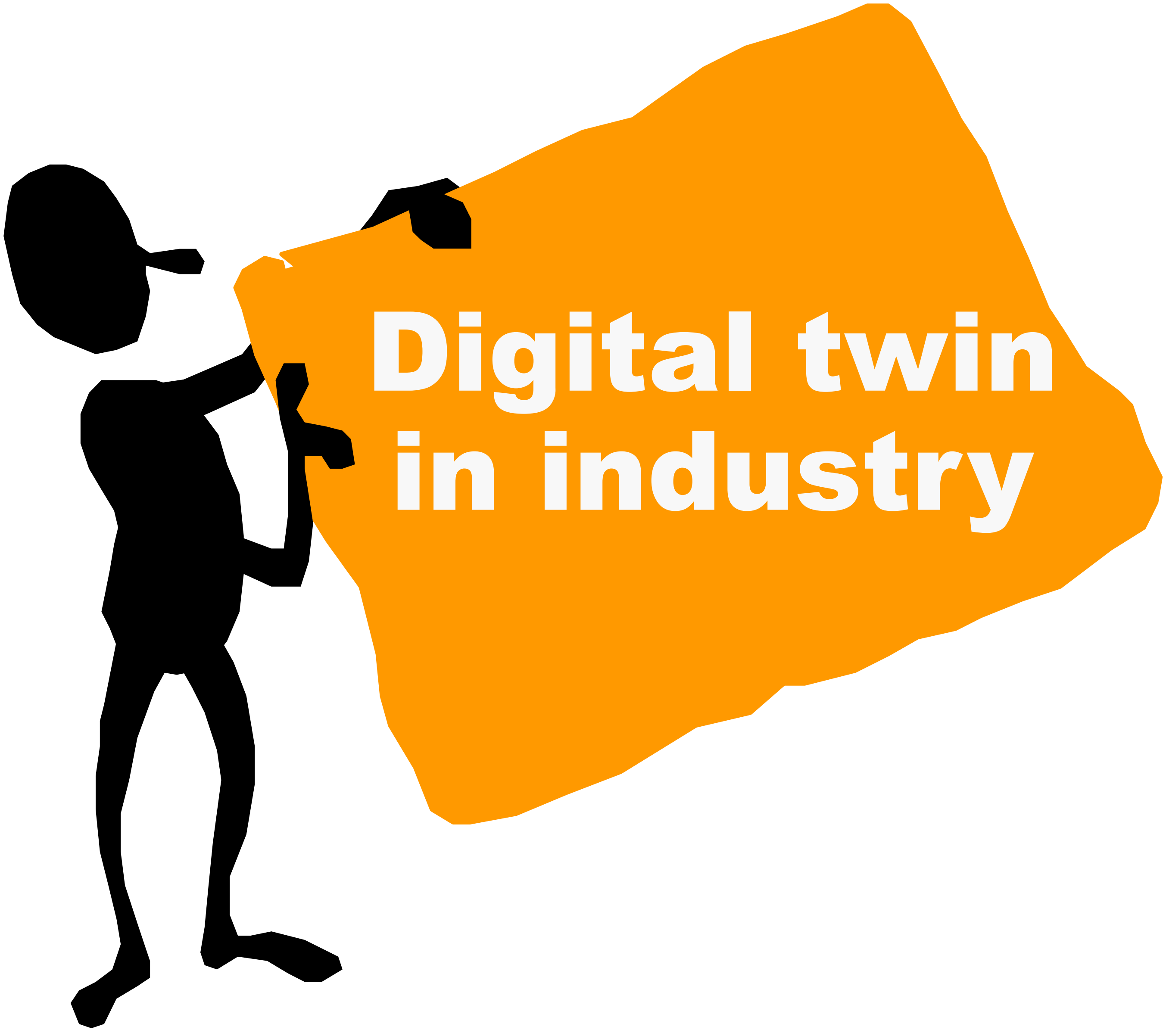
DT definitions

- **University of Cincinnati**, “A digital model of the real machine that operates in the cloud platform and simulates the health condition with an integrated knowledge from both data-driven analytical algorithms as well as other available physi… owledge”
- **University of British Columbia,** “A living model th… y adapts to changes in the environment or operation using real-time sensory d… ecast the future of the corresponding physical assets for predictive mai…
- **University of Stuttgart**, “A digital repre… contains all the states and functions of a physical asset and has possibility to… n other digital twins to achieve a holistic intelligence that allows for d… control”
- **Politecnico di Milano**, “A vir… uterized counterpart of a physical system that can exploit a real-time synch… he sensed data coming from the field and is deeply linked with Industry 4.0”
- **Chalmers**, “A digit… al factory, machine, worker, etc., which is created and can be independentl… tomatically updated as well as being globally available in real-time”
- **Beijing Institute … Technology,** “A dynamic model in the virtual world that is fully consistent with its corresponding physical entity in the real world and can simulate its physical counterpart’s characteristics, behavior, life, and performance in a timely fashion”

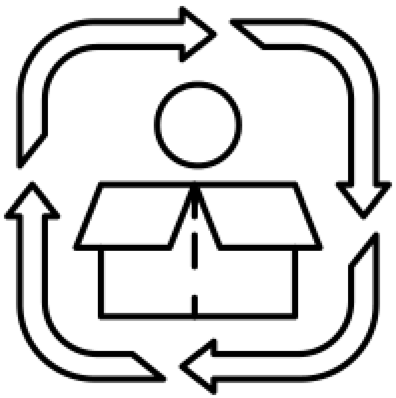
No single definition

Digital twin in industry



DT + Product lifecycle

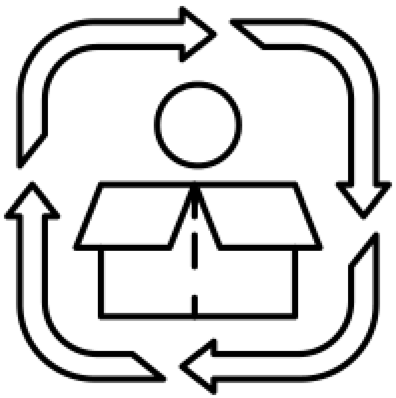
- **DT in Design, production, service, across multiple stages**



DT + Design

- A good design not only can show advantages in planning, but also has **good manufacturability**
- With high-fidelity simulation provided by the DT, the design for a product or a production system can be **validated to eliminate the potential failures** before actual execution.

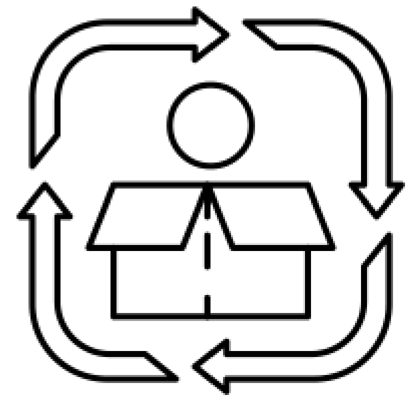
DT + Product lifecycle



DT + Production

- increasing **flexibility of production** processes, reducing energy consumption, improving product quality, etc
- as the DT offers a bridge to link the physical and virtual spaces together, it can make the virtual space mirror the physical practical situations in a timely manner and **control behaviors of the physical objects in real-time**

DT + Product lifecycle



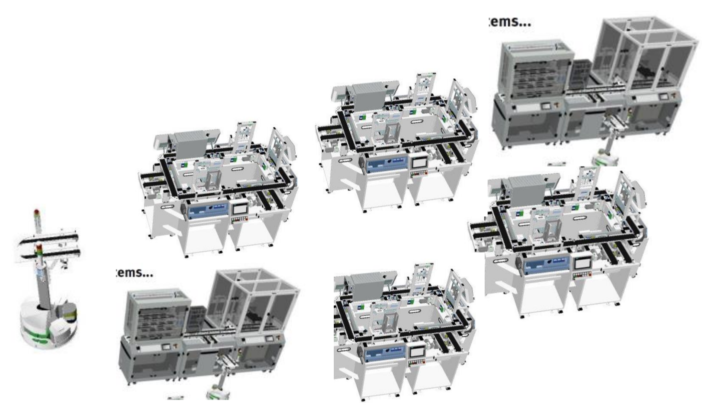
DT + Service

- Prognostic and health management PHM is a crucial step to **monitor the health of** a product, performance diagnosis and prognosis and provide design rules for maintenance
- Models and simulated data can be obtained and integrated with physical data to **generate more comprehensive and valuable information** for health condition detection and analysis

DT Application levels

The granularity of physical space can be in

- **DT Unit level** such as single person, a machine, a tool or a product. **DT** used for monitoring, fault prediction, and maintenance of a single piece of equipment
- **DT System level**: combination of more than one unit, e.g., production line. **DT** used for deal with different units, such as scheduling, progress control, and product quality control
- **DT System of systems**: include multiple of systems, e.g., entire shop-floor. **DT** used for optimization and coordination of the entire shop-floor



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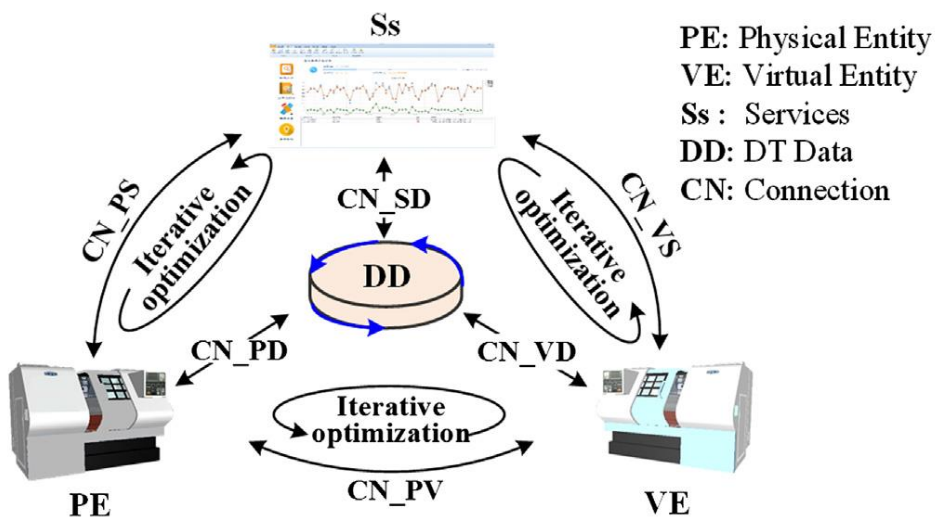
5-D DT components

Cores of DT

- Physical space Entity PE
- Virtual space Entity VE
- Connection (IoT) CN
- DT Data DD
- Services Ss

Original definition (2003)



DT concept model [1]

DT components [1]

Virtual space:

- Each physical object has a digital companion that can accurately **predict its behavior**.
- The digital companion is composed of a set of **models** that allow the digitalized physical object to be viewed in 3 dimensions on the computer
- Can reproduce the **real properties, behaviors, and rules** of the physical counterpart
- Can operate **autonomously** in the virtual space to generate a series of **simulated behaviors** "ideal behaviors" to guide the operation of the physical object
- Have the abilities to **predict problems** on the physical side even before the occurrence
- Can **validate the performances** of a product or a system before they are completed

DT components[1]

Connection:

- Enable every element in the DT (e.g., entity, model, and information system/tool) interacts with each other
- Connections can be
  - I) within physical space,
  - II) within virtual space, and
  - III) across physical and virtual spaces

DT components[1]

Data:

- Valuable **information** can be mined efficiently from the (**real-time**) data
- Data come from physical (e.g., product lifecycle) and virtual space (e.g., simulation)
- Drive the **operations** of the DT, e.g., decisions can be driven by simulated data.

DT components[1]

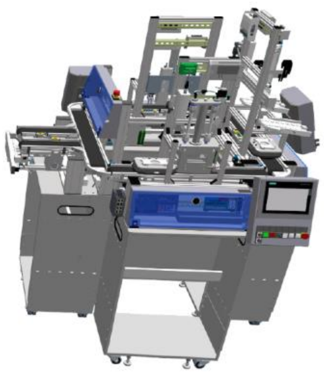
Services:

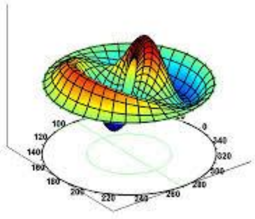
- Ss includes **services** for both the PE and the VE
- Encapsulate functions provided by the DT (e.g., evaluation, optimization, prediction, and validation) into standard services for easy and convenient usage. **No deep knowledge** will be needed.
- The services are **black boxes** that can be used without any knowledge of internal mechanisms
- For the **PE**, the Ss includes the monitoring service, PHM service, energy consumption optimization service, etc.
- For the **VE**, the Ss might include construction service, calibration service, and test service for models.

Virtual Models [1]

To reproduce the physical space entity, different types of models are built in the virtual space

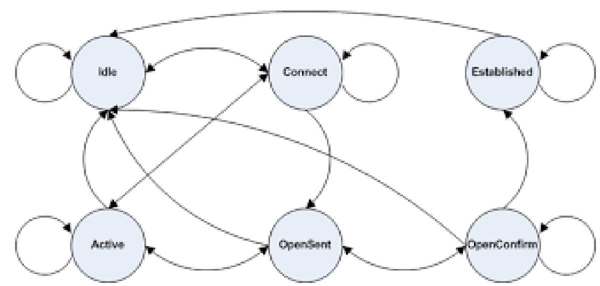
- **Geometric models**, parameters including shapes, sizes, and assembly relations are modeled to simulate assembly and machine process, logistics, …
- **Geometric model + VR/AR** can create environment similar to physical space for simulation.
- Can enrich the geometrical models with **physical factors models** e.g., force, temperature, vibration, … to conduct physical parameter changing simulation, process plan evaluation, reliability evaluation,..

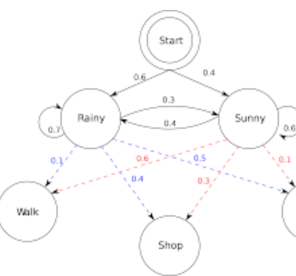


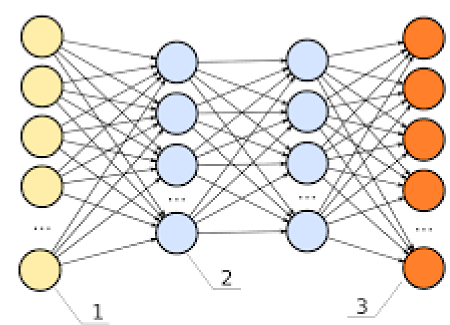


Virtual Models [1]

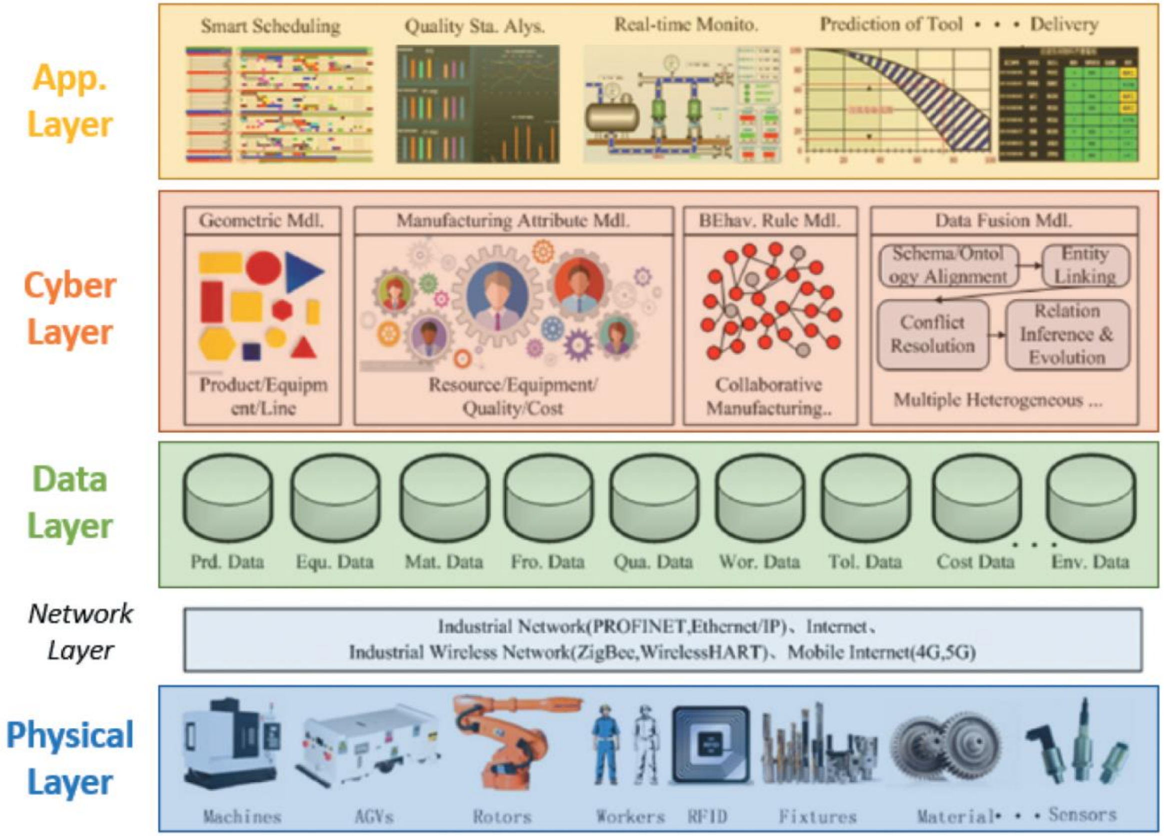
- To mimic **behaviors** of the physical entity under different conditions, methods such as neural network, Bayesian, finite state machine, and Markov chain can be used to build relationships between the parameters and the behaviors. **Behavior models** help in grasping the internal structures of the physical entity and predicting some performances in advance
- Models for **rules** can also be constructed through processing a large amount of historical data of the physical entity, based on machine learning algorithms. **Rule models** provide criteria and rules for the physical entity optimization.



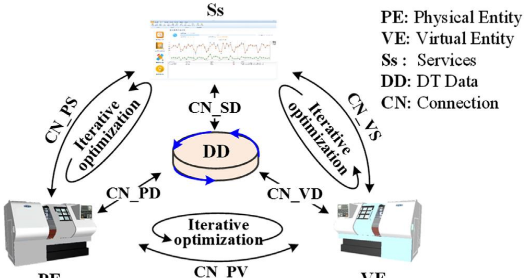




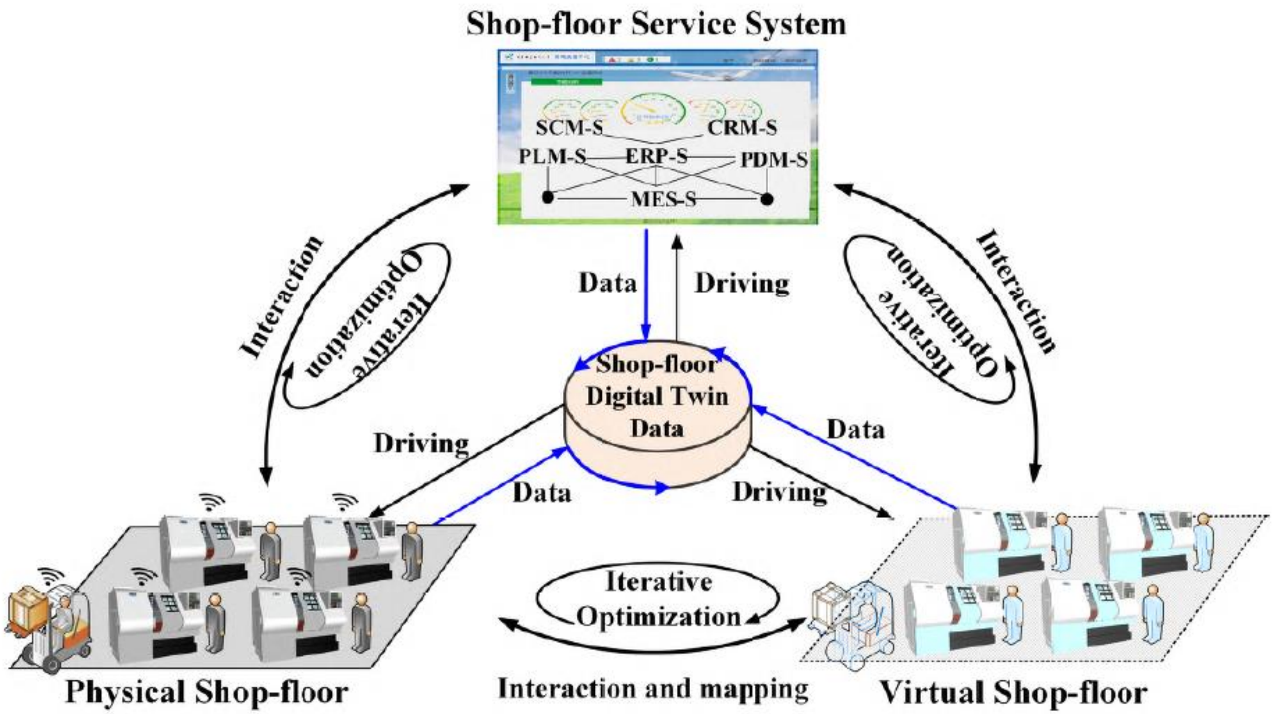
Another DT model [7]



Product Manufacturing Digital Twin Model

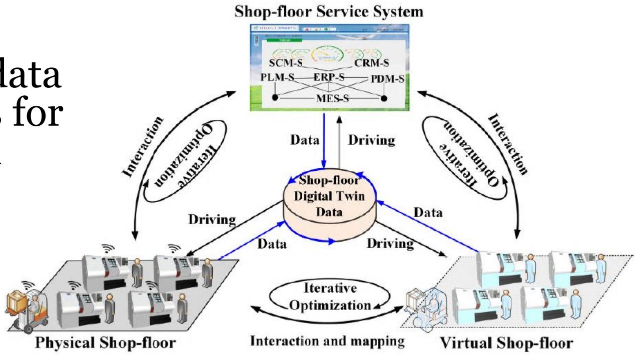


DT Shop-floor Components[3]

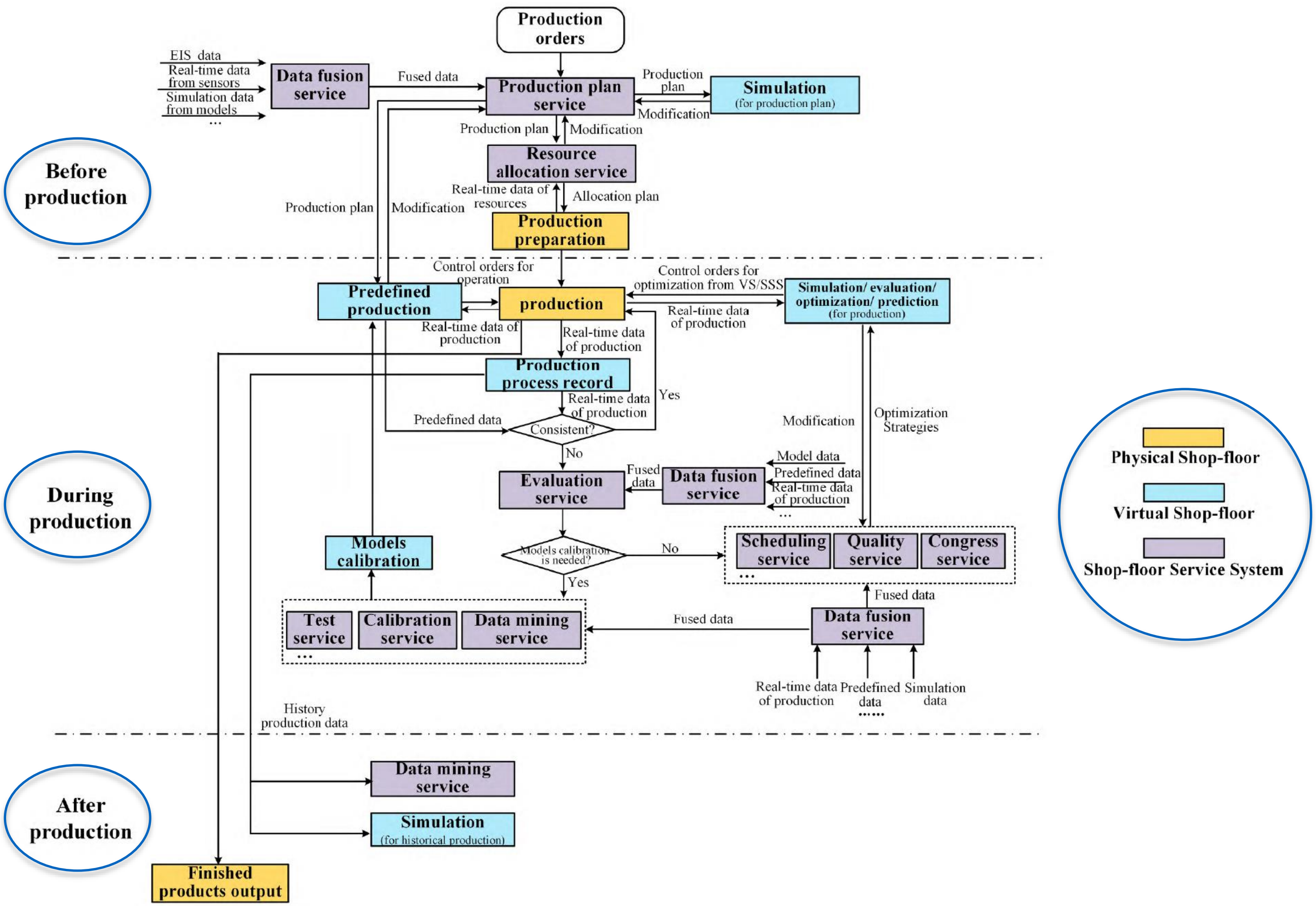


DT Shop-floor Components[3]

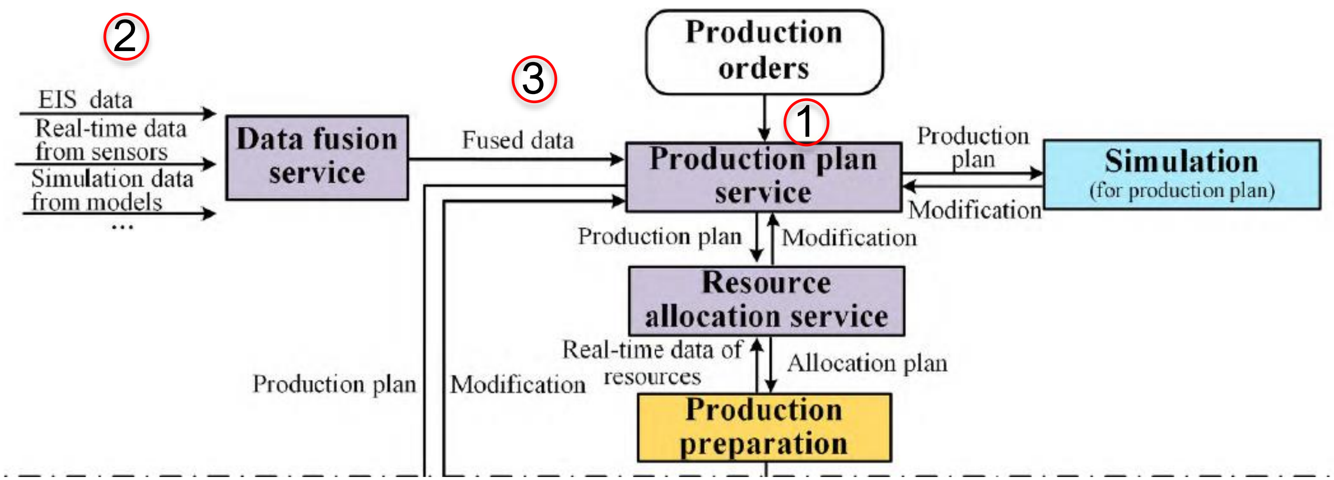
- **PS** includes a **series of entities**, such as human, machines and materials, existing objectively in physical space. Strictly following the predened orders from both VS and SSS, PS organizes production meeting the requirements of delivery, cost and quality, etc.
- **VS** consists of **models** built in multiple dimensions, including geometry, physics, behavior and rule. VS evolves with PS, providing control orders for PS and optimization strategies for SSS.
- **SSS** is an **integrated service** platform, which encapsulates the functions of Enterprise Information System (EIS), computer aided tools, models and algorithms, etc. into sub-services, then combines them to form composite services for specific demands from PS and VS.
- **SDTD** includes PS, VS and SSS **data**, the fused data of the three parts, as well as the existing methods for modeling, optimizing and predicting, etc. Data in SDTD are integrated, which eliminates the **information isolated island**



DT Shop-floor operation [3]



Before production



1- orders (e.g. delivery, quantity, cost and quality) are transmitted to the production plan service

2- data collection from

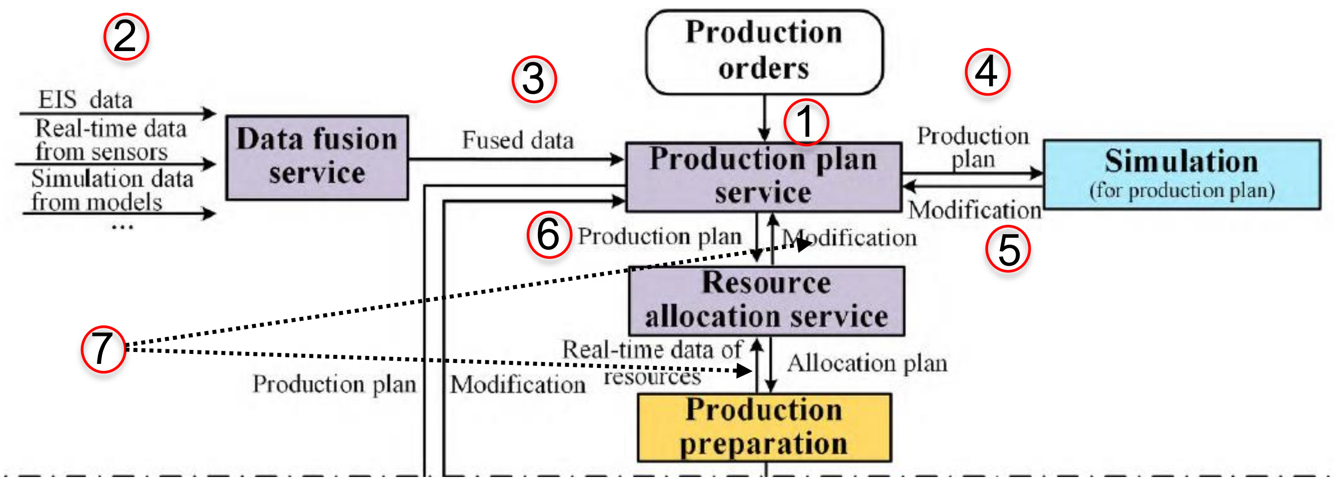
a-sensors, e.g., material stock, human workload and equipment capacity

b- simulation, e.g. prediction of equipment fault, analysis on material performance

c- Enterprise Information System EIS, e.g., product lifecycle data, process document and market data

3- data fusion service, fuses the collected data and generate consistent interpretation for the certain object.

Before production



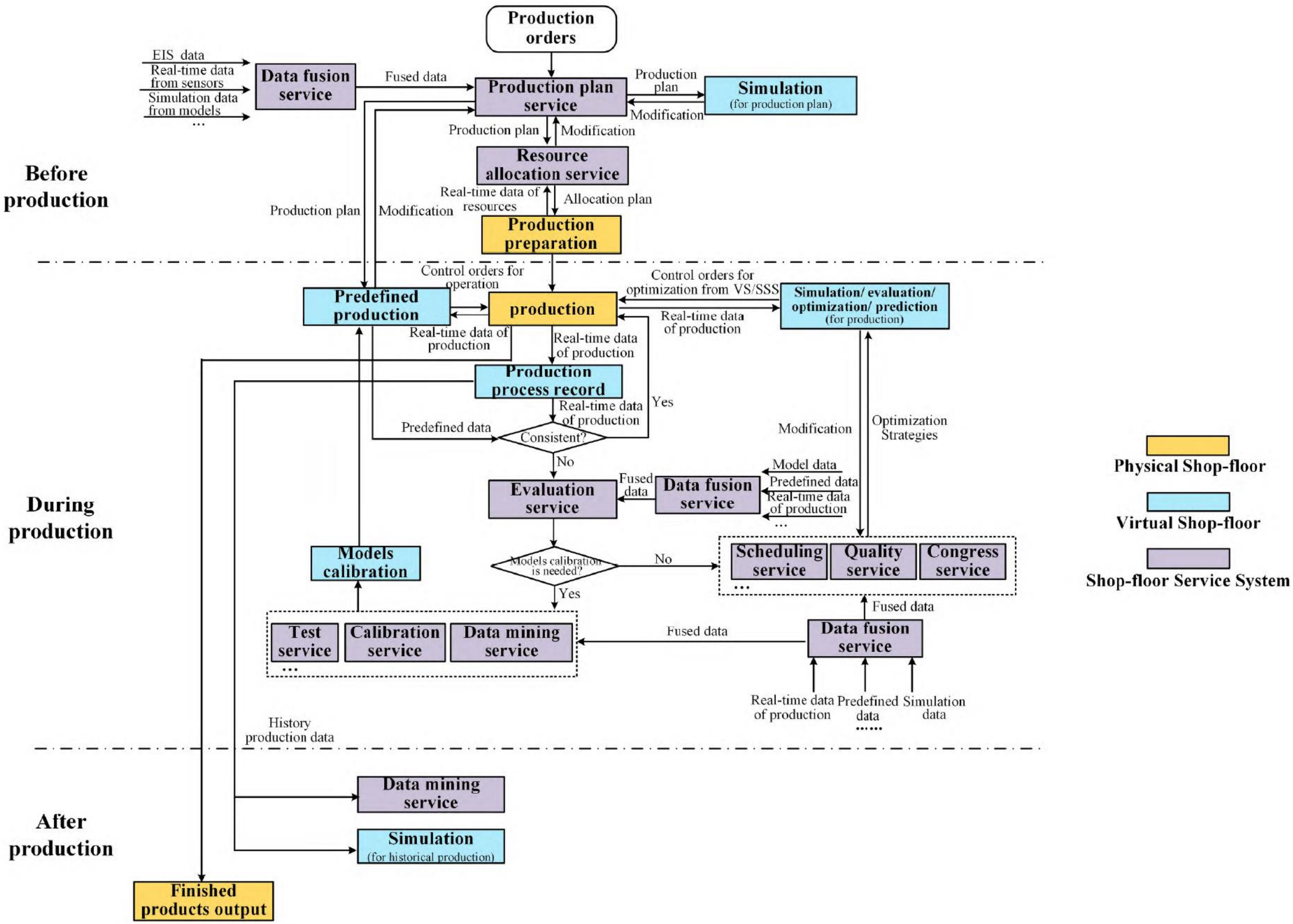
4- from step 1 and 3, production plan service produces plan and sends it to simulation for verification.

5- Simulation finds potential conflicts in the plan and sends modification strategies.

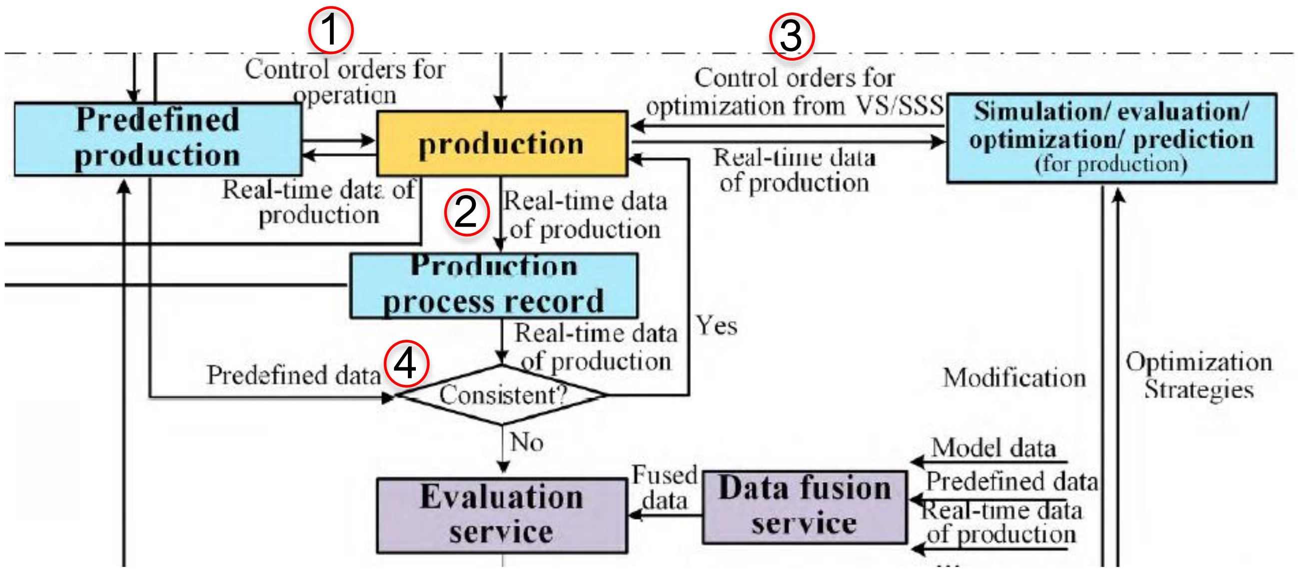
6- A revised production plan is sent to resource allocation service which guides the preparation for production

7- If the real-time states of resources change, medication advice can still be given back to production plan service

DTS operation [3]



During production



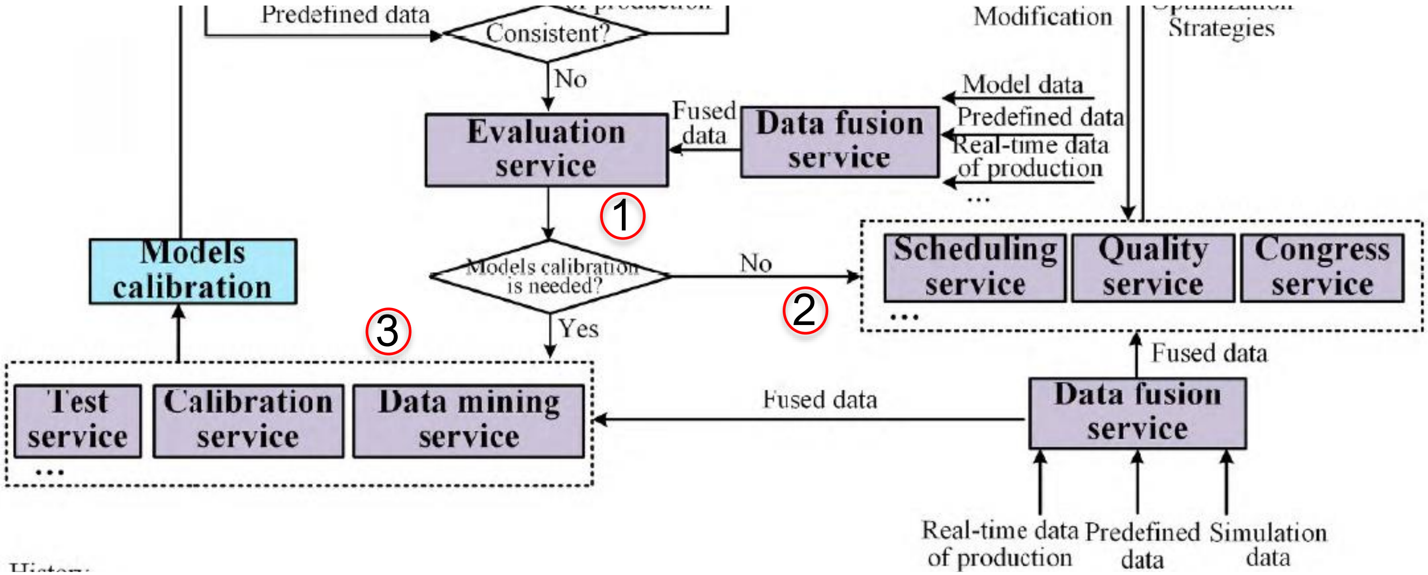
1- production plan is sent to predefined production, based on it sends control order to production to start the actual process

2- Real time data of production is generated and sent to virtual entities (simulation, production process record and predefined production)

3- Simulation/evaluation/optimization/prediction generate orders to regulate the production if needed.

4- the predefined data from VS are compared with real-time data from production continuously. If inconsistency is found, evaluation service will be triggered.

During production

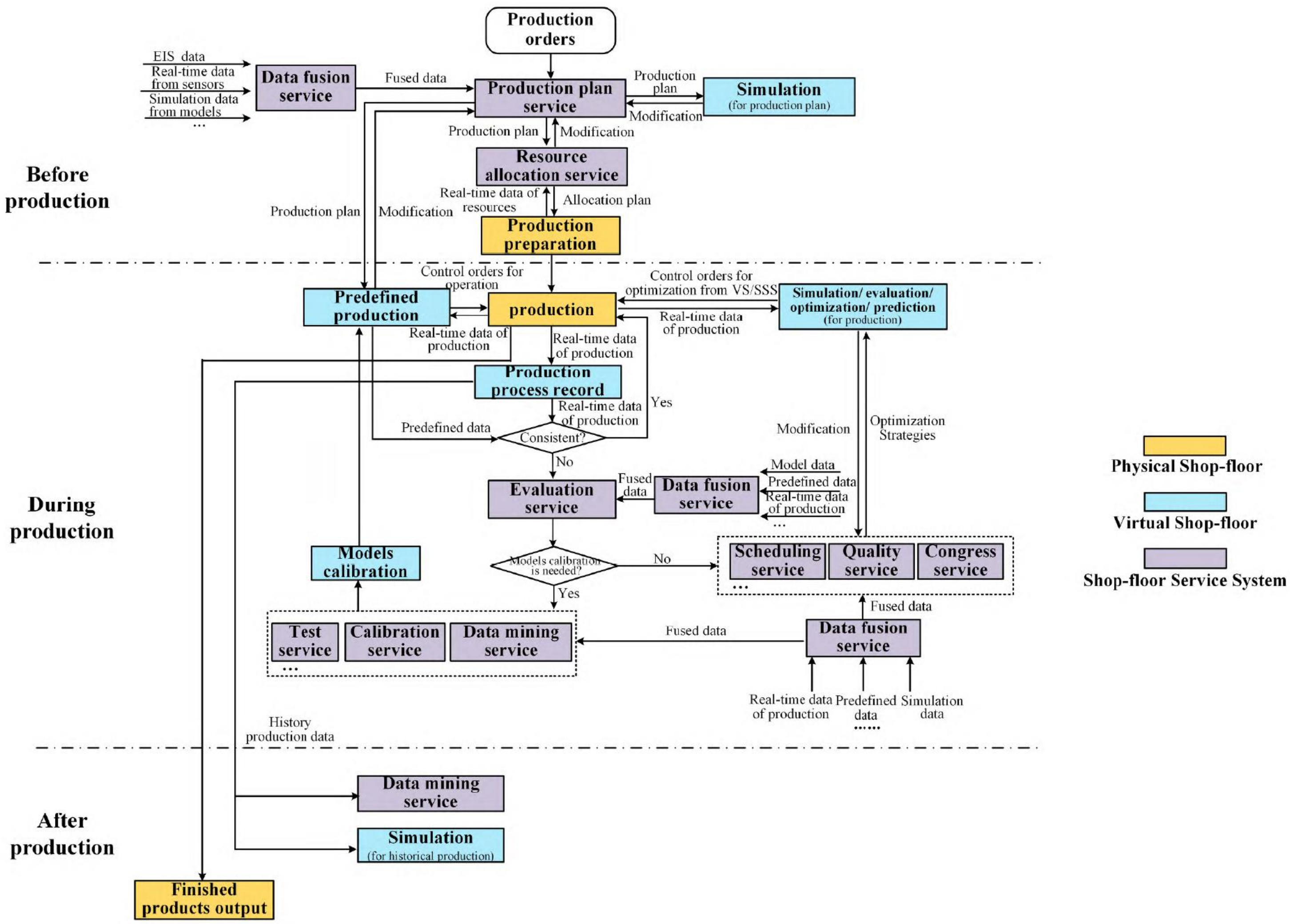


1- Evaluation service checks based on the fused data from data fusion service the source of the inconsistency if it is PS or VS

2- If problem in PS due to e.g. equipment failure, material shortage and emergency order then trigger the proper service. The service is verified first by VS the transformed into control order.

3- If problem in VS due to e.g. unreasonable setting on boundary and initial condition then services for model calibration are scheduled and implemented on VS

DTS operation [3]



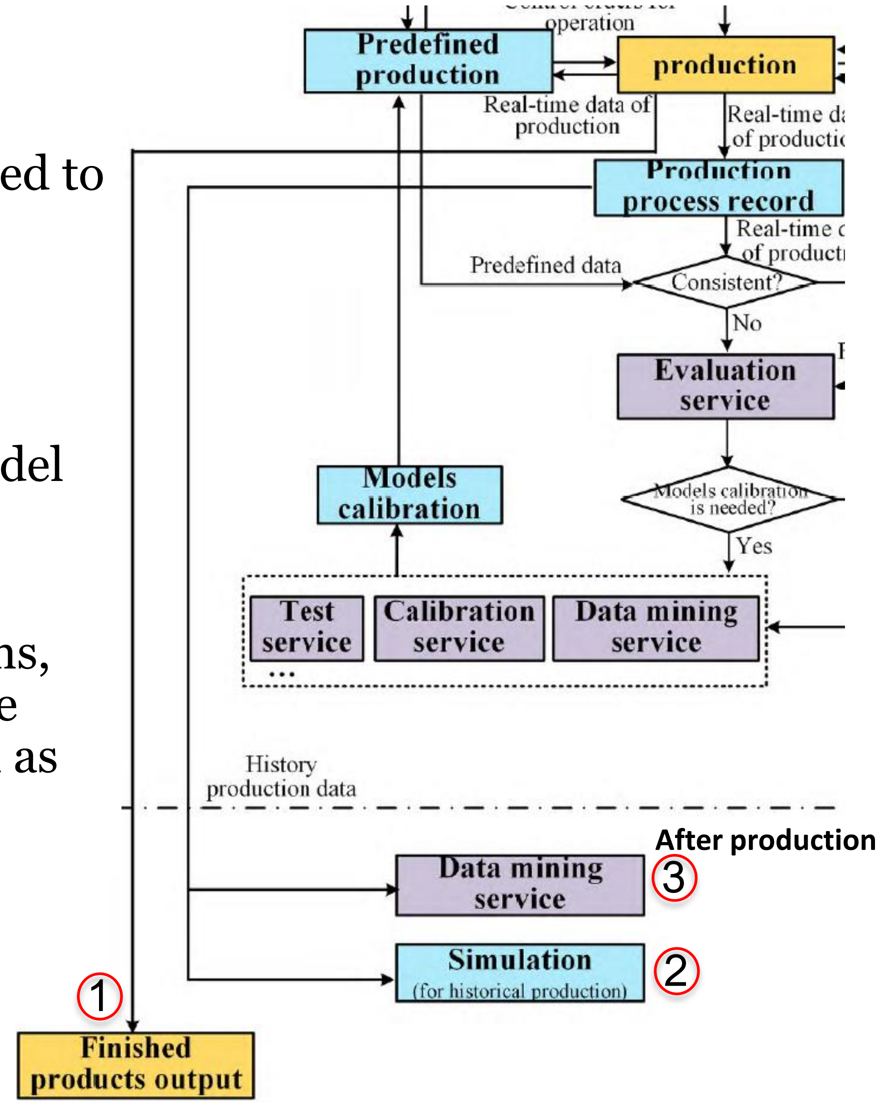
After production

1- The Finished products are transported to warehouses.

2- The history production data are achieved from the records in models.

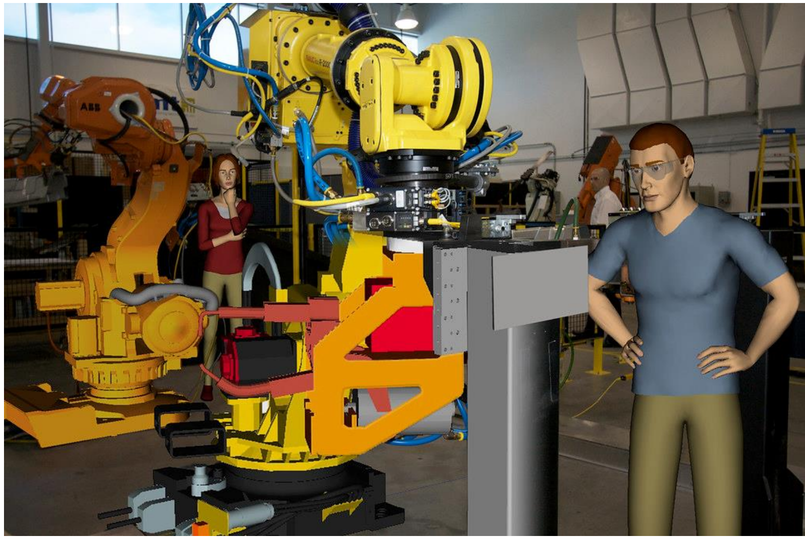
3- Based on history data, data mining service extracts new knowledge for model building and calibration.

VS can playback the historical situations, which is an effective way to find out the defects in previous productions as well as the corresponding solutions.



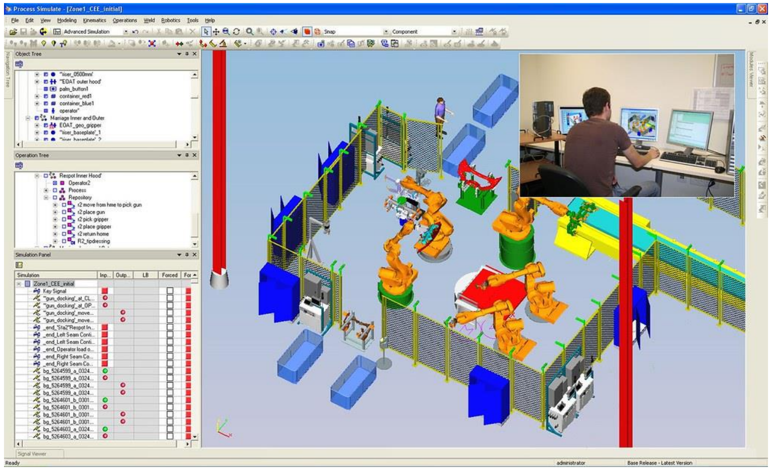
Virtual Commissioning Digital Twin [8]

- Virtual commissioning can be used to identify and resolve issues **before investment** and avoid costly adjustments during or after installation of manufacturing equipment.
- Virtual commissioning uses **simulation technology** to design, test, evaluate systems **before connecting them to the real equipment** or system
- Virtual commissioning can be used for any of the four levels on a manufacturing shop floor:
  - machine level,
  - production cell level,
  - production line level,
  - production system level



Virtual Commissioning Digital Twin [8]

- A virtual commissioning digital twin is a dynamic, **virtual representation** of its corresponding physical element that is used **to substitute** its physical element for the purpose of commissioning
- Example: virtual commissioning digital twin of a CNC machine tool has not been installed, and a virtual commissioning digital twin is designed and developed to test and optimize control strategies, control parameters, and NC programs



DT realization

- To implementation of digital twin in industry, standards will be required
  - Provide precise definitions
  - Common terminologies
  - Implementation framework and guidelines

DT related standards [8]

- **IEC TS** (The International Electrotechnical Commission Technical Specifications) **62832**, Digital Factory Framework. The specification defines a framework to establish and maintain the digital representation of a production system throughout its life cycle.
- **IEEE** (The Institute of Electrical and Electronics Engineers) **P2806**, System Architecture of Digital Representation for Physical Objects in Factory Environments.
- **IPC** (The Institute for Interconnecting and Packaging Electronic Circuits) **2551**, International Standard for Digital Twins. The standard is part of the IPC Factory of the Future standards. The IPC digital twin is comprised of the digital twin product, manufacturing process, and lifecycle frameworks.
- **ISO 23247**, Digital Twin Framework for Manufacturing. The standard series defines a framework that provides a generic guideline, a reference architecture, methods, and approaches for case-specific, digital-twin implementations

ISO 23247 Digital Twin Framework for Manufacturing

- Standard under development
  https://www.iso.org/standard/75066.html
- Provide a generic development framework that can be instantiated for case-specific implementations of digital twins in manufacturing:
  - overview and general principles
  - reference architecture
  - digital representation
  - information exchange

ISO 23247 Overview and General Principles part

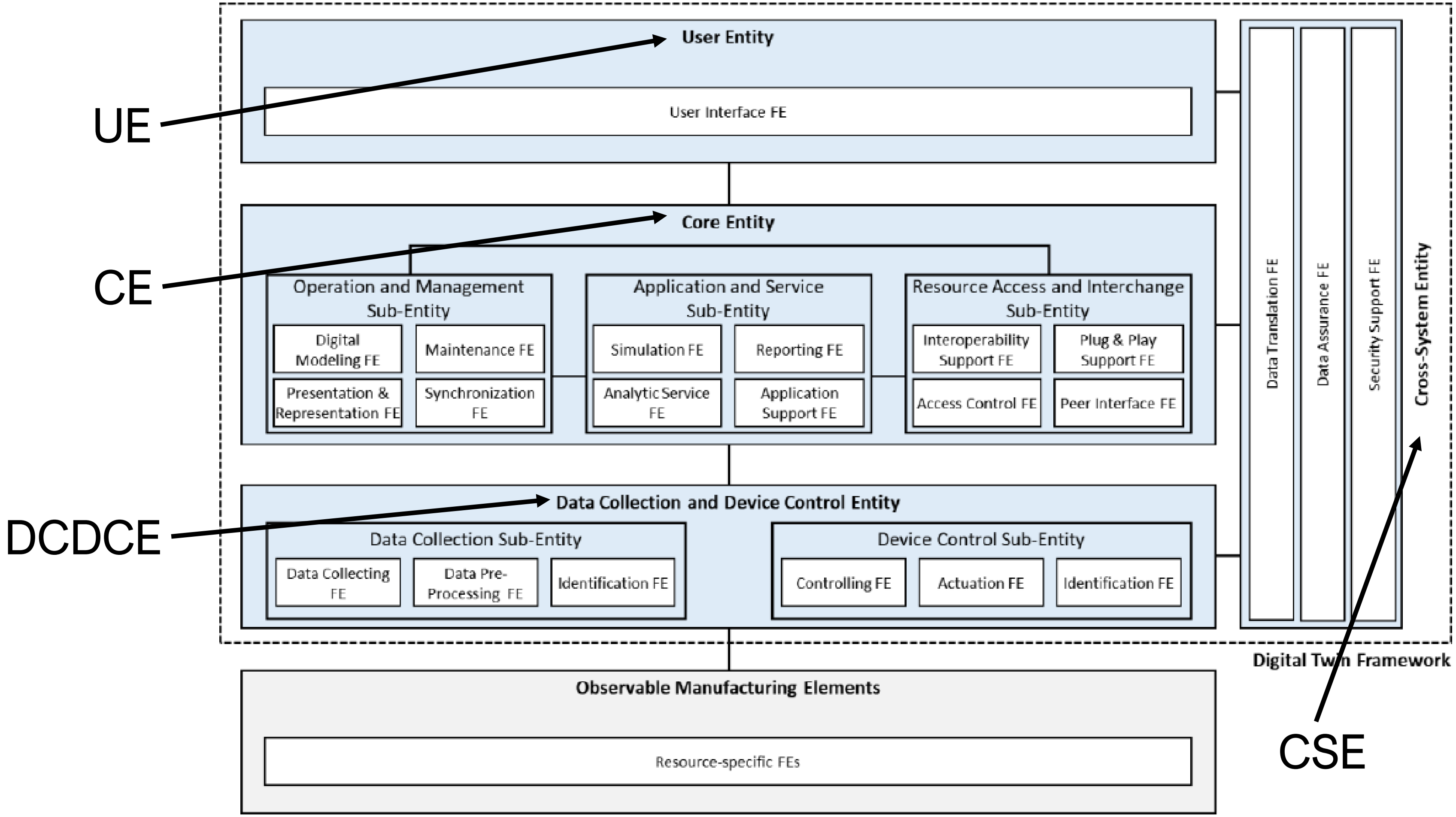
- Defines terminologies used by the standard
- Physical systems are defined as Observable Manufacturing Element OMEs
- OME is an entity that has an **observable physical presence or operation** in manufacturing. It could be personnel, equipment, material, process, facility, environment, product, or supporting document ”
- Synchronization between a digital twin and its OME

ISO 23247 Reference Architecture part

- Defines reference model from **domain** and **entity** perspectives
  - **Observable manufacturing domain**. This domain is outside of the digital twin framework.
  - **Data collection and device control domain**. This domain links the OMEs to their digital twins for synchronization.
  - **Core domain**. This domain is responsible for overall operation and management of a digital twin. It hosts applications and services such as data analytics, simulation, and optimization to enable provisioning, monitoring, modeling, and synchronization.
  - **User domain**. This domain is responsible for users' interaction with the digital twins. A user can be a human, a device, an application or a system that uses applications and services provided by the digital twins.

ISO 23247 Reference Architecture [8]

- Each domain has a logical group of tasks and functions, which are performed by the functional entities (FEs)



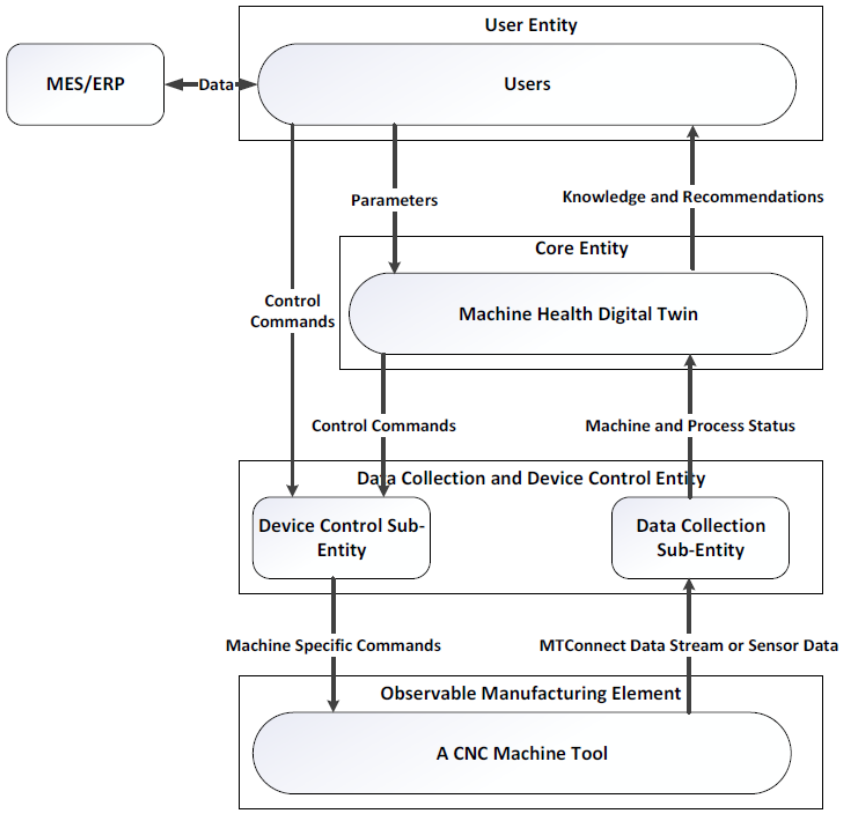
ISO 23247 Digital Representation & information Exchange parts

- **Digital Representation**
  - Describes digital representation of OMEs.
  - Existing standards should be used to represent OMEs
  - Each OME shall use the enterprise unique identifier if possible
- **Information Exchange**
  - presents technical requirements for information exchange between entities within the framework

Use case 1 Machine Health Digital Twin [8]

- A machine health digital twin can use process and equipment data to **monitor, troubleshoot, diagnose, and predict faults and failures** in manufacturing equipment.
- Machine health digital twin may include the following functionalities:
  - Define maintenance objectives and goals,
  - Collect maintenance and performance measurement data,
  - Analyze collected equipment status data,
  - Generate control commands or actionable recommendations.

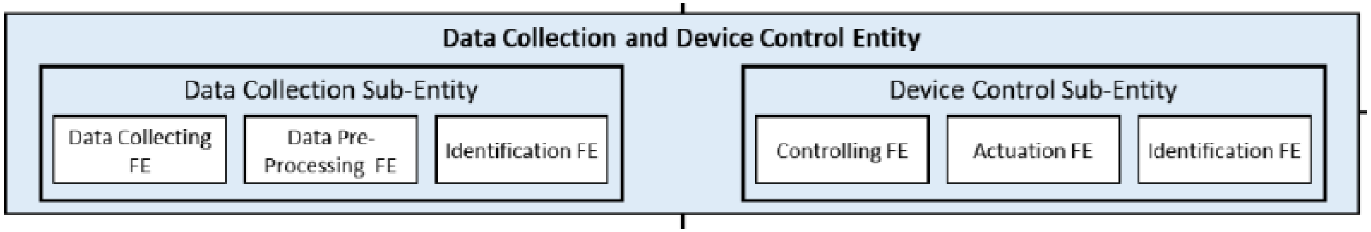
Use case 1 Machine Health Digital Twin



A mapping of the Machine Health Digital Twin to the ISO/DIS 23247 reference architecture.

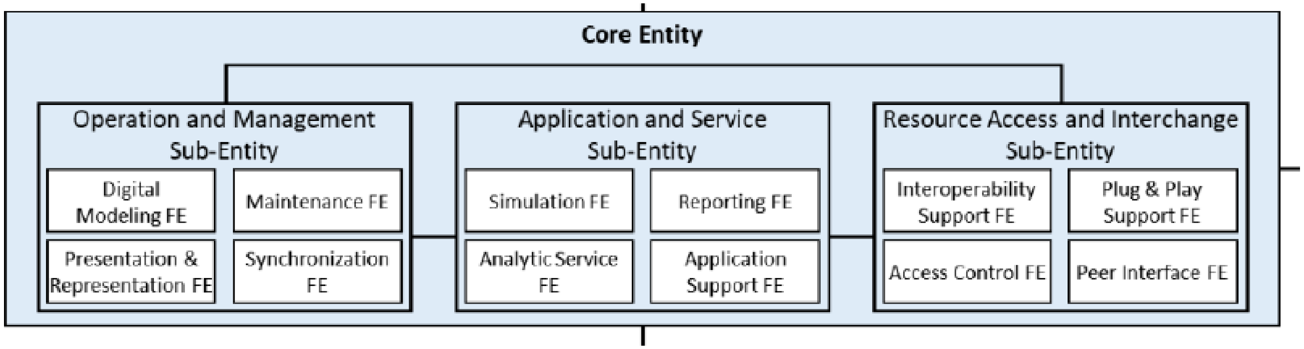
Use case 1 Machine Health Digital Twin

- Through the DCDCE, the Machine Health Digital Twin **collects, stores, and analyzes** machine **information and KPIs** such as: spindle speeds, feed rates, machine energy consumption, temperature, pressure, volume, vibrations, noise levels, and humidity
- The KPI values can reflect any **abnormalities** for certain situations
- The FEs within DCDCE include
  - Data Collecting FE.
  - Data Pre-processing FE, data cleaning, integration
  - Controlling FE. FE controls the machine through the **user** or **the digital twin**.
  - Actuation FE. according to the commands from the user or the digital twin



Use case 1 Machine Health Digital Twin

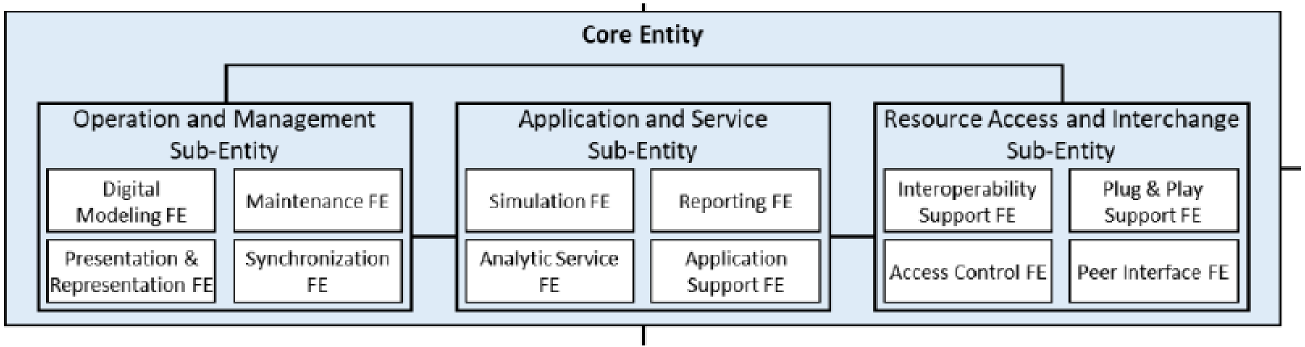
- In the CE, the machine health digital twin **simulates** the machining process and **dynamically compares** the collected machine operational KPIs with their permissible values
- Depending on the nature and severity of the problem, any major deviation from the allowed limits is addressed,
  - either by sending the machine control commands **automatically**
  - by sending notices to the **user** with recommendations;
- The control commands sent to the machine control an on/off switch, warning alarm, or automatic shut-off system.
- The machine health digital twin allows users to **visualize data** such as utilization, overall equipment effectiveness, and machine downtime
- For new faults with no prior knowledge on KPI limits, and possible solutions, experts' opinion will be **added as new knowledge** to the digital twin for future reference.



Use case 1 Machine Health Digital Twin

In the CE, the applicable FEs for the digital twin

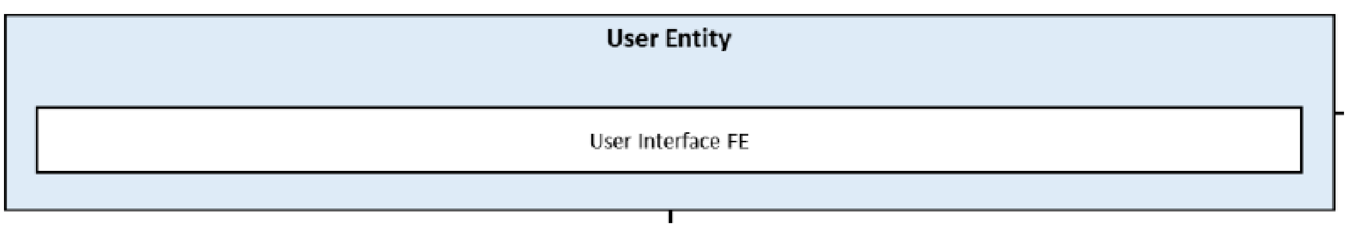
- Digital Representation FE. The FE **models** static information of the machine and dynamic data collected from machining processes to **represent** the machine's characteristics, status, and conditions
- Simulation FE. The FE **simulates** and predicts the behavior of the machine. Both normal operation data and failure data are needed to build the machine simulation,
- Analytic Service FE. The FE **analyzes** data collected from the machine, machining process, and the simulation results.
- Application Support FE. The FE **provides services** for implementing a predictive maintenance application
- Synchronization FE. The FE **synchronizes** the digital twin parameters with the status of the machine.
- Presentation FE. The FE **presents information** in an appropriate format of text, tables, charts, audio or video for human users.
- Reporting FE. The FE **generates** digital twin analysis and prediction reports.



Use case 1 Machine Health Digital Twin

In the UE,

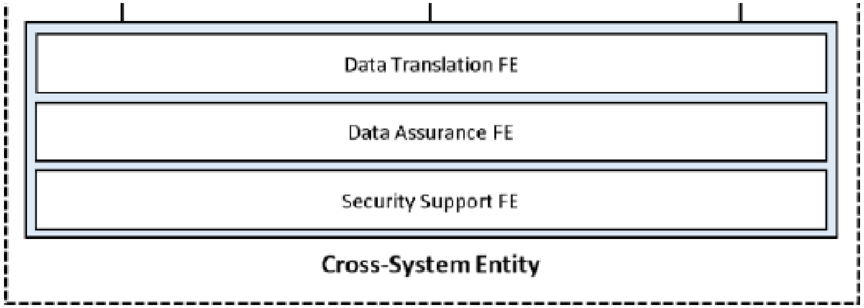
- the users may be decision makers, maintenance personnel or machine operators who **interact** with the digital twin, the machine, or existing **enterprise systems** such as product lifecycle management (PLM) systems, MES, and ERP systems.
- The actionable **recommendations** or **decisions** including suggested operating parameters are presented to the user by the digital twin.
- A corresponding **action** can be taken at an appropriate time (either online or offline) by the responsible party so that the problem can be addressed timely



Use case 1 Machine Health Digital Twin

Cross-System Entity (CSE):

- Data Assurance FE. The FE **ensures** the accuracy and integrity of the collected data.
- Security Support FE. The FE **secures** the machine health digital twin in authentication, authorization, confidentiality, and integrity.
- Data Translation FE. The FE **supports translations** of the exchanged data between entities. The translations may be through protocol conversion, syntax adaptation, and semantic awareness.



Challenges in implementing DT

- Difficulties in accessing data
  - From many different sources, e.g., legacy systems
  - Across organizational silos
  - Different parties interacting with the data from not just the enterprise, but also its partners and customers
  - A holistic approach to storing, managing and manipulating data is essential.
- Complexity of potential use cases
  - Find out where a digital twin can create value, and what its other benefits are.
- Cost, security, privacy and integration
- Trusted data
  - Data quality
  - A source of information that is unique, authoritative and consistent across the entire product life cycle
- Standards

Research at MDU

- Adapting technologies: IIoT, cloud computing, Edge computing, computer communication, embedded systems
- Simulation and modelling
- Implementation of DTs: framework, platforms, …
- Business models and value creation
- Adoption of DT: organization, skills, processes
- Festo production line at MITC

References

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[3] F Tao, M Zhang, Digital twin shop-floor: a new shop-floor paradigm towards smart manufacturing, Ieee Access 5, 20418-20427

[5] M. Grieves, Digital twin: manufacturing excellence through virtual factory replication, Whitepaper, 2014.

[6] Borangiu, T., Trentesaux, D., Leitão, P., Giret Boggino, A., Botti Navarro, V Service Oriented, Holonic and Multi-agent Manufacturing Systems for Industry of the Future, Springer, 2020

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[8] G Shao "Use Case Scenarios for Digital Twin Implementation Based on ISO 23247", Advanced Manufacturing Series (NIST AMS), National Institute of Standards

Coming seminars

We continue after the summer:

- Friday September 10
  Optimization of Production Systems in Industry 4.0

- Friday October 15

Big Data - Big Opportunities and Big Challenges

For more information visit, mdh.se/smartproduktion

Production engineering courses autumn 2021 (5 credits/course) *- open for application*

Internet of Things for Manufacturing Industry
Study period: 2021-08-30 - 2021-11-07

Lean Production
Study period: 2021-08-30 - 2021-11-07

Simulation of Production Systems
Study period: 2021-08-30 - 2021-11-07

Big Data and Cloud Computing for Industrial Applications
Study period: 2021-11-08 - 2022-01-16

Industrial maintenance development
Study period: 2021-11-08 - 2022-01-16

Industrial Project Management
Study period: 2021-11-08 - 2022-01-16

For more information, visit mdh.se/smartproduktion

Digital twin

- https://www.youtube.com/watch?v=2XAXKNcsb1M