Digital twins for advanced decision support through the lifecycle of manufacturing systems

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What is a Digital Twin?

- ***Definitions and theoretical bases***
- ***Application domains and Enabling technologies***

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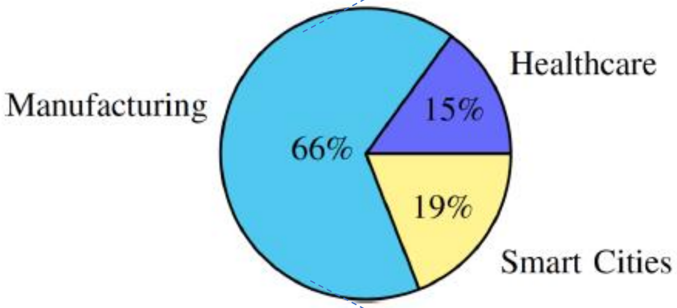
Application domains for Digital Twins

Digital Twins enable the virtualization of different kinds of entity

DIGITAL TWIN: *a virtual representation of an entity such as an asset, person or process and is developed to support new or enhanced business objectives.*

Gartner, 2019

Application domains for Digital Twins



Paper	Type	Defined Twin	Actual Twin	Broad Area	Specific Area	Technology
Bilberg, Malik (2019) [1]	Case Study	DT	DS	Manufacturing	Smart Factory	Simulation
Chhetri et al. (2019) [74]	Case Study	DT	DT	Manufacturing	Assembly Line	AI, Sensors, Simulation
He et al. (2018) [75]	Review	DT	DS	Manufacturing	Power System	Simulation, AI, Analytics
Howard (2019) [11]	Concept	DT	DM	Manufacturing	Product Development	EDA, Visualisation
Jain et al. (2019) [76]	Concept	DT	DT	Manufacturing	Fault Diagnosis	Industry 4.0
Karadeniz et al. (2019) [77]	Case Study	DT	DS	Manufacturing	Ice Cream Machines	AR, VR, Industry 4.0, AI, CPS
Kuehn (2019) [78]	Concept	DT	DS	Manufacturing	Smart Factory	Simulation
Lu (2019) [79]	Review	DT	No Example	Manufacturing	Smart Factory	Cloud, CPS, Industry 4.0
Mandolla et al. (2019) [2]	Case Study	DT	No Example	Manufacturing	Aircraft	Blockchain, Visualisation
Mawson, Hughes (2019) [27]	Case Study	DT	DT	Manufacturing	Energy Modelling	Industry 4.0
Min et al. (2019) [35]	Case Study	DT	DS	Manufacturing	Petrochemical Factory	AI, Optimisation
Qi, Tao (2018) [24]	Review	DT	DT	Manufacturing	Smart Factory	Industry 4.0 , AI, Cloud, Big Data
Shangguan et al. (2019) [80]	Case Study	DT	DM	Manufacturing	Wind Turbine	CPS
Sivalingam et al. (2018) [17]	Review	DT	DS	Manufacturing	Wind Turbine	CPS, Simulation
Tao et al. (2019) [81]	Review	DT	DT	Manufacturing	Smart Factory	CPS, Industry 4.0, AI
Tao et al. (2018) [82]	Review	DT	DT	Manufacturing	Assembly Line	CPS, Industry 4.0, AI
Xu et al. (2018) [23]	Concept	DT	DS	Manufacturing	Fault Diagnosis	CPS, Industry 4.0, AI, Transfer Learning
El Saddik (2018) [39]	Definition	DT	DT	Healthcare	Patient Monitoring	VR, AI
Laaki et al. (2019) [32]	Concept	Undefined	DS	Healthcare	Surgery Robotics	Industry 4.0, AI, VR
Liu et al (2019) [37]	Concept	DT	DT	Healthcare	Health Management, Elderly Health	Cloud, CPS
Ross (2016) [40]	Review	DT	DT	Healthcare	Predictive Health & Well-being	VR, 3D Modelling
Chen et al. (2018) [22]	Review	Undefined	DS	Smart City	Driving	Simulation, AI
Jo (2018) [15]	Review	DT	DT	Smart City	Livestock Farms	Industry 4.0
Mohammadi, Taylor (2017) [3]	Concept	DT	DT	Smart City	Infrastructure Analysis	Simulation, VR
Pargmann et al. (2018) [18]	Review	DT	DS	Smart City	Wind Farm	AR, AI, Cloud
Ruohomäki et al. (2018) [83]	Case Study	DT	DS	Smart City	3D Energy Mapping	Visualisation, Sensors Ontology

Fuller, A., Fan, Z., Day, C. & Barlow C. (2020). Digital Twin: Enabling Technologies, Challenges and Open Research. IEEE Access

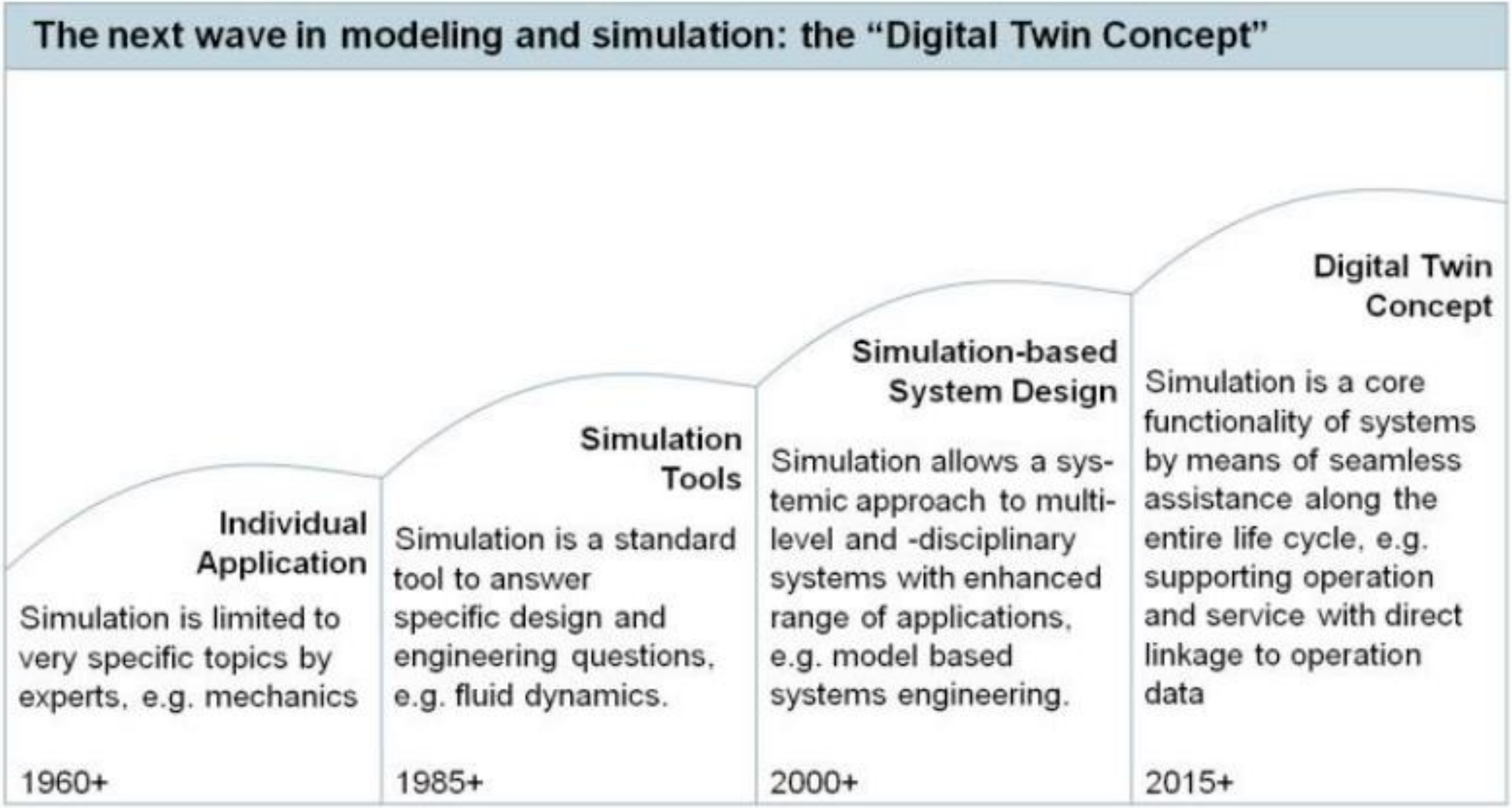
Digital Twin in manufacturing

Definition

Virtual *representation of a production system that is able to run on different simulation disciplines that is characterized by the* ***synchronization between the virtual and real system****, thanks to sensed data and connected smart devices, mathematical models and real time data elaboration.*

E. Negri, L. Fumagalli, M. Macchi, A Review of the Roles of Digital Twin in CPS-based Production Systems, Procedia Manufacturing, Volume 11, 2017, Pages 939-948

Traditional Simulation versus Digital Twin



Rosen, R., Von Wichert, G., Lo, G., & Bettenhausen, K. D. (2015). About the importance of autonomy and digital twins for the future of manufacturing. IFAC-PapersOnLine

Enabling technologies for Digital Twins

Digital Twins take advantage of a blend of enabling technologies

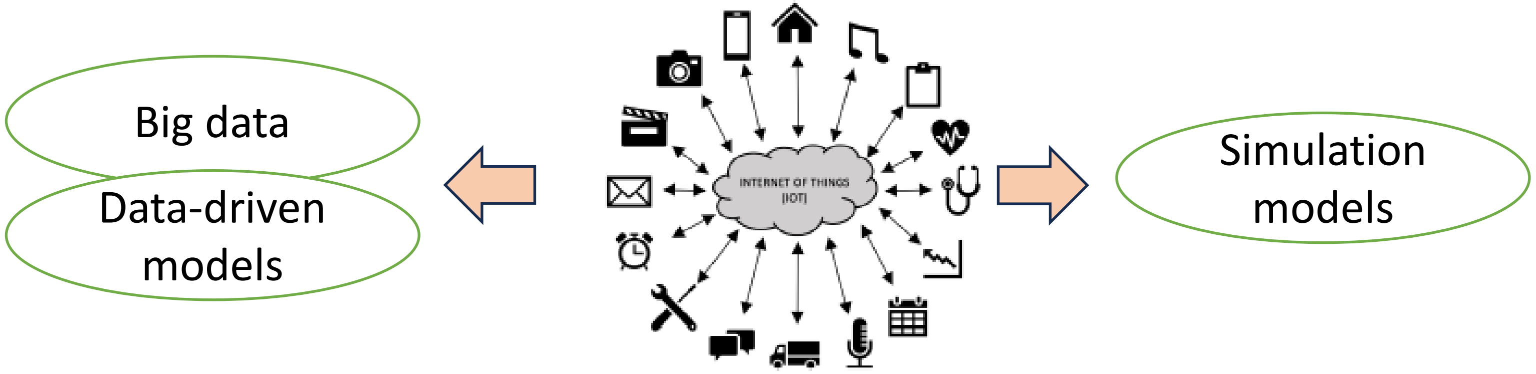
Selection of enabling technologies as foundations of Digital Twinning:

INDUSTRIAL INTERNET OF THINGS (IIOT) +

ADVANCED DATA ANALYTICS / BIG DATA ANALYTICS (Machine Learning, Deep Learning, statistical modelling) +

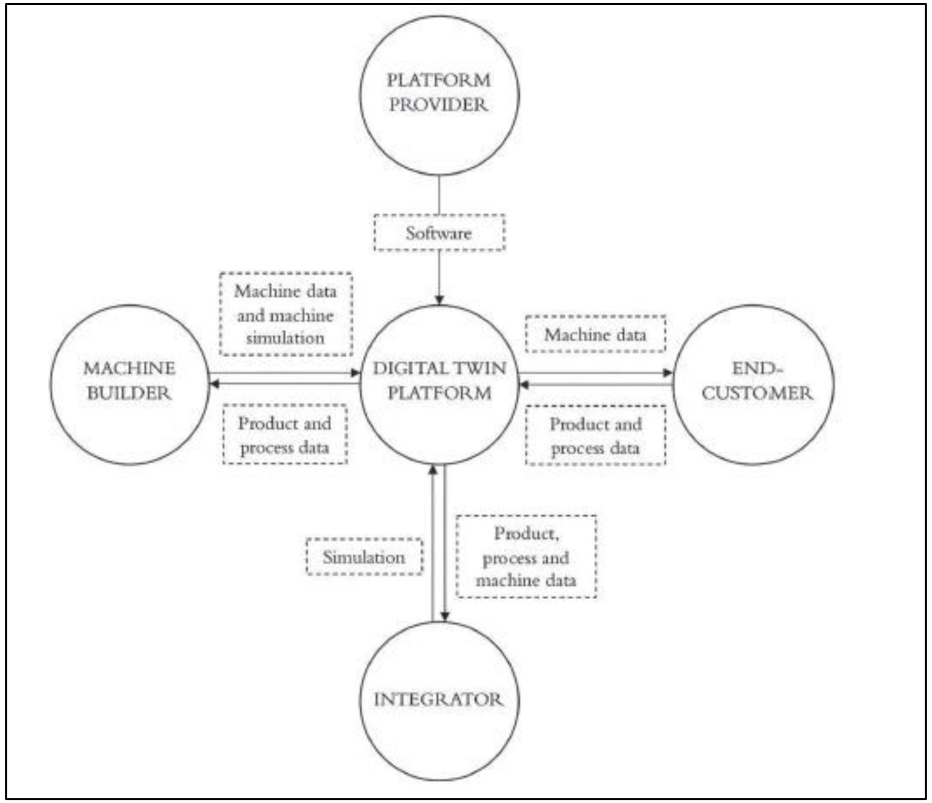
SIMULATION (Discrete event simulation, Agent Based Modelling, System dynamics, Multi-physics simulation) +

COMPUTING TECHNOLOGIES & ARCHITECTURES (Cloud-edge computing continuum, …)



Enabling technologies for Digital Twins

Digital twins rely on digital platforms to enable a collaborative practice



- Digital twins can be thought as advanced modelling constructs that require, and enable, a close collaboration of the involved actors.
- Trust between the collaborative parties could become an important barrier. Therefore, to avoid conflicts of interests among the involved actors, proper agreements should be established for trustworthy relationships.
- Four main types of actor can be generally defined, in order to set-up a collaborative practice around digital twins in manufacturing, that is (in a B2B relationship): end-customer, machine builder, integrator, platform provider.

Wiebke Reim, Ebba Andersson and Kajsa Eckerwall (2023). Enabling collaboration on digital platforms: a study of digital twins, International Journal of Production Research, 61:12, 3926-3942, DOI: 10.1080/00207543.2022.2116499

How to develop and manage Digital Twins?

- ***Multi-levelled modeling***
- ***Lifecycle management***

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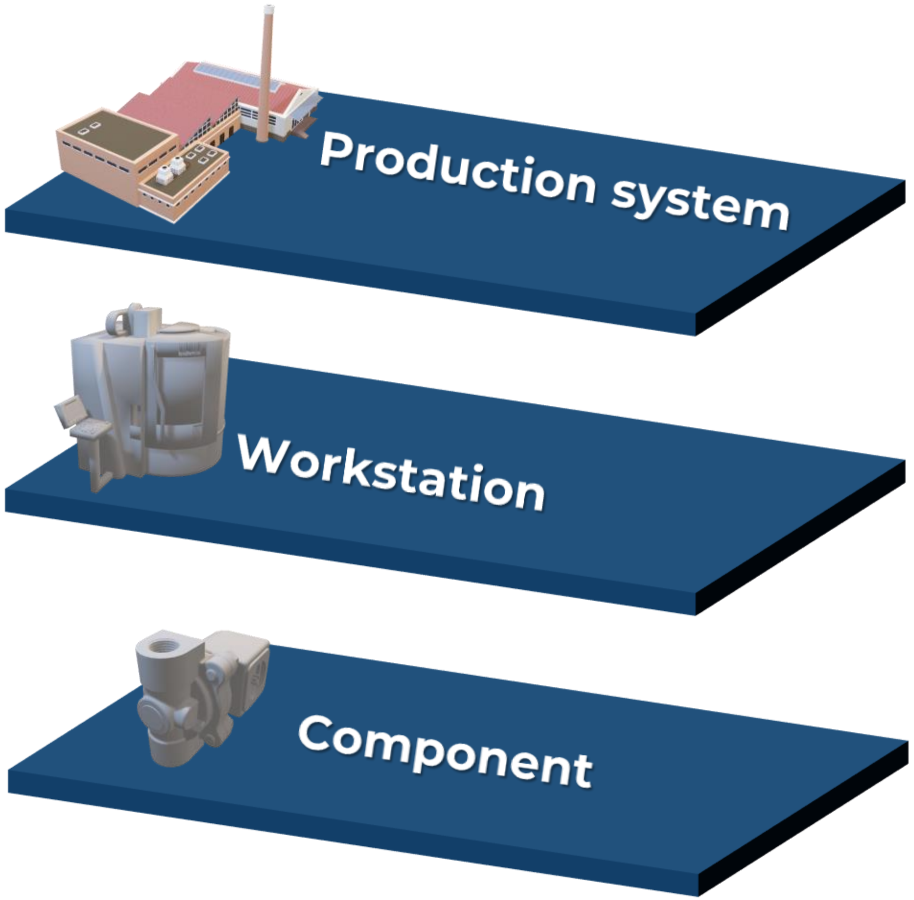
Model-based analysis through simulation

Multi-levelled modelling

- Simulations may be performed at various levels of detail for the system and objective/use case of interest.

- Modelling requirements and types of simulation can change at different levels, typically:
    - at local level: physics or multi-physics simulation;
    - at global level: discrete event simulation, agent based modelling, system dynamics.

- In order to develop a «model-based» Digital Twin simulation, we need to divide the different levels in the modelling process; this may correspond to have:
    - simulation modules for the single components;
    - global simulation for the entire system.



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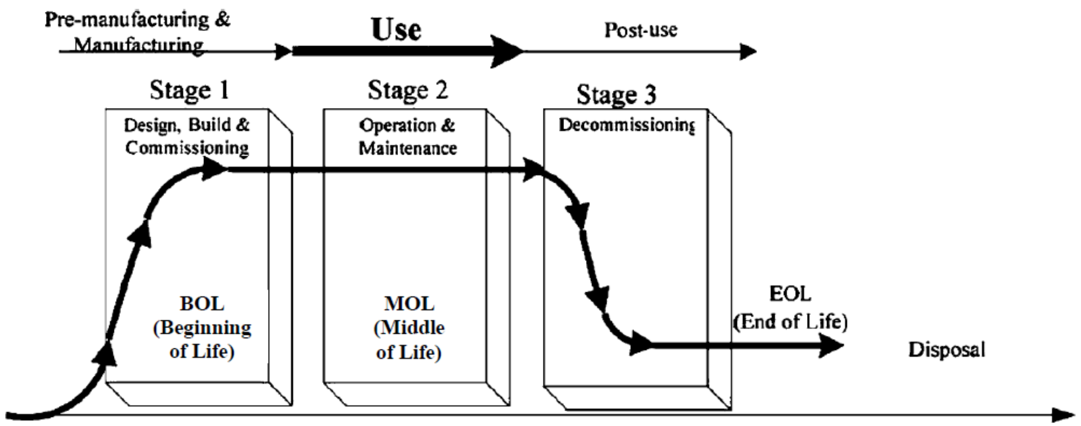
Digital Twins along the lifecycle of physical assets

Lifecycle Management: physical & digital assets through life



BOL - MOL - EOL

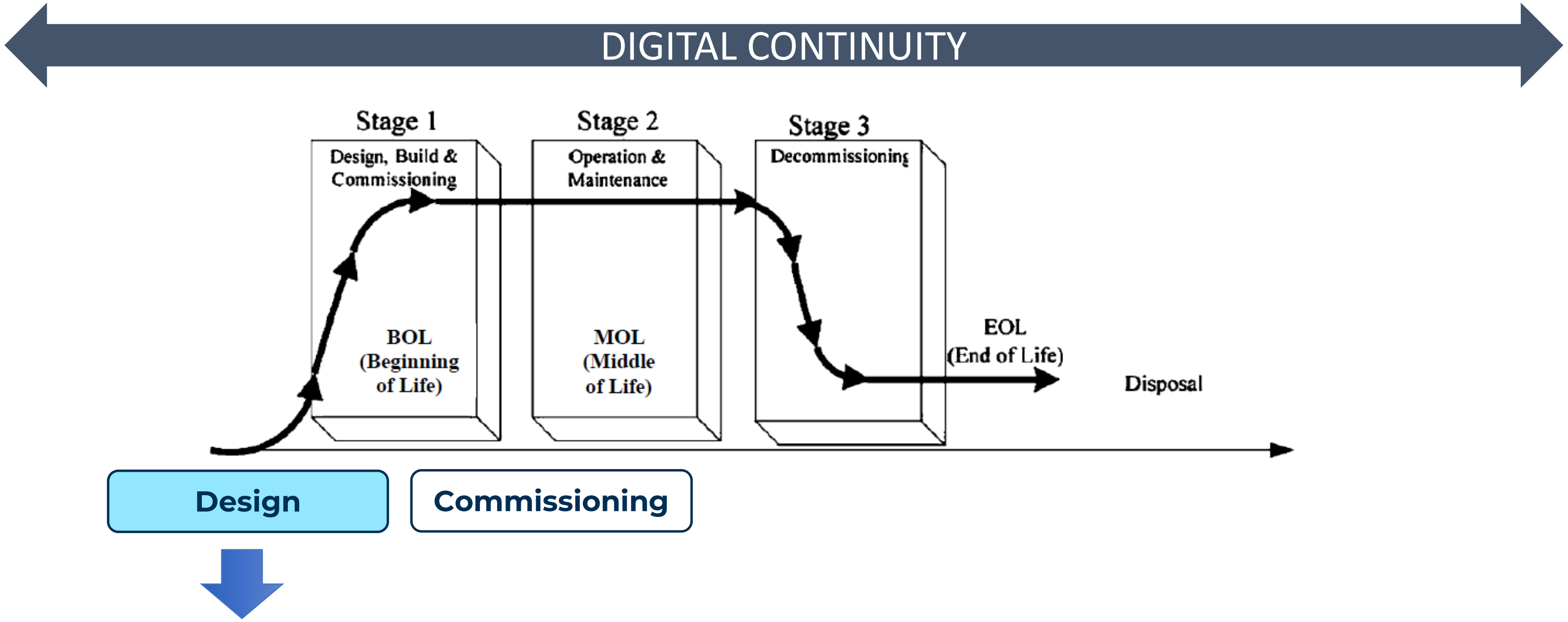
F. Badurdeen, M. Shuaib and J.P. Liyanage, "Risk Modeling and Analysis for Sustainable Asset Management", In: Mathew J., Ma L., Tan A., Weijnen M., Lee J. (eds) Engineering Asset Management and Infrastructure Sustainability, pp. 61-75, Springer, London, 2012.

→ Design
→ Commissioning
→ Operations
→ Maintenance
→ Decommissioning

- Rapid reconfigurations
- Adaptation of maintenance requirements

Digital Twins along the lifecycle of physical assets

Lifecycle Management: physical & digital assets through life

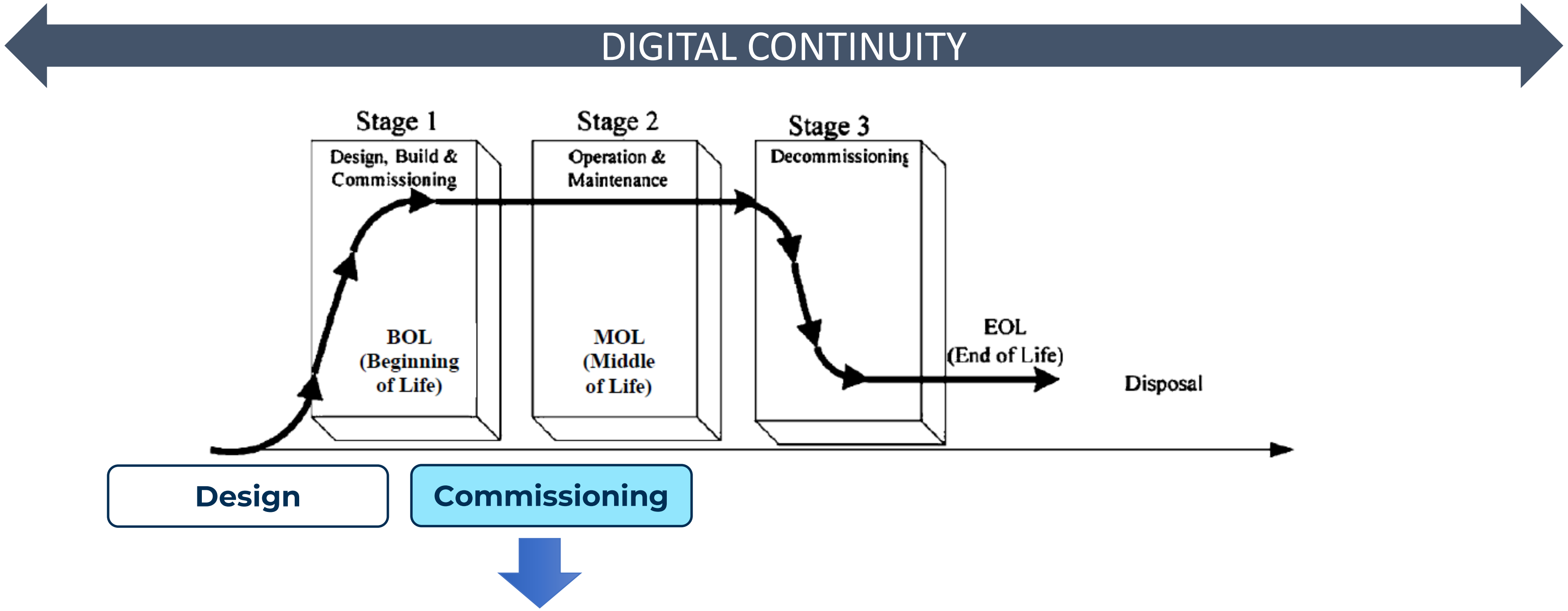


By developing the simulation models together with the physical asset, structural and behavioural descriptions can be adhering the inner functioning of the asset «as designed»

This could be the basis for the digital continuity along the whole lifecycle: changes and reconfigurations of the asset can be an update from the initial modelling

Digital Twins along the lifecycle of physical assets

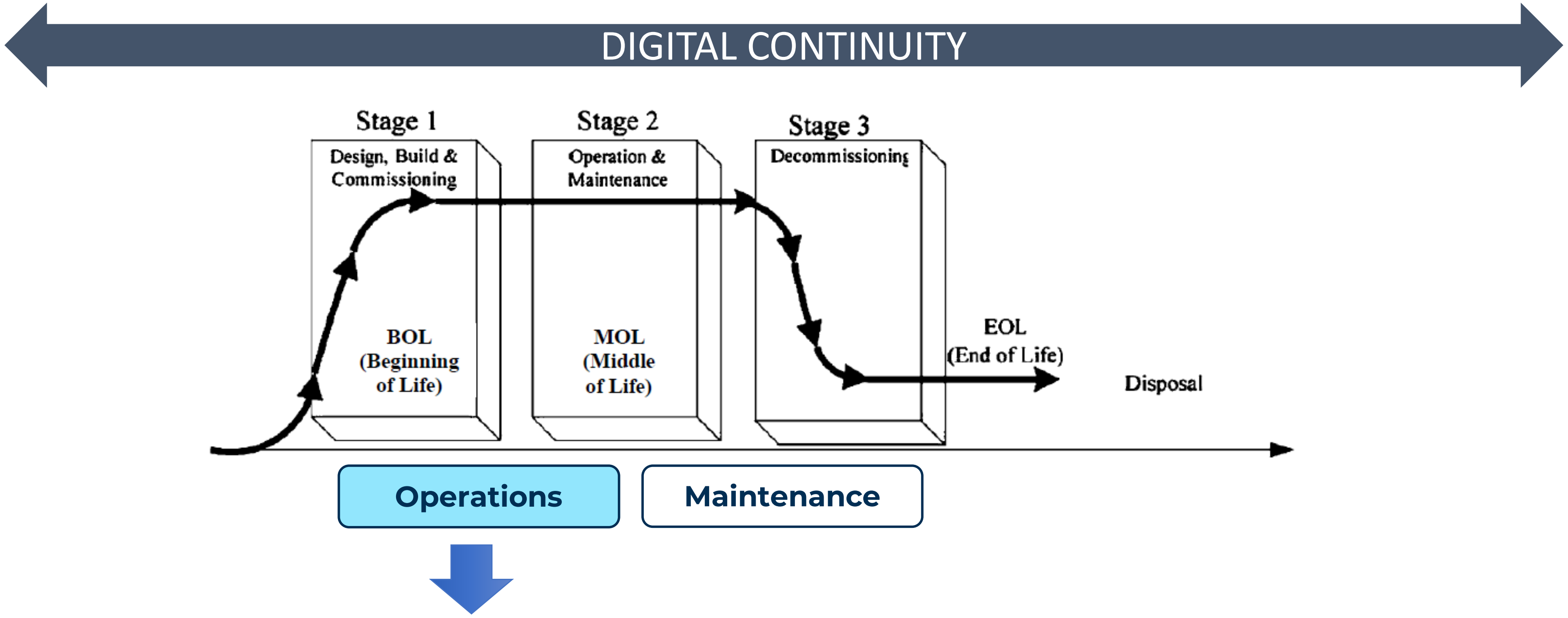
Lifecycle Management: physical & digital assets through life



Digital Twins can support the Virtual Commissioning of the systems (i.e. virtually checking that the kinematic, the dynamic and the control of the systems are working correctly)

Digital Twins along the lifecycle of physical assets

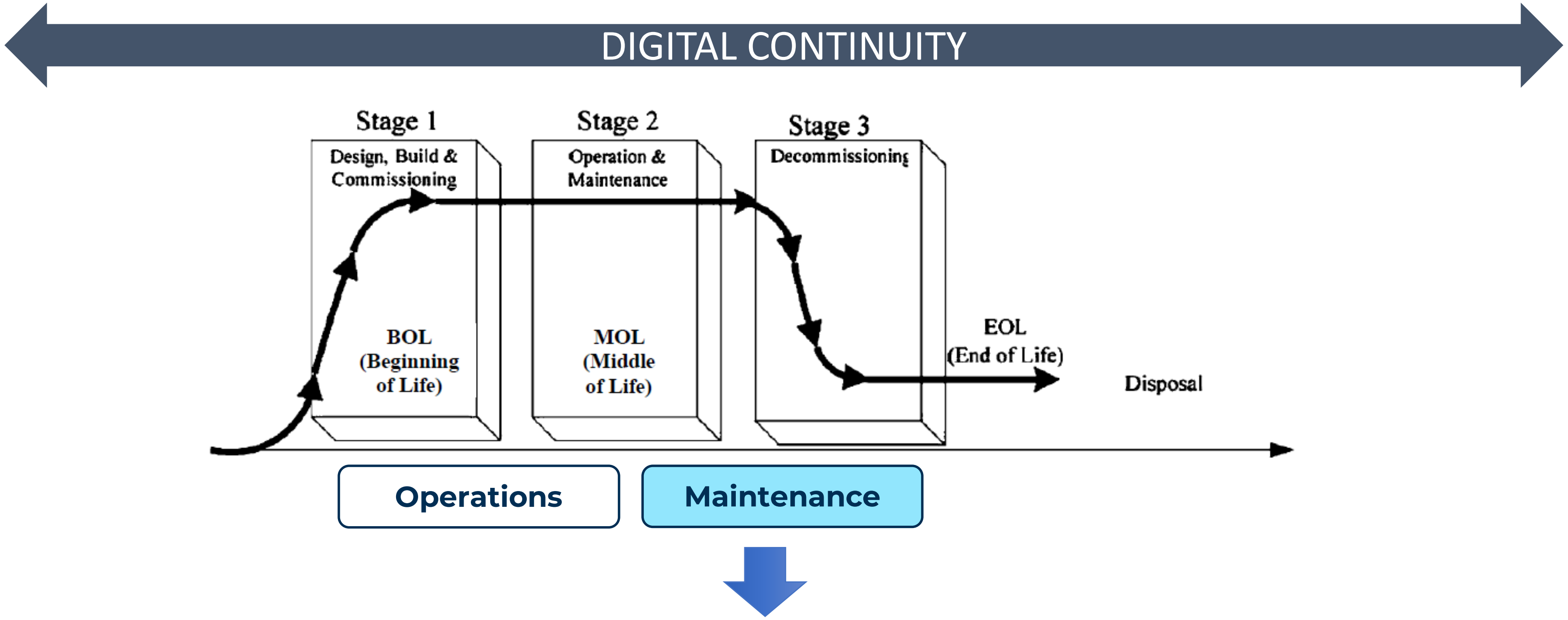
Lifecycle Management: physical & digital assets through life



The planning and control of the operations can be supported by Digital Twins, making them more aware of the current operating conditions: e.g. production planning, scheduling, workload control, quality control, …

Digital Twins along the lifecycle of physical assets

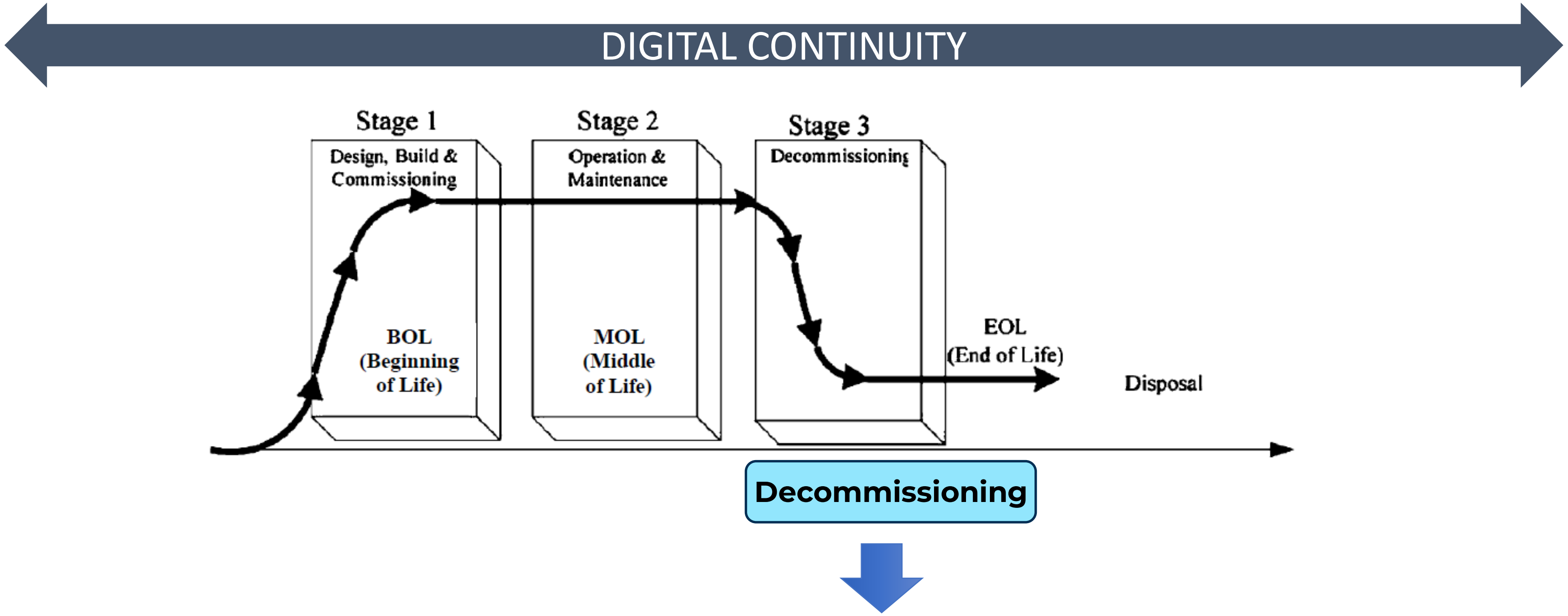
Lifecycle Management: physical & digital assets through life



Digital Twins are simulations that can also embed maintenance aspects: they can simulate various alternate scenarios and can be used to embed the prediction of failures and the degradation parameters when combined with advanced analytics techniques

Digital Twins along the lifecycle of physical assets

Lifecycle Management: physical & digital assets through life



The end of life can be supported by a great deal with the information contained in the Digital Twin as a model and as a descriptor of the production system and its reconfigurations and changes over time

Why using Digital Twins?

- ***Value of digital twins in Cyber-Physical Systems***
- ***The value of field-synchronized decision-making***

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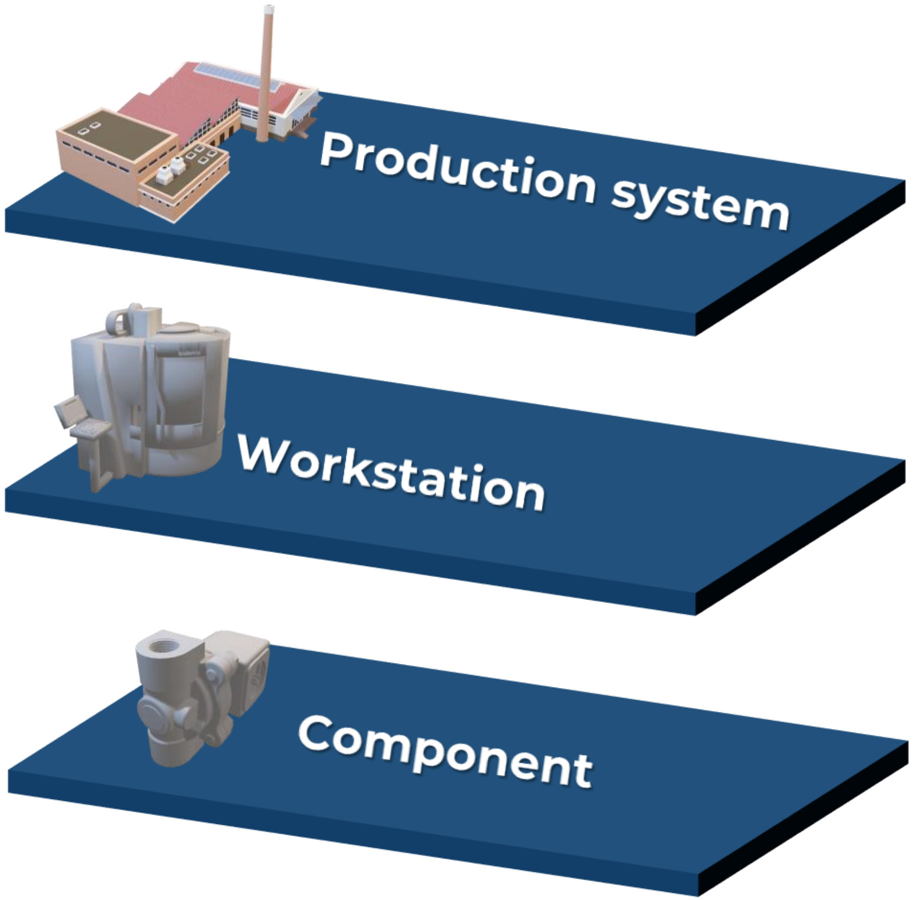
Value of digital twins in Cyber-Physical Systems

Digital twins generate value in manifold ways

- Real-time remote monitoring and control
- Predictive maintenance and scheduling
- Scenario analysis, risk assessment and treatment
- Optimization under dynamic operating conditions

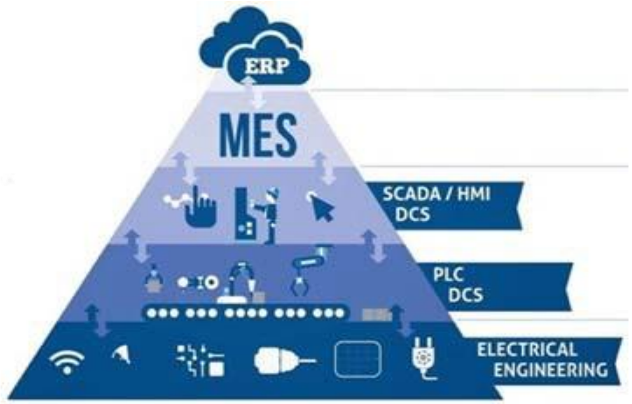
- Improved support to intra-/inter-team collaboration
- More efficient and informed decision support
- Better documentation and communication

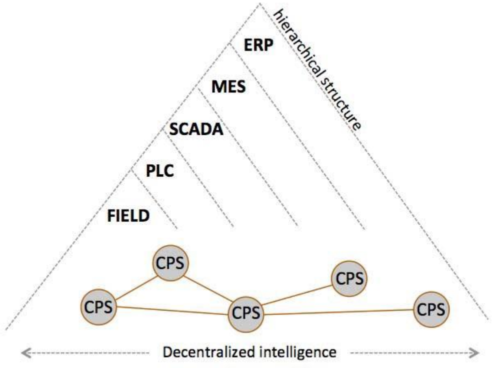
- Improved efficiency, productivity and safety of the operations



Value of digital twins in Cyber-Physical Systems

The automation pyramid evolves towards Cyber-Physical Systems where Digital Twins contribute to upgrade the decision support via engineering capabilities



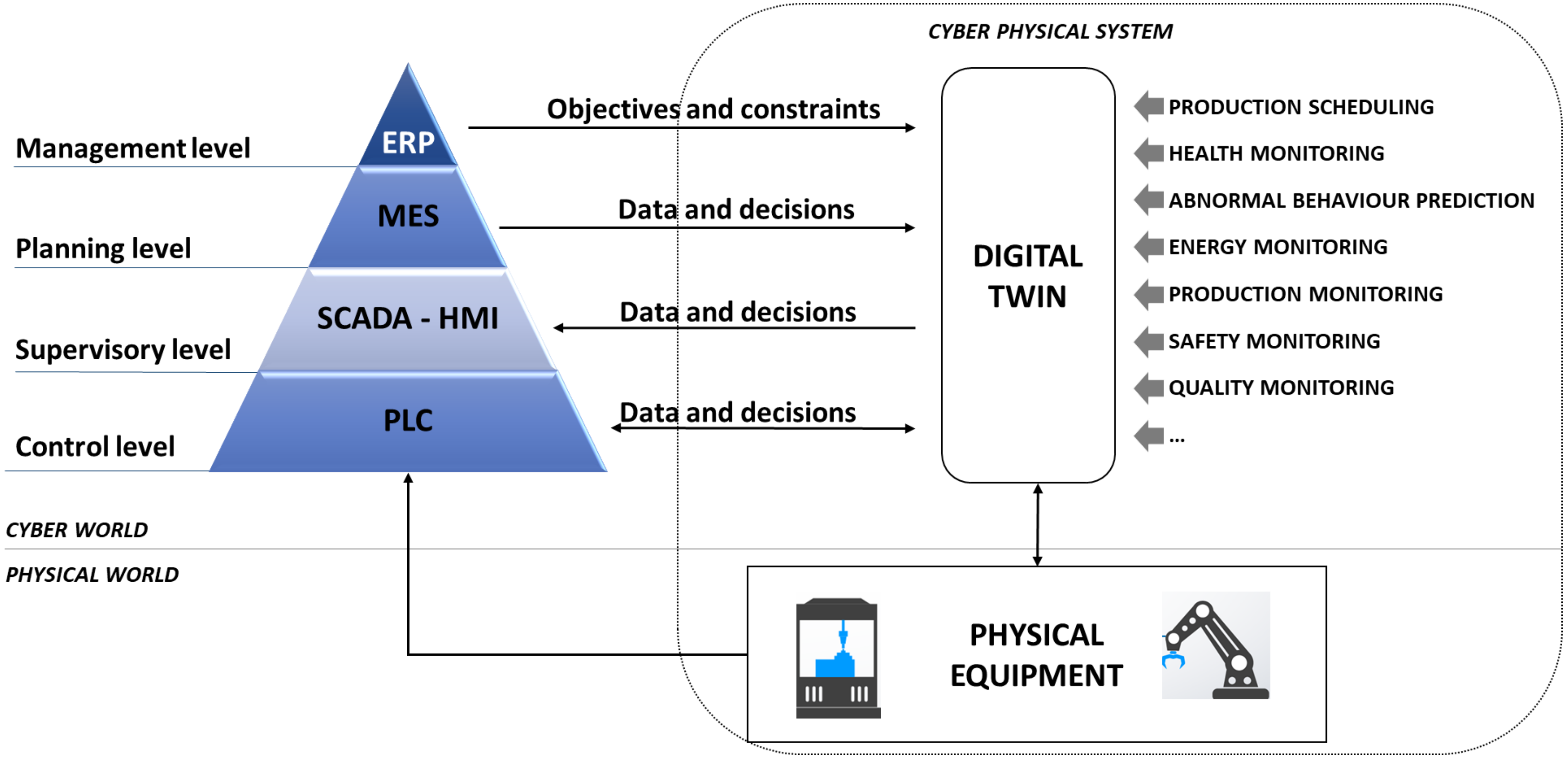


Panetto H., Iung B., Ivanov D., Weichhart G., Wang X. (2019). Challenges for the cyber-physical manufacturing enterprises of the future. Annual Reviews in Control, 47, 200-213.

Napoleone, A., Macchi, M., Pozzetti A. (2020).. A review on the characteristics of cyber-physical systems for the future smart factories. Journal of Manufacturing Systems, vol. 54, January 2020, 305-335, DOI: 10.1016/j.jmsy.2020.01.007

The value of field-synchronized decision-making

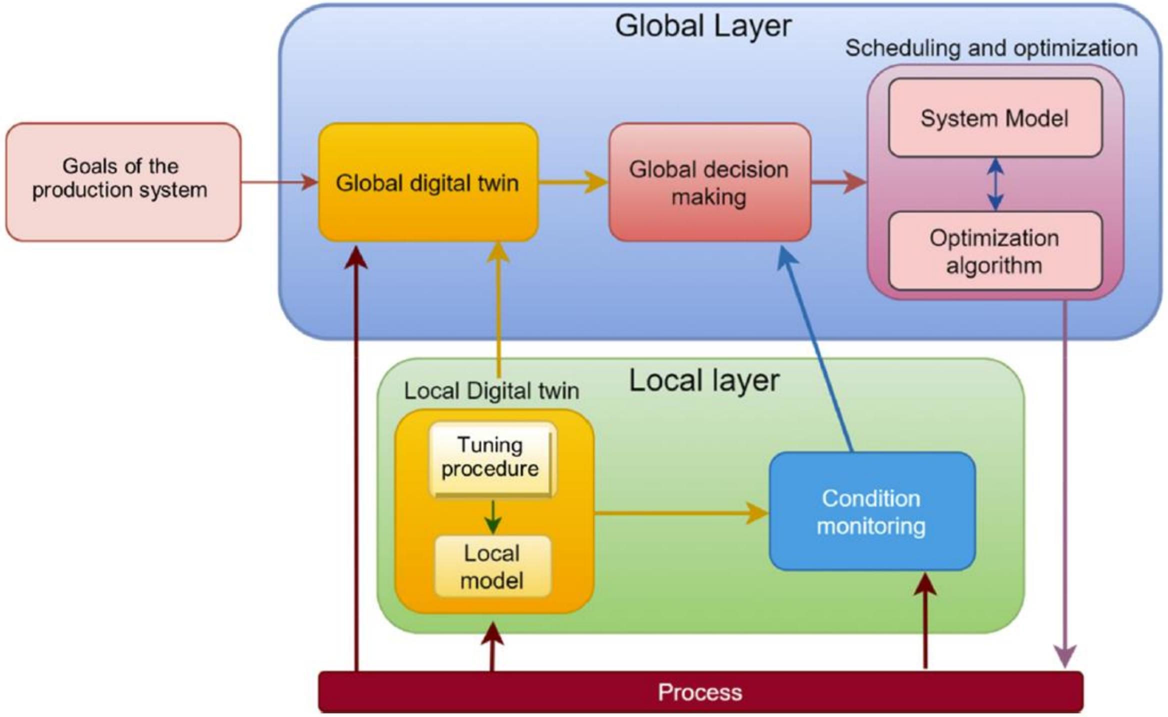
For smart operations in manufacturing, shop-floor management is a key lever to enrich by means of field-synchronized digital twins.



Negri E., Pandhare V., Cattaneo L., Singh J., Macchi M., Lee J.. Field-synchronized Digital Twin framework for production scheduling with uncertainty, Journal of Intelligent Manufacturing, vol. 32, 1207-1228, 2021

The value of field-synchronized decision-making

For smart operations in manufacturing, the shop-floor can benefit from a global and local support by Digital Twins for field-synchronized decision-making.



The framework represents a novel decision-making concept aimed at leveraging digital twins at global and local level.

- The global performance is ensured at the global layer of the framework.
- The local condition-based monitoring takes care of the performance of the physical assets at the local layer.

Villalonga A., Negri E., Biscardo G., Castaño F., Haber R.E., Fumagalli, L., Macchi M.. A decision-making framework for dynamic scheduling of cyber-physical production systems based on digital twins. Annual Reviews in Control, vol. 51, 2021, 357-373, DOI: 10.1016/j.arcontrol.2021.04.008

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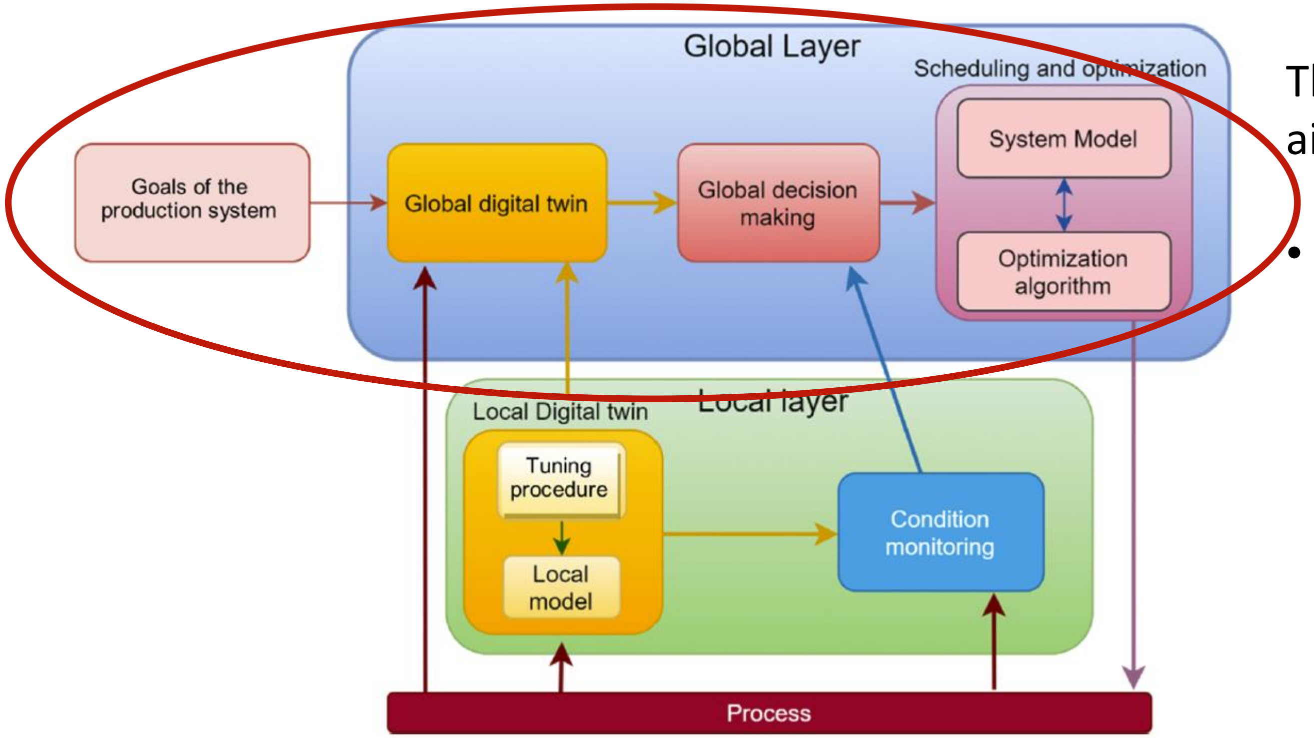

The framework represents a novel decision-making concept aimed at leveraging digital twins at global and local level.

- Global level (Production System):
  - Connecting with the digital twins of the workstations (i.e. local digital twins);
  - Decision-making based on the global production rate and the conditions of the workstations;
  - Simulating the global behavior of the system while optimizing the production schedule (simulation-based optimization).

Villalonga A., Negri E., Biscardo G., Castaño F., Haber R.E., Fumagalli, L., Macchi M.. A decision-making framework for dynamic scheduling of cyber-physical production systems based on digital twins. Annual Reviews in Control, vol. 51, 2021, 357-373, DOI: 10.1016/j.arcontrol.2021.04.008

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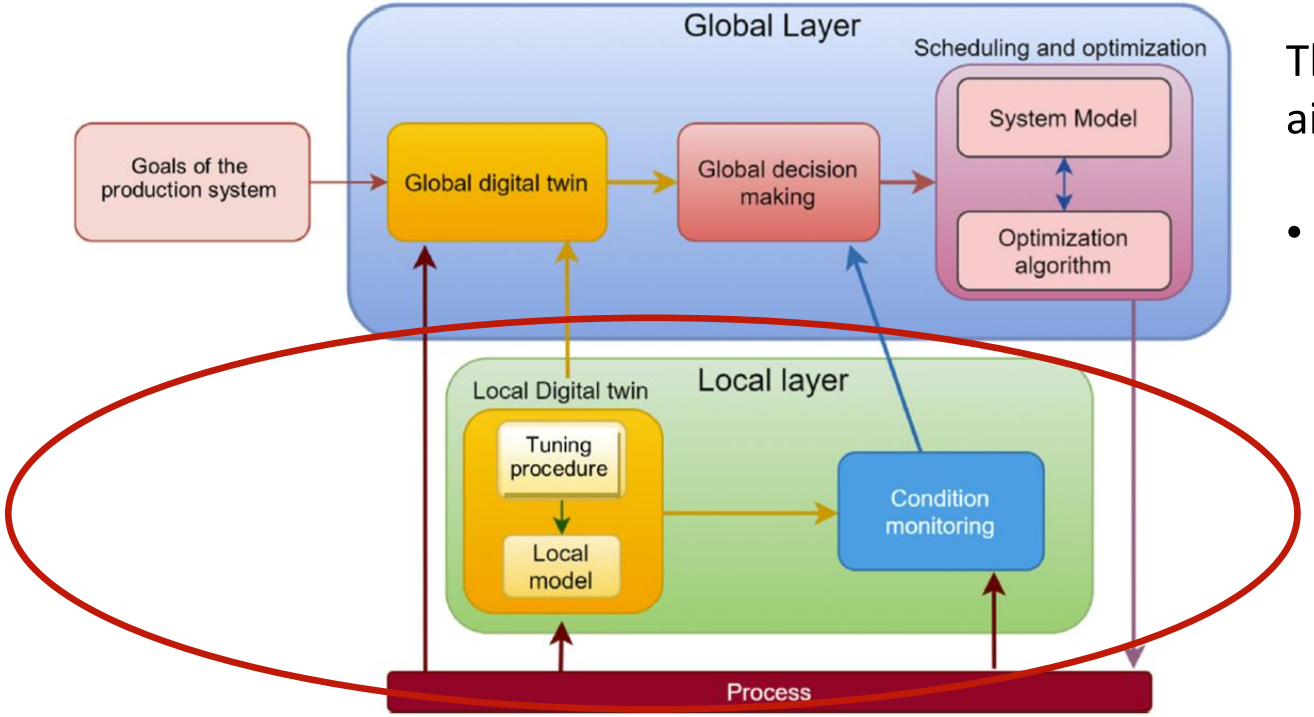

The framework represents a novel decision-making concept aimed at leveraging digital twins at global and local level.

- Local level (Workstation/component):
  - Capturing characteristics of the physical process;
  - Capturing non linearities occurring at the workstation;
  - Inferring the condition of each workstation;
  - Providing information to the global digital twin.

Villalonga A., Negri E., Biscardo G., Castaño F., Haber R.E., Fumagalli, L., Macchi M.. A decision-making framework for dynamic scheduling of cyber-physical production systems based on digital twins. Annual Reviews in Control, vol. 51, 2021, 357-373, DOI: 10.1016/j.arcontrol.2021.04.008

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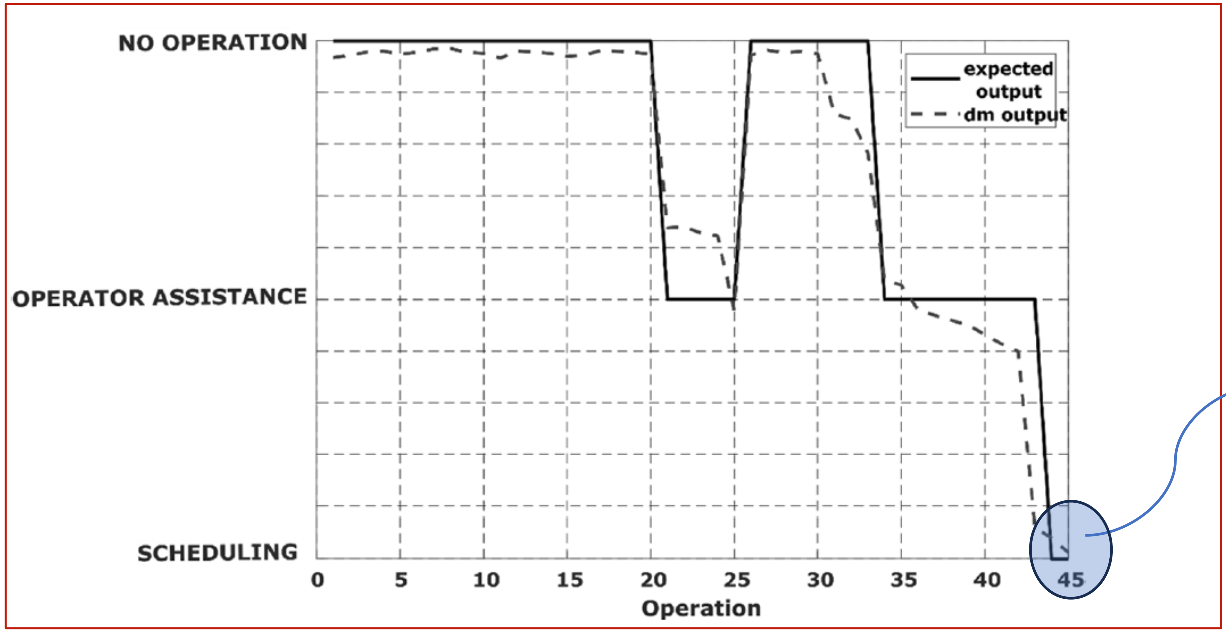
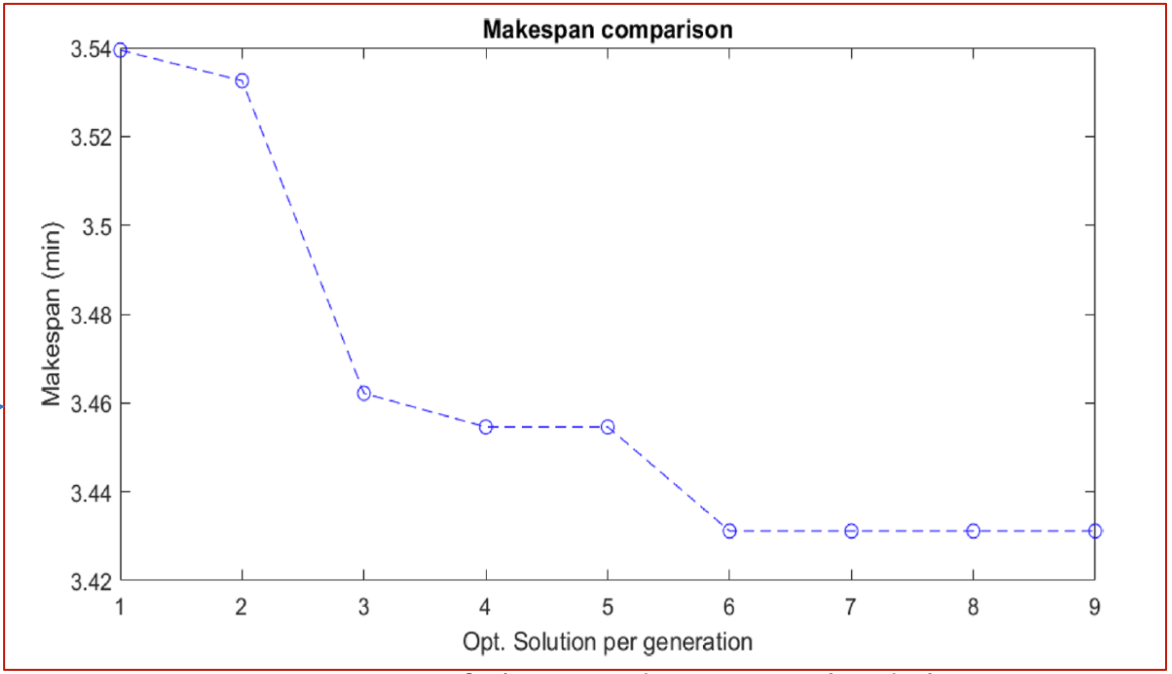


Behaviour of the global decision-making
(fuzzy inference system)



Optimization of the production schedule
(genetic algorithm + discrete event simulation)

Villalonga A., Negri E., Biscardo G., Castaño F., Haber R.E., Fumagalli, L., Macchi M.. A decision-making framework for dynamic scheduling of cyber-physical production systems based on digital twins. Annual Reviews in Control, vol. 51, 2021, 357-373, DOI: 10.1016/j.arcontrol.2021.04.008

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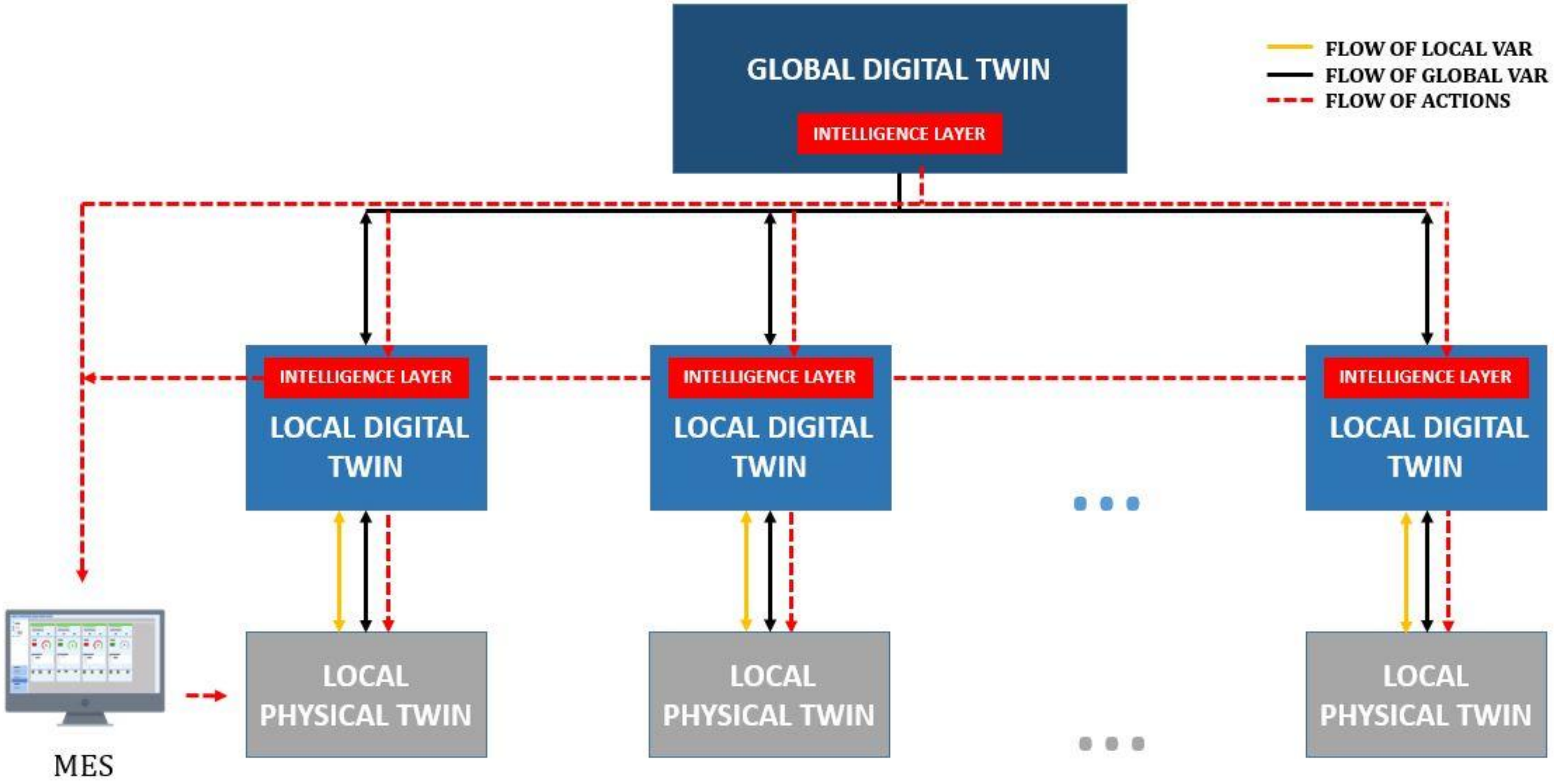
The value of field-synchronized decision-making

Smart operations in manufacturing requires proper architectures where to run the digital twins and an intelligent support to decision-making.



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What's next?

- ***New Frontiers for the Digital Twins***

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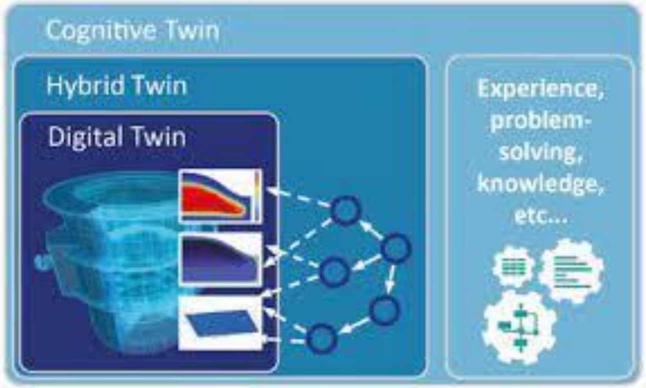
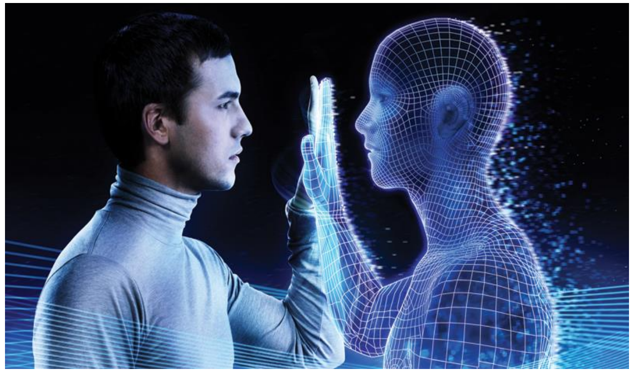
New frontiers for the Digital Twins



Cognitive Digital Twin

→ Supported by Artificial Intelligence and semantic data structuring

→ Needed to make decisions consistent with the surrounding environment



Human Digital Twin

→But this leads to various isssues of «ethics» and «privacy»
→Is man an «asset»? To which extent?
Privacy was defined as «the right to be let alone»
By American jurists Samuel Warren and Louis Brandeis in 1890
Source: Samuel D Warren and Louis D Brandeis. Right to privacy. Harv. L. Rev., 4:193, 1890.

Digital Twin & the Metaverse

→Both are defined as «virtual representation of reality»
→Are they the same thing?

THANK YOU FOR YOUR ATTENTION!

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