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Introduction to Digital Twins Concepts

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DT definition

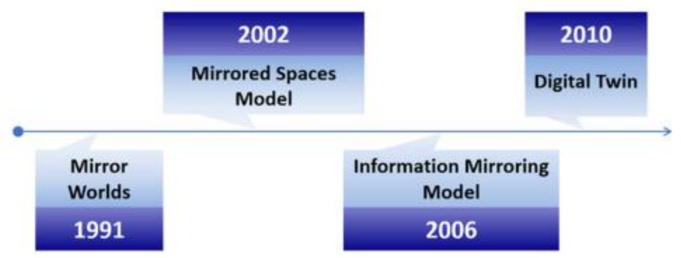
DT concept originated from the aerospace industry → NASA's roadmap(2010) on modeling & simulation→provided 1st definition for DTs:

"An integrated multi-physics, multi-scale, probabilistic simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its flying twin"

Since this NASA definition, new definitions in the literature have refer to DT as :

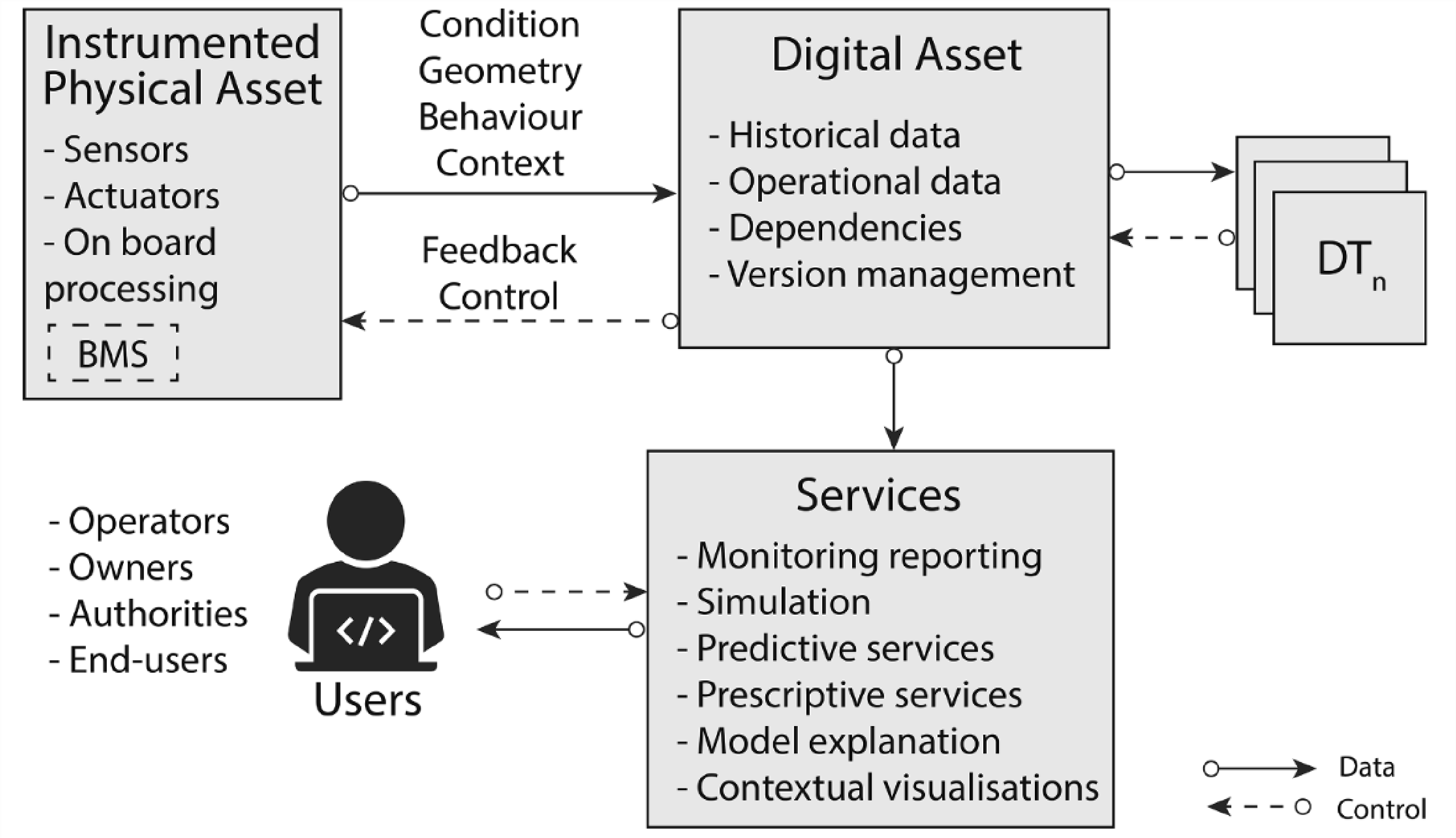
"Virtual or digital model layout", "counterpart", "doppelganger", "clone", "footprint", "software analogue", "representation", "information constructs", or "simulation of its physical counterpart"

A DT is a dynamic digital representation of an asset/ system and mimics its state or behavior in real-time and vice versa (GE Digital 2017; Bolton et al. 2018, Singh et al. 2021).



Evolution timeline of DT, Singh et al. 2021

DT conceptual ecosystem



Source: Davila Delgado, J. M., &Oyedele, L. (2021). Digital Twins for the built environment: learning from conceptual and process models in manufacturing.

DT main purpose

Bridge the gap between the real-world & Digital Systems

By shifting to a real-time event-driven development approach →quickly and effective integration of all systems

More accurate and interactive model of the real world.

DT characteristics

High-fidelity	An accurate replica of its physical counterpart in terms of appearance, content, and functionality→relying on realistic digital models for accuracy.
Dynamic	Changes alongside the physical system by maintaining a continuous exchange of data between the physical & virtual worlds → accurately mirroring behavior of its physical twin.
Self-evolving	Evolves in sync w/ its physical counterpart throughout its lifecycle, creating a closed feedback loop →adapting in real-time based on data collected from the physical twin.
Identifiable	Each physical asset has its unique DT, allowing for global identification and tracking throughout the entire lifecycle, as the data and models associated with the DT evolve along w/ the physical asset.
Multiscale & Multiphysical	Incorporates properties of physical twin at different scales, from macroscopic geometric details to microscopic characteristics, including physical properties such as structural dynamics, thermodynamics, and material properties.
Multidisciplinary	Integrates various disciplines, including computer science, engineering, automation, and physics, playing a central role in Industry 4.0.
Hierarchical	Composed of interconnected sub-models representing different components of a system→hierarchical structure that reflects composition of the physical product.

Advantages of DTs

Speed prototyping	Allows for faster design iterations and prototyping by simulating different scenarios and facilitating customization based on user needs and usage data→Enables real-time comparison between predicted and actual performance, leading to improved design decisions.
Cost-effective	Reduces prototyping costs by utilizing virtual resources, eliminating needs for physical materials and repeated testing→reduces operating costs, extends equipment life, and optimizes maintenance strategies
Improved maintenance	Anticipates defects and damage, enabling proactive maintenance scheduling. It provides optimized solutions and continuously improves system processes through the feedback loop between the DT and its physical twin.
Waste reduction	Minimizes material wastage by simulating and testing product prototypes virtually→optimized designs & reduced development costs.
Accessibility	Allows remote control/monitoring of physical devices, making them widely accessible→crucial in situations w/ limited local access
Documentation /communication	Centralizes scattered data, simplifying access and maintenance. It enables better understanding, documentation, and communication of the behavior and mechanisms of the physical twin.
Self-evolving	Evolves in sync with its physical counterpart throughout its lifecycle, reflecting any changes in either entity→matures along w/ the physical twin.

DT vs. Simulations

Major difference between a DT & simulation → data interconnection that allows exchanging information between the physical object & virtual object

Simulation

A simulation predicts future states of a physical system based on a set of initial assumptions

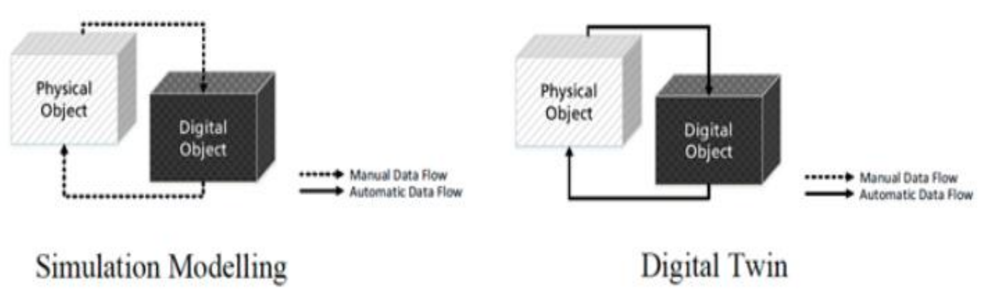
Limited capability in evaluating system performance & considering the physical part of the system

DT

A virtual environment for several simulations, with real-time data and a two-way flow of information between physical & virtual object

Increases the accuracy of predictive analytical models. Offers greater understanding for the management and monitoring of products, policies & procedures

However → increased costs



Simulation Modelling vs. Digital Twin (Krasikov , I., & Kulemin, A. N. (2020).

Classification of DTs

Hierarchal perspective

1. Unit level:

Based on geometric, functional, behavioural, & operational model of unit-level physical twin.

2. System level:

Combines unit-level DTs in a production system, facilitating data flow and resource allocation. (e.g. products like aircraft or buildings are system-level DTs.)

3. System of Systems (SoS) level:

Multiple system-level DTs are interconnected to form SoS-level DT→ collaboration between systems or departments.

Level of Integration

1. Digital Model:

Data between the physical & digital object are exchanged manually→ any changes in physical object state not reflected in the digital one, &vice versa

2. Digital Shadow:

Data from physical object flow to the digital automatically, but still manually the other way around → any change in the physical object seen in digital copy, but not vice versa

3. Digital Twin:

Automatic bidirectional flow of data between the physical & digital object→ changes in either object, physical or digital, directly lead to changes in the other.

Level of Maturity

1. Partial DT:

Contains a small number of data points, e.g., temperature, humidity, etc., which is useful in determining the connectivity & functionality of DT.

2. Clone DT:

Contains all significant and relevant data from the product/system→ prototypes & categorizing development phases

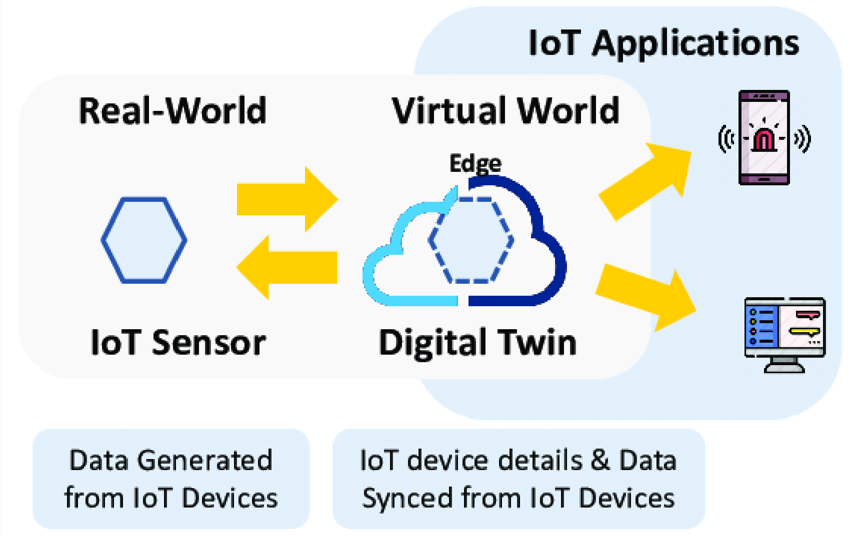
3. Augmented DT:

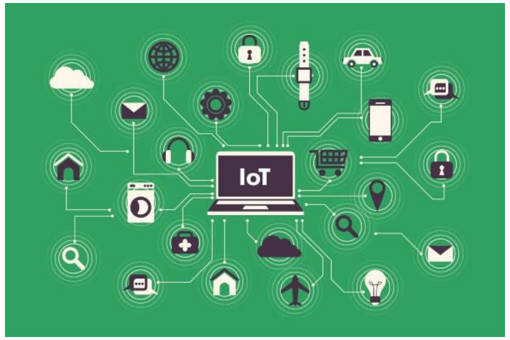
Utilizes data from the asset along with its historical data and at the same time derives and correlates the useful data using algorithms and analytics.

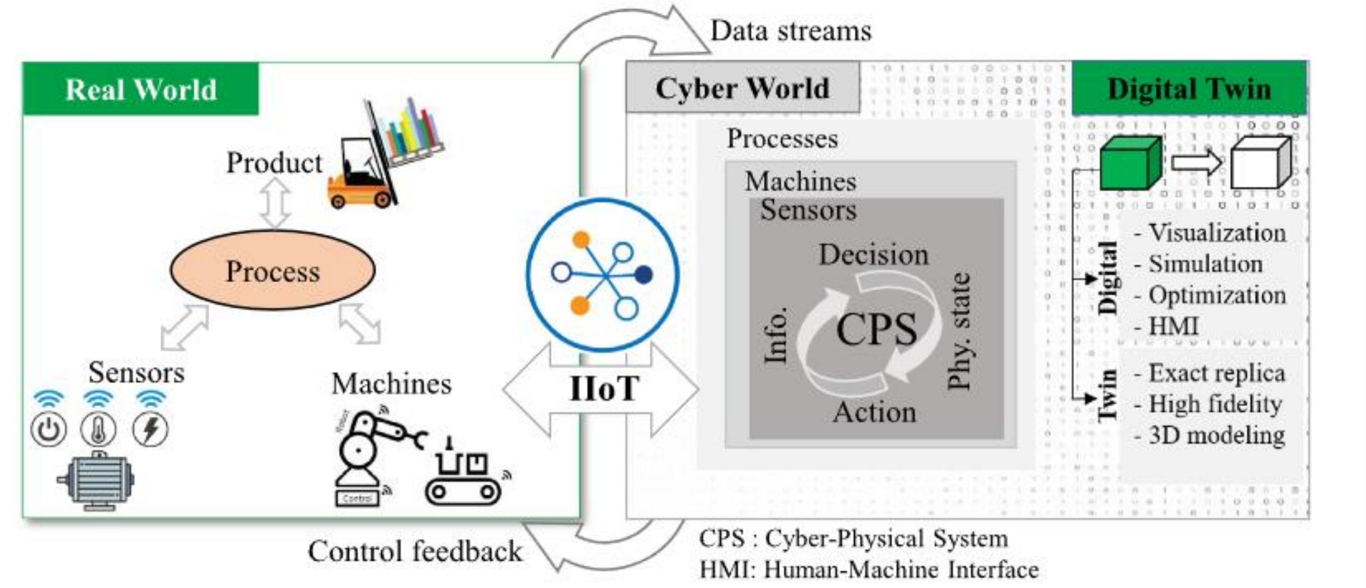
IoT's critical role (1/2)

IoT definition	**"Interconnection of sensing devices providing the ability to share information across platforms through a unified framework, developing a common operating picture for enabling innovative applications"**
Data collection	**Data collected from IoT devices such as smart meters, wireless sensor networks, as well as weather stations → utilized for the development of parameters required for DT implementation**
DT-IoT interaction	**The explosion of IoT sensors →essential for enabling live data feed** **DT depends on use of effective tools for information communication, IoT-enabled devices, and sensor-based data-capturing devices, especially for asset monitoring** **As IoT devices are refined → DT scenarios can include smaller & less complex objects**

IoT’s critical role (2/2)



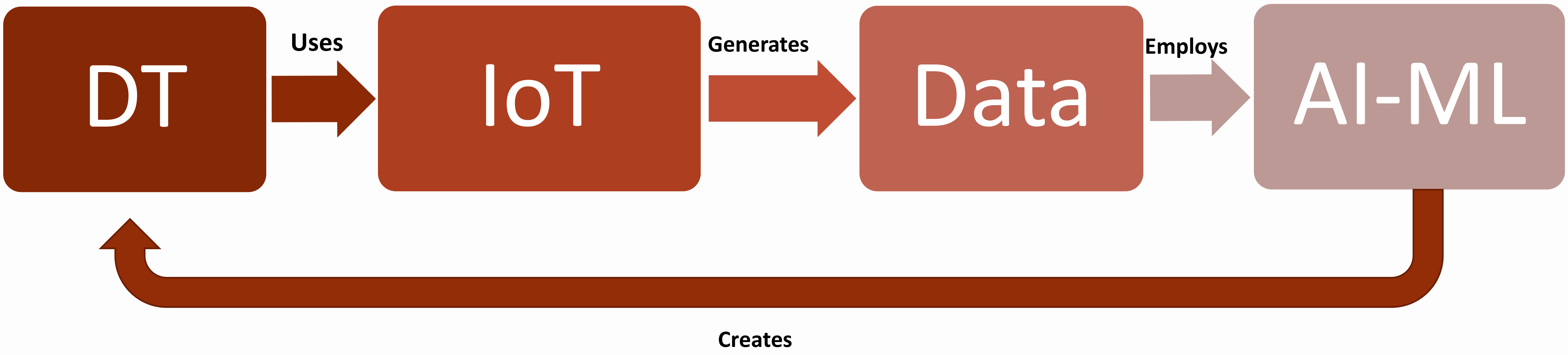




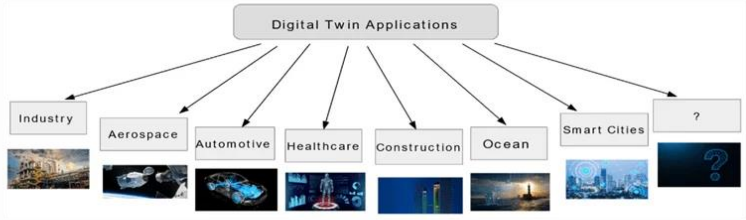
Source: Shah Zeb, Aamir Mahmood, Syed Ali Hassan, MD. Jalil Piran, Mikael Gidlund, Mohsen Guizani, Industrial digital twins at the nexus of NextG wireless networks and computational intelligence: A survey, Journal of Network and Computer Applications, Volume 200, 2022,

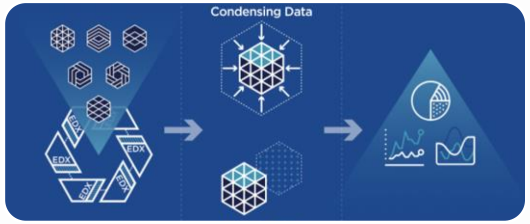
Relationship between IoT, big data, AI-ML, and DT

Several technologies come together to make DT a reality such as 3D simulations, IoT, AI, Big Data, ML, & cloud computing.



DT concepts in the built environment





DT applications

- DT found its application in industries beyond manufacturing and now supports many different applications
- -Manufacturing
  -Security
  -Healthcare
  -Automotive

Data at the core of DT

- Based on available data, different intelligent functions (e.g., AI, ML module, simulation) could be realized for advanced decision-support
- Examples:
  - Transportation prediction,
  - Energy usage optimization
  -Asset anomaly detection

DT related with the built environment

- More precisely : Architecture, Engineering, Construction, and Facility management (AEC/FM) sectors
- DTs are particularly examined in the context of smarter cities/buildings

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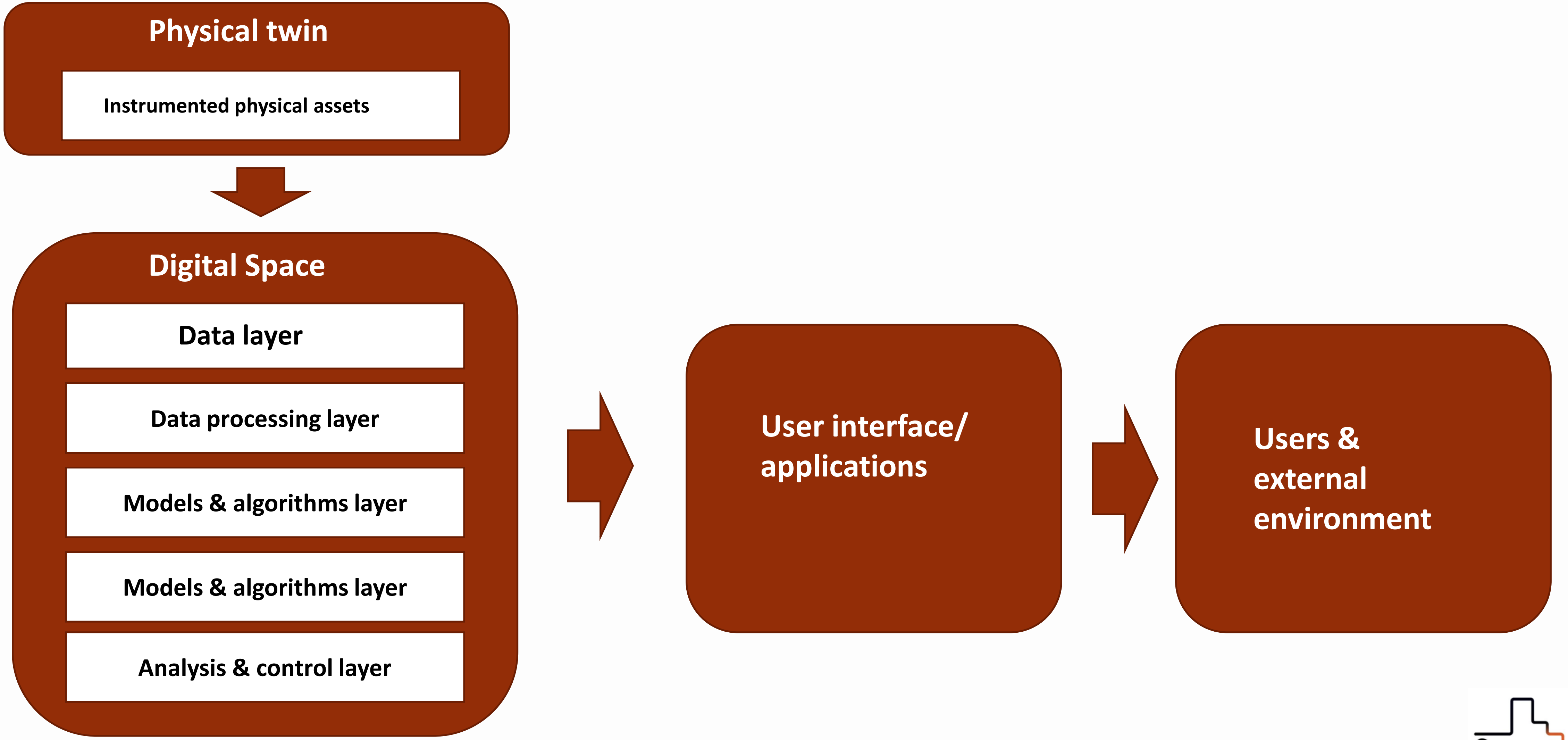
Conceptual system architecture for a DT



DT architecture principles

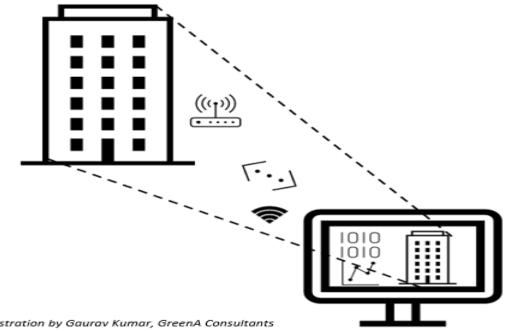


Illustration by Gaurav Kumar, GreenA Consultants

To construct an effective DT architecture in the building level, the following strategies should be examined

Architecture to be developed using a unified, hierarchical,& extensible approach →implemented in different scales from assets (e.g., pump) to a building

Besides data collection & acquisition, assets need to be connected and relevant information regarding their life cycle (e.g., maintenance history) should be collected as well.

Interaction & communication channels w/ humans are needed to provide in-time services.

Data visualization →essential to monitor current condition & activities in DTs. However, integrating data from different systems → challenging due to varying data requirements and intended uses across applications.

Adapted from: Lu, Qiuchen & Parlikad, Ajith Kumar & Woodall, Philip & Xie, Xiang & Liang, Zhenglin & Konstantinou, Eirini & Heaton, James & Schooling, Jennifer. (2019). Developing a dynamic digital twin at building and city levels: A case study of the West Cambridge campus. Journal of Management in Engineering.

Flow chart for DT development at building level

Select a specific building & confirm the targets and core functions of this DT creation

↓

Establish the digital modelling approach for this building

1. The selection of modelling approaches (e.g., BIM)	2. The confirmation of information level

↓

Establish interoperability procedure and data compatibility & visualisation

Confirm data resources, exchange, sharing, visualisation , integration methods and platforms

↓

Establish a new asset/data resource/ technology development strategy

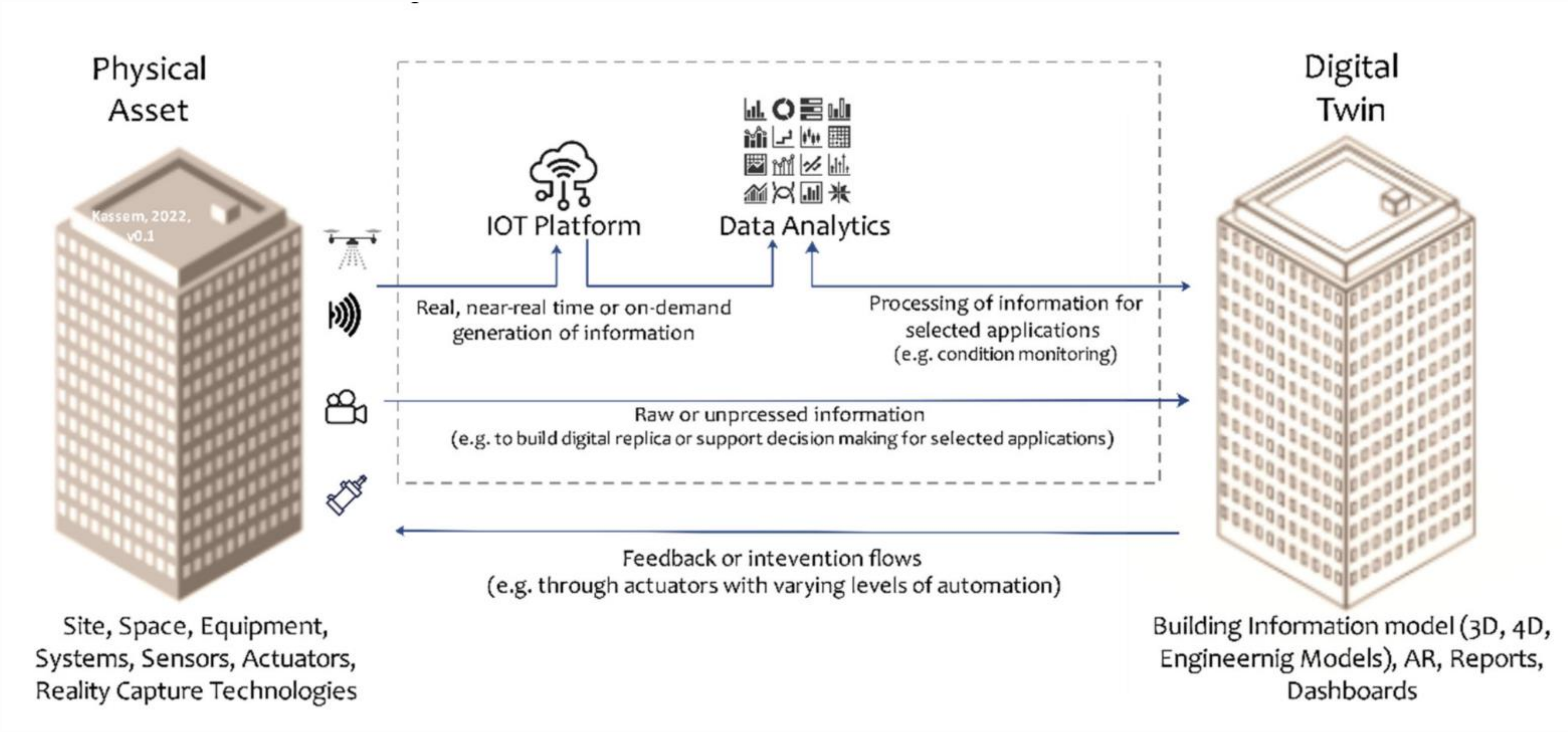
↓

Establish a quality and security control strategy

1. The confirmation of quality assurance methods (e.g., data correctness)	2. The confirmation of security methods (e.g., ID)

Adapted from: Lu, Qiuchen & Parlikad, Ajith Kumar & Woodall, Philip & Xie, Xiang & Liang, Zhenglin & Konstantinou, Eirini & Heaton, James & Schooling, Jennifer. (2019). Developing a dynamic digital twin at building and city levels: A case study of the West Cambridge campus. Journal of Management in Engineering.

Main components to create a DT of a building



Source: *Shahzad, M., Shafiq, M. T., Douglas, D., & Kassem, M. (2022). Digital Twins in Built Environments: An Investigation of the Characteristics, Applications, and Challenges. Buildings, 12(2)*

Key challenges of DT implementation

Interoperability & lack of common standards : Buildings operation data need to be collected/ shared from different project stages,actors (e.g.,designers, manufacturers, constructors)

W/o a standard for data records among data sources→difficult to know whether a data record in one system (e.g., a particular device) is the same entity referred to in another data record in another system

A key challenge in adopting digital twins in the built environment sector is the lack of "an all-inclusive toolset"

Cost-effectiveness through successful case studies is essential for the uptake of new technologies

Data quality can be lost when extracting data from source systems

Even if the data extraction process is perfect, if the data from the source systems contains errors → propagate to the DT

A key problem in a DT is timing & frequency of synchronizing different copies of data in order to provide up-to-date data to decision makers

DTs with a requirement to monitor engineering assets in real time, a continuous stream of data will be needed, which shifts the trade-off toward high synchronization costs

Overall, a cultural change in the builte nvironment sector is essential for fostering digitalization, including the adoption of DT

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