# Digital Twins: A Survey on Enabling Technologies, Challenges, Trends and Future Prospects

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# 5. Digital Twin: Use Cases and Services

## A. Use Cases – Smart Factory and Industry 4.0

- The current vision of Industry 4.0 **aims** to cut the costs of production, build efficiency and give companies an increasingly versatile approach to production.
- Rather than a centralized control unit delivering instructions to each machine to carry out linear sequential steps, individual machines now inter-communicate directly enabling the partly-finished product to be passed straight on to the next station.
- This decentralisation through modularisation and the IoT increases flexibility, opportunity and efficiency.
- By not having to communicate with a centralized unit, the production line can run more smoothly and efficiently.
- In addition to increased efficiency, the new security sensors built into the autonomous modular systems create a safe working environment for human operatives, ensuring robots halt if they encounter an obstruction.
- This has the added benefit of workers being able to touch a robot to stop its motion without the need to activate an isolator.
- The decentralization of manufacturing processes and the increasing demand for customization leads to a need for adaptive and intelligent production equipment. (The DT aims to address this challenge.)

# 5. Digital Twin: Use Cases and Services

## A. Use Cases – Infrastructure

- Makarov et al. investigated the design concept of a DT, coining two new types of system and splitting the definition of a DT into four parts.
- A pre-DT is defined as a virtual prototype for a system to reduce technical risks and root out design problems before development.
- Any issues with the system found on the virtual twin can be solved and corrected on the physical system.
- An adaptive DT uses a user interface, linking the two systems, allowing the virtual twin to understand the preferences from the human operators in different scenarios.
- It contains unsupervised ML for pattern detection in the physical system environment. The results found to reduce repair costs and increase quality control for a lowered amount of product defects.

# 5. Digital Twin: Use Cases and Services

## A. Use Cases – Smart Factory and Industry 4.0

- Shop floor designs are initially tested against unit level Key Performance Indicators (KPI) and are only selected for the subsequent level testing if they satisfy them.
- A triage-based system filters out the designs that do not meet KPI requirements at each level during the virtual implementation of the shop floor.
- In the physical space, the selected designs are implemented gradually across all levels, and the real performance of the designs help optimize the KPIs in the virtual domain.

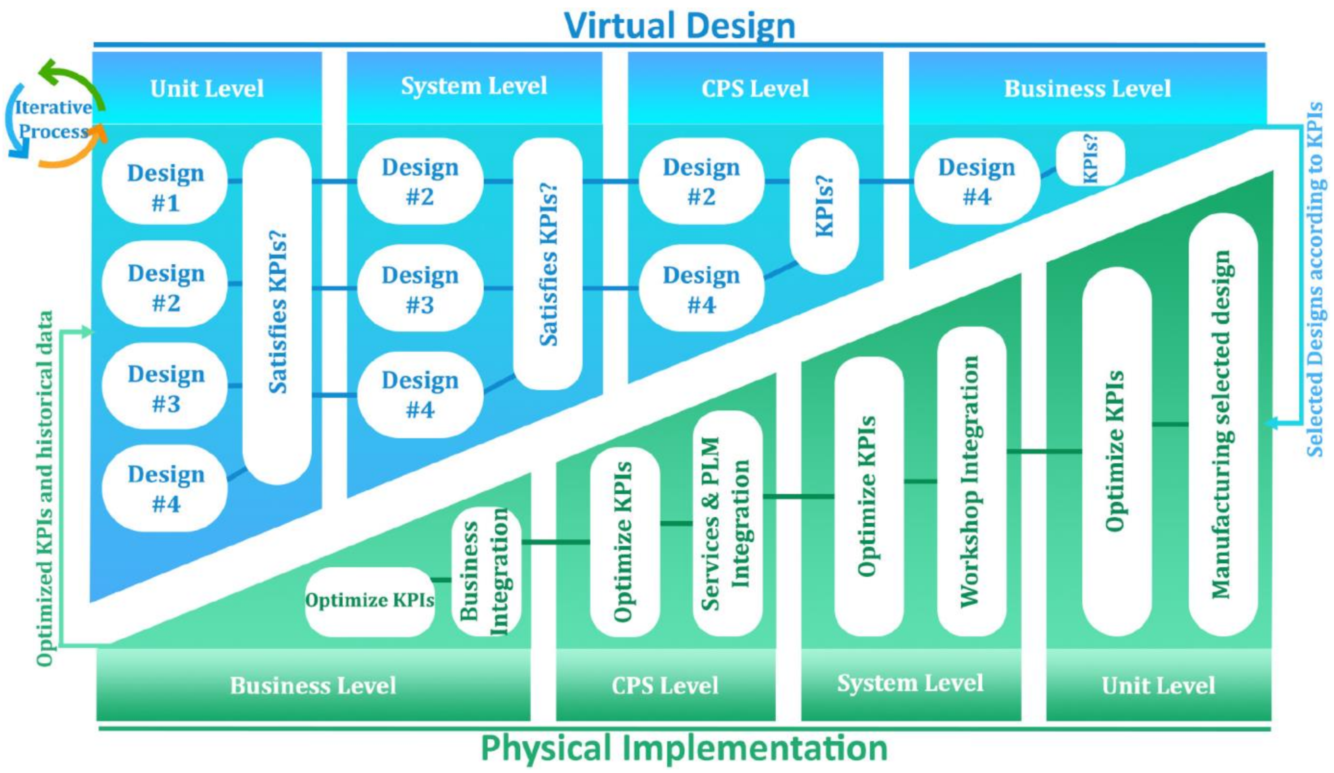


Fig. 6. Digital Twin framework for smart manufacturing

*KPI = Key Performance Indicators

(핵심 성과 지표)

# 5. Digital Twin: Use Cases and Services

## A. Use Cases – Infrastructure

- In other research, Preuveneers et al. proposed the use of safeguarding systems throughout the software of the DT system.A pre-DT is defined as a virtual prototype for a system to reduce technical risks and root out design problems before development.
- These safeguarding systems, coined “software circuit breakers (SW 회로 차단기)” are designed to handle local system errors to stop faults propagating through the levels of the DT, as these have the potential to be catastrophic.
- Such local failures can include: Missing sensor data, Broken Sensors

# 5. Digital Twin: Use Cases and Services

## A. Use Cases – Infrastructure

- Civil infrastructures are highly valuable assets, having vital societal roles and involving a large number of people at every stage of its complex working life from initial conceptual drawings, 3D numerical model, construction activities to operational service, as shown in Fig. 7.
- Infrastructure management has been a subject of intense research activity, aiming to maximize their safety and service life while minimizing the building and maintenance costs.

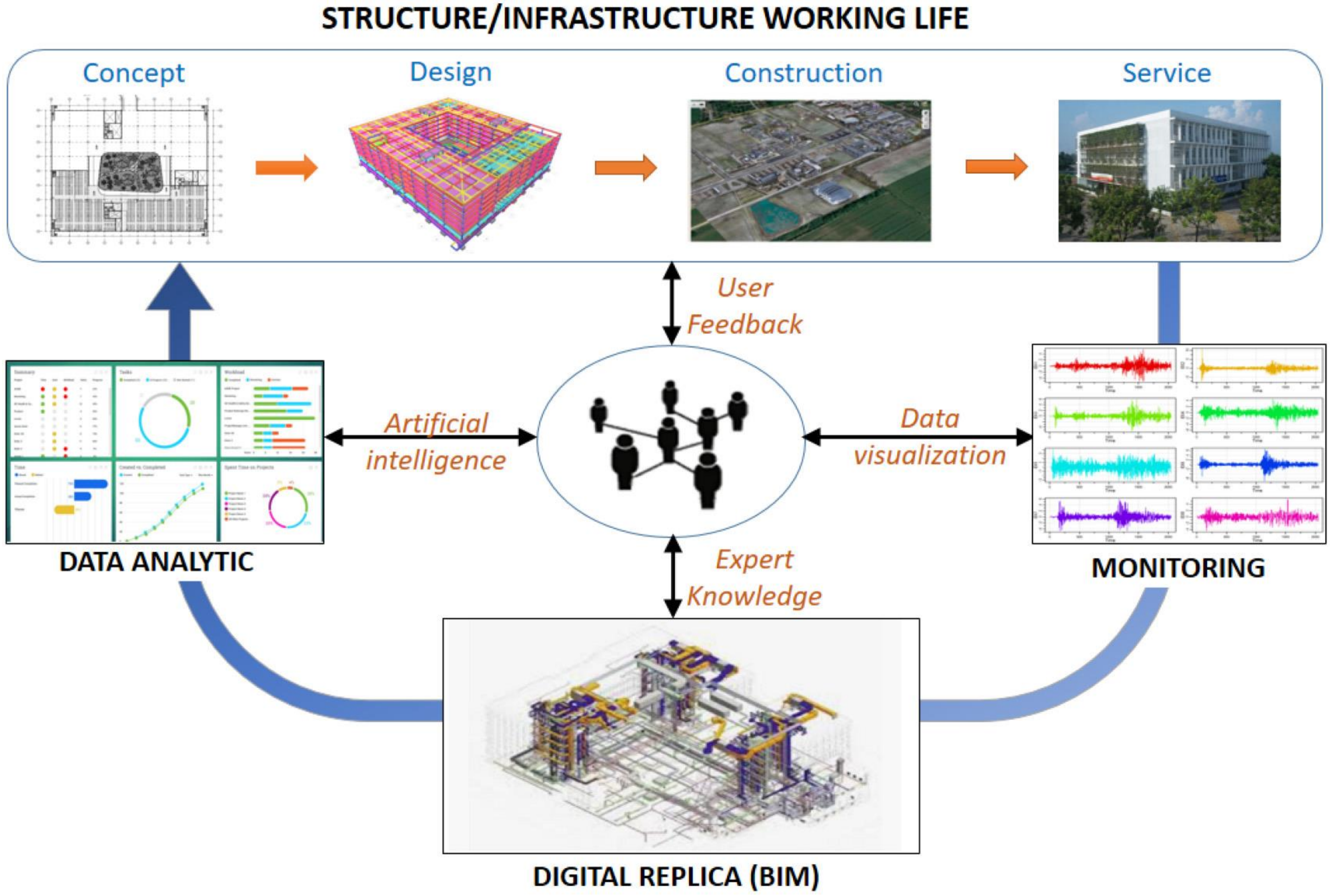


**Fig. 6. Digital Twin in infrastructure.**

# 5. Digital Twin: Use Cases and Services

## A. Use Cases – Infrastructure

**a) Smart Building**

- A building consists of a number of components spanning different domains from energy, ventilation, heating, air-condition, plumbing, mechanics, and so on. Thus, having effective building management is challenging, especially with a high-rise building or a commercial complex
- Lu et al. [127] have developed a smart O&M management tool using DT specialized in detecting anomalous behaviors. At first, a dynamic and distributed data integration component was built to integrate heterogeneous data from various daily-updated databases using corresponding object IDs. Secondly, intelligent anomaly detection functions were implemented using the BOCD to identify suspected change points, related time instants, locations, and even elaborate the causes of the change points.
- Thyssenkrupp, in collaboration with Microsoft [129], developed a DT framework for the elevator system in a high-rise building in Rottweil, Germany. The new advanced elevator, which could move both vertically and horizontally, was equipped with IoT systems and deployed via the Azure DT framework.

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# 5. Digital Twin: Use Cases and Services

## A. Use Cases – Infrastructure

**b) Smart Infrastructure**

- Ganguli and Adhikar [130] thoroughly presented a DT for a Single Degree Of Freedom (SDOF) dynamic system, in which a double time-scale system was proposed the first time. Specifically, the fast time scale reflected the dynamic responses of the real system and the slow one for the DT, and it was found that such a multiple time-scales DT was able to capture effects of mass and stiffness evolution on the SDOF simultaneously.

- Ding et al. [131] proposed a DT for a steel bridge construction using BIM and IoT data from embedded sensors, able to dynamically monitor the construction processes and key related factors such as site resources, business processes, field workers, as well as their live interaction, thus ensuring a lean construction.

# 5. Digital Twin: Use Cases and Services

## A. Use Cases – Infrastructure

**c) Smart City**

- In an attempt towards sustainable growth of the city as well as a better quality of life for citizens, Francisco et al. [137] investigated a DT paradigm for Smart City using spatio temporal data.
- At first, a digital replica of the city is rebuilt in a virtual space using the Unity cross-platform.
- after that, the researcher can navigate across the virtual city via VR devices. In addition, an AR crowd-sourcing module allows for integrating feedback of citizens about real infrastructures into the platform parallelly. By doing so, the triangle interaction human-infrastructure-technology is captured, analyzed, and updated, serving to improve the sustainability and wellness of the city.

# 5. Digital Twin: Use Cases and Services

## A. Use Cases – Towards 5G/6G With Digital Twin

- The future Industry 5.0 paradigm envisages removing any physical limitations and building in virtual connectivity and capabilities that will enable the seamless interaction between devices, humans and infrastructure [142].
- Even though this digital transformation across various industries will enable applications that serve different purposes, they all have something in common: dependency on reliable and strong connectivity enabled by the underlying next generation network infrastructure (e.g., 5G/6G).
- The fifth generation networks is already a key component in I4.0, since, even in the DT technology, the connection of components and devices is of utmost importance and communication latency is expected to be less than a few milliseconds.
- In this context, the relationship between 5G/6G and DT can be seen from two different point of views. The first one, sees the 5G/6G network as an enabler for different DT applications, while the second one sees the DT as an enabler for 5G/6G by looking at the DT of the network itself. Both point of views are addressed in this section.

# 5. Digital Twin: Use Cases and Services

## A. Use Cases – Towards 5G/6G With Digital Twin

- Communication technology is going to be the foundation of industrial IoT, hence in [143] authors have presented a detailed overview of 5G wireless transmissions and their application prospects according to cyber-physical-based manufacturing systems.
- In [144] authors have taken an industrial robotic arm as a use case and have performed an analysis of simulated robot with the effects of simulated network for CPPS.
- The three types of networks used between robot controller and robot are wired link, public LTE and the 5G uRLLC network. The results showed that 5G outperforms LTE and wired network in terms of productivity as well as the processing time increased by 50%.
- Smart manufacturing is one of the most important vertical industries identified by 5GPPP and with the maturing of network virtual functions and 5G, use of Virtual Network Functions (VNF) in smart manufacturing is gaining popularity in research community. To this context the authors of [149] have presented a use case in the manufacturing industry using the experience of a manufacturing company named Weidmuller Group.

# 5. Digital Twin: Use Cases and Services

## A. Use Cases – Towards 5G/6G With Digital Twin

- 6G envisions network speed of 100 to 1000 times faster than that of 5G for accommodating new service classes like further enhanced mobile broadband (FeMBB), ultra-massive machine type communication (umMTC), and enhanced ultra-reliable and low latency communication (eURLLC) [153] and latency less than 1ms for ensuring safety in mission critical communications and IIoT applications [154].

- DT has great potential to provide for a digital environment where future generation networks like 6G can evolve. Integrating DT within mobile networks is gaining popularity in the industry from major tech companies like Ericsson, Huawei and Nokia [155].

# 5. Digital Twin: Use Cases and Services

## A. Use Cases – Towards 5G/6G With Digital Twin


**Fig. 8. The vision for DT-enabled next generation communications.**

- DT has the capability to continuously monitor and analyze the performance of the network, predict any unanticipated failures and optimize the network performance by triggering intelligent decisions accordingly.
- Figure 8 illustrates a vision of the 6G DT that facilitates the live virtual replica of the whole or parts of the 6G network to perform continuous monitoring and assessment through a closed loop process between the physical entities and the digital counterparts. The 6G DT powered by AI will enable design and performance improvements and real time optimized operations enforced on the physical 6G network.

# 5. Digital Twin: Use Cases and Services

## B. Services – Anomaly Detection

- It is observed that uni variate or multi-variate models with single or multi step detection models have significant effect on Anomaly detection applications performance.
- The primary sources of data for such anomaly detection applications are derived from industry runtime data from the connected IoT devices or historical data from database logs available.
- Data set identification and creation based on the user specific applications is also determining factor to improve the performance of the anomaly detection application.

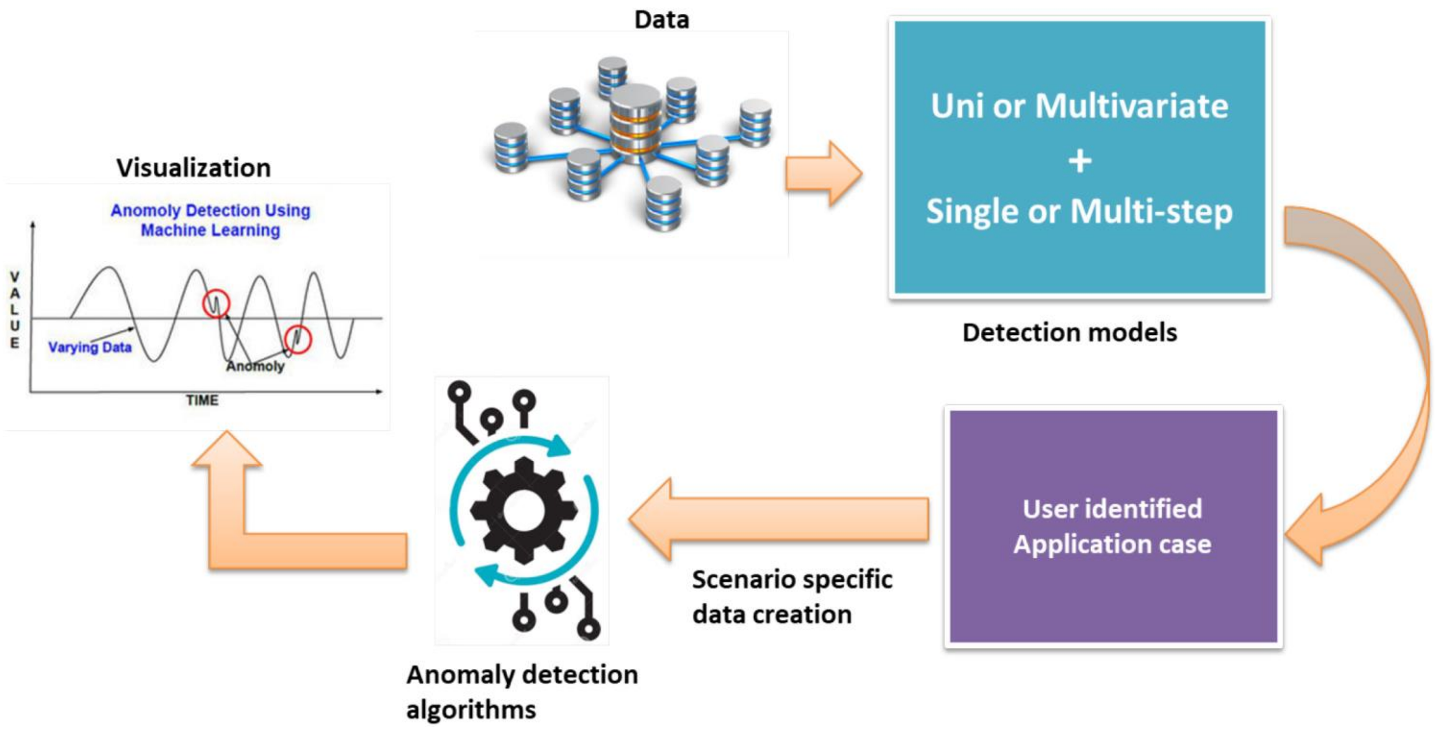


Fig. 9. DT application: Anomaly Detection Framework.

# 5. Digital Twin: Use Cases and Services

## B. Services – Predictive Maintenance

- The advantages in terms of cost, time, and resources that PdM can demonstrably bring to the industry have been long sought-after.
- Significant research effort has already been invested into developing working architectures that can accurately predict a machine’s failure (i.e., self-diagnosing).
- Wang et al. [164] proposed a basic architecture that outlines the components of a PdM system’s pipeline: data acquisition, data analysis & state detection, health assessment and prognosis, and maintenance actions & alerts.
- Although at a first glance these functional blocks might seem rudimentary, they in fact represent the founding pillars that support PdM services, and they are predominant in many framework proposals to this day.
- Liang et al. in [170] proposed a layered architecture for a low latency deployment of a Convolutional Neural Network (CNN)—based prognosis system.

# 5. Digital Twin: Use Cases and Services

## B. Services – Predictive Maintenance

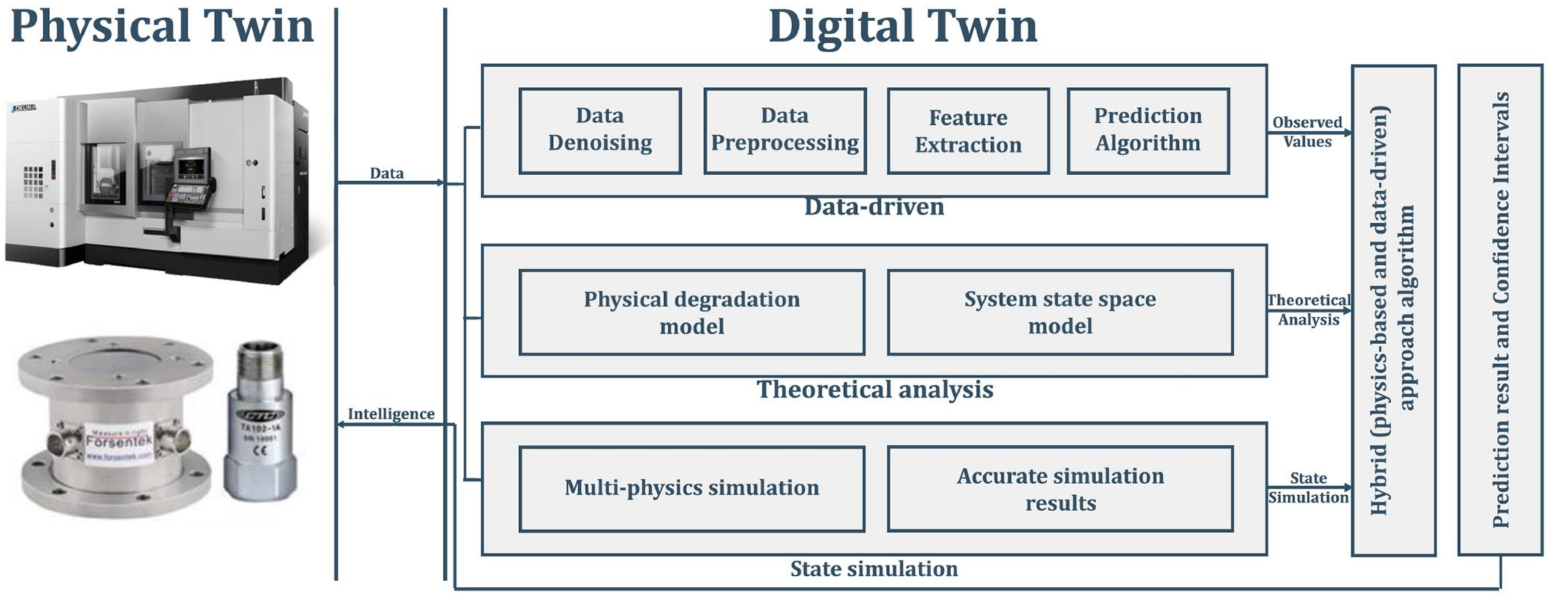


**Fig. 10. DT-based PdM scheme using hybrid modeling.**

- A compromise between the complex, but transparent physics-based models and efficient, but opaque data-driven models, are hybrid models, where researchers have used both approaches simultaneously in order to leverage the advantages from both of them.
- In this context, Luo et al. [171] have proposed a DT-based PdM scheme that uses physics-based degradation and simulation models to generate theoretical baselines for the machine state, as well as data-centric models that consume real-time streams of data from the sensors installed in the machine.

# 6. Digital Twin: Case Studies

## A. A Look at the Tea Industry in India

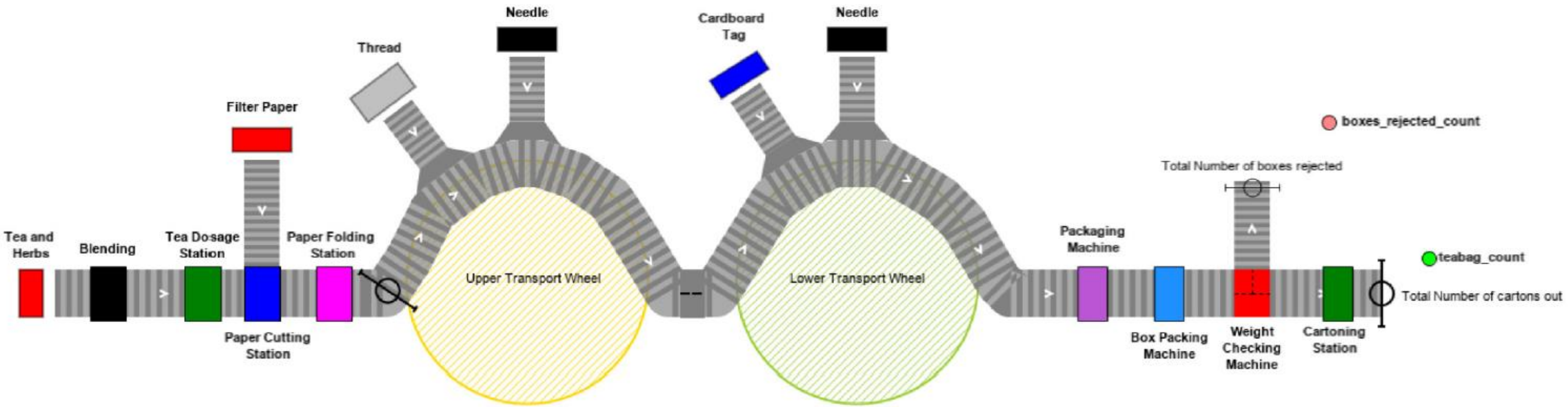


**Fig. 11. Conveyor Belt Snapshot of a Tea Manufacturing Plant.**

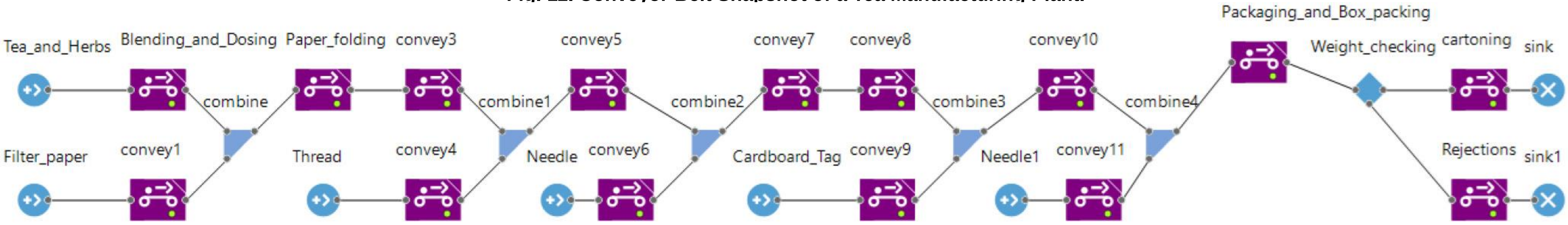


**Fig. 12. Steps in the Process of Tea Manufacturing.**

# 6. Digital Twin: Case Studies

## B. Festo Cyber-Physical Factory

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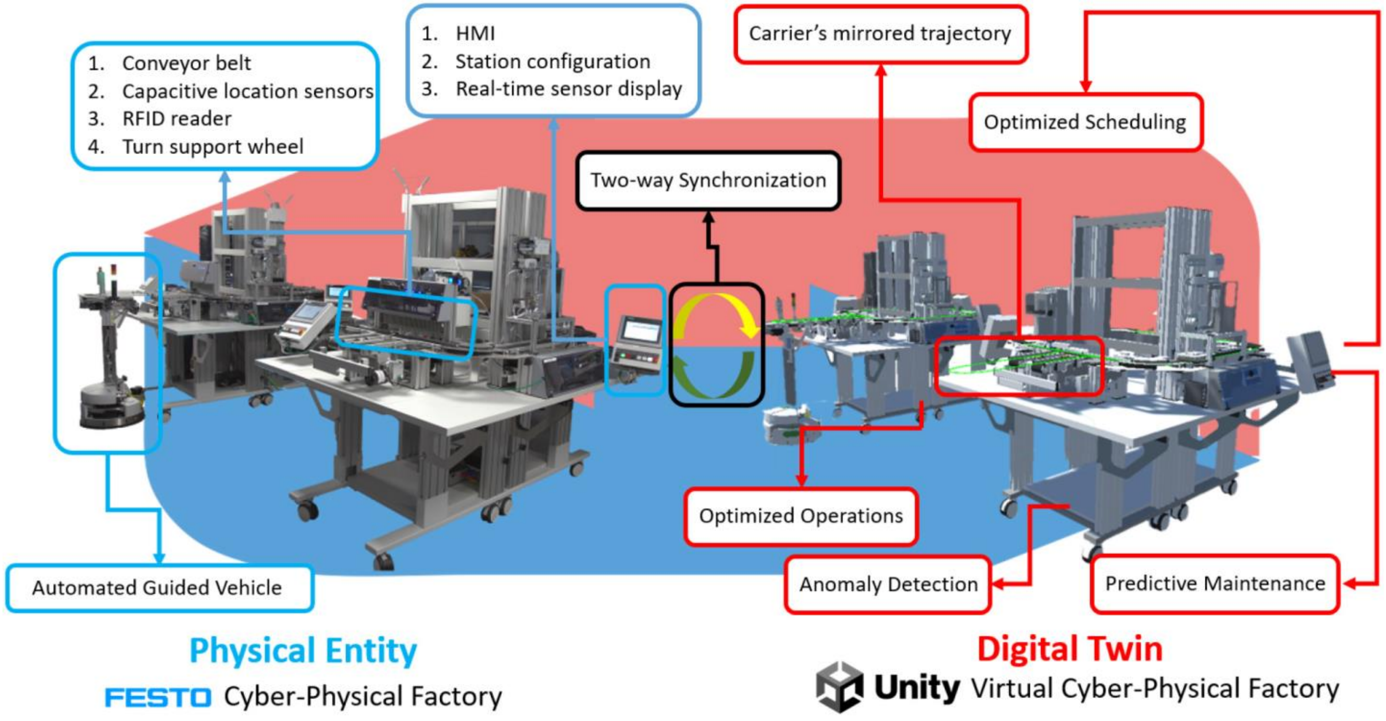
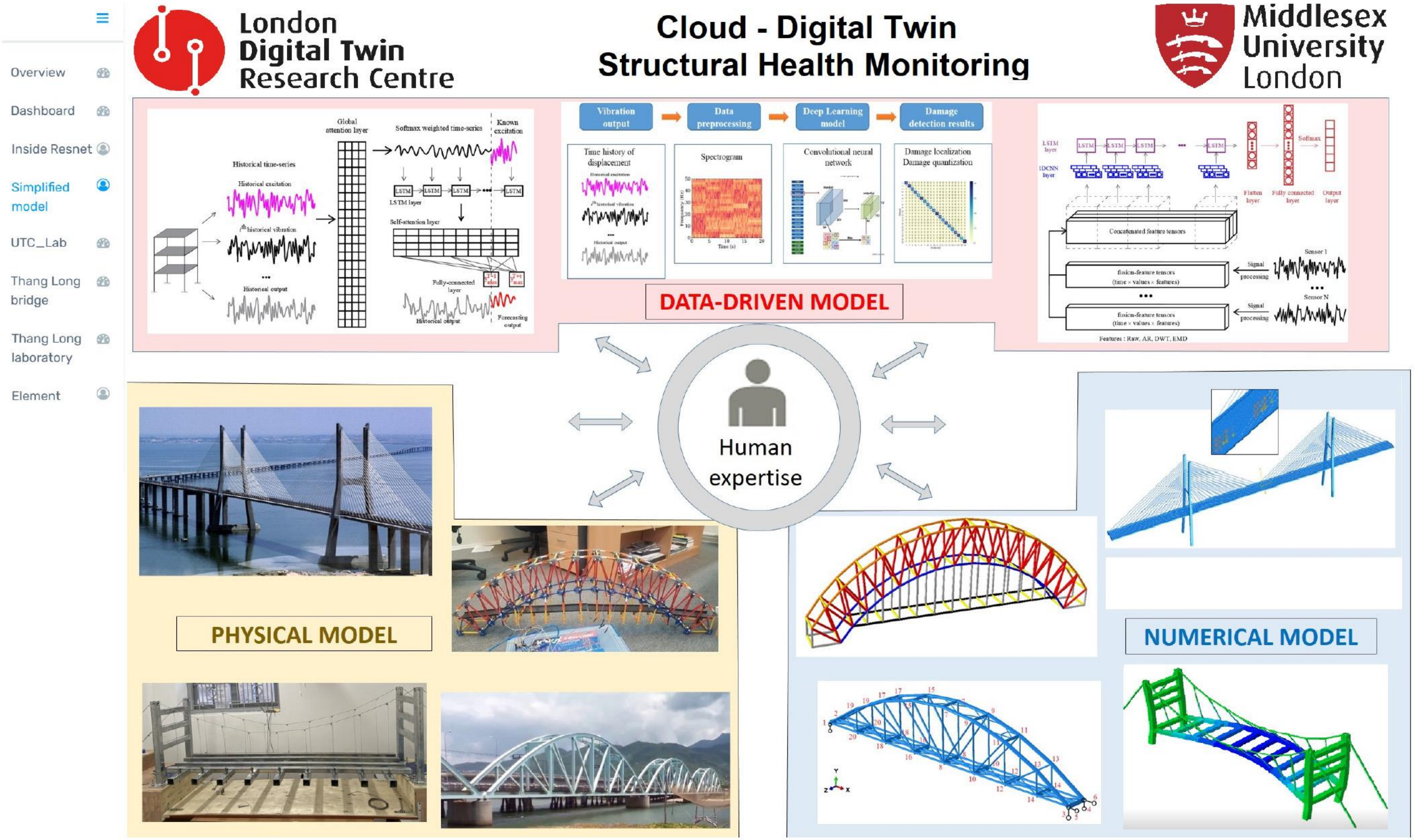



**Fig. 13. Digital Twin in I4.0.**

# 6. Digital Twin: Case Studies

## C. Structural Health Monitoring for Vietnam bridges



# 7. Lessons Learned, Research Challenges and Future Directions

## A. Investment Costs

- Businesses still remain reluctant to implement the DT because of its envisioned development costs and difficult-to-quantify ROI.

- As a matter of fact, it is rather challenging to put a price on the DT because of its multi-disciplinary nature and use-case-specific particularities.

- Additionally, the DT is rarely a product that generates directprofit, since its core philosophy focuses primarily on saving costs.

- With the exception of DT solution providers and the healthcare industry, where the DT can indeed be a source of revenue, other entrepreneurs will need detailed and longterm plans of investment that emphasize the merits of DT development before diving into such expenditures.

# 7. Lessons Learned, Research Challenges and Future Directions

## B. Social and Ethical Challenges

- DTs of phenomena that include human interactions and behaviours acquire complexity simply due to the involvement of multiple disciplines.
- For example, DT models of cities for monitoring pandemic behaviour have included social geographers, economists, medical practitioners as well as computer scientists.
- Arriving at a shared understanding, common language and a way of working demands new methodological approaches as well as intuitive access to underpinning theory from different disciplines.
- STDTs can be used for discovering new questions, demonstrating trade-offs or experimentation with prevailing theories that lack empirical understanding.
- The complexity, multi-level and range of modelling required to represent a socio-technical problem domain within a DT require choices to be made in determining the scope and detail of the environment to be modelled.

## C. Fidelity and Rate of Synchronization

- A common misconception about the DT is that the virtual twin should reflect the physical twin in its entirety, and that it should gather and process all of its data in almost real-time.

- However, these feats are not currently feasible, and certainly not always necessary.

- As specified in our definition of the DT, provided in Section II, the virtual representation’s fidelity and rate of synchronization are specific to the DT’s use-cases.

- As such, the DT’s granularity and twinning rate requirements can be more, or less, lenient, depending on its applications. The more stringent demands for real-time, granular mirroring could be encountered in the healthcare industry, for scenarios where the DT is used to facilitate remote surgery.

# 7. Lessons Learned, Research Challenges and Future Directions

## D. Standardisation Efforts

- One of the most important features that could accelerate the adoption of DTs within various industries is their modularity. This could enable the rapid reproduction of DT processes and their components.
- However, this dynamic environment could become very complex, with different digital twins custom built for different purposes, specific equipment type, specific manufacturers, etc., these represent factors that could inhibit the adoption and implementation of DTs acrossmultiple industries. These complexities could be eliminated through standardisation.
- Recently, one of the subcommittees of the Joint International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC) Technical Committee has widened its scope and terms of references to include DT, looking now into standardization in the area of IoT and DTs, including their related technologies.
- The ISO 23247-14 standard for DT framework for manufacturing is currently under development.
- Consequently, the current lack of standardised approaches when modelling digital twins open up new challenges when dealing with their interoperability in order to maximize the interconnectivity.

# 7. Lessons Learned, Research Challenges and Future Directions

## E. Data Ownership and Governance

- One of the most important features that could accelerate the adoption of DTs within various industries is their modularity.As a matter of fact, it is rather challenging to put a price on the DT because of its multi-disciplinary nature and use-case-specific particularities.
- This could enable the rapid reproduction of DT processes and their components.
- The IDS(Industrial Data Space) concept represents a virtual data space that enforces data ownership within a distributed environment, based on open standards and existing technologies as well as common governance models for data economy.
- As DTs are seen as part of I4.0, the IDS model could be the answer for DTs data ownership and governance.
- In parallel, an effort for constructing an Information Management Framework (IMF) for the National Digital Twin is carried out in [197], where the goal is to create a common national information resource that can sustain a country-wide DT.

## F. Data Security

- The first one addresses the security of the DT itself, starting from the physical servers that host the DTs up until the safety and integrity of the software and data communication links that animate the DT.
- The second approach is about how the DT itself can provide security to its real twin, as an additional valuable offering. This section will touch on both of these aspects of security within DTs.
- One of the central components of a DT is the communication medium that enables the symbiotic relationship between the physical and virtual twins. This link effectively transports all the data between the two entities, so it stands to reason that it needs to guarantee impeccable data security.
- Every time data flows to, and from, the real twin, or in-between the servers hosting the DT itself, the risk of losing important information is high, which calls for increased attention to preserving data integrity [198].

# 7. Lessons Learned, Research Challenges and Future Directions

## G. Artificial General Intelligence, Beyond Human Performance

- McCarthy’s proposal identified AI as a machine that behaves “in ways that would be called intelligent if a human were so behaving”, whereas nowadays, AI is sometimes used to refer to systems that reach or surpass human performance in specific tasks [206], [207]. The former interpretation corresponds to what is today understood as Artificial General Intelligence (AGI), while the latter is an appropriate example of Artificial NarrowIntelligence (ANI).

- In order for the DT to become truly self-evolving, just like humans and animals are, it needs to be able to implement a level of creativity that can make maximal use of its physical twin’s unique features.

- Validation metrics aside, while current AI systems can definitely learn to perform tasks even beyond human-level performance, they also lack comprehension, and therefore cannot offer transparency into their “reasoning” [208]. This lack of transparency invokes skepticism, and can even impede development of DTs or Ais due to lack of trust.

# 8. Conclusion

- This paper took an in-depth look at the existing and expanding Digital Twin-related literature, and we drew some lessons that will help the researchers in this field consolidate their understanding of the DT and choose future directions that need further development.
- Overall, the DT finds itself accelerating in full force towards I4.0, and its endless perceived potential makes it a central and evermore popular player in the race.
- Its enabling technologies are continuously evolving, and each step towards their improvement brings us closer to making true DTs a reality.
- In the era of AI, the focus falls on the data, and the DT finds itself in the middle of an information loop: it needs to be fed carefully considered data to power its complex ML algorithms, and then it further allows a better understanding of that data via its interactive and predictive feats.
- With some challenging puzzles in the way, the DT is steadily heading towards the automation of industrial processes.

# Thank you

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