Harvesting the Power of Digital Twins

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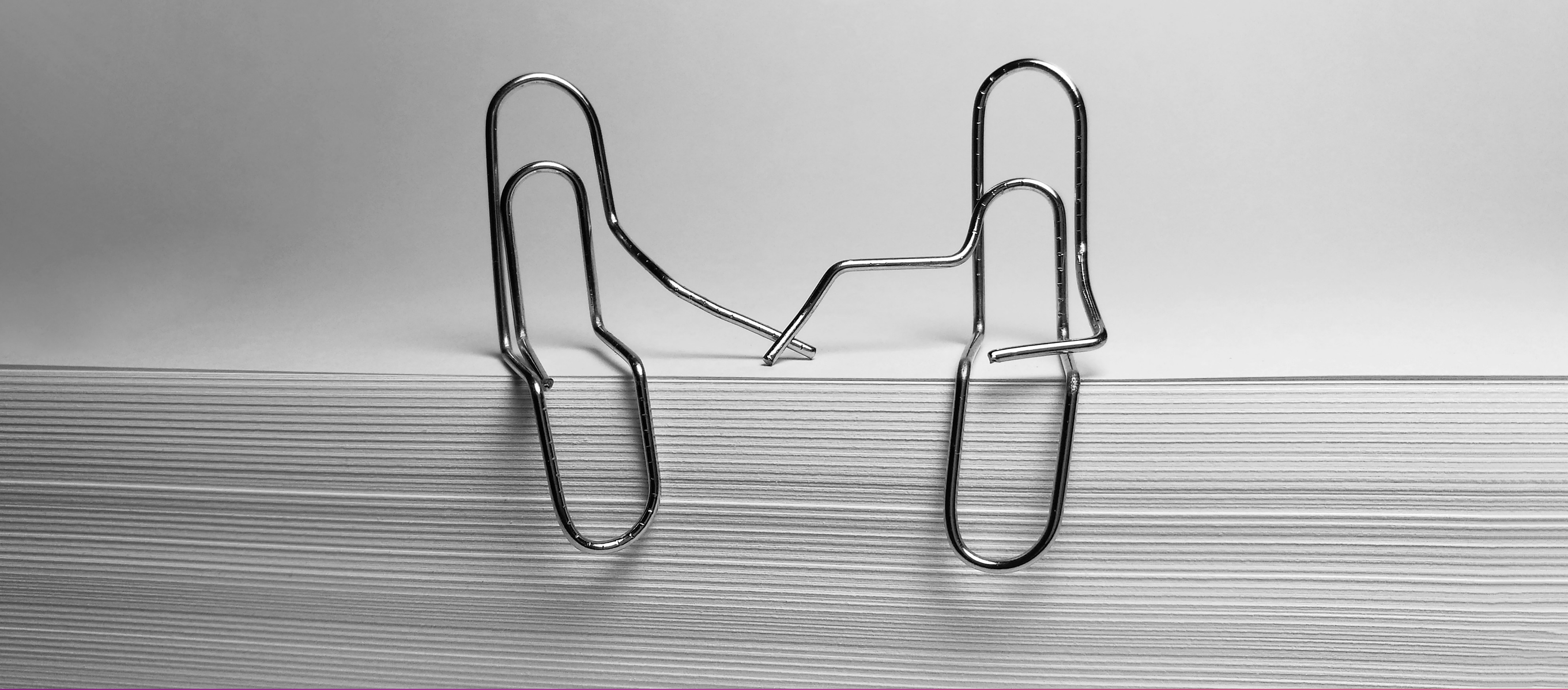
Human Digital Twins for fostering Prosocial Behaviour (HDT-PROSOCIAL) PID2022-140907OB-I00 funded byMICIU/AEI/10.13039/501100011033/ y por FEDER, UE.



Digital Twins

Introduction

What is a Digital Twin?

Digital Model — Manual flow → Physical Twin

Physical Twin — Manual flow → Digital Model

- **Digital representation** of an element, process, or system of the physical space (physical twin).

Andreas Wortmann.
"**Digital Twins Definitions**" (112 definitions 😱 😱)

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IFAC-PapersOnLine
Volume 51, Issue 11, 2018, Pages 1016-1022

Digital Twin in manufacturing: A categorical literature review and classification

Werner Kritzinger, Matthias Karner, Georg Traar, Jan Henjes, Wilfried Sihn

Image cc: https://www.linkedin.com/pulse/storytelling-digital-twin-leyla-farah-gxzjc/

What is a Digital Twin?

Digital Shadow — Manual flow → Physical Twin

Digital Shadow ← Automatic flow — Physical Twin

- Digital representation of an element, process, or system of the physical space (physical twin).
- **Synchronizes** the physical and cyber worlds so when something happens in the physical world, the DT is updated to reflect the new information


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What is a Digital Twin?

Digital Twin → Physical Twin

Automatic flow

Physical Twin → Digital Twin

Digital Twin:

- Digital representation of an element, process, or system of the physical space (physical twin).
- **Synchronizes** the physical and cyber worlds so when something happens in the physical world, the DT is updated to reflect the new information
- Interacts continuously with its physical twin to **control** or **predict** its **behavior**

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Do Digital Twin exist?

Digital Twin → Automatic flow ← Physical Object

21,3 % (356)

17 % (140)

Journal of Systems and Software
Volume 193, November 2022, 111361

A Cross-Domain Systematic Mapping Study on Software Engineering for Digital Twins ☆

Manuela Dalibor [a] [1], Nico Jansen [a], Bernhard Rumpe [a], David Schmalzing [a], Louis Wachtmeister [a], Manuel Wimmer [b], Andreas Wortmann [c]

2023 IEEE 20th International Conference on Software Architecture (ICSA)
13-17 March 2023

Standardisation in Digital Twin Architectures in Manufacturing

Enxhi Ferko; Alessio Bucaioni; Patrizio Pelliccione; Moris Behnam

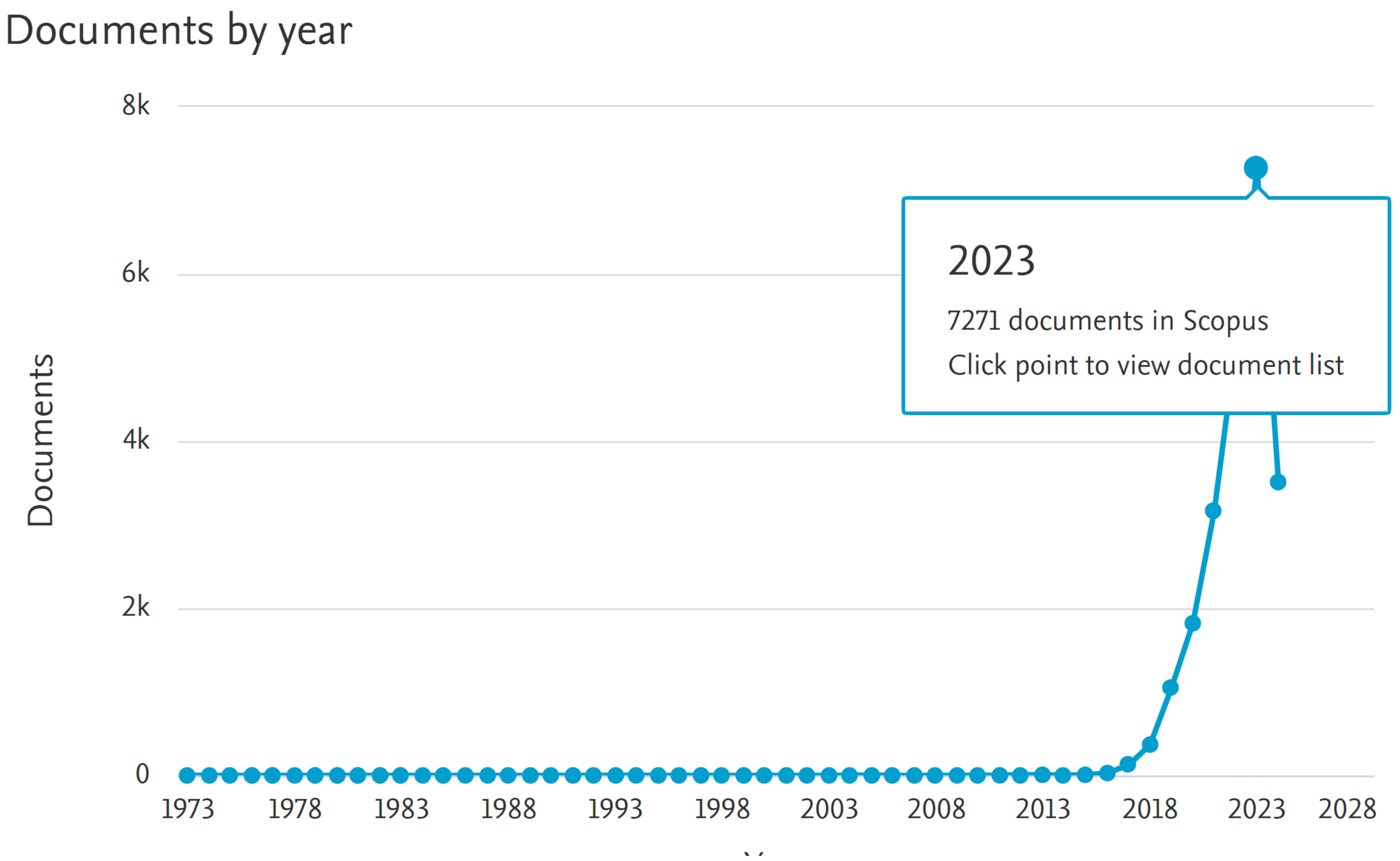
Image cc: https://www.linkedin.com/pulse/storytelling-digital-twin-leyla-farah-gxzjc/

Benefits and Purposes of Digital Twins

Promise

- Increase of 15% in efficiency
- Reduction of 13% in maintenance costs
- Digital twin market is expected to grow from $3.5 billion in 2020 to $73.5 billion by 2027

Research


Documents by year
8k
6k
4k
2k
0
Documents
1973
1978
1983
1988
1993
1998
2003
2008
2013
2018
2023
2028
2023
7271 documents in Scopus
Click point to view document list

Manufacturing

Scheduling Optimization

- **Deep Reinforcement Learning algorithms**: K. Xia, C. Sacco, M. Kirkpatrick, C. Saidy, L. Nguyen, A. Kircaliali, and R. Harik, “A digital twin to train deep reinforcement learning agent for smart manufacturing plants: Environment, interfaces and intelligence,‘’ J. Manuf. Syst., Jul. 2020

Quality control

- **Artificial Neural Networks**: S. Zhang, C. Kang, Z. Liu, J.Wu, and C. Ma, “A product quality monitor model with the digital twin model and the stacked auto encoder,'' IEEE Access, vol. 8, pp. 113826113836, 2020.

Prototyping

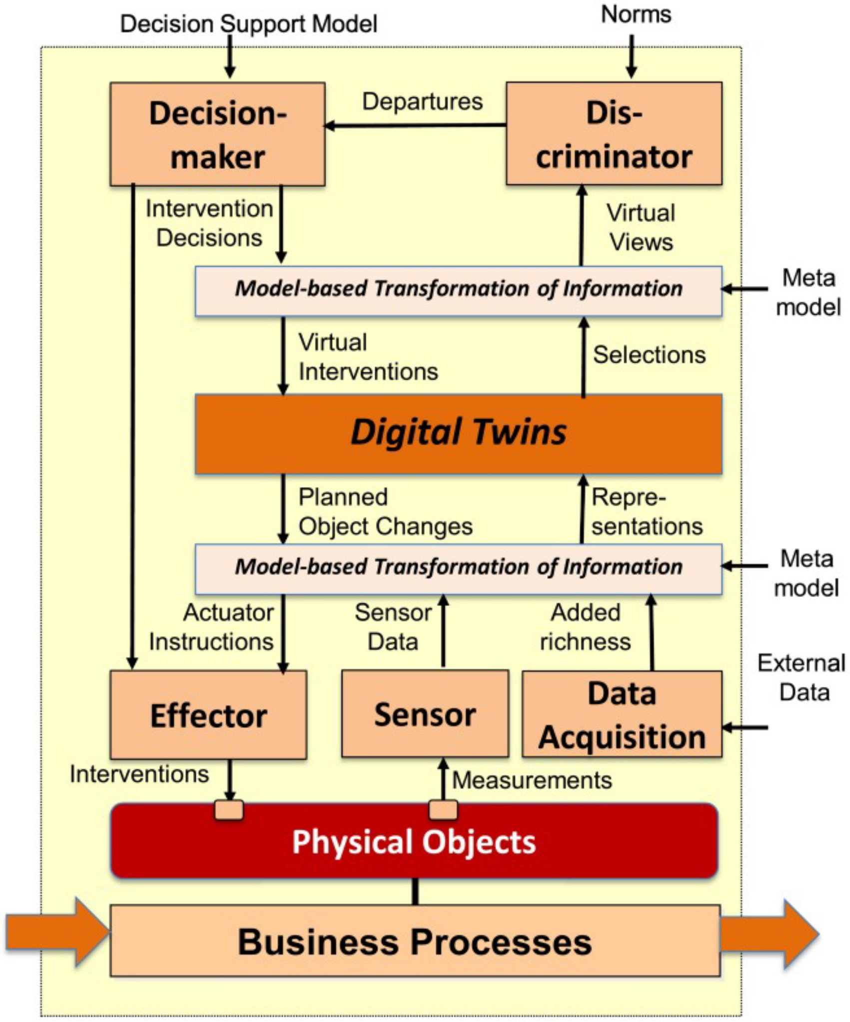
- **Machine Learning**. F. Tao, J. Cheng, Q. Qi, M. Zhang, H. Zhang, and F. Sui, “Digital twin driven product design, manufacturing and service with big data,'' Int. J. Adv. Manuf. Technol., vol. 94, nos. 912, pp. 35633576, Feb. 2018

Prognostics and Health Management (PHM)

- **Artificial Neural Networks**: F. Tao, M. Zhang, Y. Liu, and A. Y. C. Nee, “Digital twin driven prognostics and health management for complex equipment,'' CIRP Ann., vol. 67, no. 1, pp. 169172, 2018.

Agriculture

- Optimize
  - irrigation
  - resources usages
  - machinery
  - crop yield
  - animal welfare (farms)



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Agricultural Systems
Volume 189, April 2021, 103046

Digital twins in smart farming

Cor Verdouw [a b], Bedir Tekinerdogan [a], Adrie Beulens [a], Sjaak Wolfert [a c]

Urban Planning

PFG (2020) 88:99–112
https://doi.org/10.1007/s41064-020-00092-2

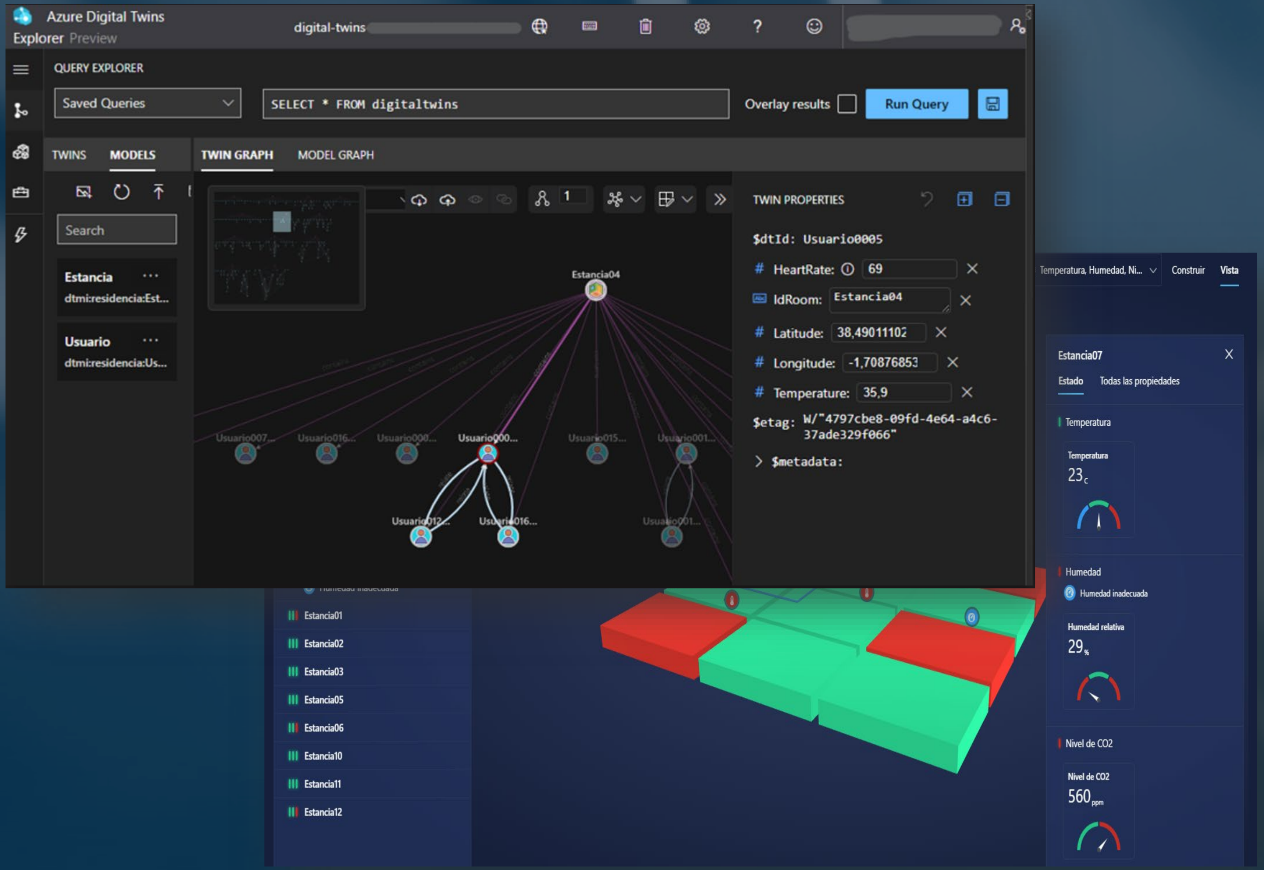
ORIGINAL ARTICLE

The Digital Twin of the City of Zurich for Urban Planning

Gerhard Schrotter[1] · Christian Hürzeler[1]

- Optimize:
  - City infrastructure
  - Traffic flow
  - Energy consumption
- Create better community
- Existing prototypes for cities in Singapore, Turkey, Australia, New Zealand, and many in the EU: Amsterdam, Cambridge, Palermo, Paris, Cartagena, ...

Healthcare



- Design:
  - Drug Development
  - Virtual Organs
- Planning surgeries
- Optimization of hospital lifecycle
- Personalized healthcare
- Diseases Control and Prevention

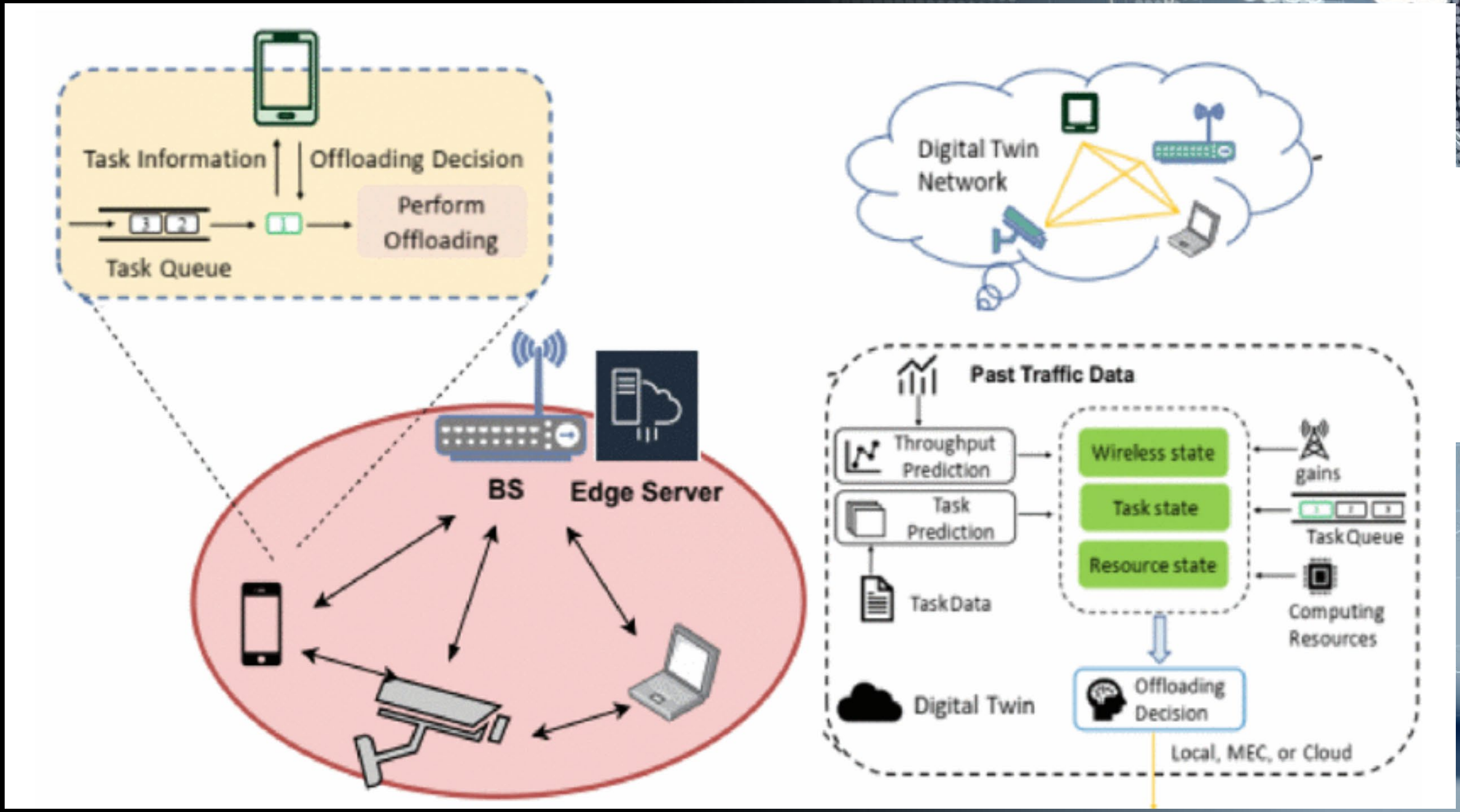
Springer

Home > Proceedings of the International Conference on Ubiquitous Computing & Ambient Intelligence (UCAmI 2022) > Conference paper

Digital Twins-Based Data Fabric Architecture to Enhance Data Management in Intelligent Healthcare Ecosystems

Aurora Macías, David Muñoz, Elena Navarro & Pascual González

Information and Communication Technologies



Perspectives of Digital Twin-Empowered Distributed Artificial Intelligence for Edge Computing

Publisher: IEEE Cite This PDF

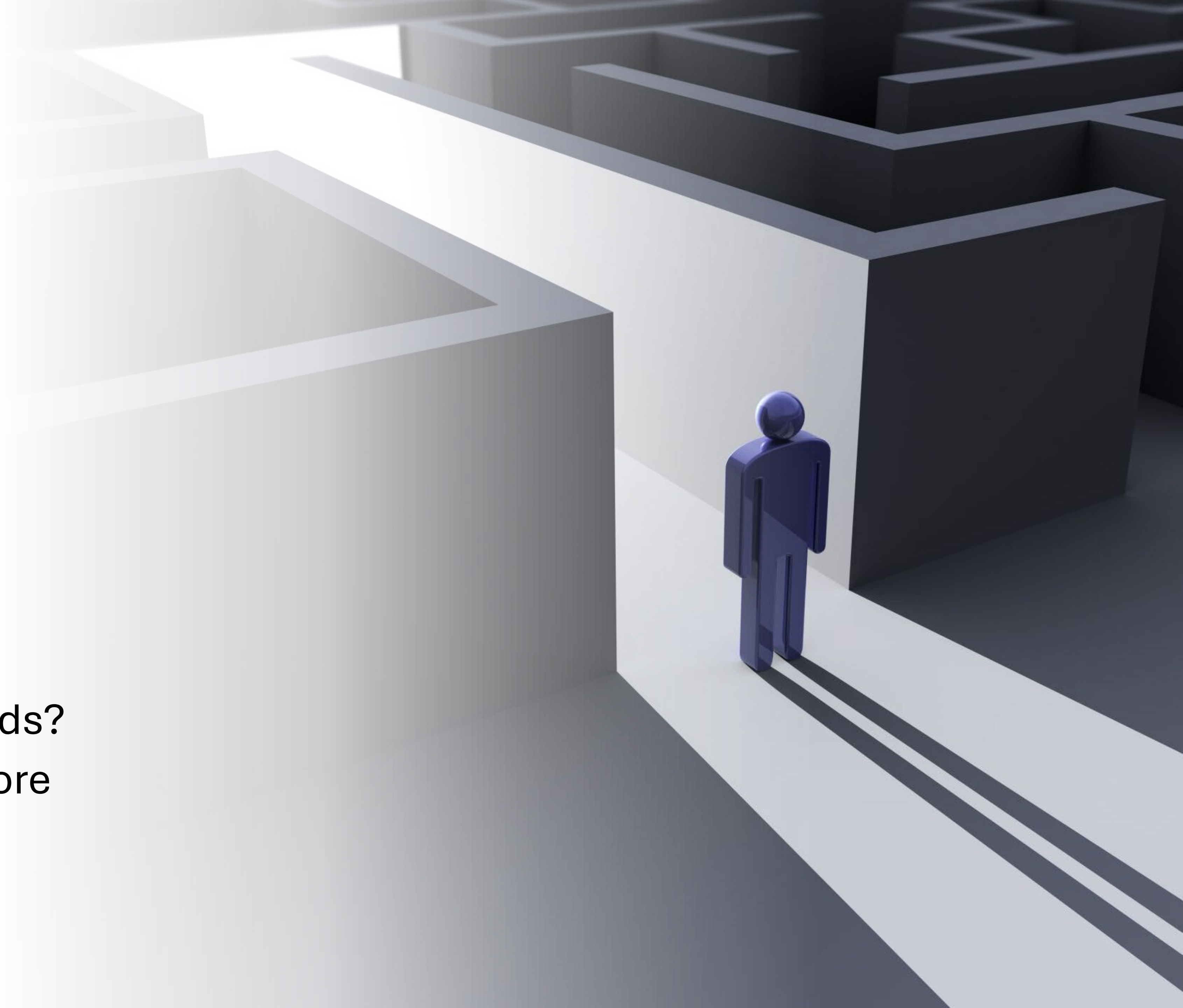
Hoa Tran-Dang ; Dong-Seong Kim **All Authors**

Developing Digital Twins

Main challenge

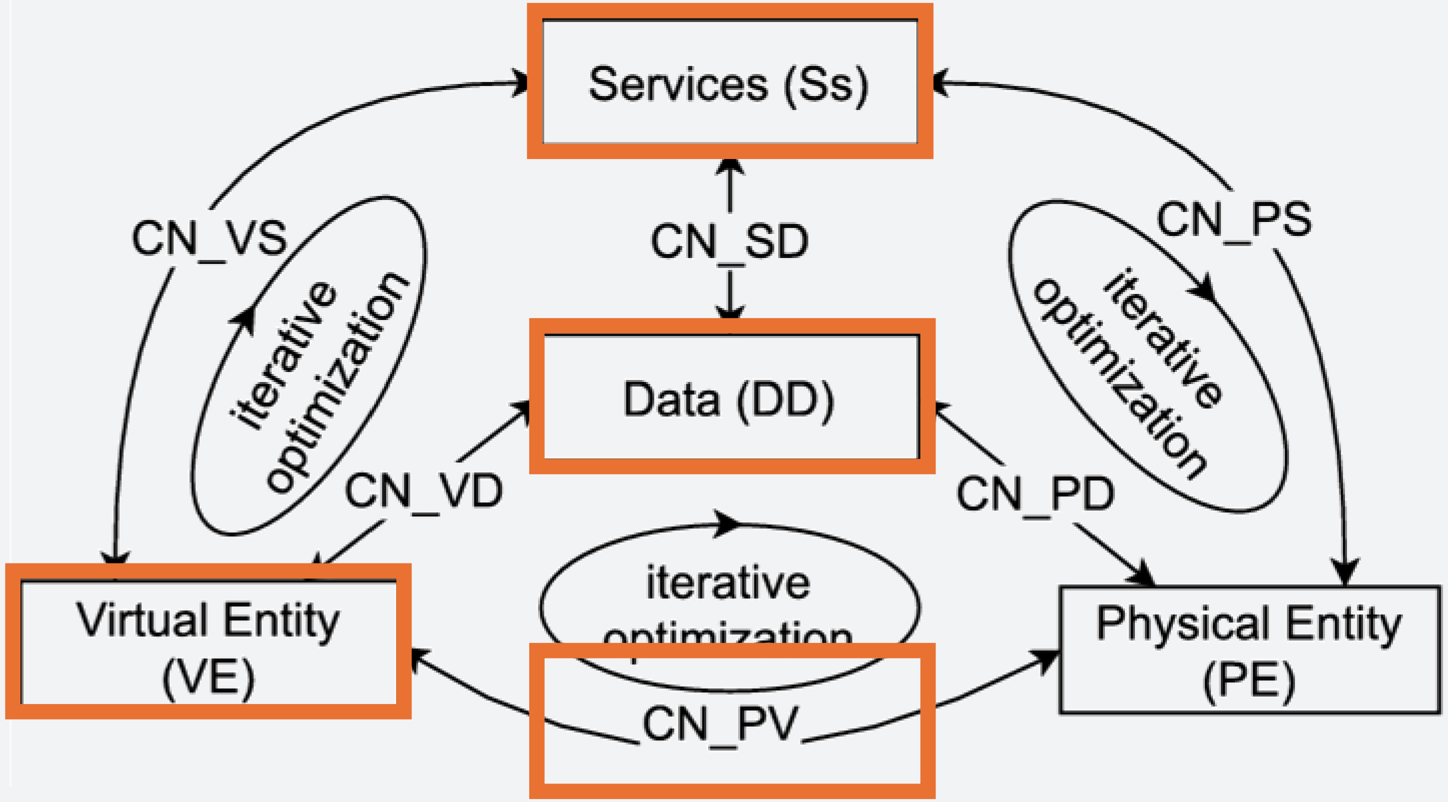
Developing DT

- How are DT developed?
- How are DT validated and verified?
- How are DT maintained?
- Are there suitable standards?
- Which Frameworks are more frequently used for DT development?



Developing DT

- Few domain-agnostic proposals
- There are no proposal empirically evaluated (low maturity level)
- Not a common understanding about **which components** a DT should have
- Just an agreement about, at least, **model**, **data**, **sync**, and ***services***



ELSEVIER
CIRP Annals
Volume 67, Issue 1, 2018, Pages 169-172

Digital twin driven prognostics and health management for complex equipment

Fei Tao [a], Meng Zhang [a], Yushan Liu [a], A.Y.C. Nee [(1) b]

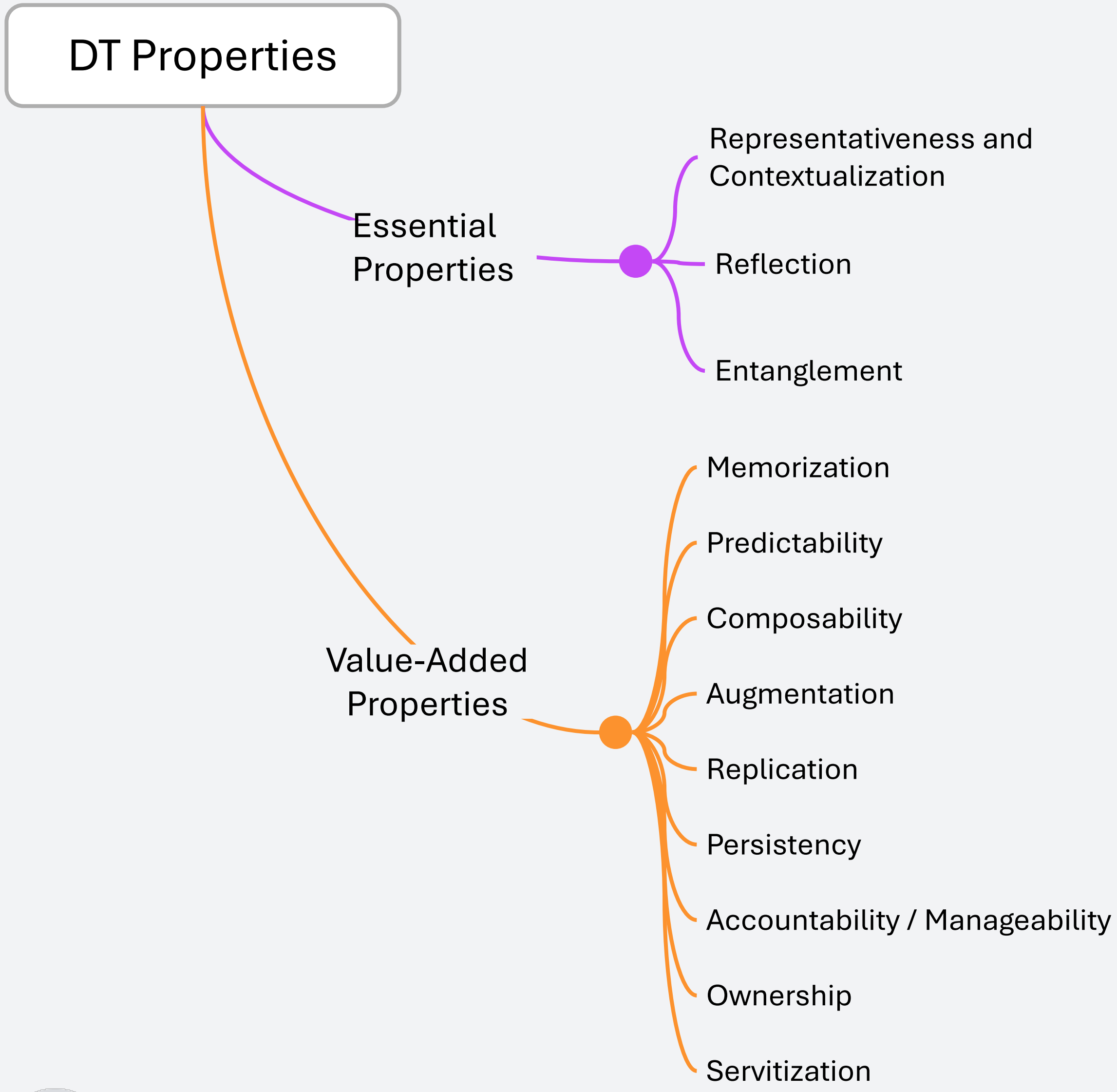
Developing DT

ELSEVIER

Information and Software Technology
Volume 174, October 2024, 107503

Analysing the synergies between Multi-agent Systems and Digital Twins: A systematic literature review

Elena Pretel, Alejandro Moya, Elena Navarro, Víctor López-Jaquero, Pascual González



Proceedings of the IEEE

Digital Twin in the IoT Context: A Survey on Technical Features, Scenarios, and Architectural Models

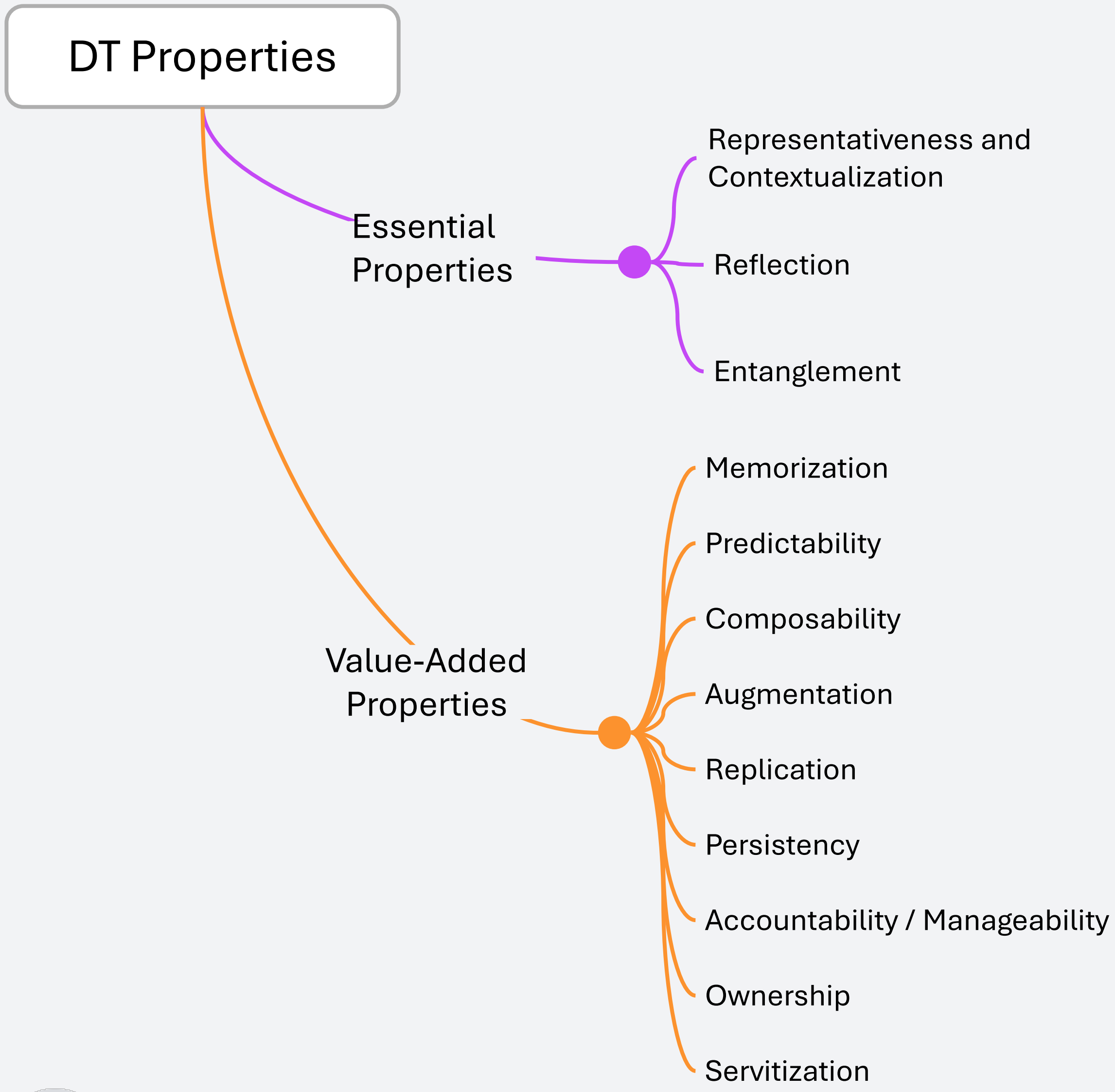
Roberto Minerva; Gyu Myoung Lee; Noël Crespi
Publication Year: 2020 , Page(s): 1785 - 1824
Cited by: Papers (339)

Developing DT

2023 IEEE 20th International Conference on Software Architecture (ICSA)
13-17 March 2023

Architecting Digital Twins Using a Domain-Driven Design-Based Approach*
Aurora Macías; Elena Navarro; Carlos E. Cuesta; Uwe Zdun
Publication Year: 2023 , Page(s): 153 - 163

- Why?
  - Domain-agnostic
  - Framework Independent
  - Empirically evaluated
  - Defined according to a **conceptual framework**



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Roberto Minerva; Gyu Myoung Lee; Noël Crespi
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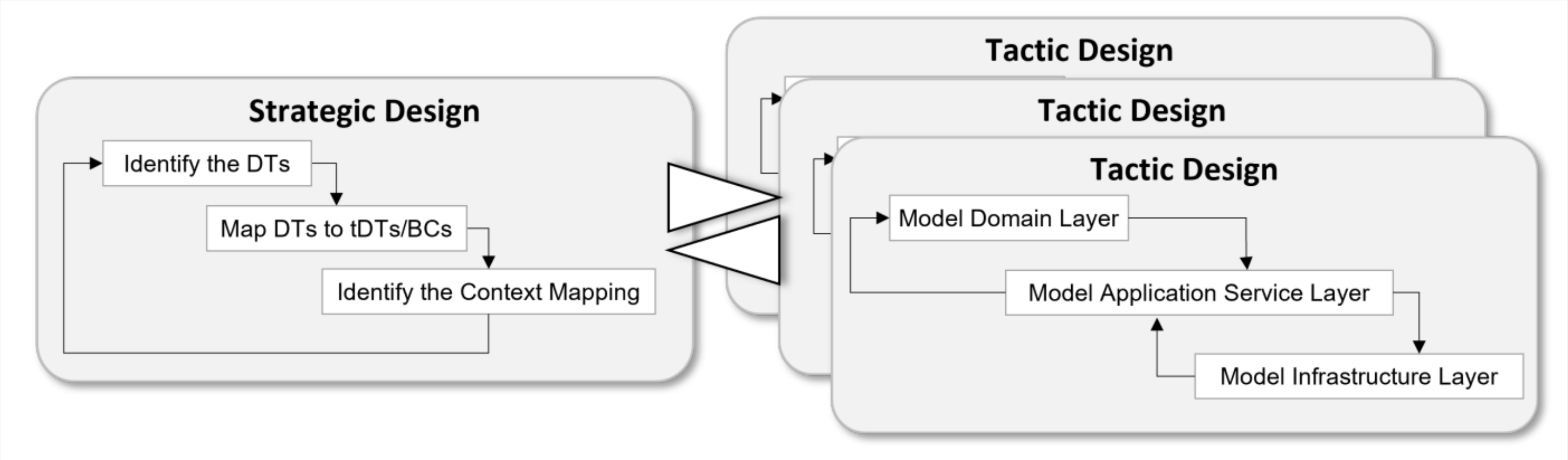
A DDD-inspired Proposal for Architecting Digital Twins

The DDD-inspired proposal provides a **method for identifying**

- the corresponding **types of DTs** (tDT)
- the description of their **internal structure** and **domain model**
- the connection pattern, that is, the **relationships** among tDTs

Strategy: defines **boundaries** and **relationships**

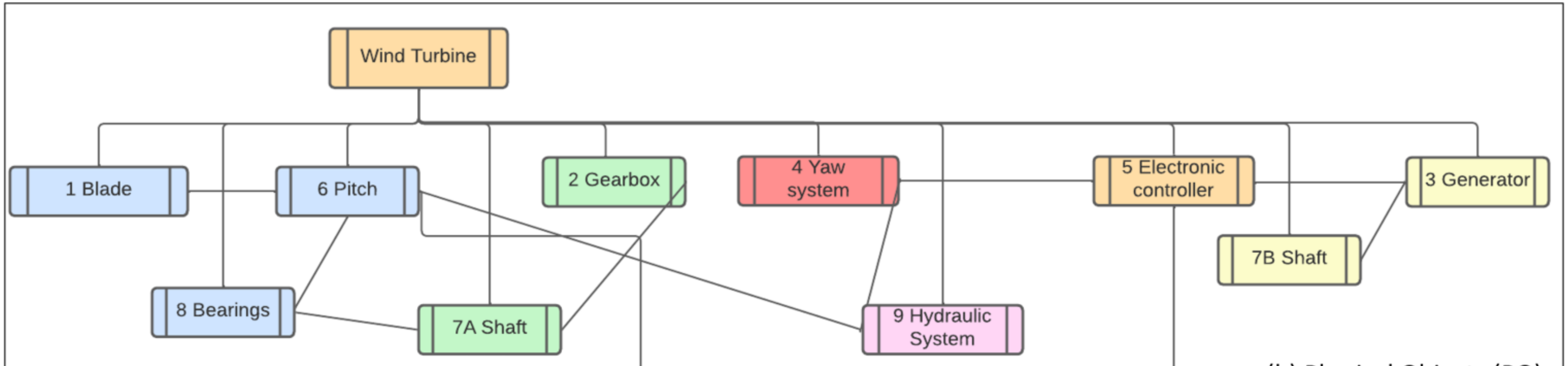


Tactics: describe the internal **architecture** of each DT

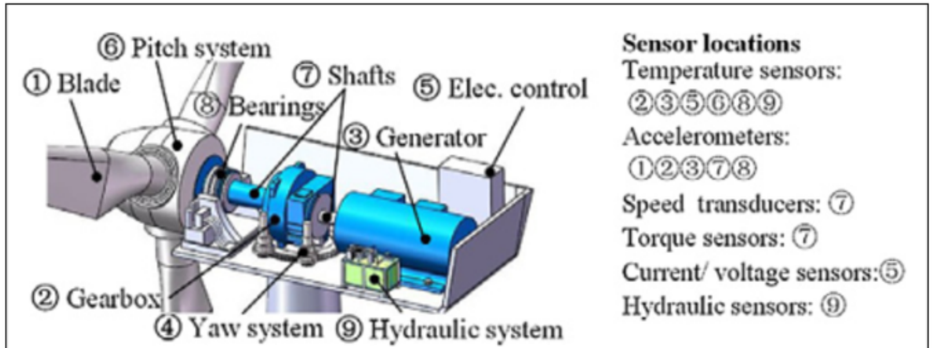
Strategic Design

1. **Identify DTs**
   Likely **contexts of use**/**Bounded Contexts** regarding time and space: a different DT for each one.
2. **Map types of DTs to Bounded Contexts (BCs)**
   Different **types of DTs** (tDT) in the system (not individual DT instances).
   Every tDT ≅ BC works as an **independent system fragment**.
3. **Identity the Context Mapping**
   Interaction among BCs: **integration points** between BCs and **data flow** between them.

Strategic Design: Case Study: Wind Turbine

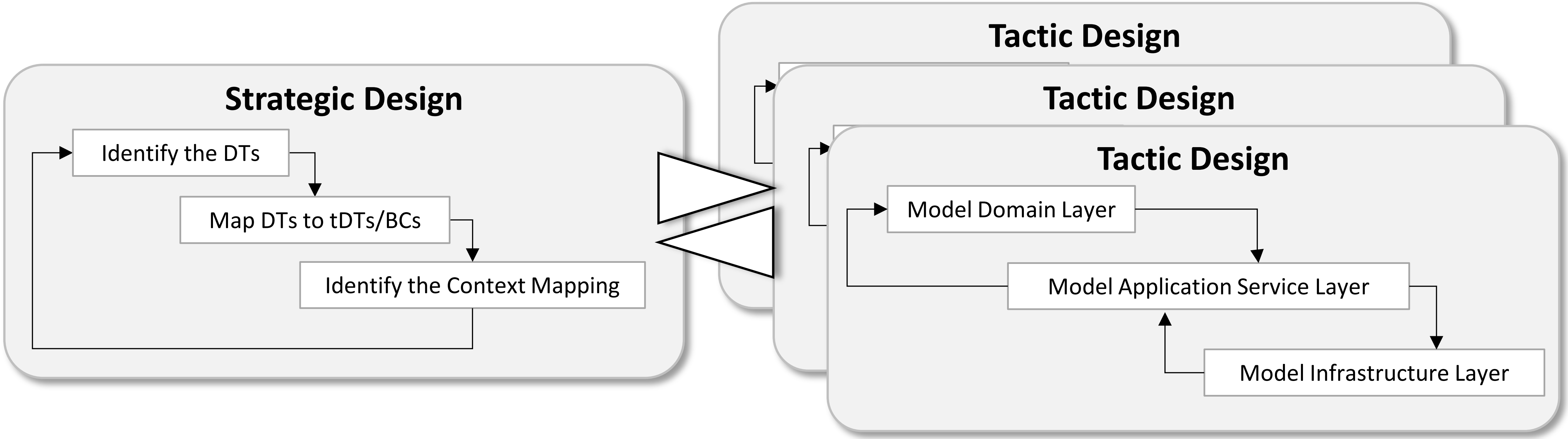


(b) Physical Objects (PO)



(a) Graphical description

Tactic Design

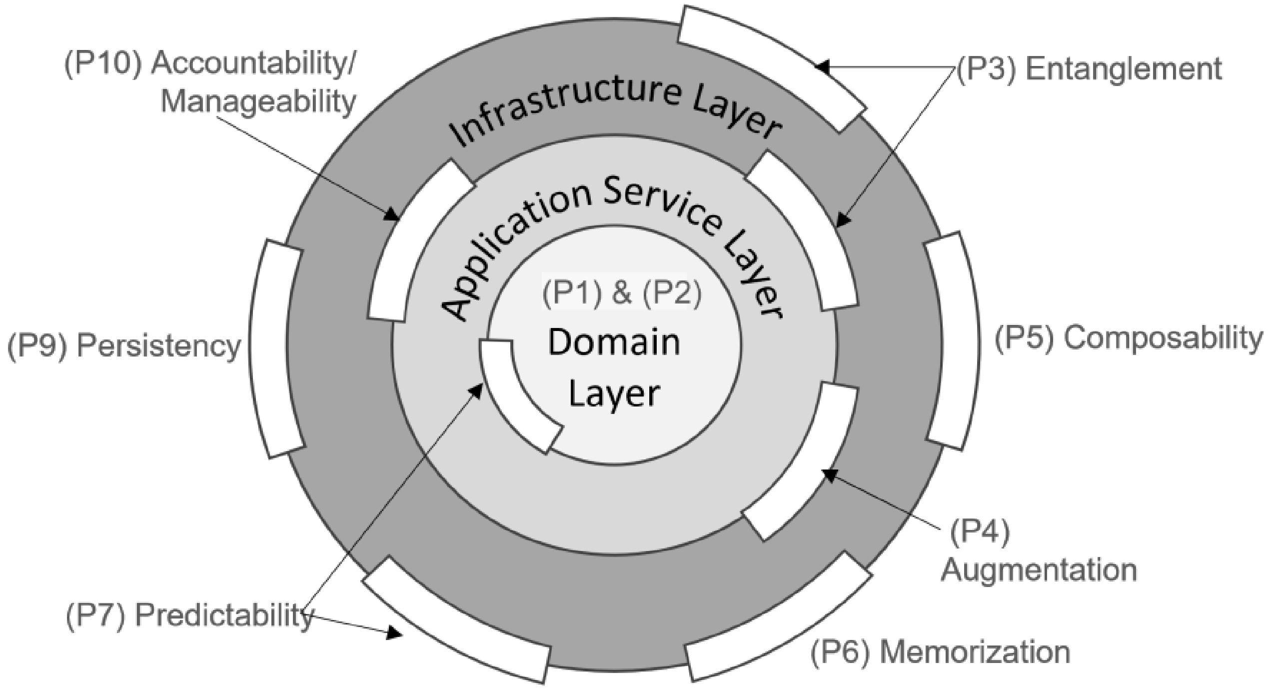


Tactic Design

A **decision tree:** every desired **DT property can be mapped to a certain architectural construction**; the resulting structure would depend on the set of chosen capabilities.

DT Properties	DDD concepts
(P1) Representativeness & Contextualization	Entity Value Object Aggregate
(P2) Reflection	
(P3) Entanglement	Event Sourcing
(P4) Augmentation	Open Host Service
(P5) Composability	Context Mapping Messaging
(P6) Memorization	Event Sourcing Repository
(P7) Predictability	Domain Services Event Sourcing Integration Services
(P8) Replication	Integration Services
(P9) Persistency	Event Sourcing Repository
(P10) Accountability & Manageability	Open Host Service

Trace of DT properties to the Architecture



DT Properties

(P1) Representativeness: the DT must **mimic the status and features** of the physical twin

(P1) Contextualization: **only information and features of the Physical Twin relevant to the context of use**

(P2) Reflection: a physical entity is timely and **univocally represented** using the values of the attributes, status and behaviour of its DT

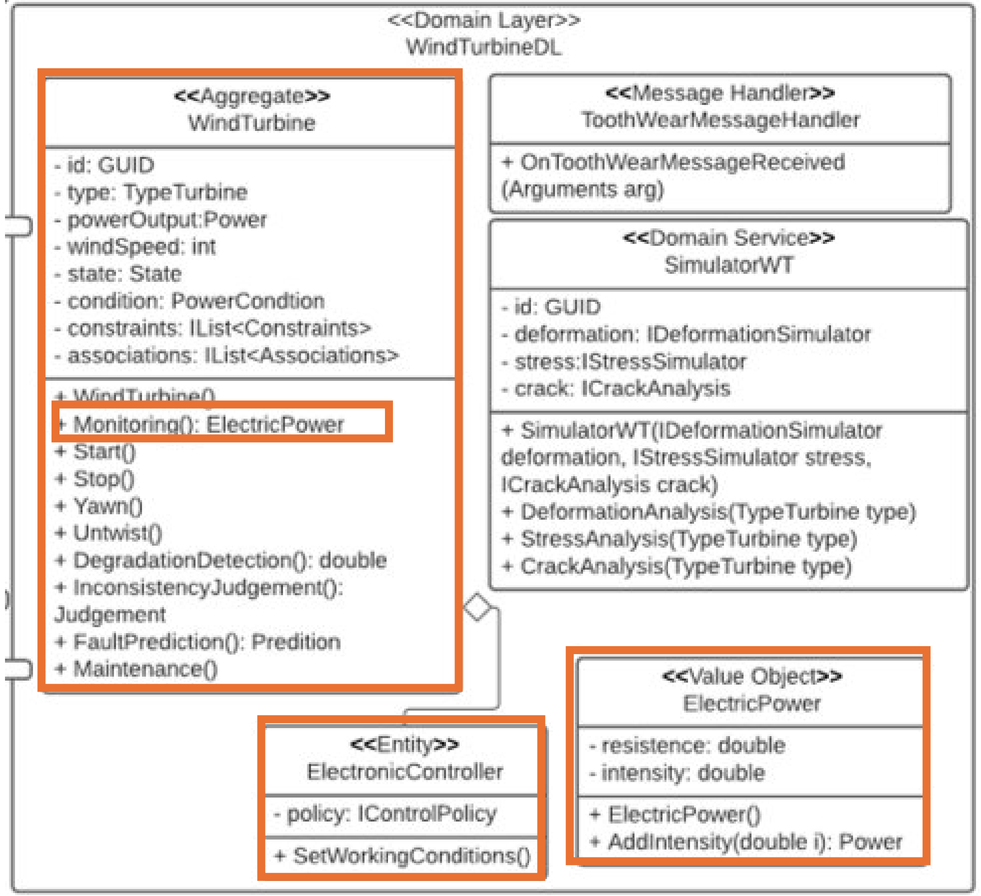
Domain Layer

- Captures the **logic of the domain** to satisfy the use case of the DT. Focus on the DT's **rules, logic and workflows**, without introducing **any technological detail.**
- Responsible for (P1) Representativeness & Contextualization and (P2) Reflection

Entity. Each **concept univocally identified** in the DT's domain model. May be **mutable** over time according to needs, that is, its state may change.

Value Object. Every concept that is **immutable** in the DT. A (complex) **property of an Entity**.

Aggregate. **Composition** of one or more Entities and Value Objects. Used to **maintain transaction consistency** within a DT, that is, to maintain which business rules must be satisfied once a transaction ends.



DT Properties

(P4) Augmentation: the DT can enhance the physical twin by augmenting its functions and features exposing an API that facilitates the management of the PO

(P10) Accountability/manageability: a DT should provide facilities (API) to deal with damages or problems of both its physical twin and itself (as part of the public API)

Research challenges:

- **Augmentation for DT Reuse**: Except for some limited cases, it is not practiced widely due to challenges such as legal restrictions, inadequate tool support, lack of information, and experience
- **Built-in accountability:** It is scarcely supported by the existing proposals

Application Service Layer

Application Service Layer. Publishing of a public API including every service that a DT offers to its clients ((P4) Augmentation and (P10) Accountability/manageability).

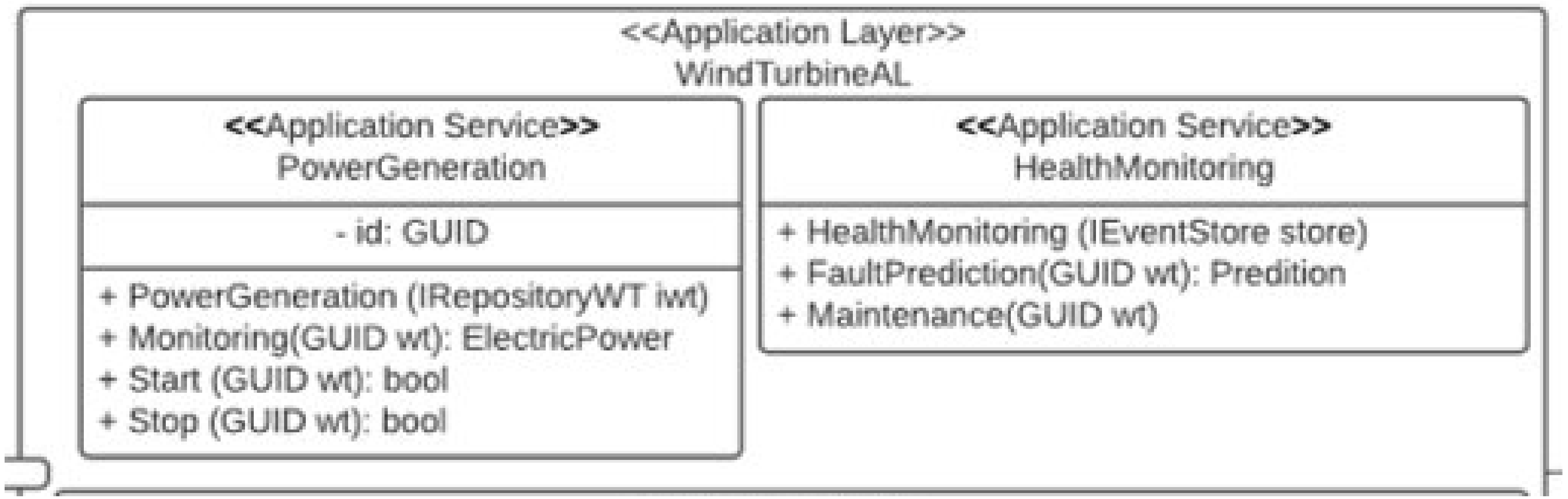
Delegates to the other two layers, when needed, due to **dependency inversion**.

Main features to support:

A. Relevant **business use cases as application services**. It abstracts the domain logic hiding the details of the Domain Layer
B. Notification about changes in the status of domain objects that may affect other system elements (e.g. notification to the physical twin about any change in their DTs).
C. Facilities to deal with **potential problems or damages**, as **part of the API**.

Application Service Layer

Responsible for publishing **a public API** including every service that a DT offers to its clients ((P4) Augmentation and (P10) Accountability/manageability).



Infrastructure Layer

Responsible for all the **technical capabilities** of the DT architecture isolating and protecting the other layers against changes, unnecessary dependencies from clients, or infrastructural issues.

DT Properties	DDD concepts
(P1) Representativeness & Contextualization	Entity Value Object Aggregate
(P2) Reflection	
(P3) Entanglement	Event Sourcing
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(P5) Composability	Messaging
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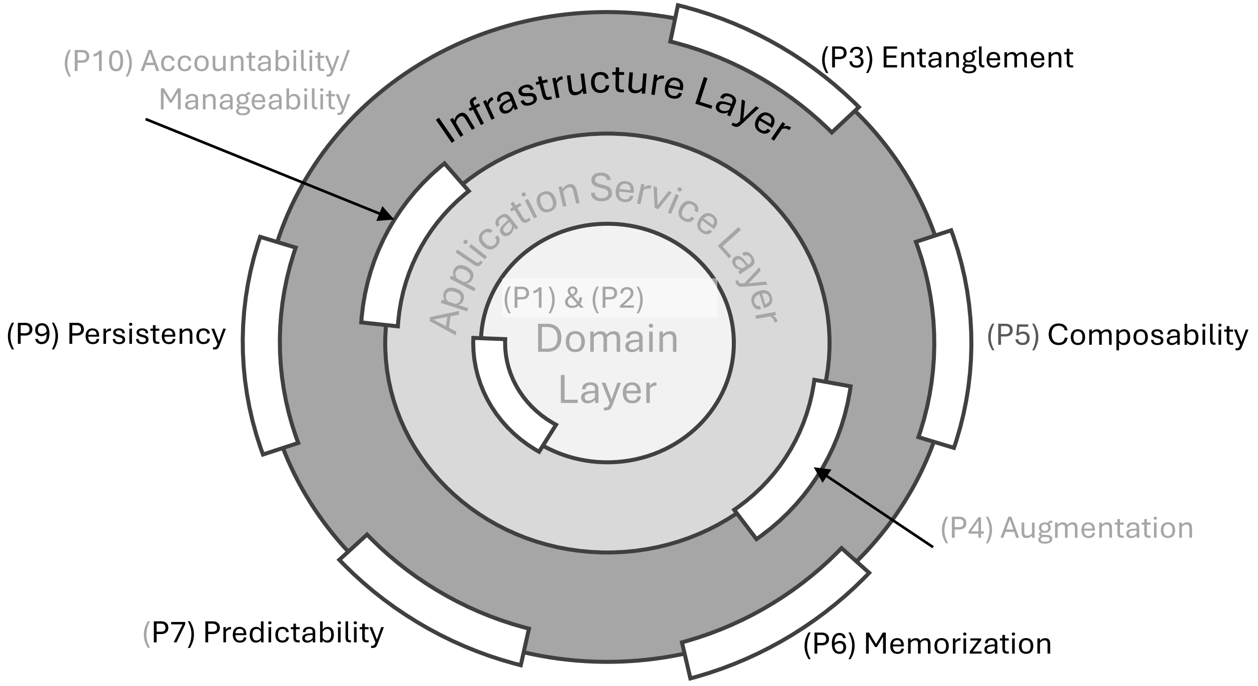
(P8) Replication	Integration Services
(P9) Persistency	Event Sourcing Repository
(P10) Accountability & Manageability	Open Host Service



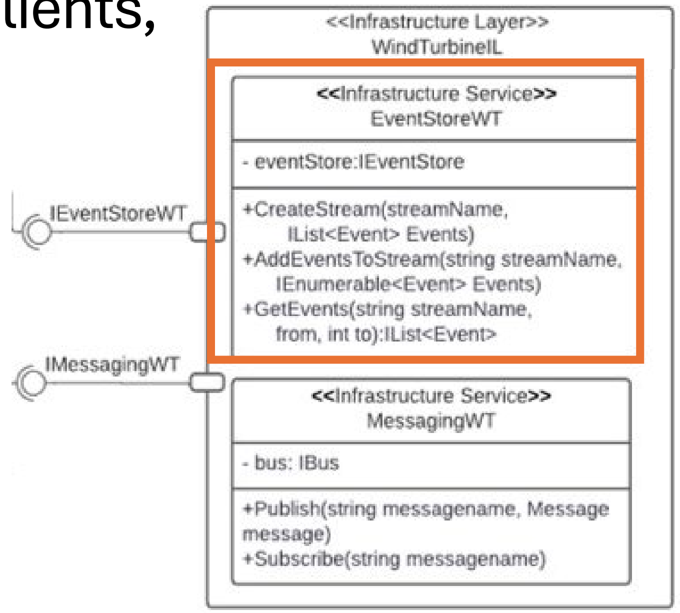
DT Properties

(P3) Entanglement: information representing the physical entity must be received in real-time (or close to real-time) by the DT

(P6) Memorization: ability to store all DT’s **meaningful past and present data** and the context of when and where such data originated for their later analysis

Infrastructure Layer

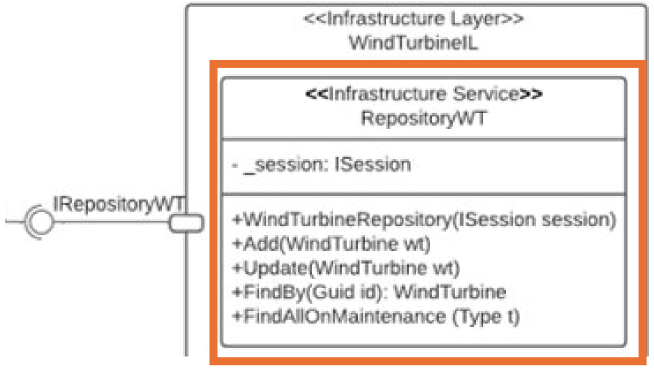
Responsible for all the **technical capabilities** of the DT architecture isolating and protecting the other layers against changes, unnecessary dependencies from clients, or infrastructural issues.



Designing for **Entanglement** and **Memorization**:

Event Sourcing: **chronologically receiving and storing the sequence of events** emitted by a physical entity to synchronize the digital twin.

Repository: façade that removes the complexity of some persistence frameworks and maintains a clearcut difference between the domain model and the data model used to interact with clients.



DT Properties

(P3) Entanglement: information representing the physical entity must be received in real-time (or close to real-time) by the DT

(P6) Memorization: ability to store all DT's **meaningful past and present data** and the context of when and where such data originated for their later analysis

Decisions while designing for Entanglement and Memorization:

- Time-based **vs** Event-based
- Data fusion techniques to use:
  - homogenous sources **vs** heterogeneous sources
  - data-level fusion techniques
  - feature-level fusion techniques
- **Data-fusion evaluation**

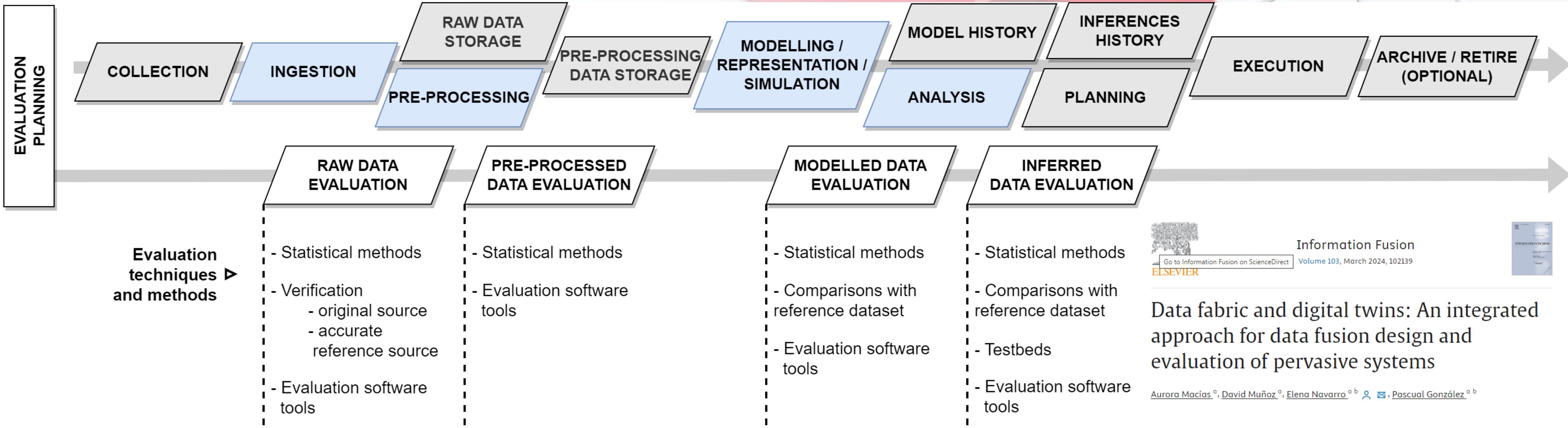
Research Open Challenge:

- **Fidelity** of the DT: how much and how well does the DT reproduce the original object and its status and features?

DT Properties

(P3) Entanglement: information representing the physical entity must be received in real-time (or close to real-time) by the DT

(P6) Memorization: ability to store all DT's **meaningful past and present data** and the context of when and where such data originated for their later analysis



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Information Fusion
Volume 103, March 2024, 102139

Data fabric and digital twins: An integrated approach for data fusion design and evaluation of pervasive systems

Aurora Macías [a], David Muñoz [a], Elena Navarro [a b], Pascual González [a b]

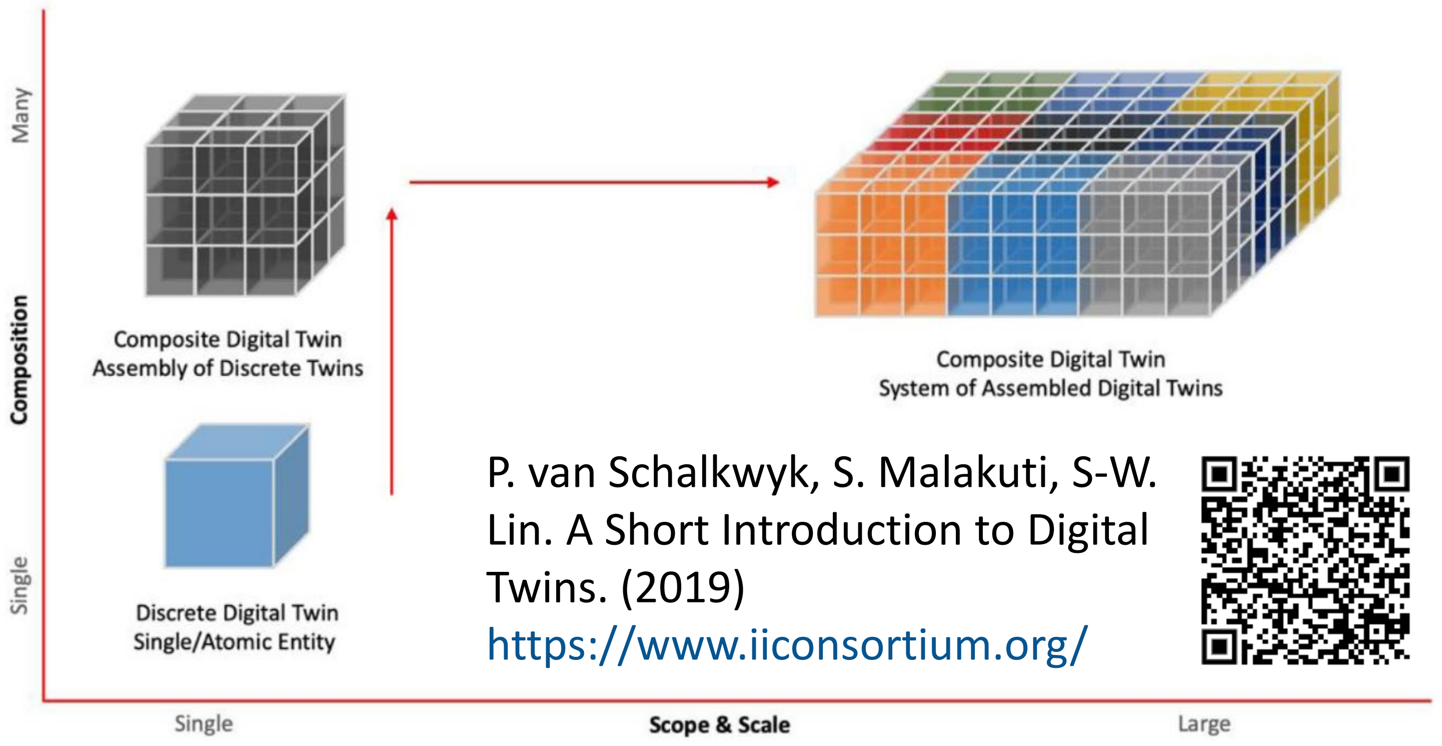
DT Properties

(P5) Composability: ability to group DTs into a composed one so that both the individual and composed objects can be observed and controlled

One of the **main reseach Challenges** claimed by most of the literature reviews:

Issues:

- Reusability
- Security
- Privacy
- Trustworthiness
- **Interoperability (Multi-domain)**



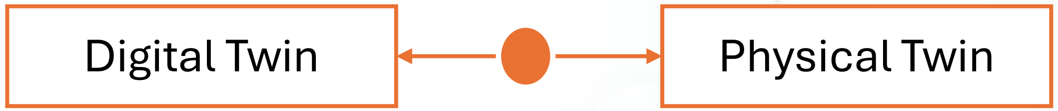
P. van Schalkwyk, S. Malakuti, S-W. Lin. A Short Introduction to Digital Twins. (2019) https://www.iiconsortium.org/

DT Properties

(P5) Composability: ability to group DTs into a composed one so that both the individual and composed objects can be observed and controlled

Issues: Interoperability:

- **Data silos**: do not support efficient ways to exchange data
- **Data spaces**: improve collaboration, facilitate analytics capabilities and development of smart ecosystems



A. Digital Twin Interoperability

B. Systems of Systems: Interoperability (Multi-domain)

DT Properties

(P5) Composability: ability to group DTs into a composed one so that both the individual and composed objects can be observed and controlled

Issue:

- Interoperability

StandICT.eu 2023

ICT STANDARDISATION OBSERVATORY AND SUPPORT FACILITY IN EUROPE

ISO TC 184 Smart Manufacturing
ISO 23247-1,2,3,4 Reference architecture

ISO TC 92 Firesafety

ISO/TC 163 Thermal performance and energy use in the built environment

ISO TC 59 Buildings and civil engineering works

ISO/IEC JTC1SC41 Digital Twin

IEC TC 57 Power systems management and associated information exchange

ISO TC 205 -Building environment design

IEC TC 65 -industrial process measurement -control and automation

ISO/TC 211 - Geographic information/Geomatics

ISO TC 268 SC1Smart community infrastructures
IEC SyC-Smart Cities

ISO TC 299 Robotics

ISO TC 204 - Intelligent Transport Systems

Infrastructure Layer

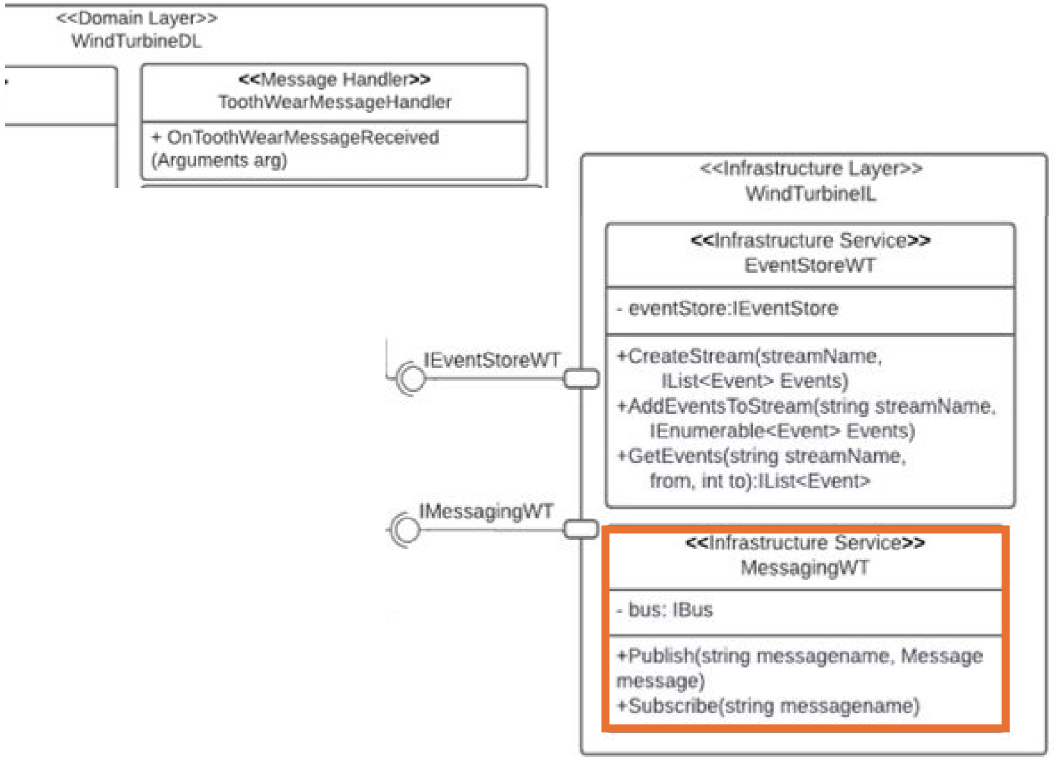
Responsible for all the **technical capabilities** of the DT architecture isolating and protecting the other layers against changes, unnecessary dependencies from clients, or infrastructural issues.

Designing for **Composability:**

Messaging supports **communication among components decoupling** them

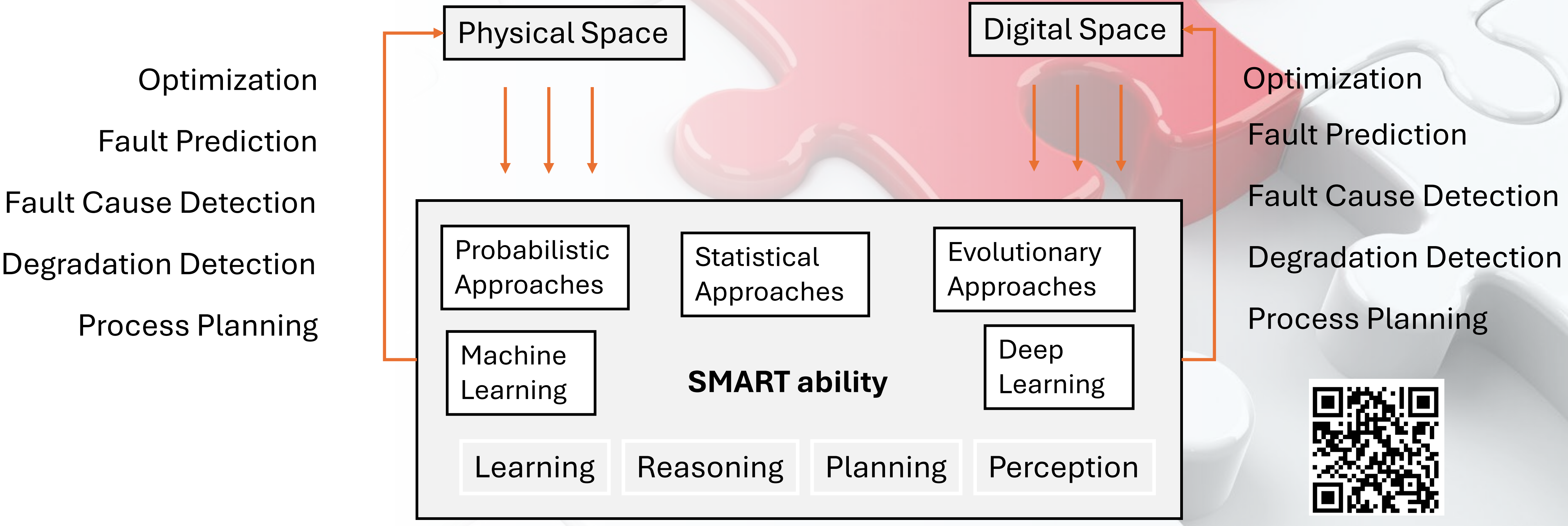
Decisions:

- Time-based updated **vs** Event-based update



DT Properties

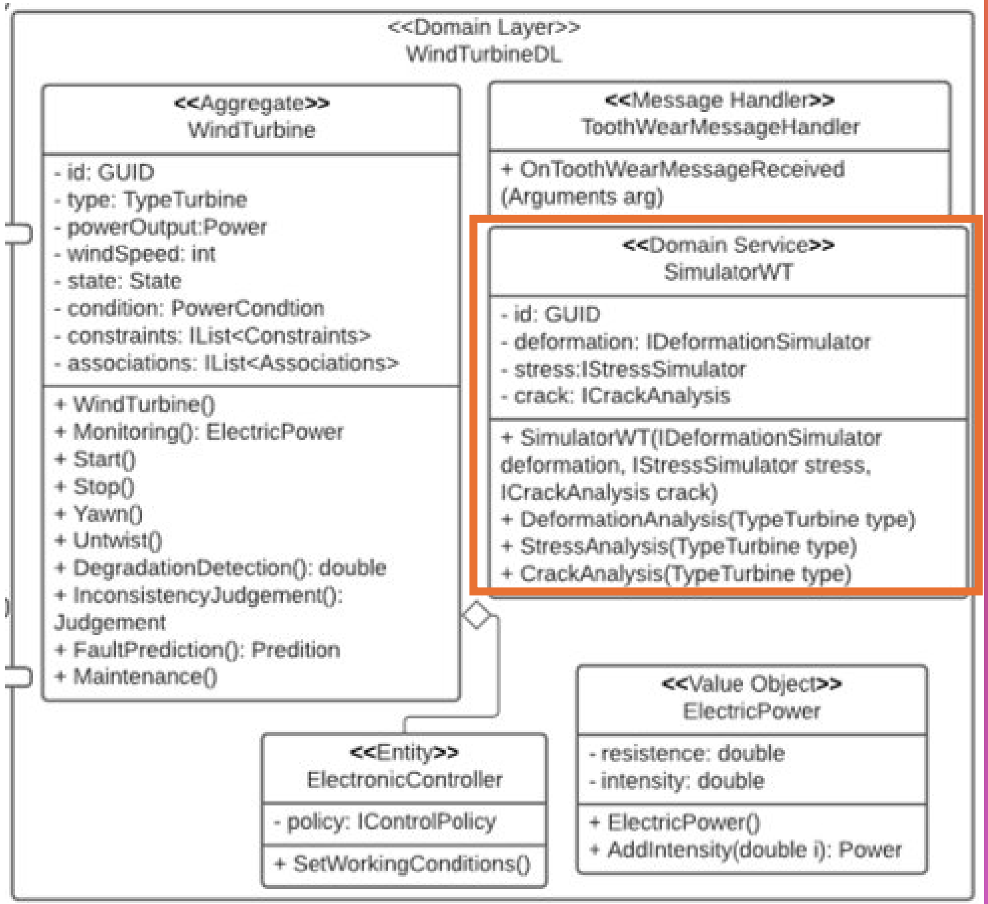
(P7) **Predictability:** a DT may be used to simulate the behaviour and interaction with other DTs to determine the outcomes in a likely future or context



(P7) Predictability

Two alternatives for its design:

- **Domain Services** that use the **behavior of the DT** using Entities, Value Objects and Aggregates, as well as relying on the Application Service Layer for any technical detail due to **dependency inversion**.
- **Integration Services**
  - integrate other systems or applications to use external testbeds, experimentation settings, etc.
  - maintain both the Application Service and Domain layers agnostic from these technologies: modified or replaced at convenience.

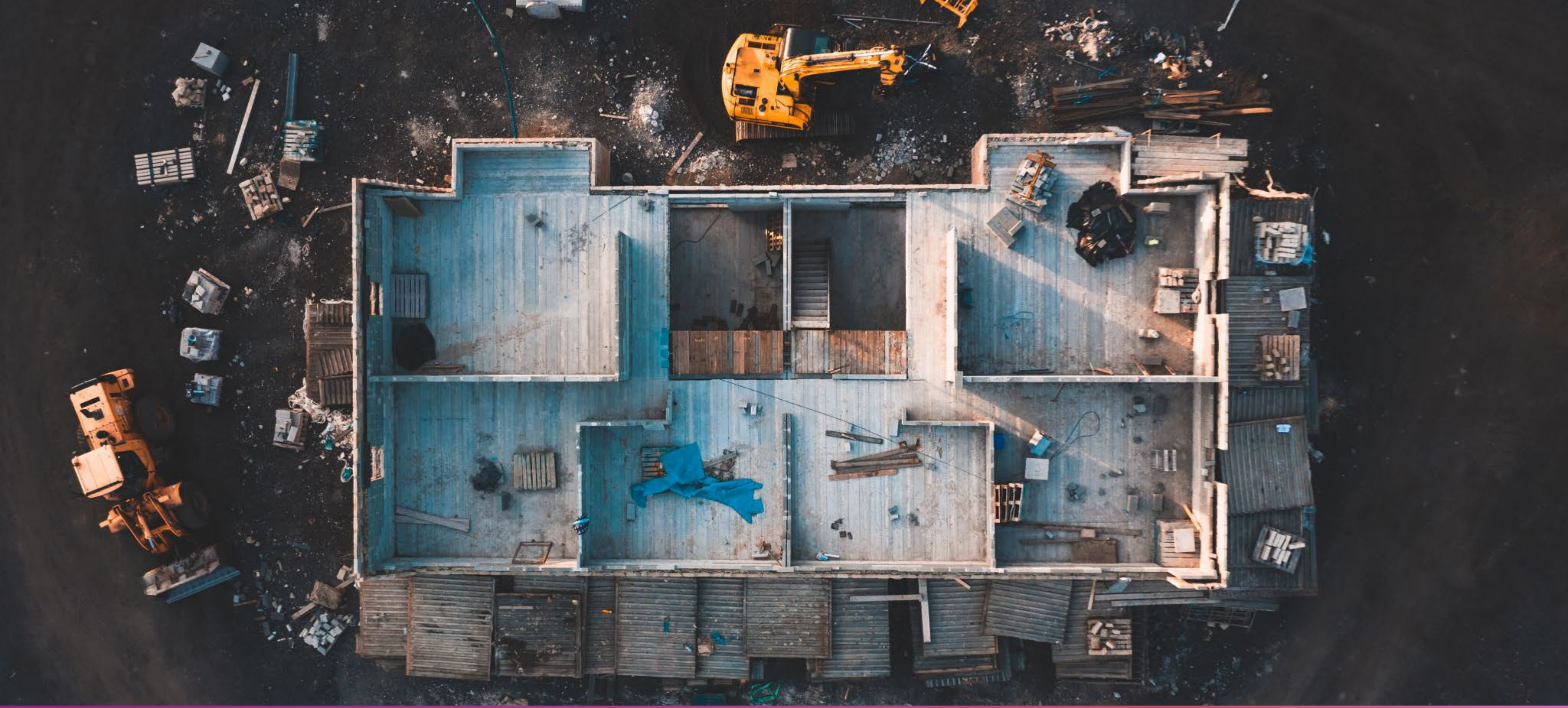


DT Properties

(P7) **Predictability:** a DT may be used to simulate the behaviour and interaction with other DTs to determine the outcomes in a likely future or context

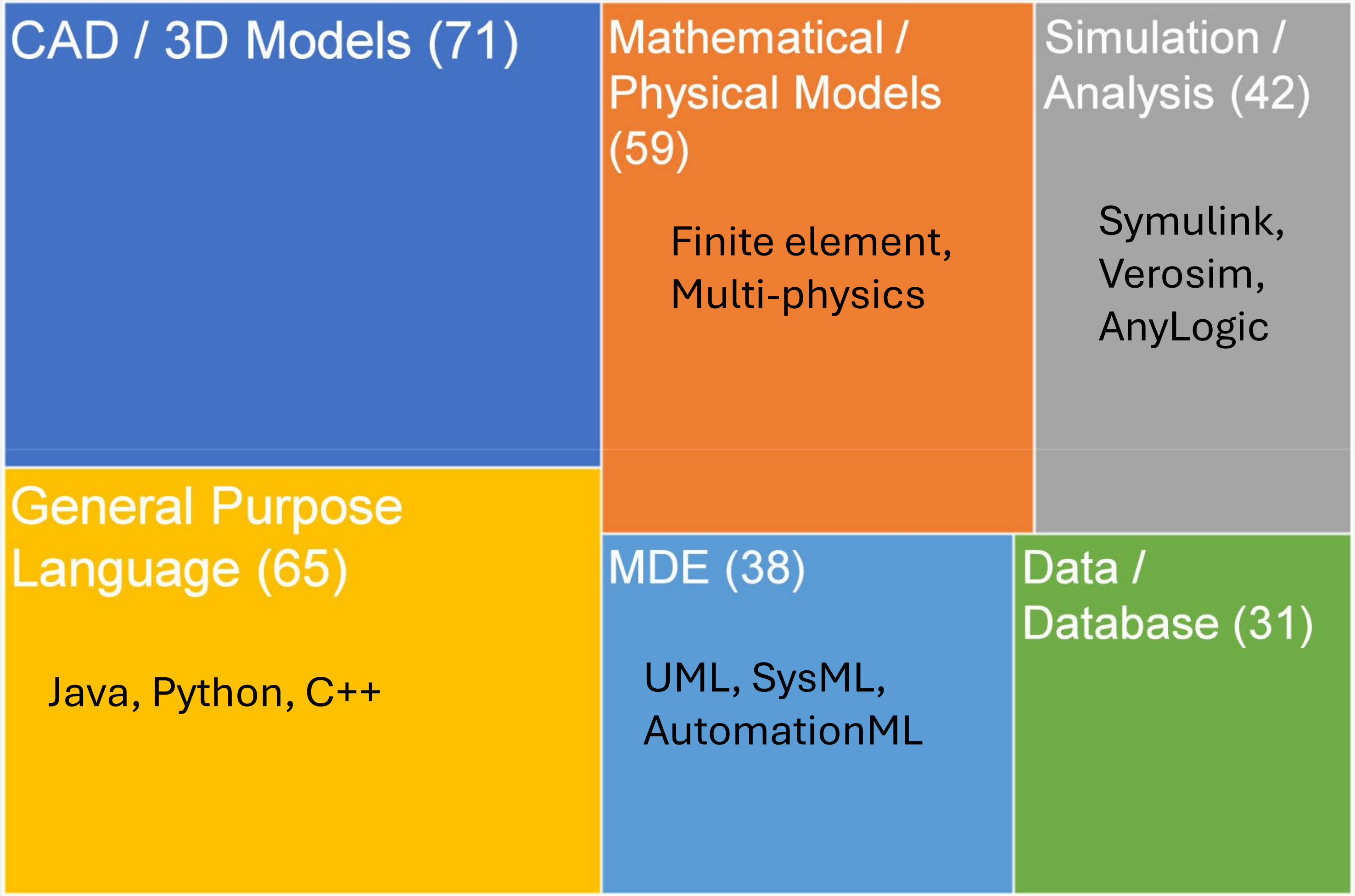
Research Challenge: DT and **Collective Intelligence**

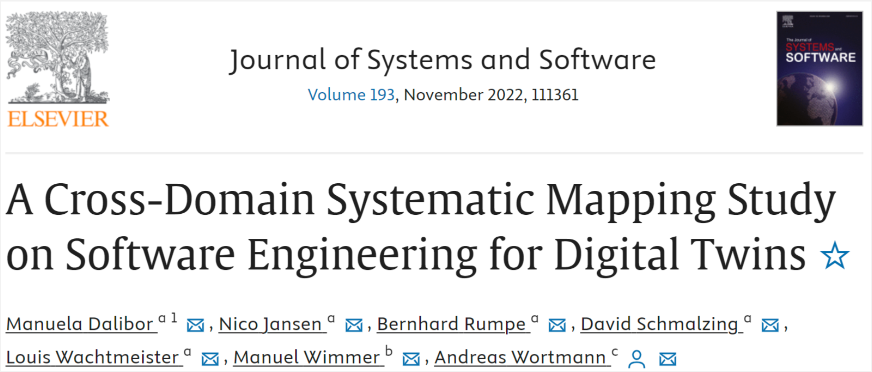
- No empirical studies exploring multiple DTs that can be of a similar nature (fleet) working collaboratively for optimization, planning, etc
- No empirical studies of diverse DTs for optimization, planning, etc.



Frameworks for developing DT

Tooling for implementation





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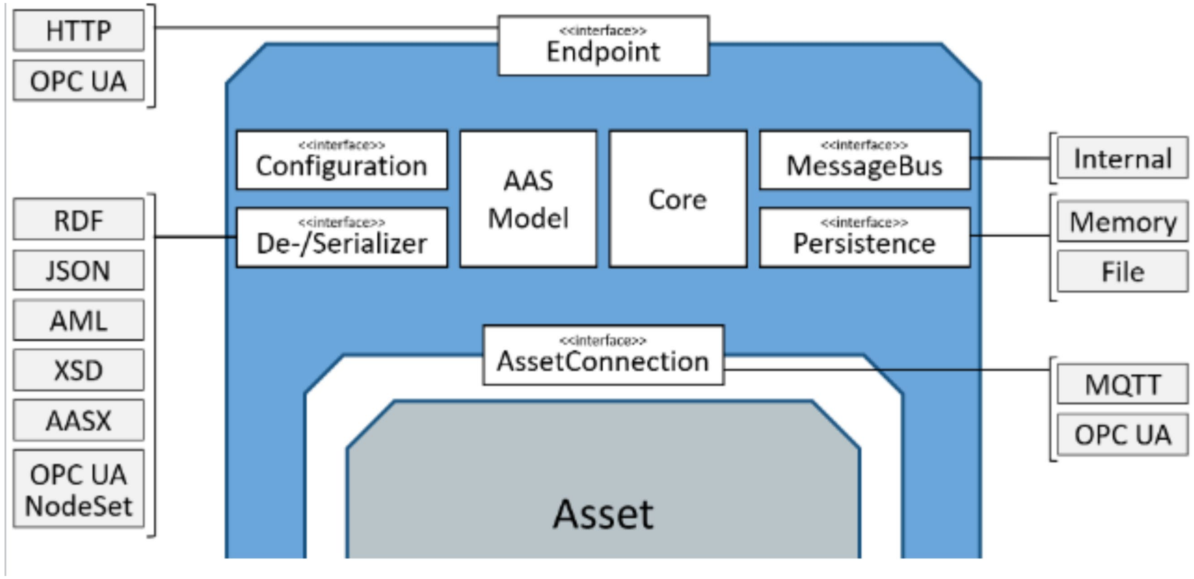
Journal of Systems and Software

Volume 193, November 2022, 111361

A Cross-Domain Systematic Mapping Study on Software Engineering for Digital Twins ☆

Manuela Dalibor [a] [1], Nico Jansen [a], Bernhard Rumpe [a], David Schmalzing [a], Louis Wachtmeister [a], Manuel Wimmer [b], Andreas Wortmann [c]



Open Source: Apache License 2.0

Asset Administration Shell Standard (AAS)

- Implementation of Digital Twins for Industry 4.0
- Aligned with **ISO 23247**
- Active contribution to Industrial Digital Twin Association (IDTA)
- Java-based software ecosystem for creating and managing I4.0-compliant and data-sovereign digital twins
- Multiple synchronized endpoints
- Connect to assets using arbitrary communication protocols (OPC UA, MQTT)
- Message Bus to monitor interactions & react to events
- Usage as CLI, Docker or embedded
- **No** implement any **security mechanisms**

European Interoperability Framework for Smart Cities – EIF4SCC

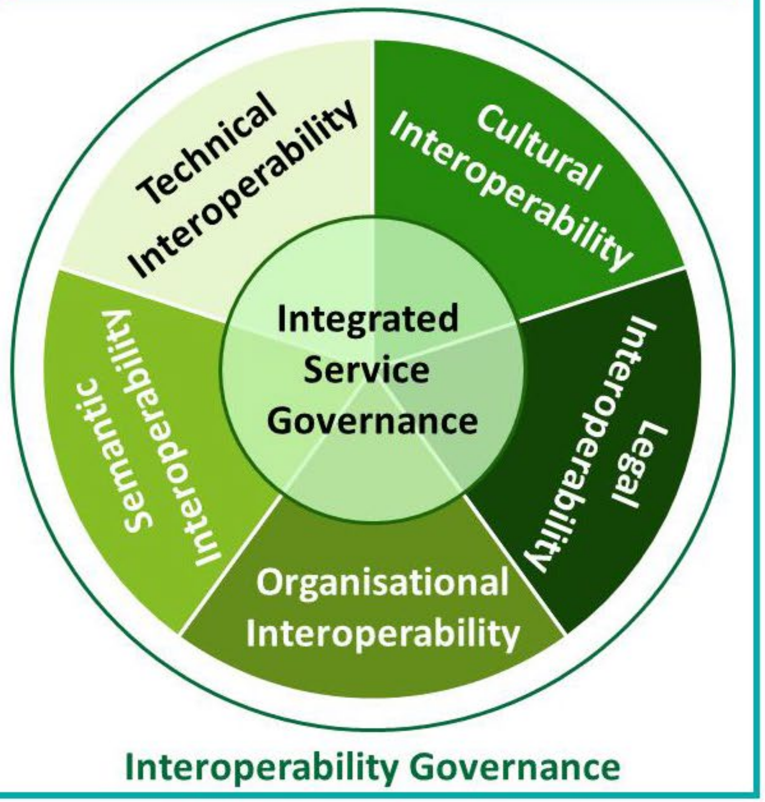
Concepts

- Interoperability
- Smart City/ Community
- EIF4SCC

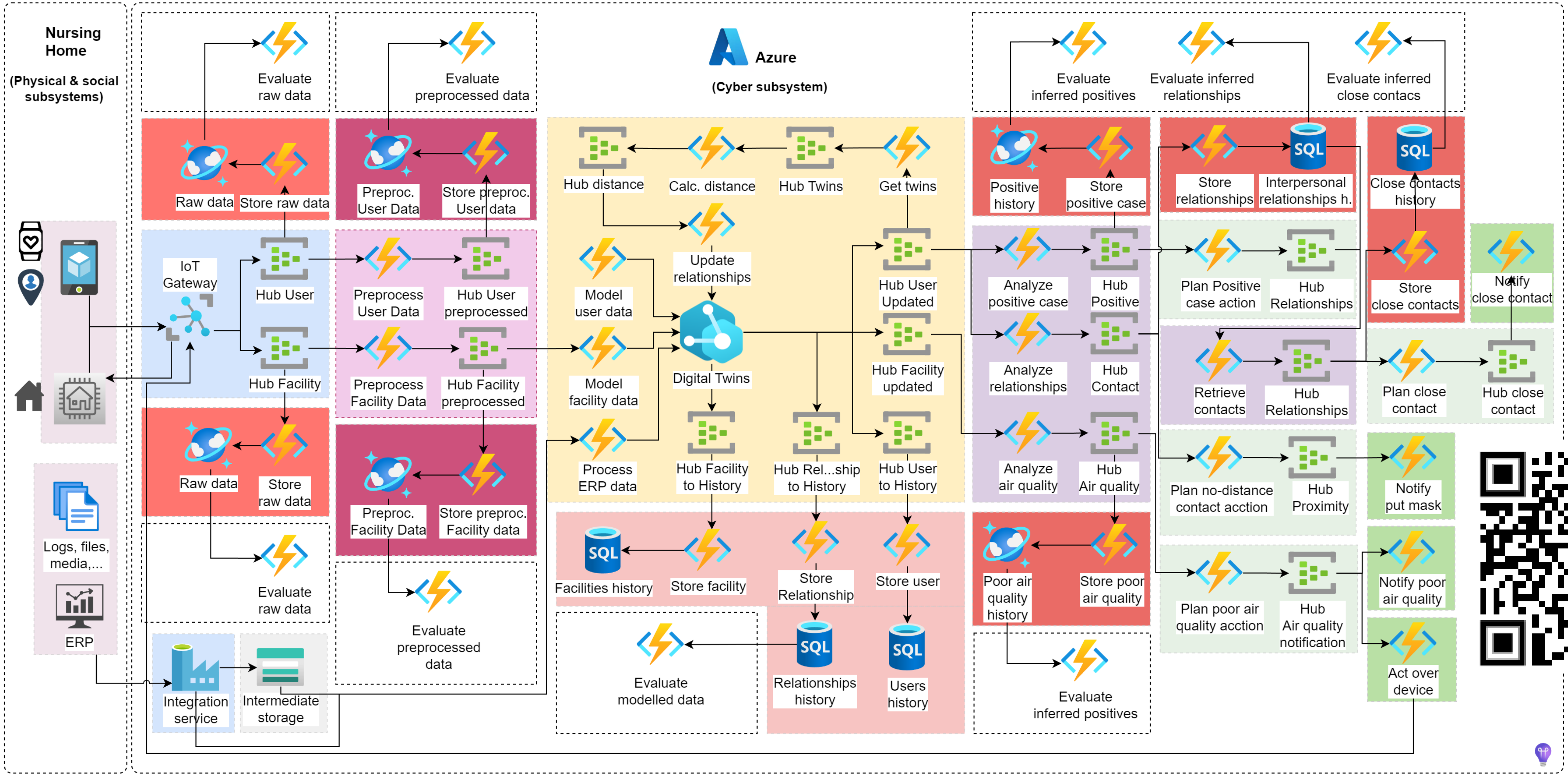
Principles

- A Human-centric approach
- A city needs-led approach at EU level
- The city as a participatory driven and open innovation ecosystem
- Ethical and socially responsible access, use, sharing and management of data
- Technologies as key enablers

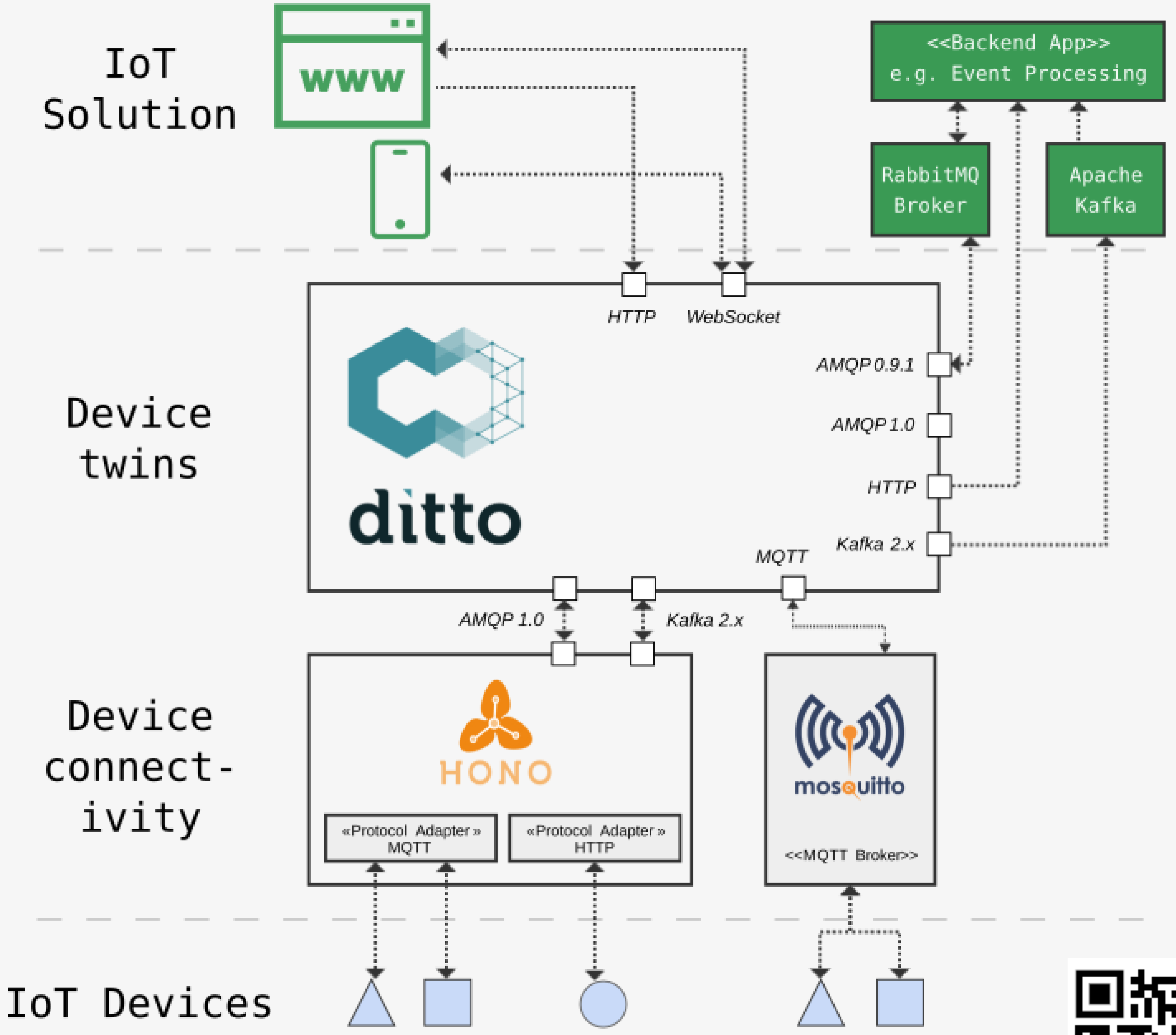
Elements



Digital Twins



Azure services: Data Factory, Storage, IoT Hub, Event Hubs, Functions, Digital Twins, Azure SQL, CosmosDB, Application Insights

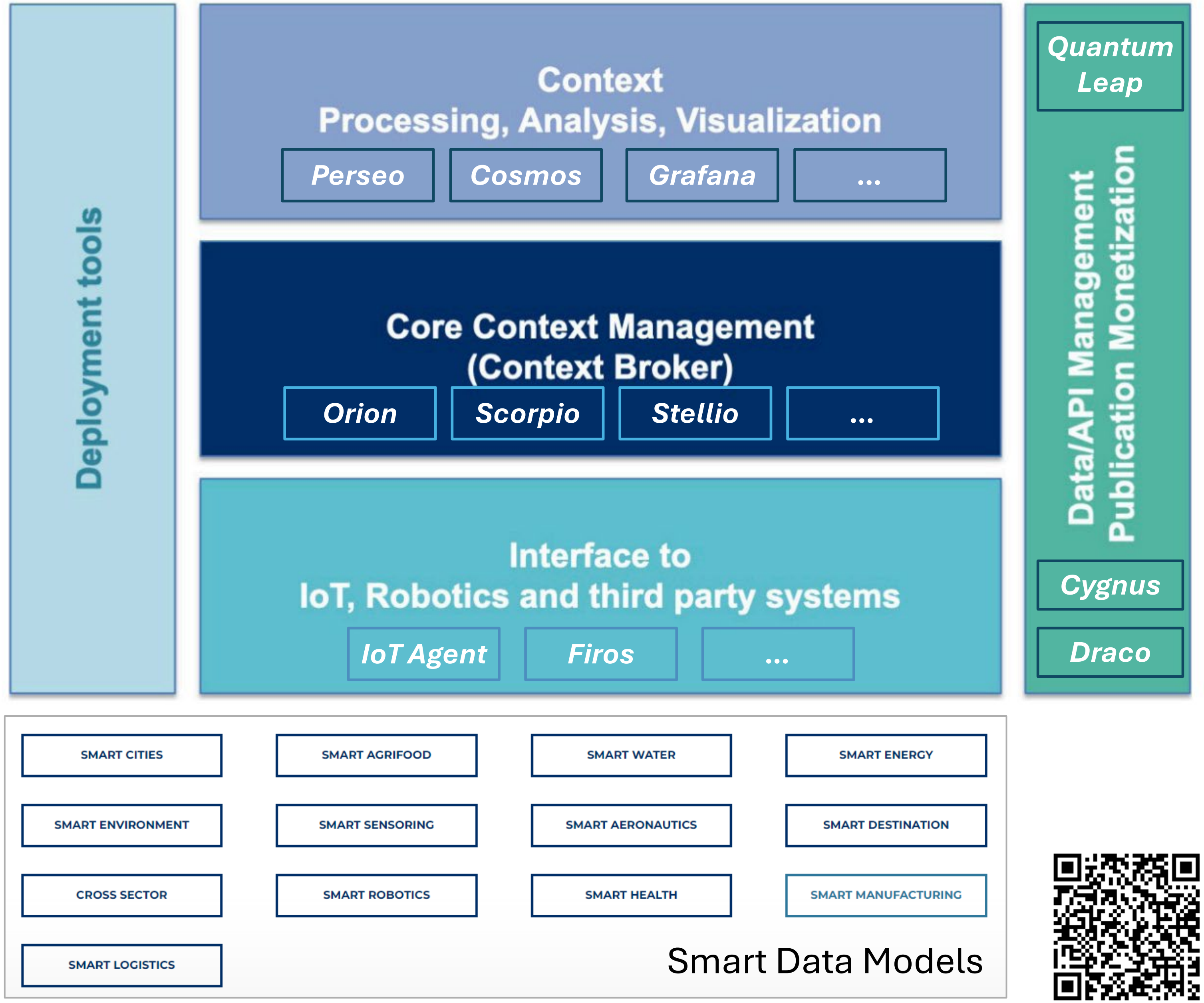


ditto

- Eclipse Ditto is an open-source framework helping you to build digital twins of devices connected to the internet
- Ditto acts as IoT middleware, providing an abstraction layer for IoT solutions interacting with physical devices via the digital twin pattern.
- It is by design domain agnostic and thus may be used in industrial, residential, agricultural and many other IoT domains.
- Digital twins managed in Ditto can also be integrated into other existing backend systems by creating arbitrary connections to such foreign systems utilizing the supported protocols
- Devices are integrated via a device connectivity layers like Eclipse Hono™ or e.g. MQTT brokers like Eclipse Mosquitto

FIWARE

- A curated framework of Open-Source Platform components for:
  - Interaction between IoT sensors and other devices, as well as vertical intelligent solutions and other information systems.
  - Processing of historical and real-time current data to extract valuable information to make smart decisions and plans.
  - Creating dashboards and generating reports, including KPI monitoring and analysis.



Conclusions and Challenges

- DTs are becoming ubiquitous: a major **impact** on industry and society
- **Software Engineering for DT** is not yet a reality
- Many **challenges** for research
  - Tools and methodologies
  - Standarization
  - Interoperabiliby
  - DT composition
  - etc

Harvesting the Power of Digital Twins

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Human Digital Twins for fostering Prosocial Behaviour (HDT-PROSOCIAL) PID2022-140907OB-I00
funded by MICIU/AEI/10.13039/501100011033/ y por FEDER, UE.

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

Cofinanciado por la Unión Europea

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