ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Distributed and Hybrid Digital Twins for Low Latency Applications:

the Pros of Exploiting Edge Cloud Computing and the Challenges for Simulation

SIMULTECH 2023, Rome, Italy, July 12

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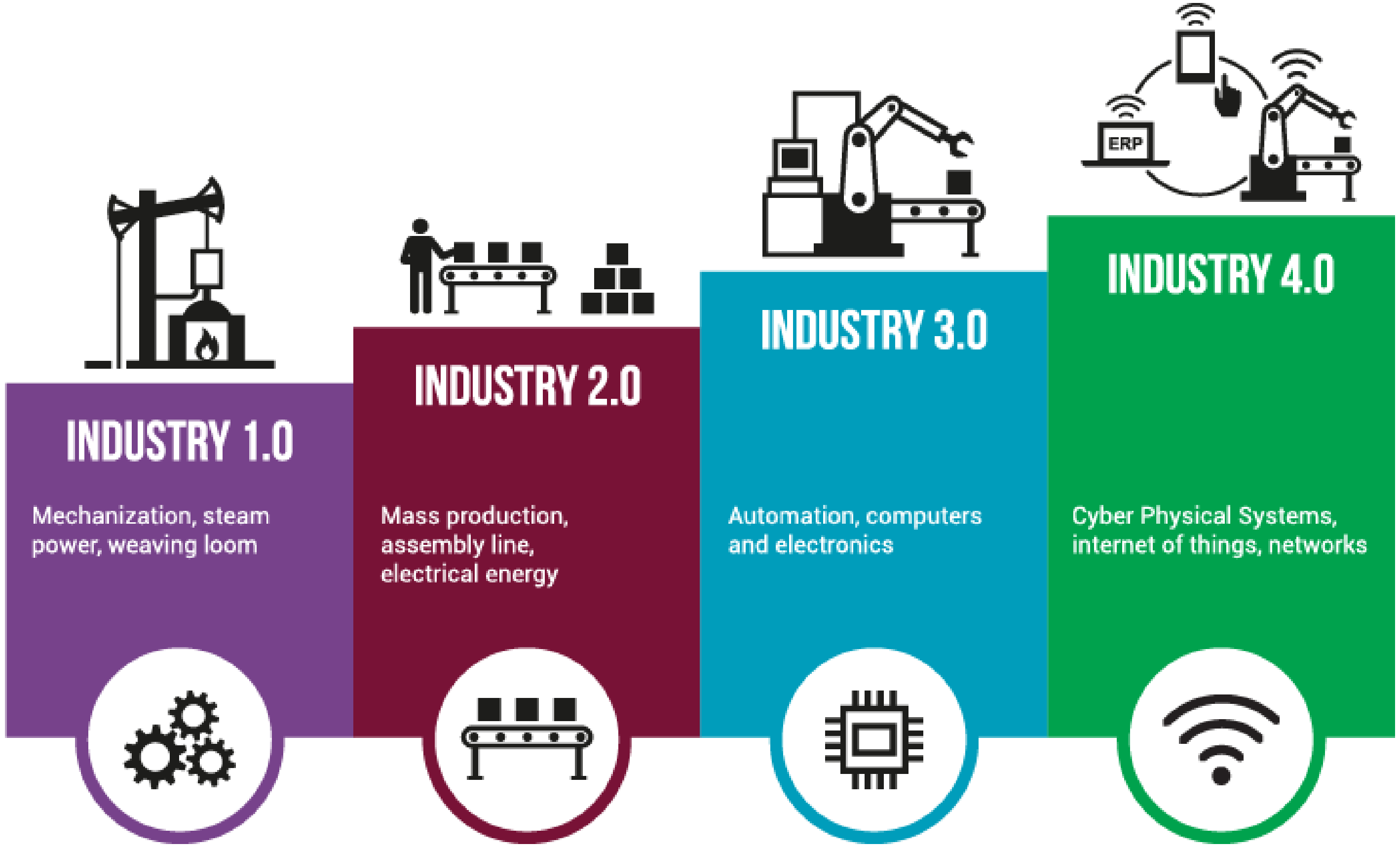
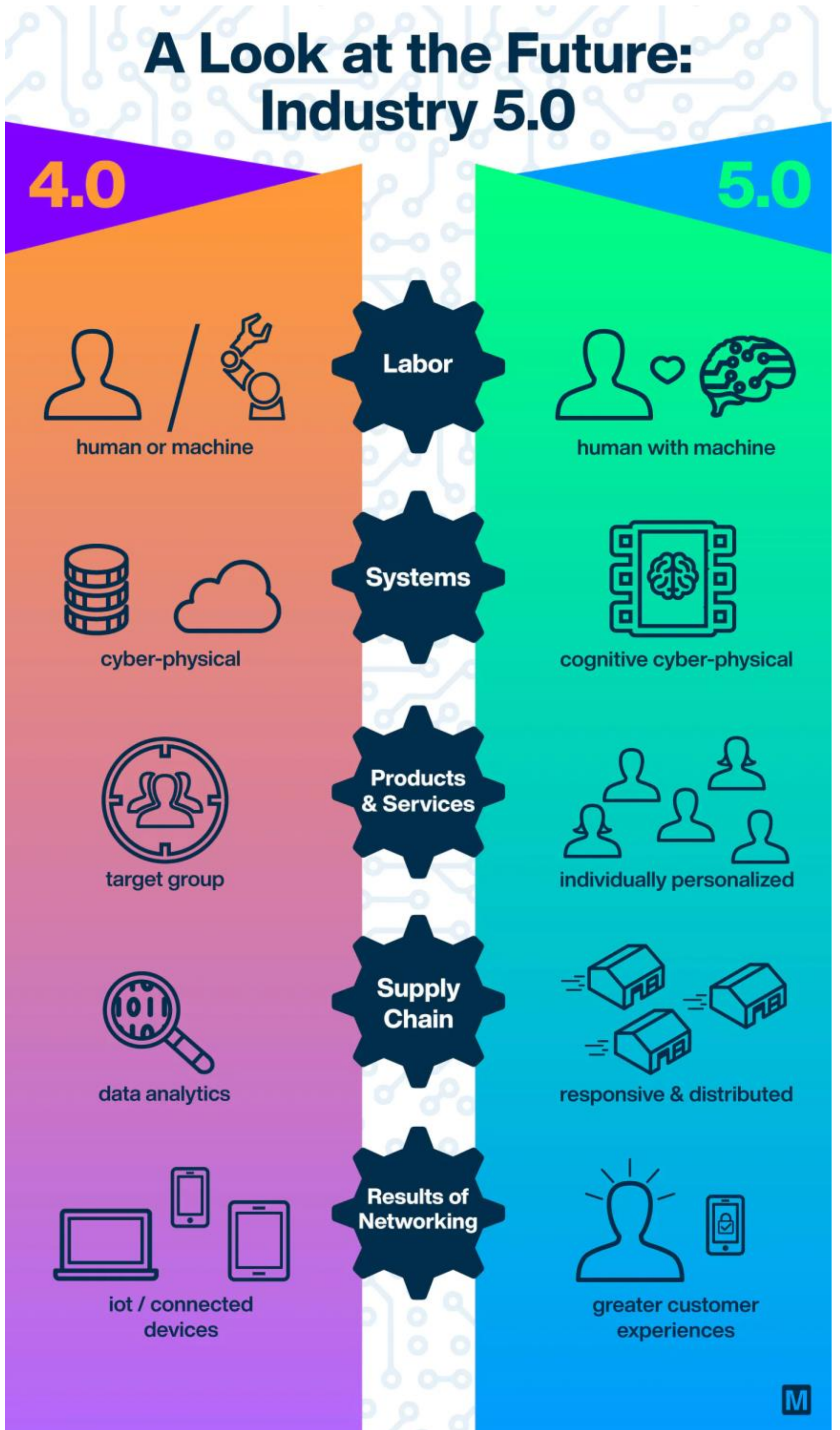
Industry 5.0: which role for digital twins and distributed intelligence?





The BI-REX Competence Center for Enterprise 4.0

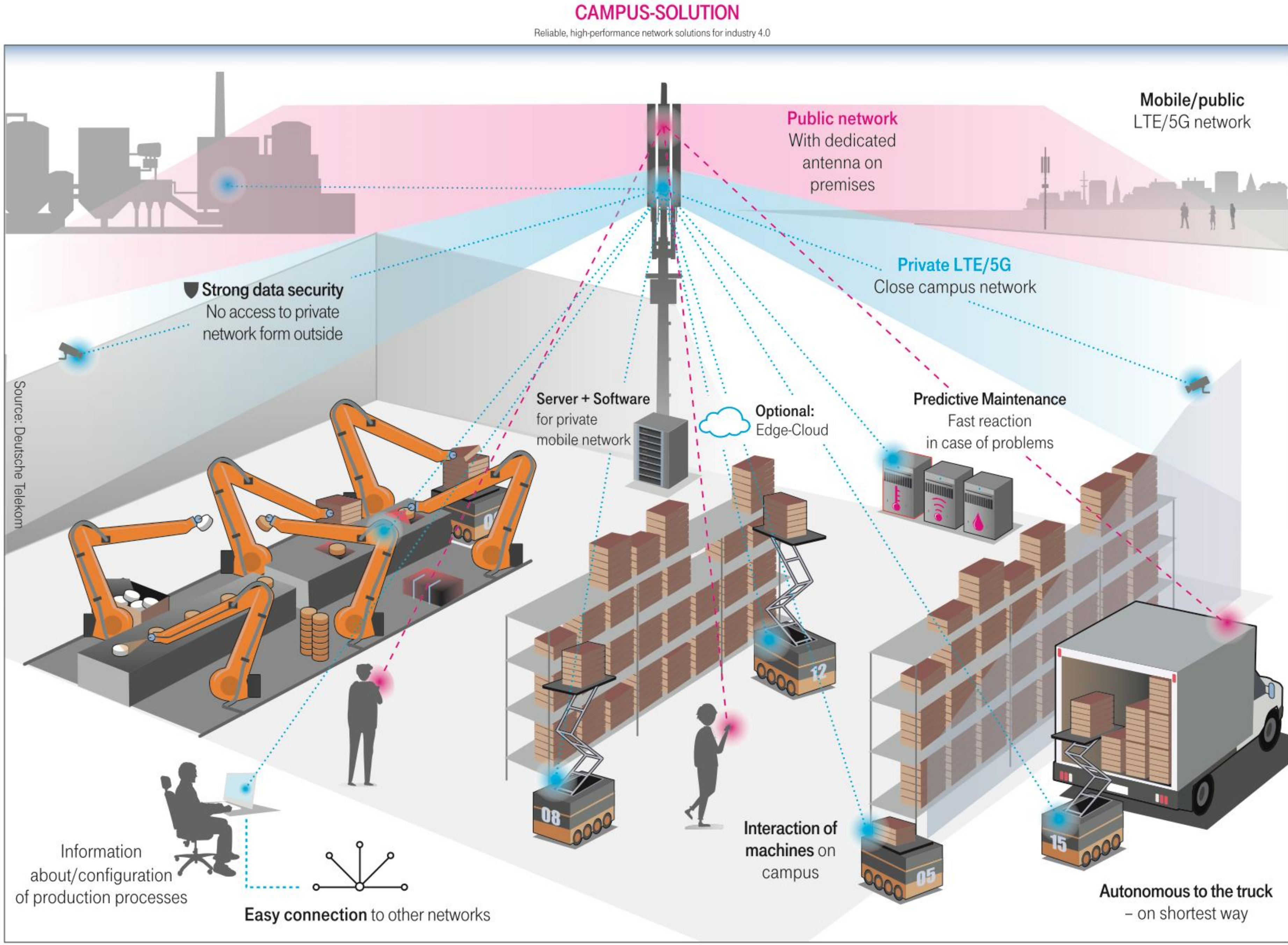
bi-rex

Big Data Innovation & Research Excellence

http://bi-rex.it/

5G Campus Networks

- Small in-the-field testbed for TSN
- Integration with industrial gateways and edge cloud nodes
- Platform for integration and experimentation



Digital Twins: towards a definition

A digital twin is a ***digital replica (of a physical counterpart) that is accurate enough*** that it can be the basis for decisions given a specific purpose

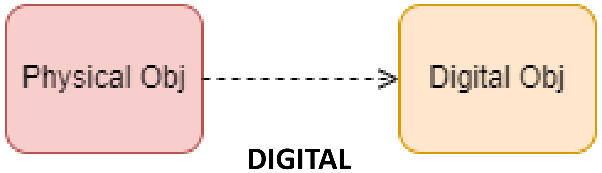
Creating value by linking data, models, and processes

- The replica is often connected to ***IoT big data streams***
- The replica is aided by new ICT infrastructures, based on the ***cloud continuum***

Digital Twins: towards a definition

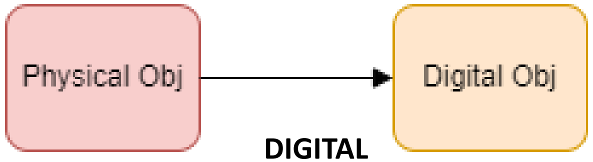
- Digital counterpart of a physical object
  - Structure
  - Interaction
  - Global behaviour

- Digital twin as bidirectional communication flow between physical and digital object



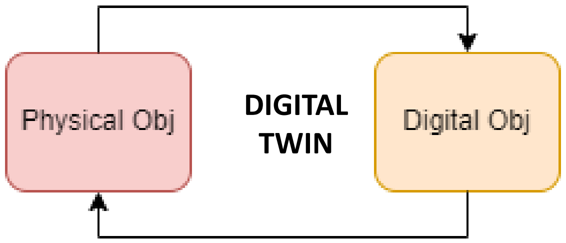
DIGITAL MODEL

The digital object is a static reproduction of a physical one. Every change to the digital model has to be done manually



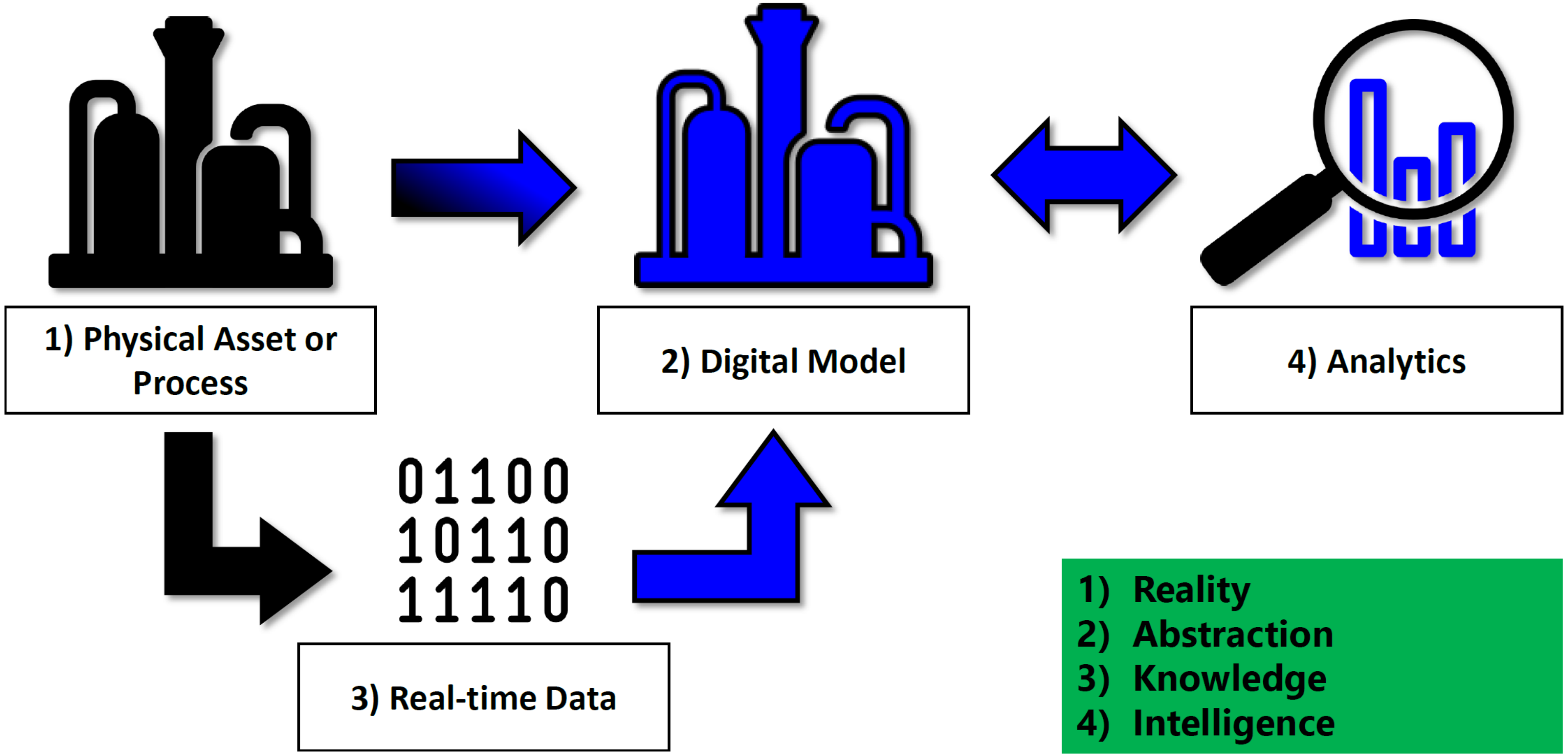
DIGITAL SHADOW

The digital object is a dynamic reproduction. The update of the digital model is automatic. Data flow just in one direction



The digital object is a dynamic reproduction. Data flow in both directions. Every change to the digital model has an effect on the physical one

HYBRID Digital Twins

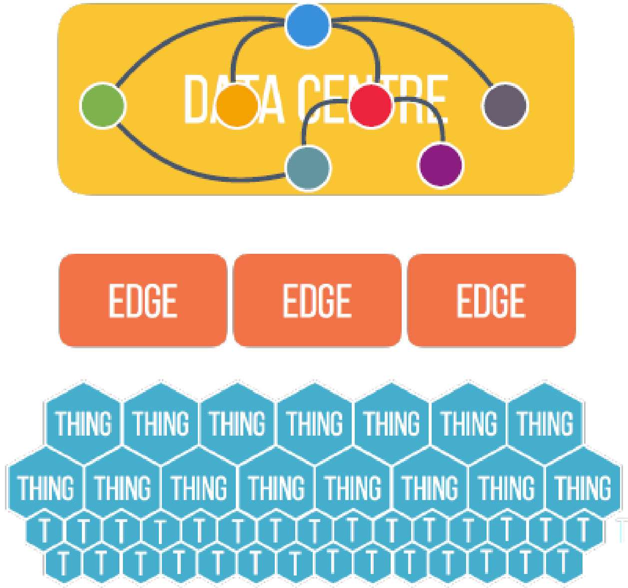


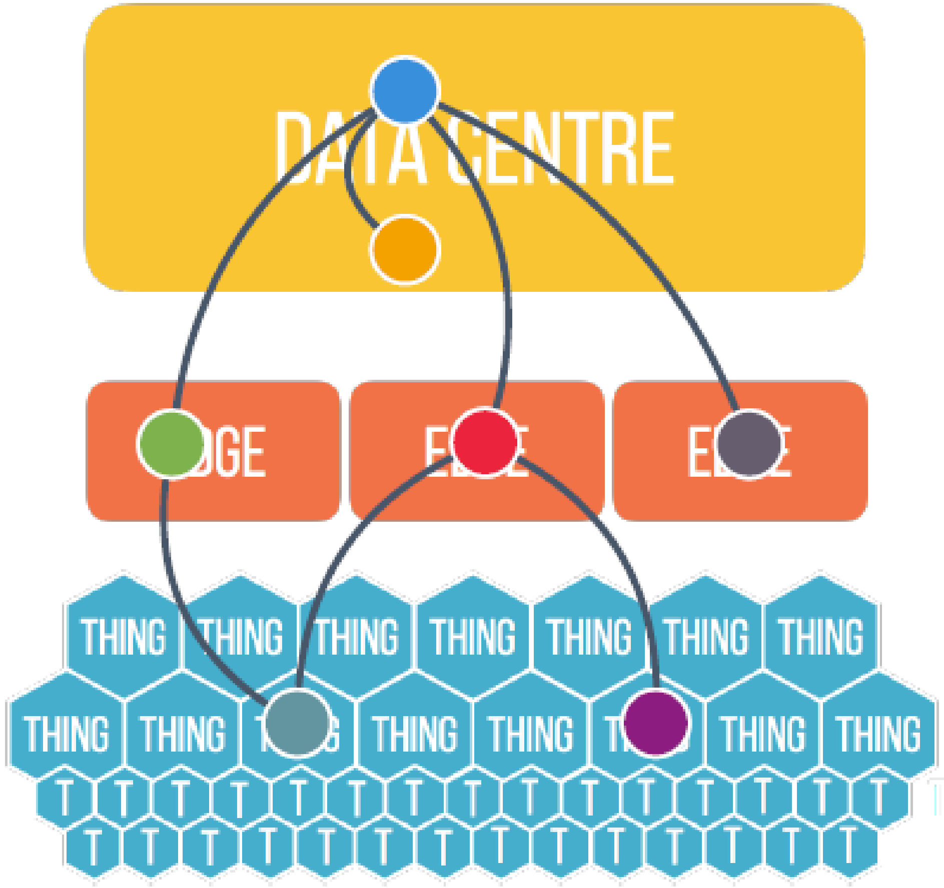
1) Reality
2) Abstraction
3) Knowledge
4) Intelligence

Distributed Digital Twins: Towards the Cloud Continuum

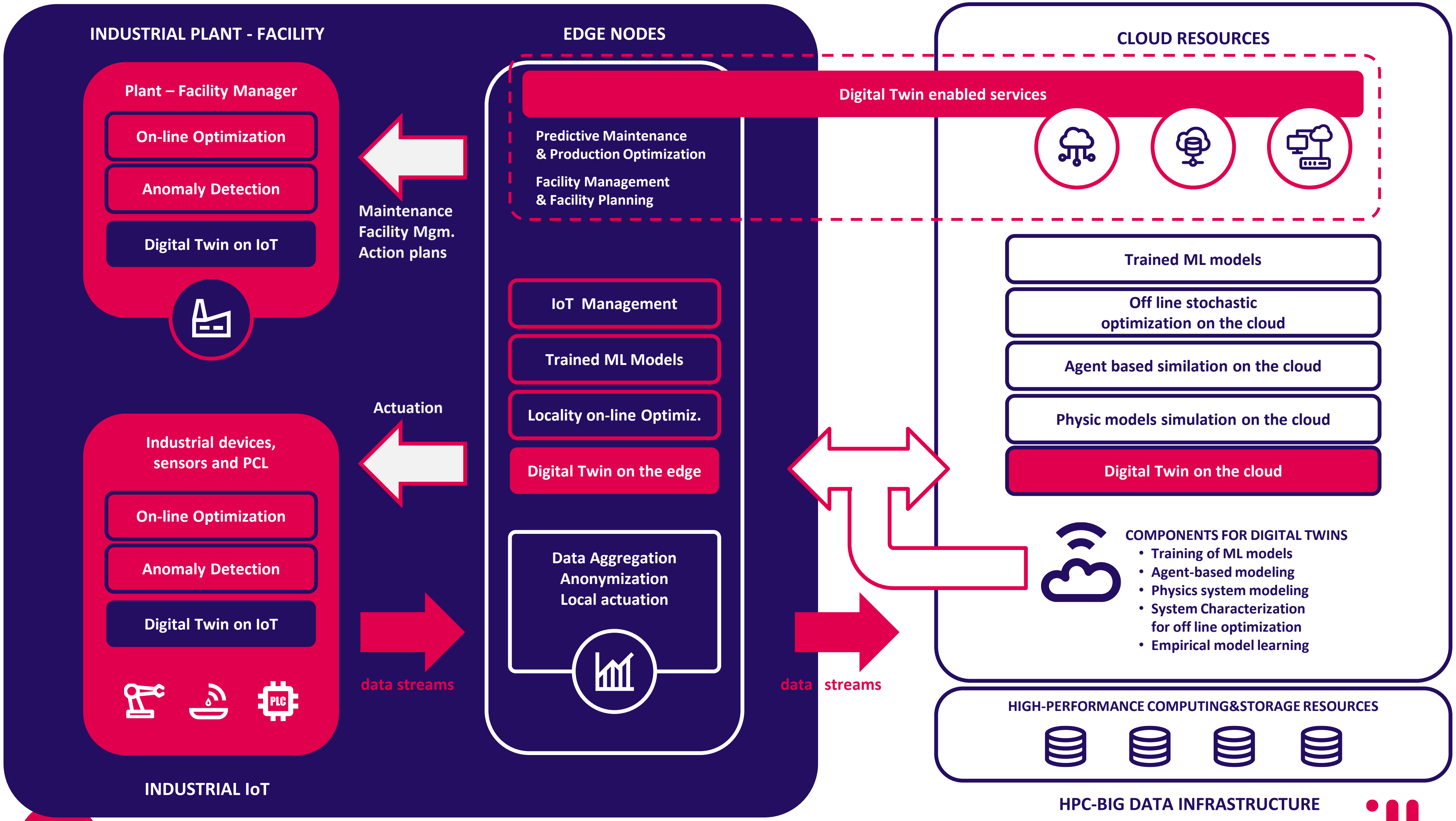
A Different Reality...

Due **latency**, **throughput**, **connectivity**, **cost** and **security** only a **restricted class of IoT/IIoT applications** that are **compatible** with the **cloud-centric mode**





The Concept of DISTRIBUTED AND HYBRID DIGITAL TWINS



IoTwins

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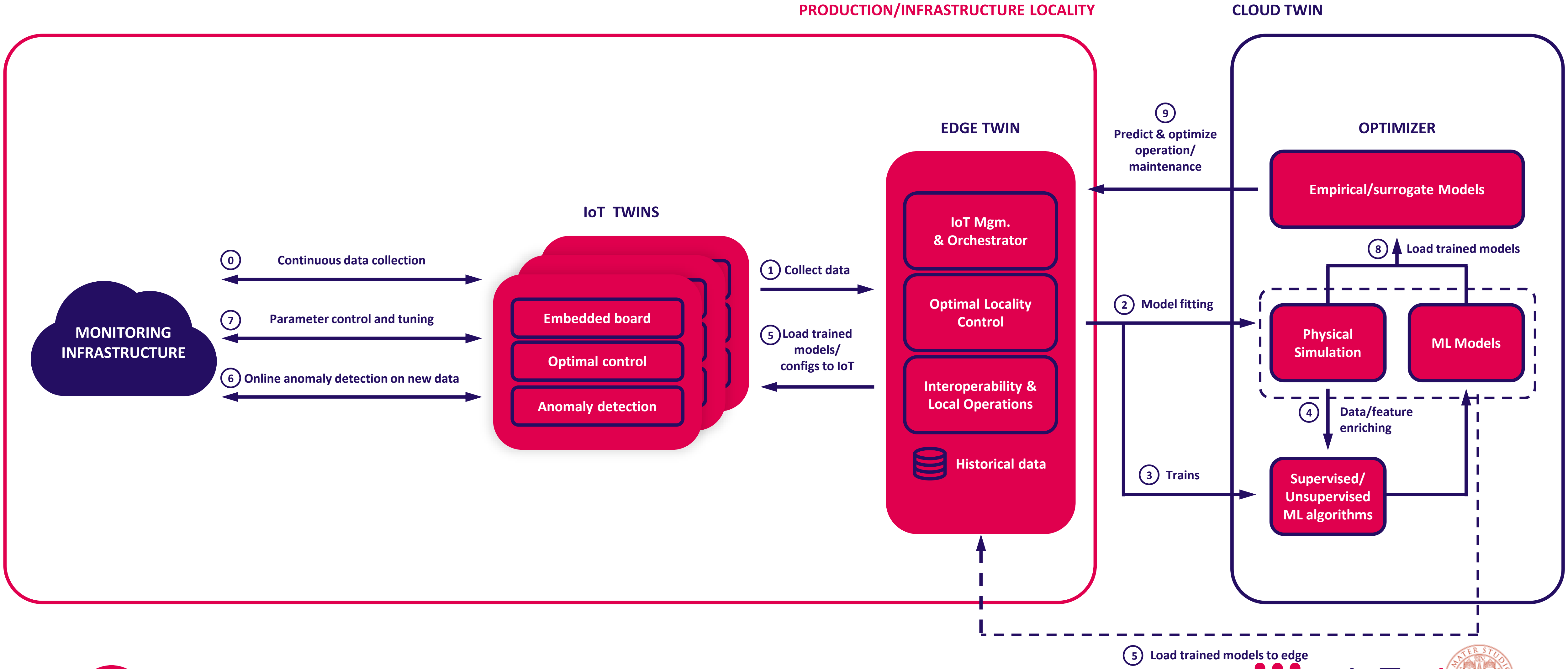
Training Hybrid and Distributed DTs in the CLOUD CONTINUUM



IoTwins

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How do Digital Twins fit in?

Digital Twins are part of the digitization strategy, they require:

- a ***vision*** on digitization
- purpose in the processes
- the means to operate it
- the ***adaptivity*** of the ***organization***

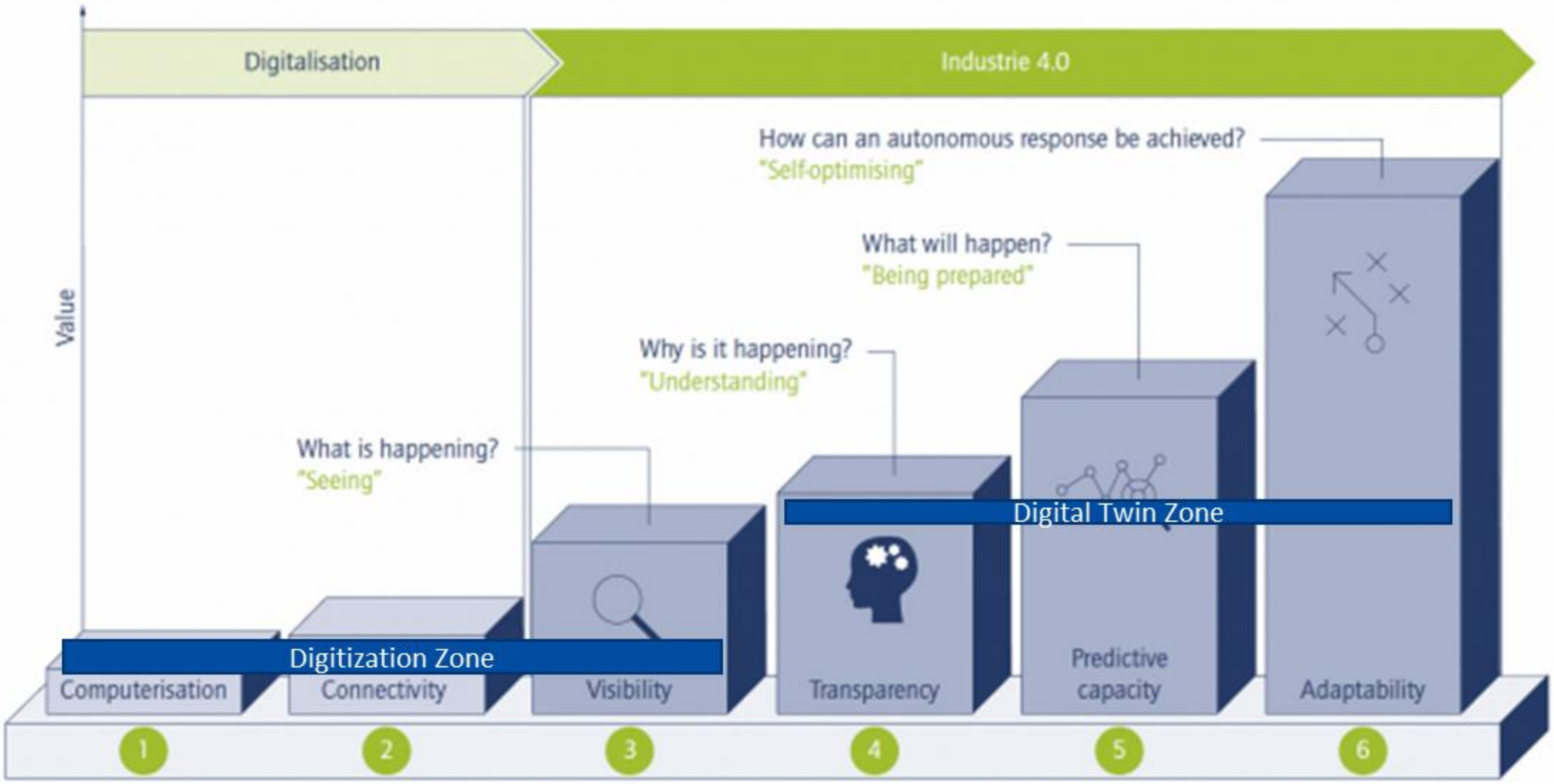


Figure 5: Stages in the Industrie 4.0 development path (source: FIR e. V. at RWTH Aachen University)

For which purposes?

The IoTwins Project

IoTwins
BIG DATA OPTIMIZE INDUSTRY AND SERVICES

TYPE OF ACTION
INNOVATION ACTION

PROJECT REFERENCE
857191

START/END
SEPTEMBER 2019 – AUGUST 2022

TOTAL COSTS
€ 20,029,818.75

EU CONTRIBUTION
€16,422,552.01

CALL IDENTIFIER
H2020-ICT-2018-2020

TOPIC
ICT-11-2018-2019 - HPC AND BIG DATA ENABLED LARGE-SCALE TEST-BEDS AND APPLICATIONS

COORDINATOR
BONFIGLIOLI RIDUTTORI

IoTWINS AT A GLANCE

20	16	23	1	12	3
M€ total value	M€ EU Funding	Partners	Platform	Testbeds	Application areas

- A European project to lower barriers for the uptake of Industry 4.0 technologies to optimize processes and **increase productivity, safety and environmental impact**.
- A technological platform allowing a **simple and low-cost access to big data analytics functionality**, **AI services and edge cloud infrastructure** for the delivery of digital twins in manufacturing and facility management sectors.
- 12 large scale testbeds, organized in three areas: **manufacturing, facility management and replicability/scale up** of such solutions.

A TECHNOLOGICAL PLATFORM TO FEED 12 TESTBEDS

technological platform

IOT-edge-cloud infrastructure and Big Data services for SMEs

INFN Istituto Nazionale di Fisica Nucleare · Fraunhofer FOKUS · CINECA · Alma Mater Studiorum A.D. 1088 · THALES · BSC

AI services for Digital Twins

7 testbeds

Manufacturing Testbeds

KK Wind Solutions · Bonfiglioli · GCL International · TTTech · Etxetar · Fill

Barça Innovation Hub Reinventing Sport · SIEMENS · CINECA · BSC

Facility Management Testbeds

5 replicability testbeds

Platform for Replicability, Scalability and Business Model

esi get it right · cetim · MARPOSS · GCL International

Barça Innovation Hub Reinventing Sport · INFN Istituto Nazionale di Fisica Nucleare · BSC · Arts et Métiers Sciences et Technologies

12 LARGE SCALE TESTBEDS

manufacturing

1. **Wind turbine predictive maintenance** | Bonfiglioli, KK Wind Solutions
2. **Machine tool spindle predictive behaviour** | FILL
3. **Predictive maintenance for a crankshaft manufacturing system** | ETXE-TAR
4. **Predictive maintenance and production optimization for closure manufacturing** | GCL International

facility management

5. CAMP NOU – Sport facility management and maintenance | Futbol Club Barcelona
6. EXAMON – Holistic supercomputer facility management | CINECA
7. Smart Grid facility management for power quality monitoring | SIEMENS

replicability

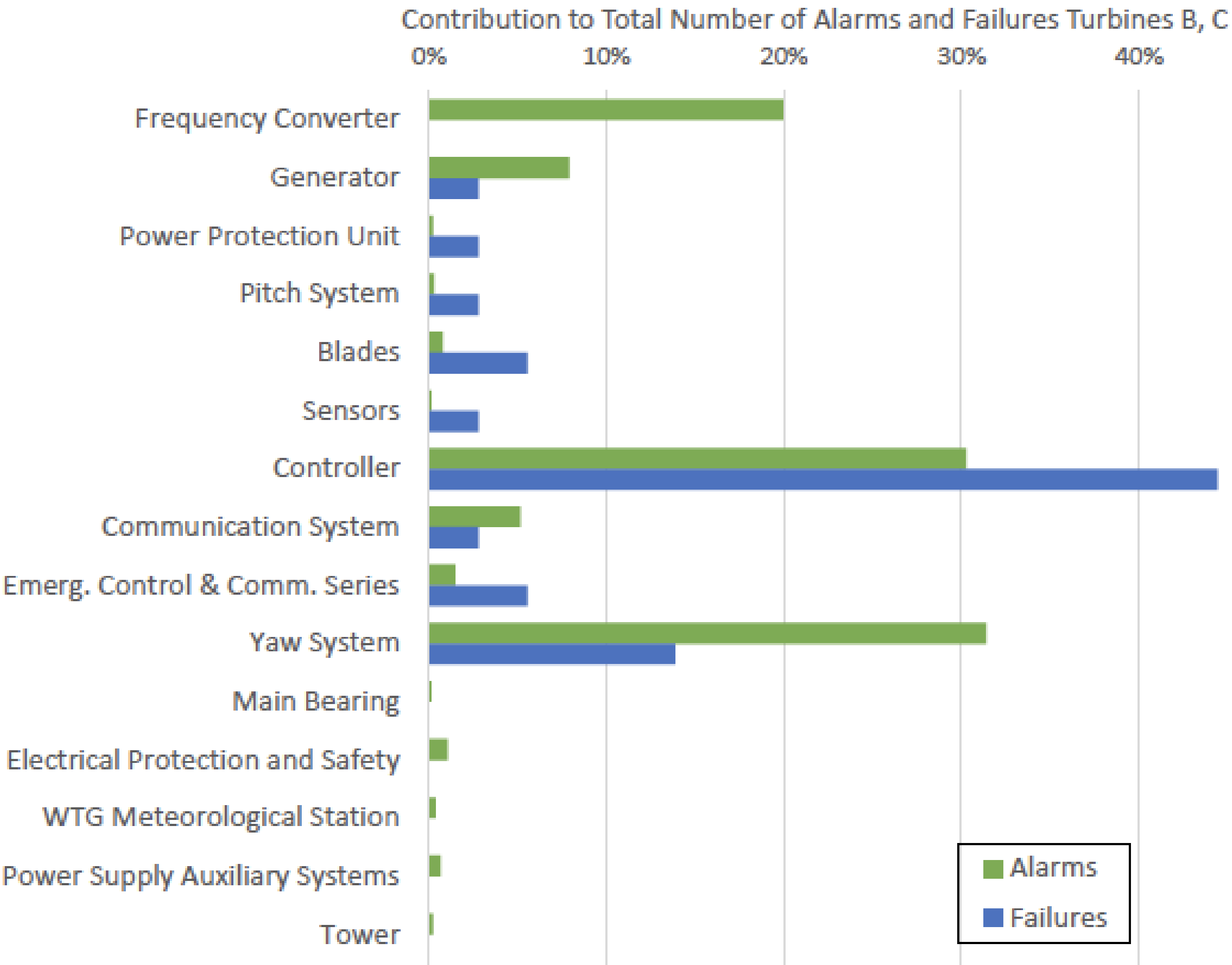
8. Patterns for smart manufacturing for SMEs | Centre Technique des Industries Mécaniques
9. Standardization/homogenization of manufacturing performance | GCL International
10. EXAMON replication to other datacentres facilities | Istituto Nazionale di Fisica Nucleare, Barcelona Supercomputing Center
11. CAMP NOU replicability towards smaller scale sport facilities | Futbol Club Barcelona
12. Innovative business models for IoTwins PaaS in manifacturing | Marposs


manufacturing
Testbed #1
Wind Turbine
predictive maintenance
Vestas

Predictive Maintenance in Industry

- Maintenance is a strategic business asset
  - ***Reduced downtime***
  - ***Reduction of production losses***
  - ***Breakdown reduction***

- Three levels of maintenance
  - **Reactive**: a fault occurs and is managed
  - **Preventive**: maintenance performed regularly on a machine to reduce the possibility of failure
  - **Predictive & Prescriptive**: maintenance plan optimized on the probability of failure



Predictive/Prescriptive maintenance for wind turbines

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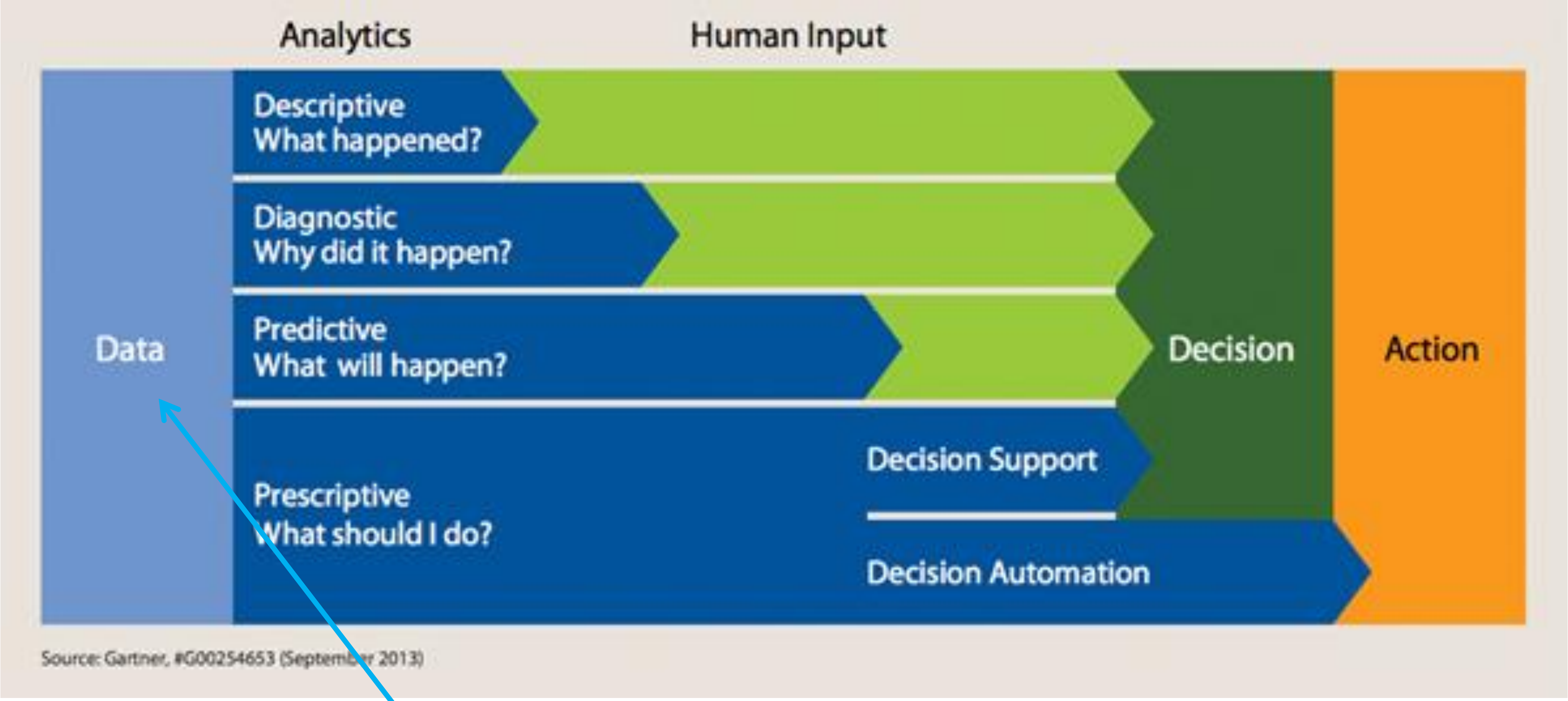
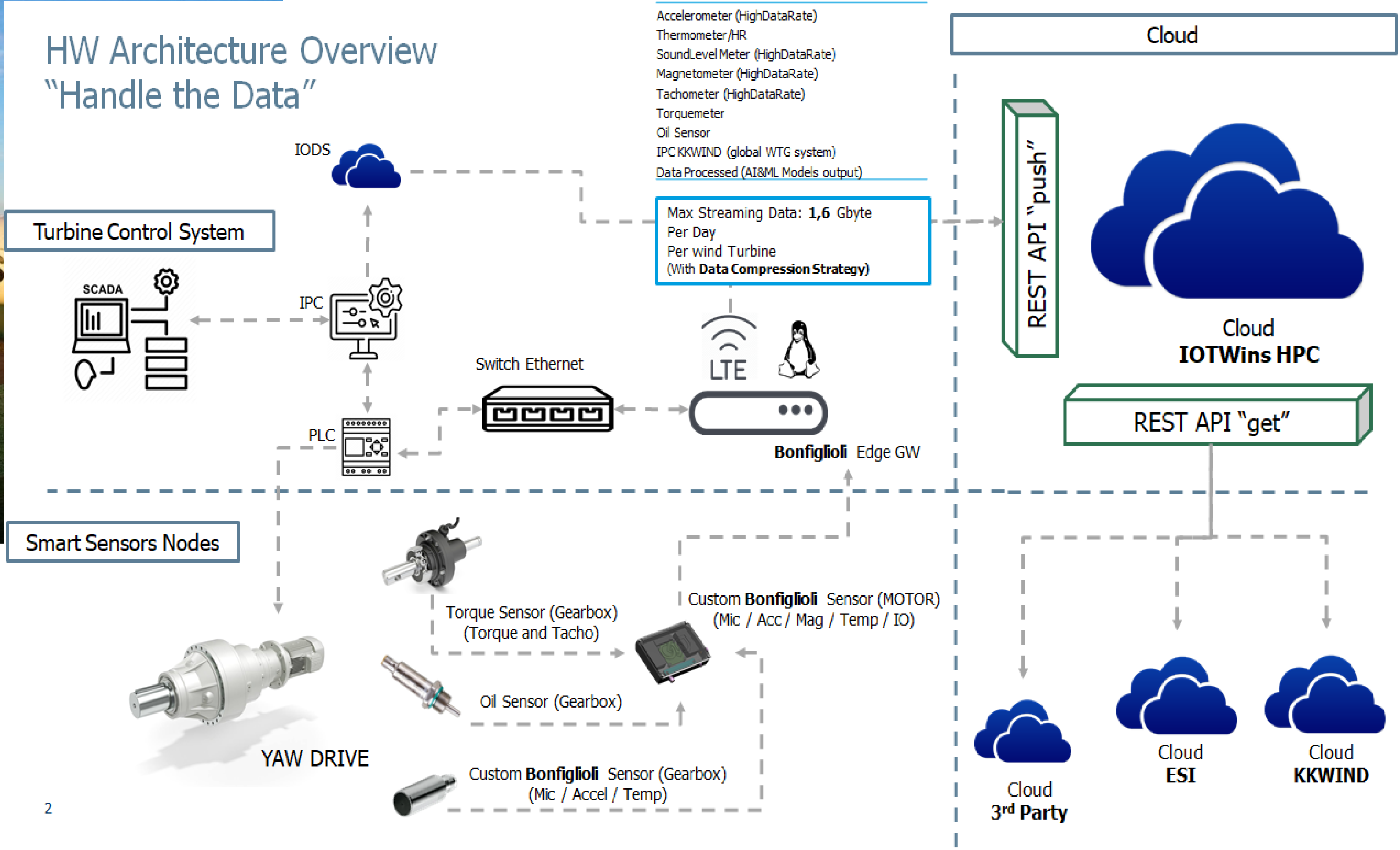
Decision Support System



Data and their quality are essential



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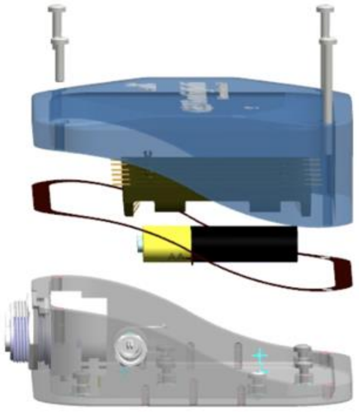
Predictive/Prescriptive maintenance for wind turbines

Multi Sensor Node prototype design and manufacturing

- The system is able collect external sensor input and stream to the Edge
- The Multi sensor Node is equipped several sensors like:
    - Vibrometer
    - Accelerometer
    - Microphone
    - Magnetometer
    - Temperature
    - Relative Humidity
- It transmits to the edge data via WiFi



manufacturing

Testbed #4

Predictive maintenance and production optimization for closure manufacturing

TESTBED #4 PREDICTIVE MAINTENANCE AND PRODUCTION OPTIMIZATION FOR CLOSURE MANUFACTURING

manufacturing

In complex closures manufacturing (spirits closures can have up to 15 different components) several production phases occur and different technologies and machinery are used.

This testbed will optimize production management and implement predictive maintenance for operation improvement and cost reduction.

Key features will be

- **the remote and real-time performance and status monitoring** of all the industrial assets and the detection of anomalies;
- the **improved scheduling process** leveraging real-time data from the production floor, properly linking it to the scheduling **ERP system for production optimization**.

The testbed will foresee the design and deployment of **redundant IoT modules** able to

- **to log data** at high sample rates;
- **to fuse data** coming from a first pilot series of machines;
- to install a **new module of the industrial IoT platform ThingWorx** for predictive maintenance and performance improvement;
- to integrate **a data-driven anomaly detection system.**

INVOLVED PARTNERS

GCL International | CINECA | INFN

IoTwins

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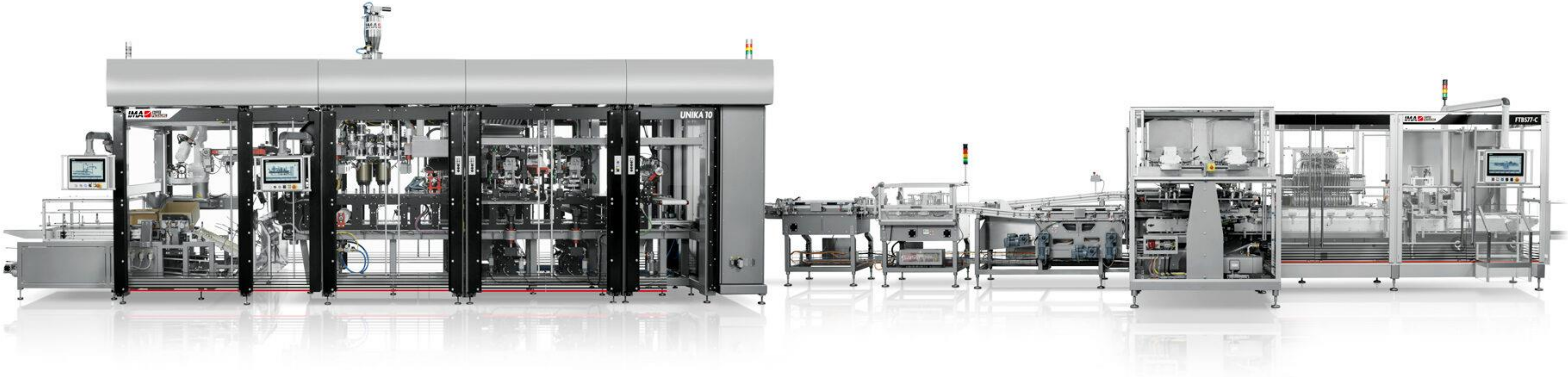


AIM: relevant reduction of ***defects*** and ***material/product/energy waste***

With hard challenging constraints on quality of service (in part. ***latency***)

facility management

Testbed #5

Camp Nou

sport facility management and maintenance

TESTBED #5 CAMP NOU SPORT FACILITY MANAGEMENT AND MAINTENANCE

facility management

CAMP NOU testbed focuses on the management of facilities involving the flow of large crowds, both during normal operation and during maintenance and construction projects. The digital twin is based on Machine Learning and Agent-Based Modeling for pedestrian simulation. Current crowd management systems are not capable of seizing large parallel computational power, and their usability for rapid question answering is limited. **This testbed will be performed during the renovation of Camp Nou, the home stadium of Football Club Barcelona** - the largest sport facility in Europe with a capacity of almost 100.000 seats.

FCB will reconvert all the area and facilities into the best sporting and entertainment complex in the world. The renovation plan foresees both the improvement of the football stadium, expanding its capacity, and the opening of all the private areas around the stadium (28.000 m^2) to the public, while integrating it harmoniously with the neighborhood.

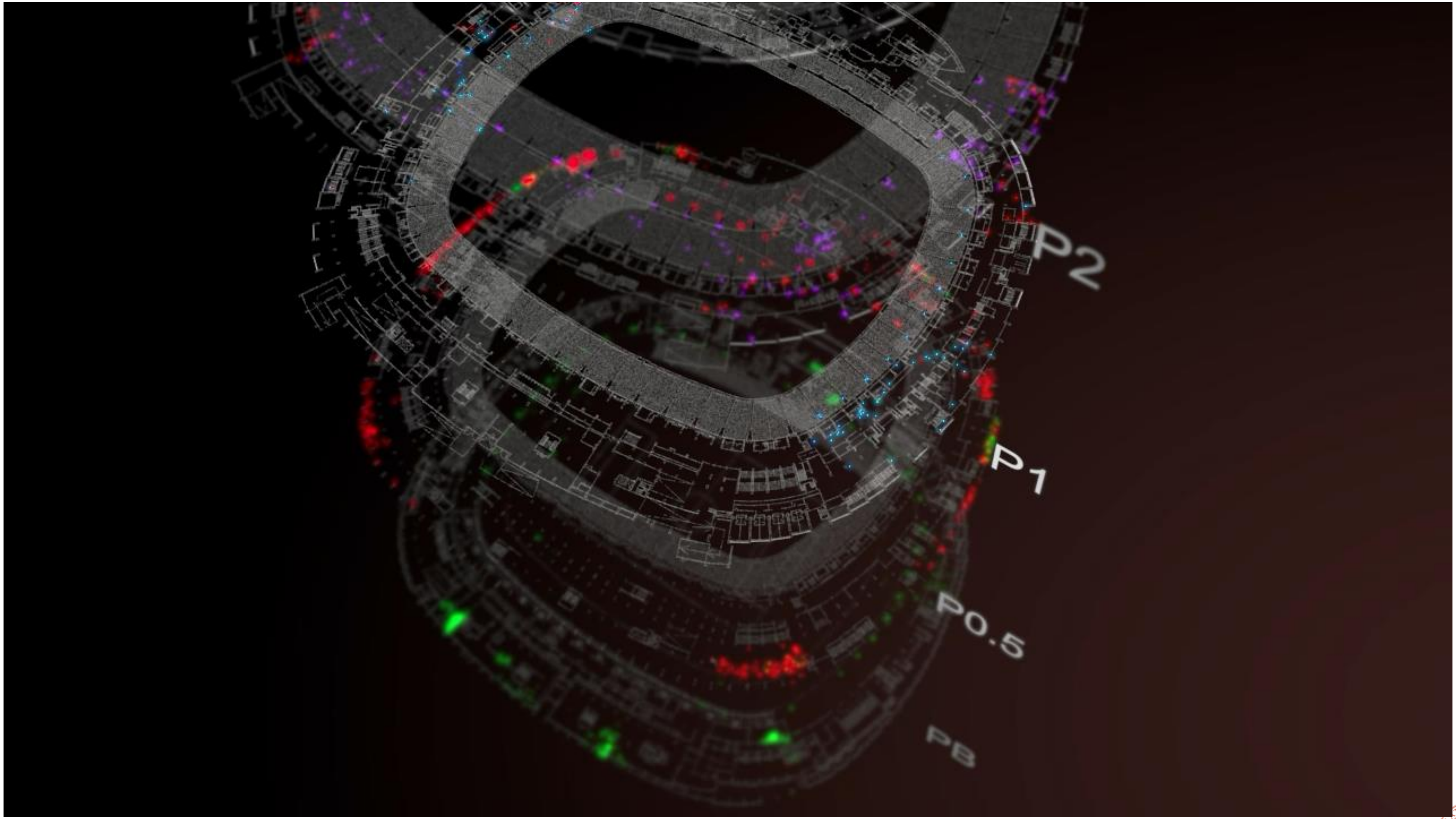
This testbed aims to analyze how crowds move both historically and in real-time using a robust IoT and big data infrastructure to collect, transmit and process data in real-time

- https://www.youtube.com/watch?v=5kxomB-UWqc

INVOLVED PARTNERS

BARÇA INNOVATION HUB | Barcelona Supercomputing Center

The Digital Twin of the Nou Camp Nou Stadium in Barcelona



The Digital Twin of the Nou Camp Nou Stadium in Barcelona

- WiFi data collection being transformed to use Indigo/IoTwins infrastructure in collaboration with INFN (now using an intermediate temporal solution)
- Cameras tested succesfully on a match, but delivery of full order pushed back until March 2022!!!
- Systems tested on stadium during match

Testing videos (phones)

NVIDIA Jetson Xavier NX

Device video (operational)

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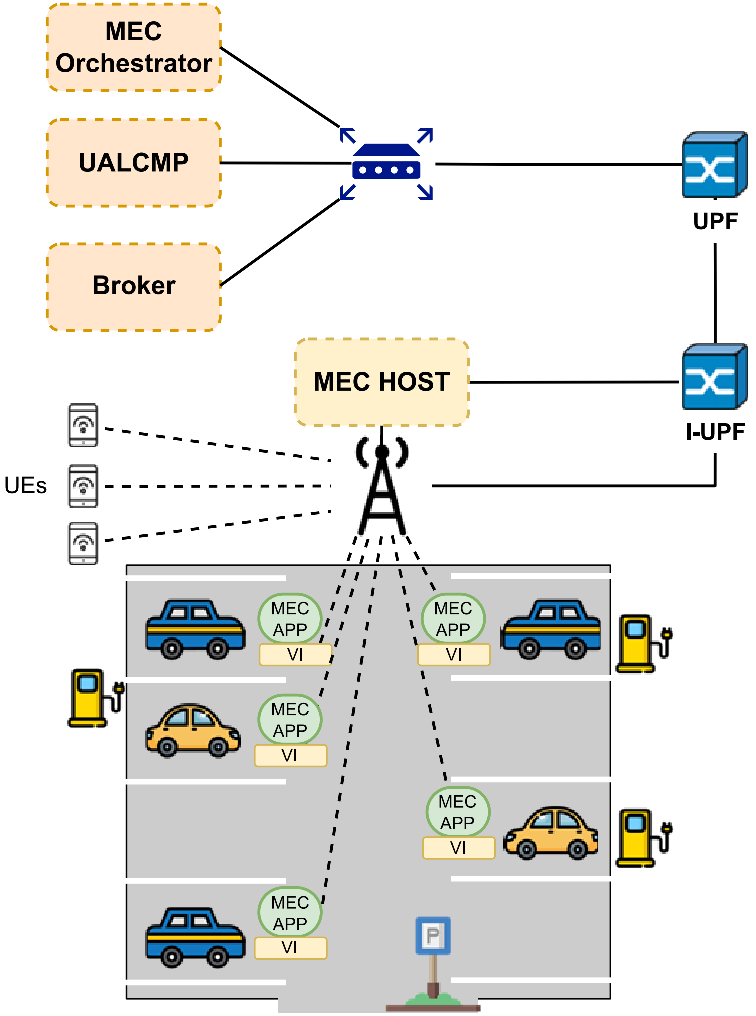
Advanced Research on Digital Twins calls for:

- *Simulation tools*
- *Advanced testbeds*

A Simulation Tool for MEC-Compliant Vehicular Cloud Computing Scenario

A platform that **facilitates the design, testing, and enhancement of applications** relying on the **vehicular computing paradigm** in 5G environments

- Works with the **event-based simulator OMNet++**
- Exploits **Simu5G** as communication library
- Supports **stationary vehicles** – parking lots – as dynamic resource sources



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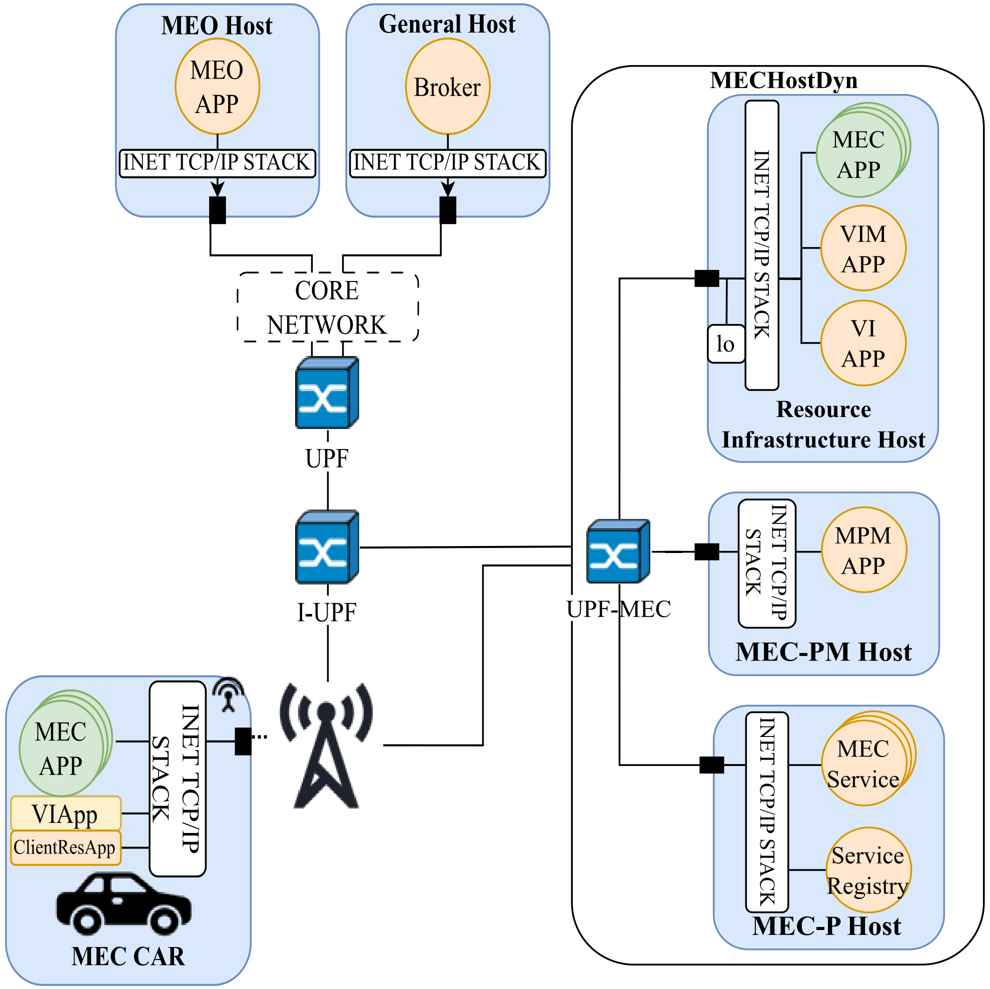
Simulation Tool: OMNet++ Modules

- **MECCar Module**: it wraps a 5G-enabled device, by adding **computational resources** and running applications **enabling MEC-App hosting**
- **MECHostDyn Module**: it contains enhanced MEC-compliant simple modules that consider the **architecture dynamicity**. They prepare, manage, and allocate resources dynamically provided by vehicles
- **General Host (Broker)**: it handles **resource pooling** of several MEC-Hosts and relies on a publish-subscribe model to collect MEC-Host AoI subscriptions



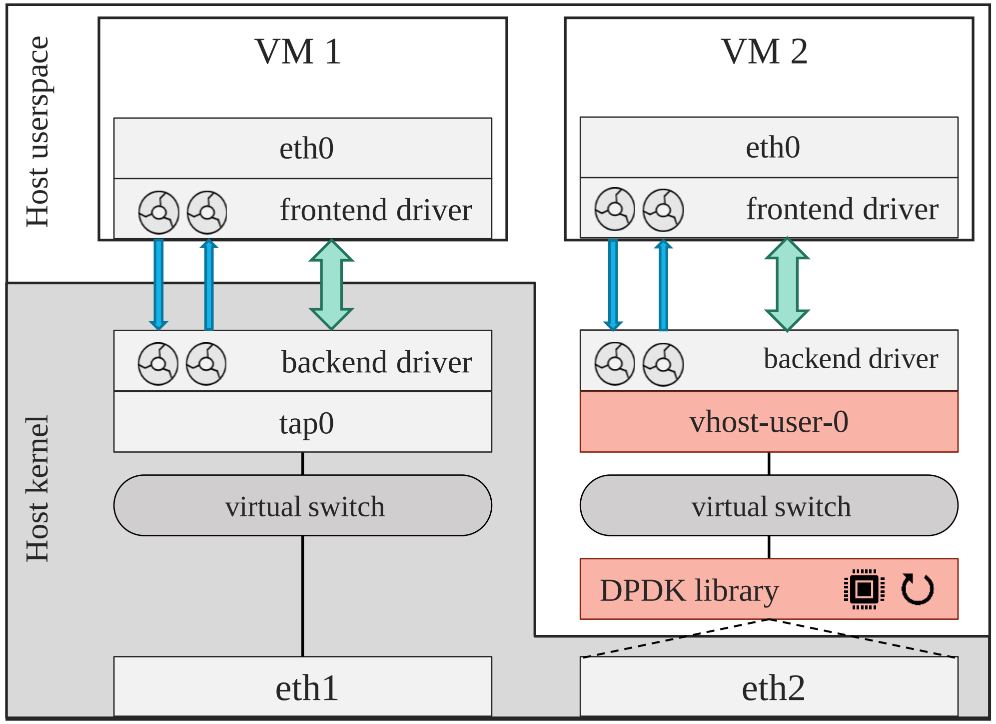
Advanced Tesbeds: TSN-enabled Virtual Environments for ULL communications

Main sources of **datapath overhead** are in the kernel networking stack: *data copies, context switches, etc* [3]

However, ***TSN scheduling*** is performed by the ***guest networking stack***

OUR SOLUTION

- ***Guest kernel*** is untouched
- ***Host kernel*** is bypassed using **DPDK**, a library for userspace packet processing



Kernel-based paravirtualization

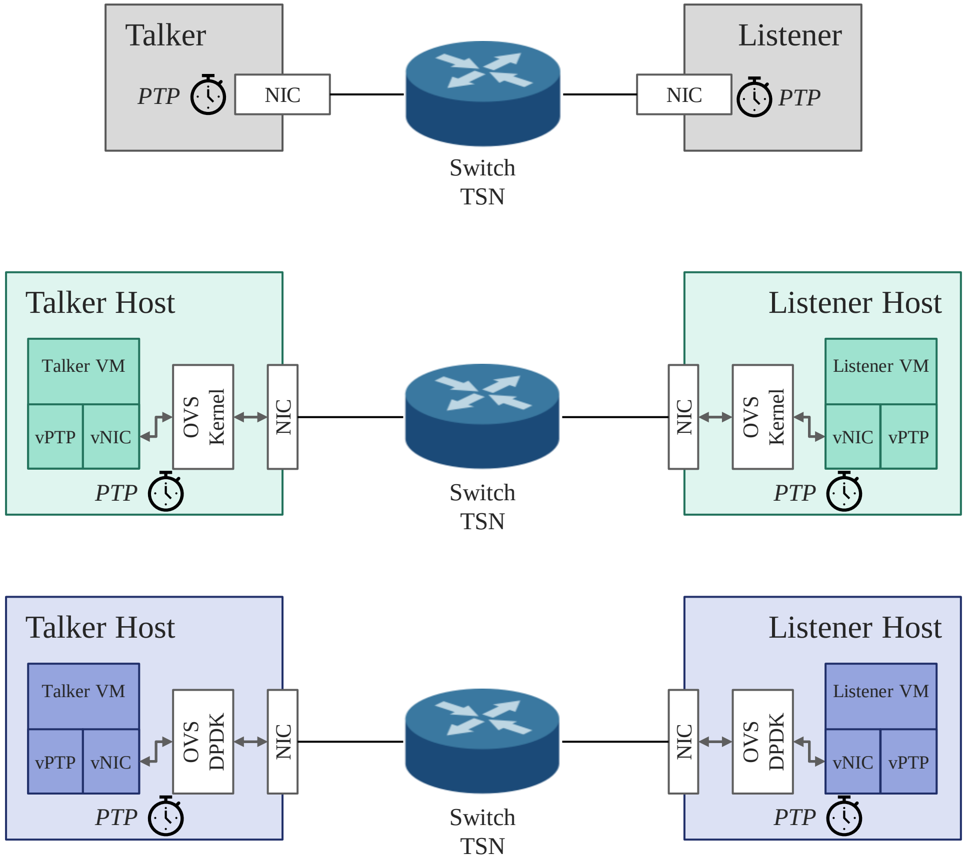
Userspace paravirtualization

[3] Cai, Qizhe, et al. "Understanding host network stack overheads." Proceedings of the 2021 ACM SIGCOMM 2021 Conference. 2021.

TSN-enabled Virtual Environments for Ultra-low Latency (ULL) communications

GOAL Show that ***virtualized TSN applications*** preserve ***sub-millisecond E2E latency*** and good ***determinism***

Assuming ***60%*** of the budget reserved for ***5G WAN propagation,*** we set the ***latency threshold to 0.4 ms***



TESTBED SETUP

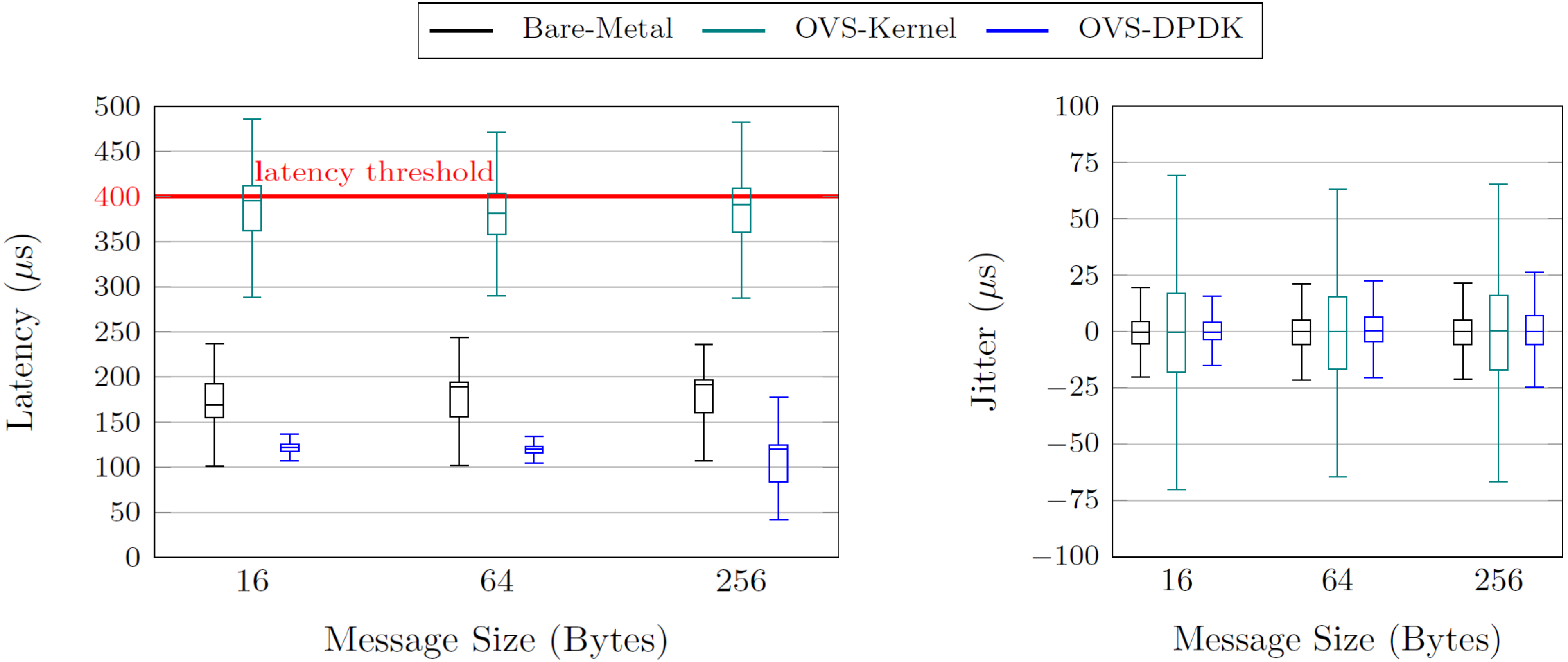
- ***2 UP Xtreme boards*** (***Talker*** and ***Listener***)
    - 4 1Gbit TSN NICs (Intel I210)
    - Intel Core i3-8145UE CPU with 2/4 cores
    - 8GB of RAM
    - OS - Ubuntu 20.04 with Linux kernel 5.4.0
- ***1 TSN-compliant*** Relyum RELY-TSN-BRIDGE ***switch***

TEST APPLICATION One ***publisher***, one ***subscriber***, each running ***baremetal*** or in ***VMs*** on a separate hosts. Exchange UDP packets with ***1ms publishing cycle***

Evaluation: E2E Latency and Jitter

The experiment demonstrates our solution's ability to ***support TSN applications in virtual environments***, with latency stable **< 400us**

→ The ***OVS-DPDK setup*** performs even better than bare-metal thanks to kernel bypassing



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Resource disaggregation and containerization in the C2TC

Typical C2TC applications are ***disaggregated*** and ***containerized***:

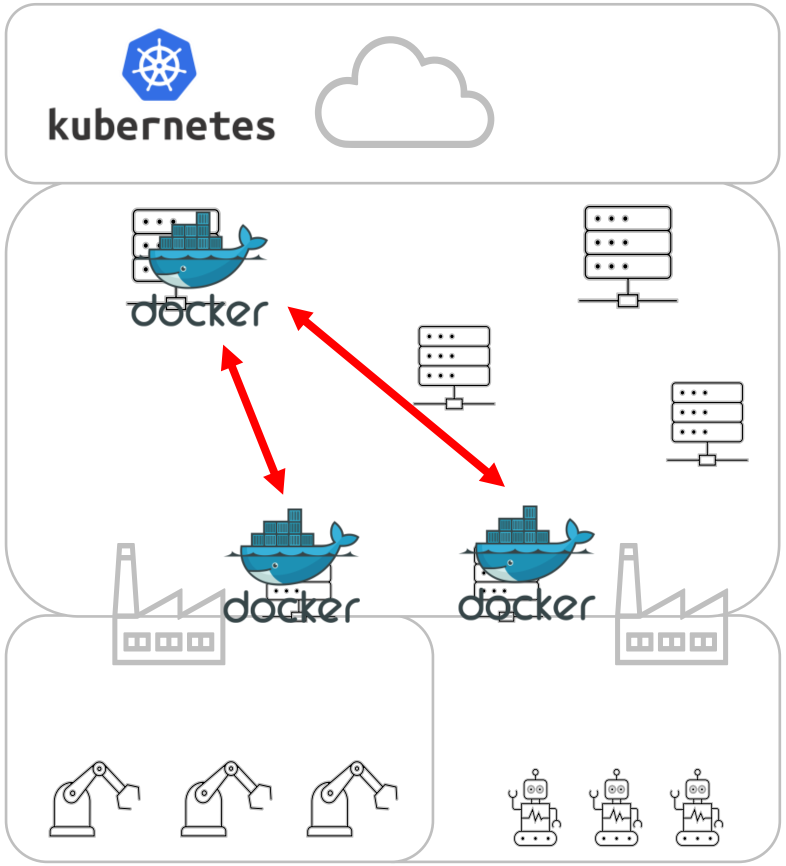
- Applications are designed as ***interacting components***
- Each component lives in an ***isolated container***

Orchestrators (e.g., Kubernetes) can optimize the placement of these components based on:

- Application requirements
- Edge node capabilities (e.g., CPU available)

However, orchestrators currently ***do NOT consider networking*** in placement decisions, even if network delays might ***disrupt the operations*** of applications with:

1. ***Ultra-Low Latency***
2. ***Deterministic behavior***



Flannel and the overhead of container overlay network

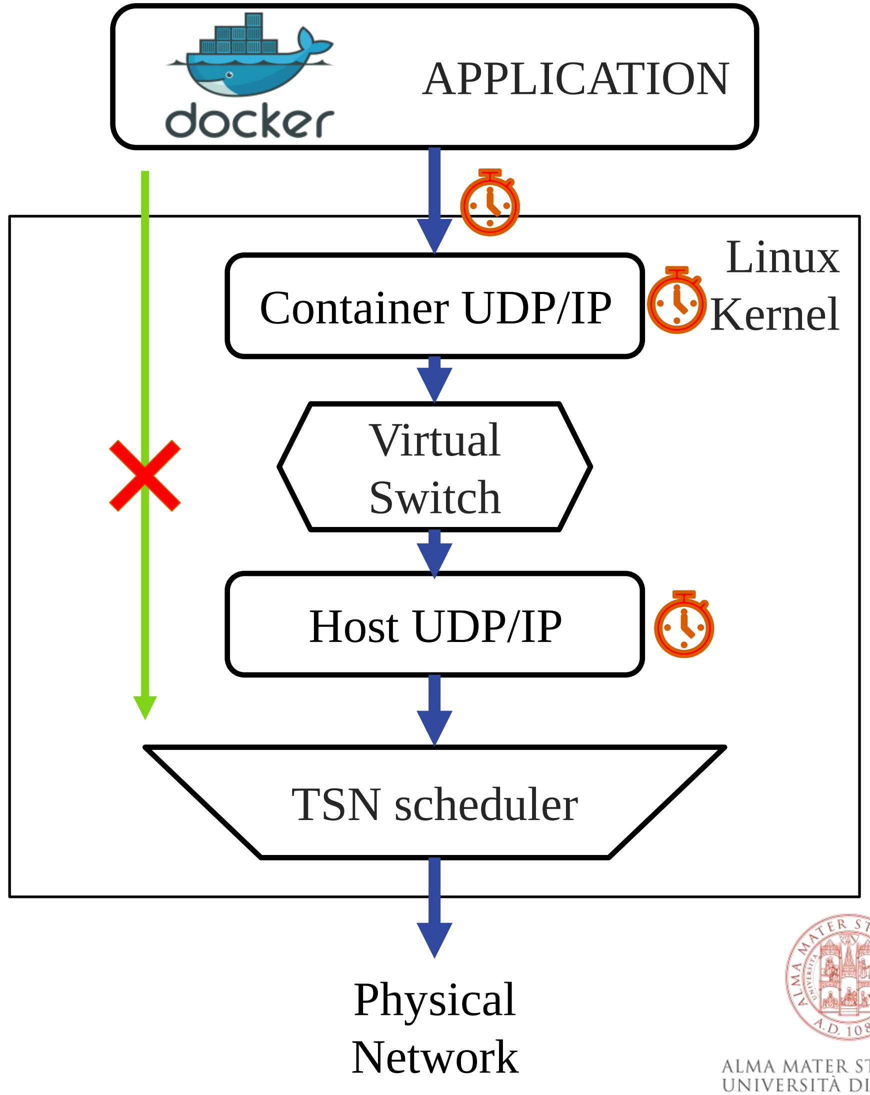
Kubernetes can create ***overlay networks*** among containers through a set of ***Container Network Interface*** *(CNI)* plugins

There are many CNI plugins, e.g., *Flannel*

Although with different tools and mechanisms, they set up the same network configuration, introducing ***two crucial issues*** for mission-critical applications:

1. Multiple instances of the ***kernel-based*** network stack

2. Impossibility to ***configure TSN*** protocol parameters



ESFRI 2021 Roadmap Update
SLICES Hearing

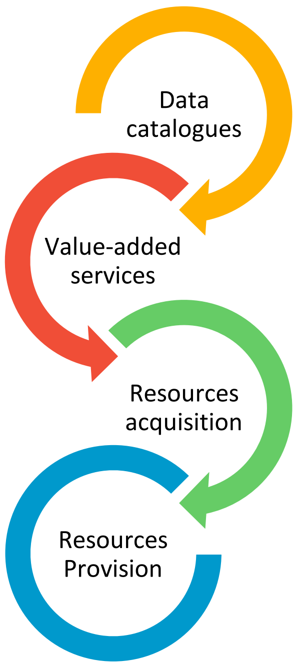
14 April 2021

SLICES in a nutshell

- ***Digital transformation*** is at the heart of our society!
- There is ***no*** digital transformation ***without digital infrastructures***
- Launched in 2017, **SLICES** is an **RI** to support the **academic and industrial research community** that will design, develop and deploy the **Next Generation** of **Digital Infrastructures:**
  - **SLICES-RI** is a **distributed RI** providing several **specialized instruments** on challenging research areas of Digital Infrastructures, by **aggregating** networking, computing and storage **resources** across countries, nodes and sites.
  - ***Scientific domains***: networking protocols, radio technologies, services, data collection, parallel and distributed computing and in particular cloud and edge-based computing architectures and services.

www.slices-ri.eu

what we offer



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Fully Controllable, programmable Virtualized Digital Infrastructure Test Platforms

USA NSF PAWR (Platforms for Advanced Wireless Research): NSF + Industry, 100M€, 2017-2022

NSF Fabric: NSF, 20 M€, 2019-2023

Colosseum: NSF-DARPA, 20+7,5M$, 2017-2025.

China CENI
Chinese Experimental National Infrastructure
2018-202239
190 M€

What do we consider services/infrastructure/testbeds/nodes in ESFRI SLICES?

- ***National Node*** = country, because of contracts with countries
- ***Central Hub*** = central organization body (legal), not technical
- ***Federation*** = organization should not be like a '(loose) federation', but there is a central ERIC structure
  - Technically: ' federation techniques' for distributed RI could be possible -> in this meeting we are only looking architecture wise
- ***Testbed/site/infrastructure***
  - Testbed can span countries. Coherent entity of one or more sites managed by single team
  - Site: physical location (so single country)
  - National Node is a collection of Sites
  - A site and a testbed are both a collection of resources
  - Interconnection between sites are owned/managed by the sites and by, e.g., Geant or Central Hub in the middle (interconnection exchange)
  - Central components of SLICES (owned and managed by the Central Hub organization)

slicesRI

What do we consider services/infrastructure/testbeds/nodes in ESFRI SLICES?

- ***Services (from end-user perspective)*** = what will we advertise to users
  - e.g., 5G core, 5G network, resources, analysis of data (e.g. wireless data), machine learning, simulation/emulation, visual orchestration of experiment/workflow, energy measurement

- Overall, ***SLICES is a distributed RI consisting of a Central Hub and interlinked National Nodes***, and needs to:
  - have a unique specific name and legal status and governance structure with clear responsibilities and reporting lines, including international supervisory and appropriate external advisory bodies
  - have legally binding attributions of coordination competences and resources to the Central Hub
  - have a common access policy and provide for a single point of access for all users with a support structure

- ***ITU Q.4068: testbed: Platform to realise scientific tests within new technologies on an environment fully controlled by experimenters***

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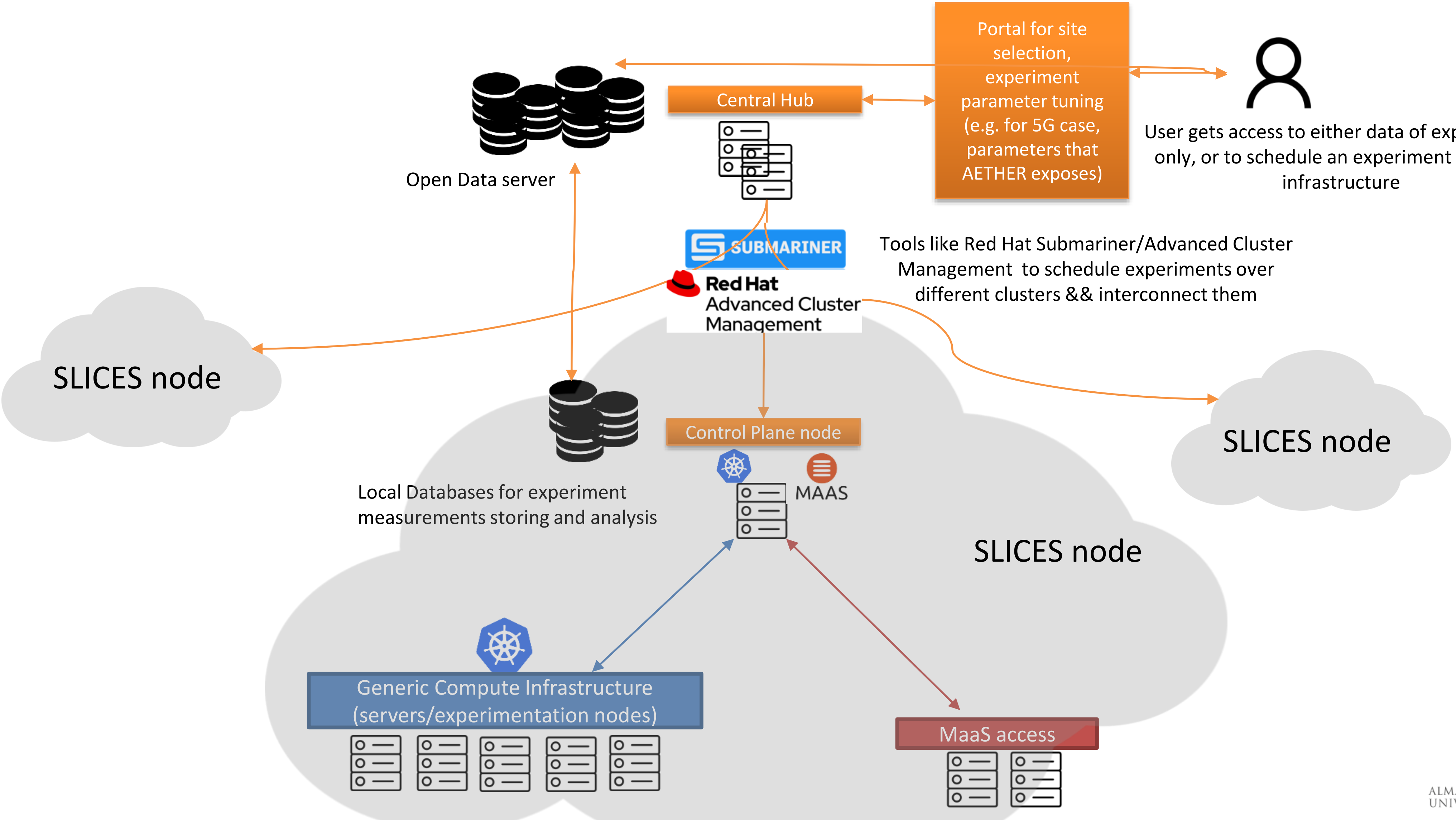
SLICES-Hub Blueprint – User Plane



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In super-short:

- **Research on Digital Twins calls for *advanced simulation tools and testbeds, INTEGRATED***
- ***Big opportunities related to 5G/6G***
- ***Big opportunities related to AIoT (AI-enabled IoT)***
- ***Open technical challenges associated with QoS, energy efficiency, integration with large-scale federated testbeds***

… And thanks a lot for Your kind attention!

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