Cyber-Physical Tests Beds

for Validation of Large-Scale Smart Grid Applications

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Online Training Series on the Digitalisation of Smart Energy Systems

February 22, 2024, online

Agenda

- Introduction & motivation
  - Distributed software and the electrical grid
  - From component to system level validation
  - Previous work @AIT & research direction
- Automated Cyber-Physical Testing and Validation Framework
  - Scalable Data Exchange with the physical layer
  - Model representation
  - Interlayer communication
  - Workflow
- Demo: Agent based distributed optimization - IEEE 123 buses

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INTRODUCTION

Motivation and Previous Work

Motivation

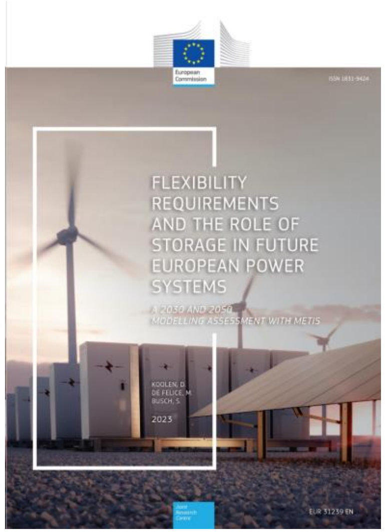
- European Green Deal
  - **2030**
    - 55% reduction in greenhouse gas
    - 42.5% renewable energy generation
  - **2050**
    - carbon neutrality
    - 80% renewable energy generation

EU's demand sectors are expected to transition towards electricity, particularly the **transport and heating** sectors.

intermittently available renewable energy will require **higher flexibility** to ensure functioning grids

2023 EU-JRC report:

- flexibility requirements will more than **double by 2030** and **grow 7 times by 2050**



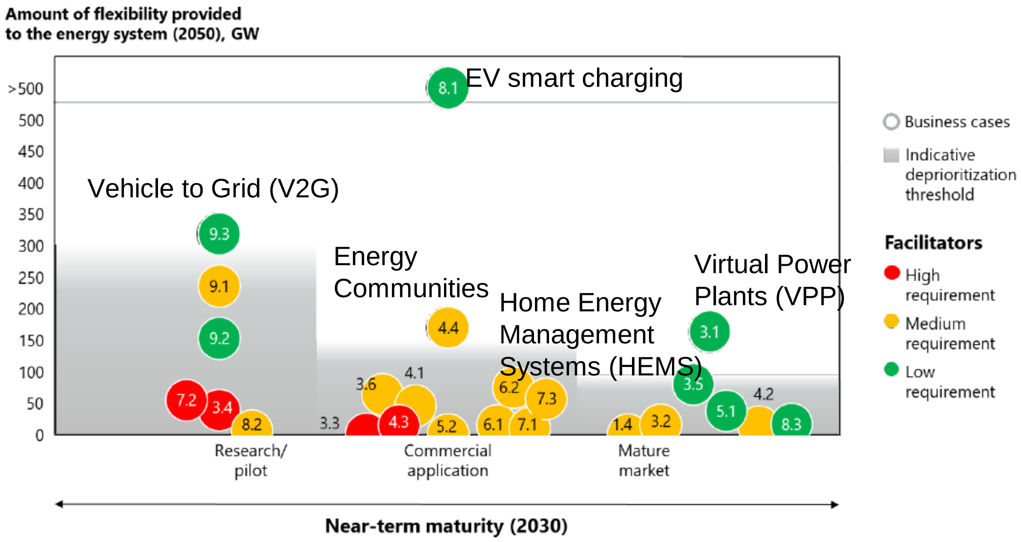
A European Green Deal. [Online]. Available: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en
A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. [Online]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52018DC0773
Flexibility requirements and the role of storage in future European power systems. [Online]. Available: https://publications.jrc.ec.europa.eu/repository/handle/JRC130519

Motivation

- **Digitally enabled flexibility** – one of the players in the energy transition program

- 2022 ENTEC report on Digitalisation of Energy Flexibility identifies **30+ business cases**

- Projections for 2050
  - ~60% of all dispatchable renewable energy (165 GW), will be aggregated into VPPs.
  - 59 Millions EVs will use smart charging
  - 7 million EVs will participate in V2G

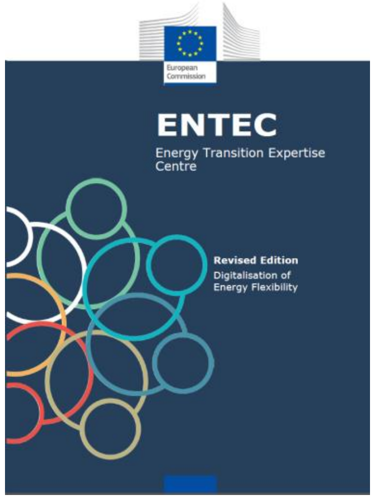


Massively Distributed Software Applications Acting on the Critical Electrical Energy Supply Infrastructure

How to investigate the impact of these systems at scale?

How to systematically test & validate before deployment?

How to approach the cyber-physical nature of these systems?

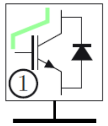


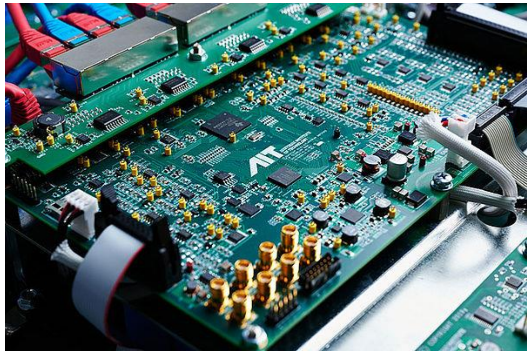
Digitalisation of Energy Flexibility. [Online]. Available: https://op.europa.eu/en/publication-detail/-/publication/c230dd32-a5a2-11ec-83e1-01aa75ed71a1/language-en

Modern power systems components

Complex cross-domain systems:

- Power Hardware (e.g. power electronics, electrical machines, etc.)
- Control Hardware
- Complex Control Structures
- Embedded software
- Embedded communication

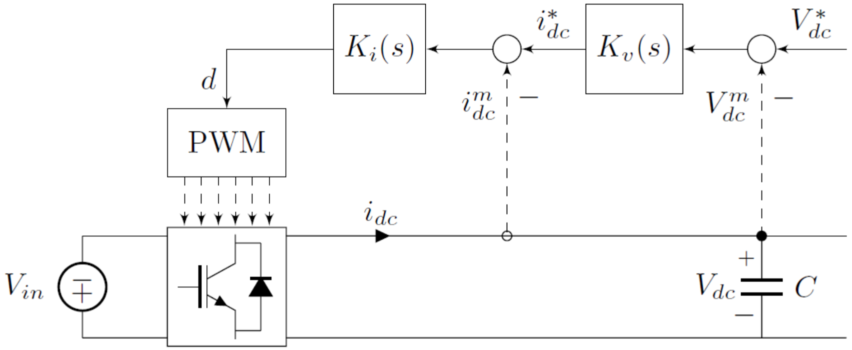




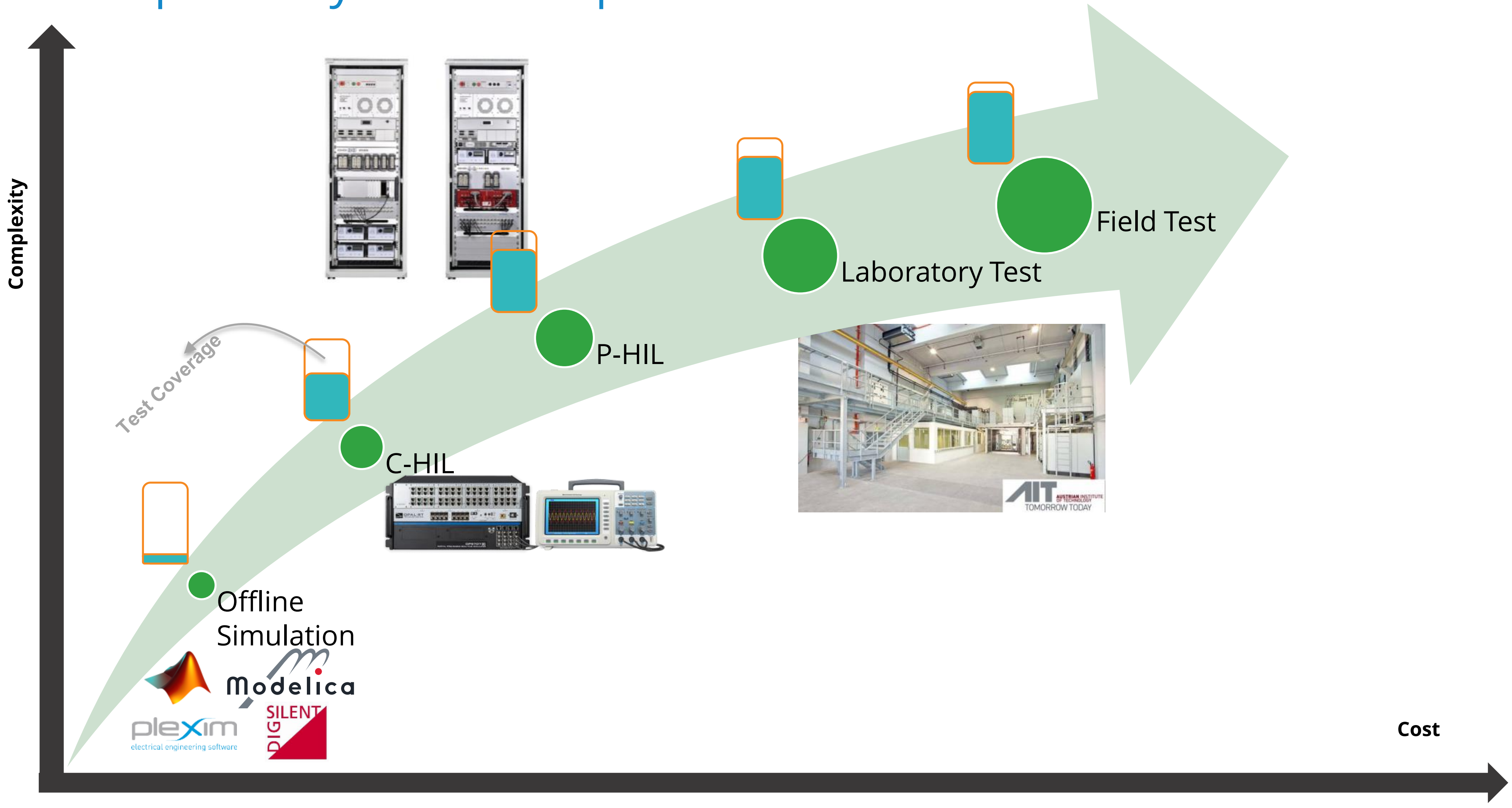
```
//    EPwm1Regs.AQCTLA.bit.ZRO = AQ_CLEAR;          //
//    EPwm1Regs.AQCTLA.bit.CAU = AQ_SET;
//    EPwm1Regs.AQCTLB.bit.ZRO = AQ_CLEAR;
//    EPwm1Regs.AQCTLB.bit.CBU = AQ_SET;

    EPwm1Regs.AQCTLA.bit.ZRO = AQ_SET;          // PWM
    EPwm1Regs.AQCTLA.bit.CAU = AQ_CLEAR;
    EPwm1Regs.AQCTLB.bit.ZRO = AQ_SET;
    EPwm1Regs.AQCTLB.bit.CBU = AQ_CLEAR;

    EALLOW;
    EPwm1Regs.HRCNFG.all = 0x0;
//    EPwm1Regs.HRCNFG.bit.EDGMODE = HR_REP;      //ME
    EPwm1Regs.HRCNFG.bit.EDGMODE = HR_FEP;
    EPwm1Regs.HRCNFG.bit.CTLMODE = HR_CMP;
    EPwm1Regs.HRCNFG.bit.HRLOAD  = HR_CTR_ZERO;
    EDIS;
```

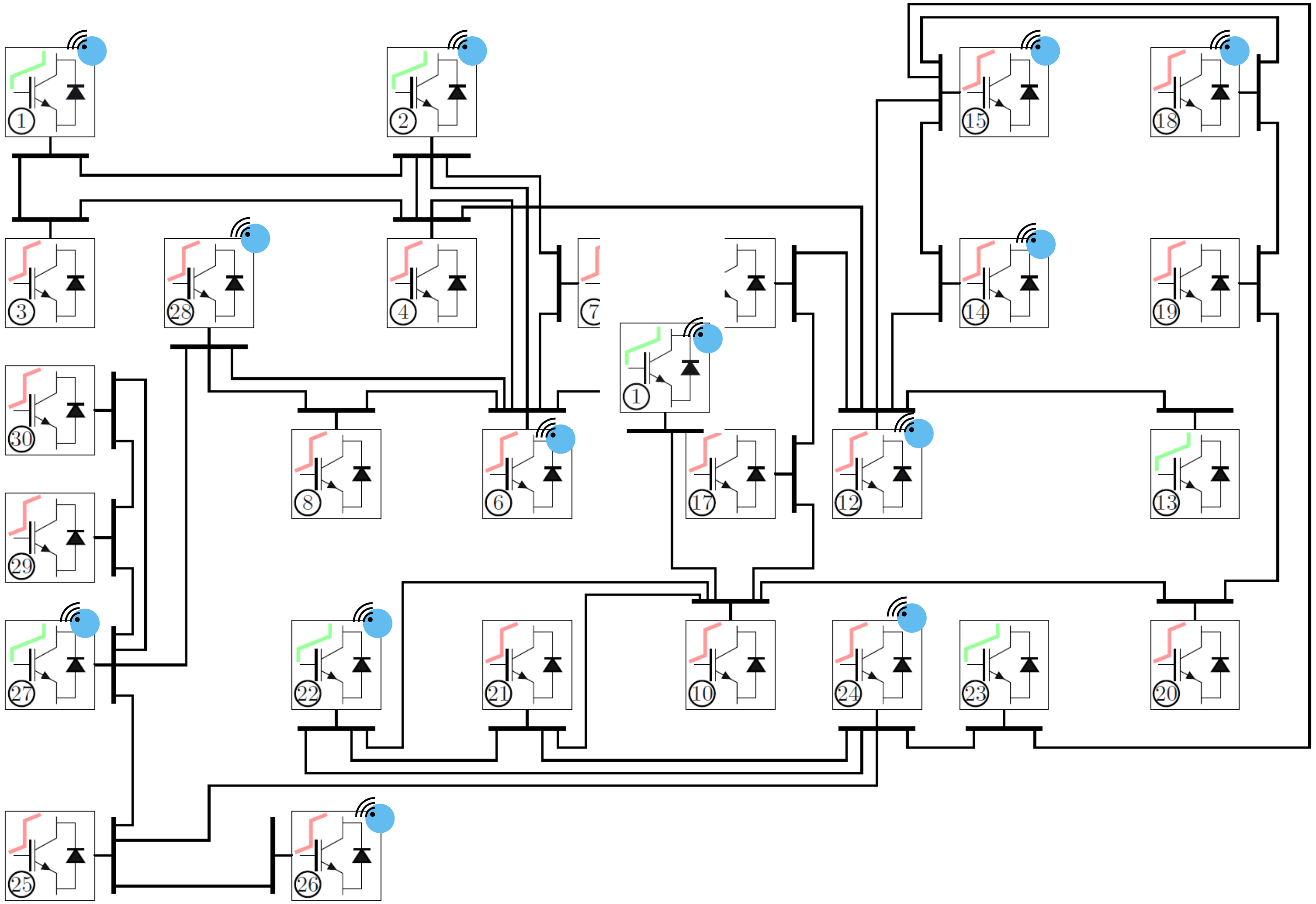


Modern power systems components



Testing, Validation, and Investigation Approaches (SoA)

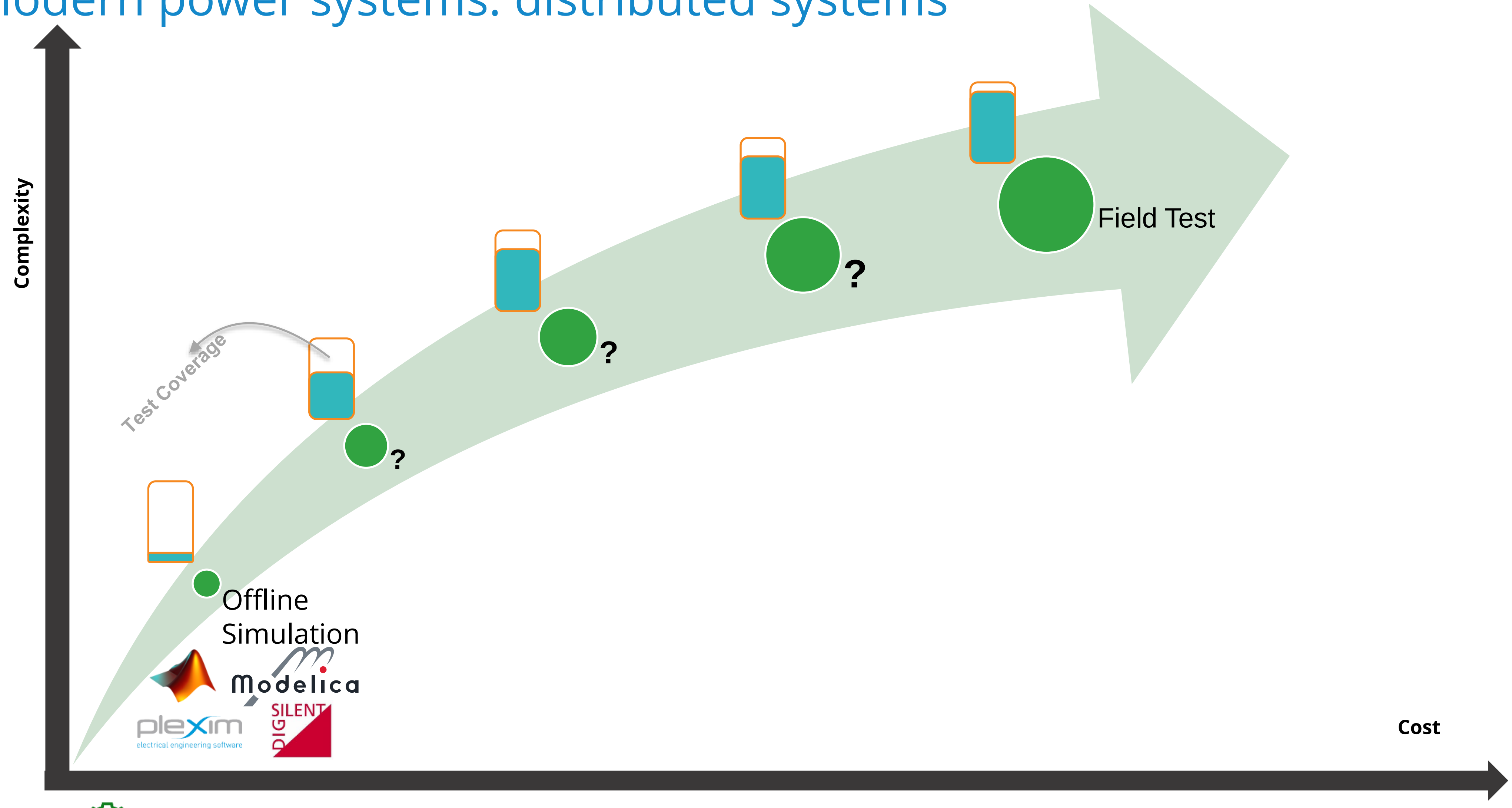
Modern power systems: distributed systems



Complex cross-domain systems:

- networked components
- distributed computing resources
- communication
- complex software architectures
- Hierarchical/distributed control

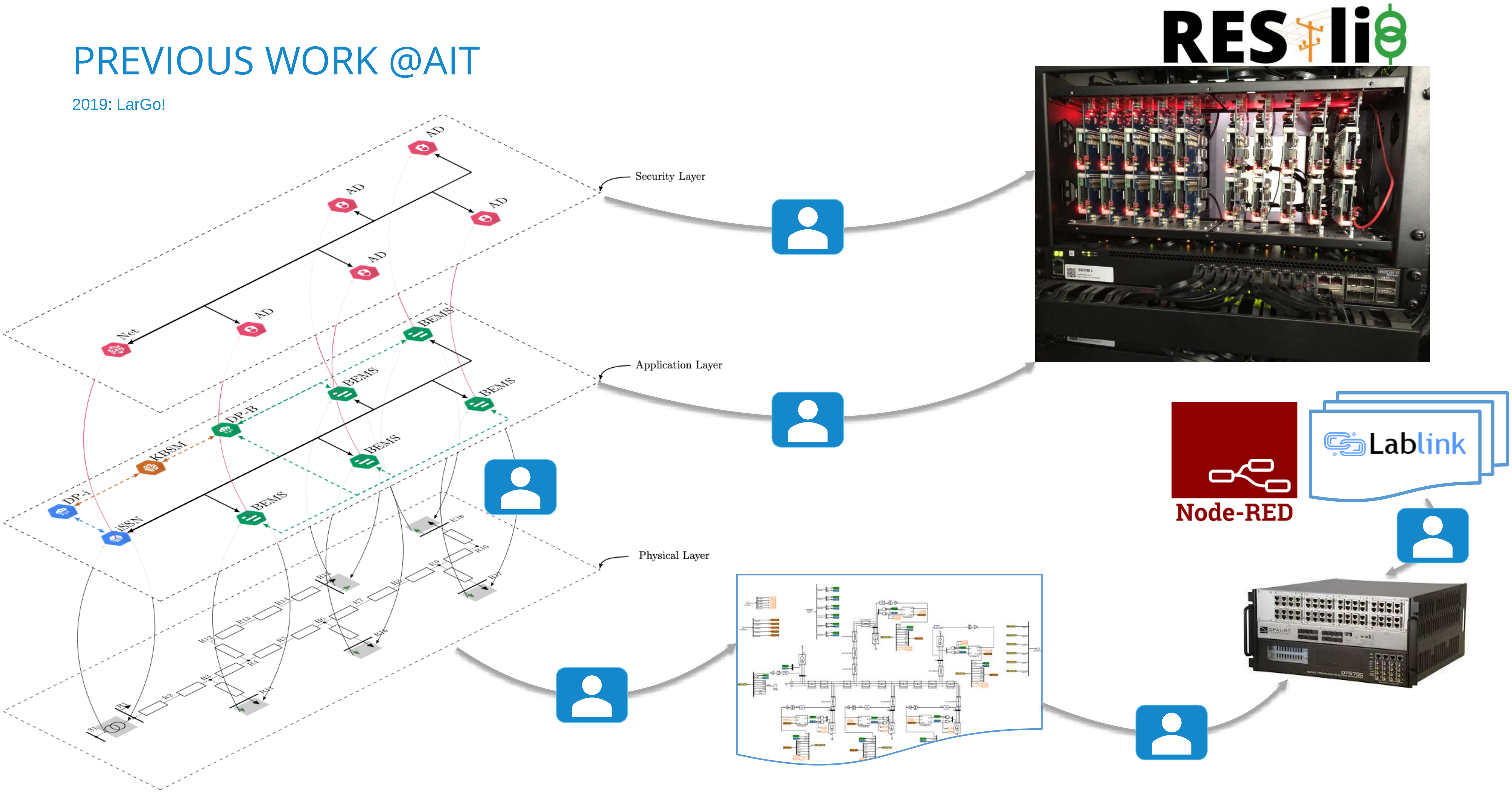
Modern power systems: distributed systems



– no proper tools for handling complex *system-in-the-loop* validation scenarios

PREVIOUS WORK @AIT

2019: LarGo!

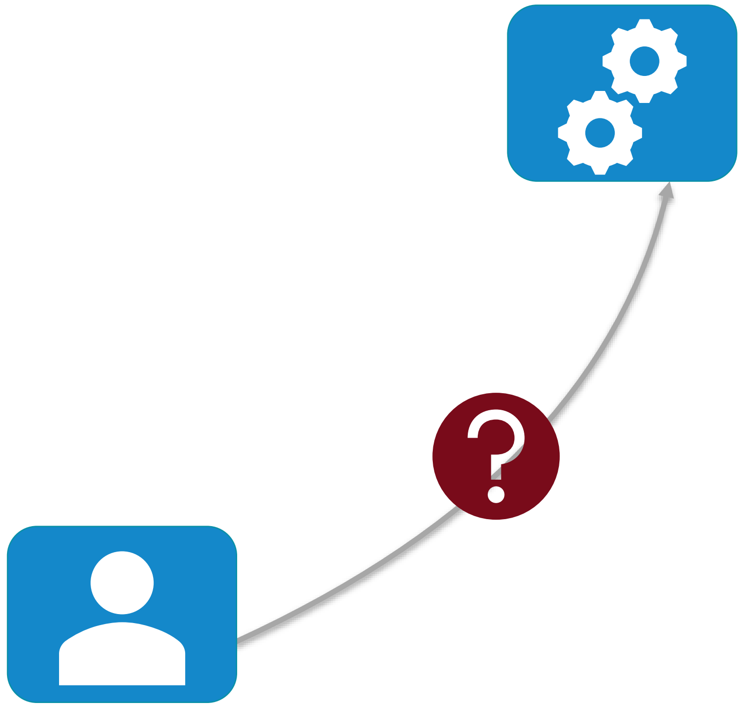


PREVIOUS WORK @AIT

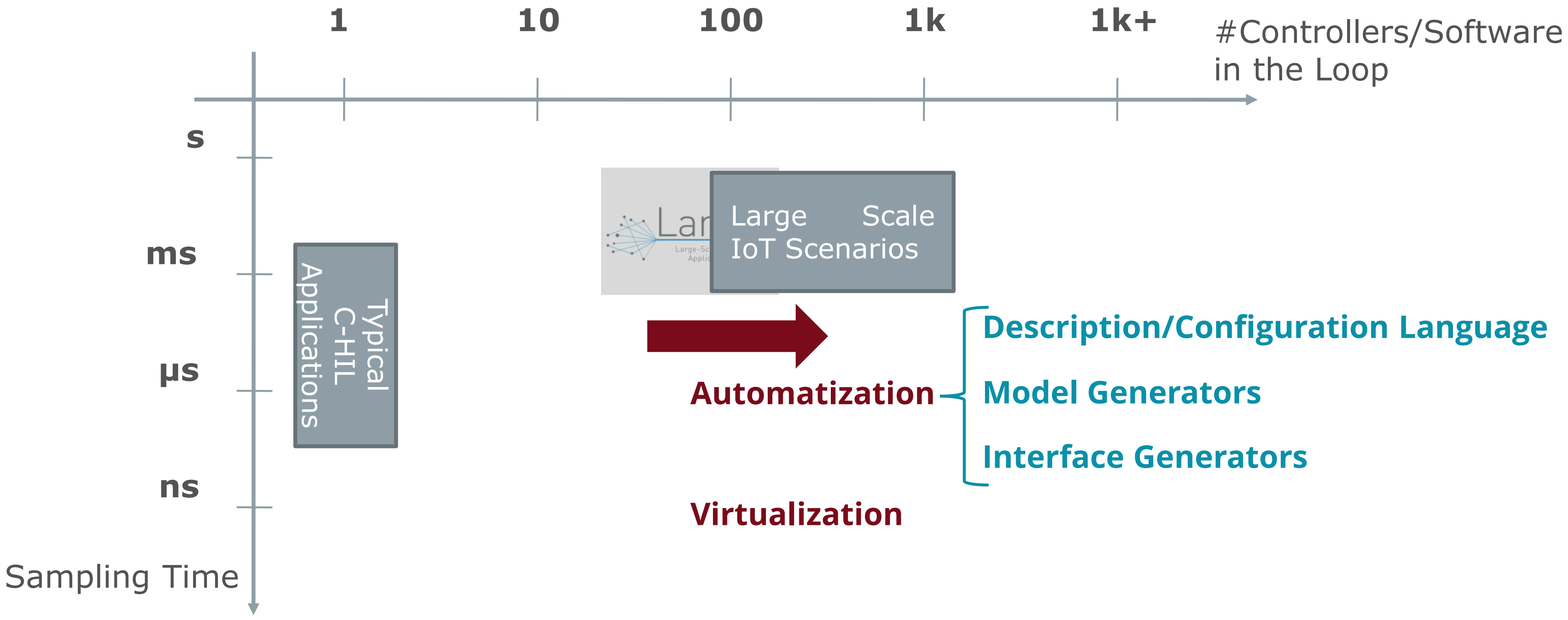
- Lesson learned:

System level validation is not an easy task!

- The complexity of simulation **configuration & coordination** increases considerably as the number of interconnected components grows
- Scalability of current approach is limited
  - Opal-RT – Lablink interface has limited throughput
  - 20 RPIs
  - **Manual processes** (e.g., modeling, interface definition, scenario execution, etc.)



PREVIOUS WORK @AIT



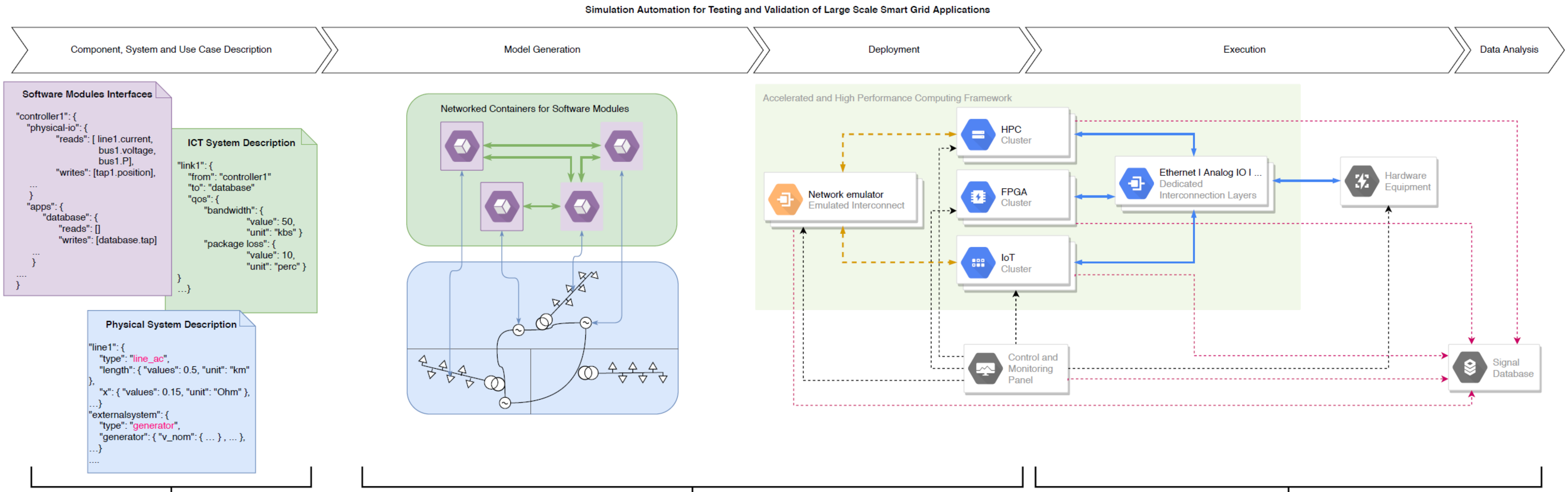
Automatization

- **Description/Configuration Language**
- **Model Generators**
- **Interface Generators**

Virtualization

Streamlined data-exchange with Opal-RT

PREVIOUS WORK @AIT



Use Case & Test Case Definition Tools

e.g.:
- increase all loads @T1 with 10%
- drop Link1 in the communication @T2
- stop controller1 @T3
- deploy controller2 @T4
- monitor bus1.voltage, tap1.position
- bus1.voltage should remain between limits at all time

Automatic Model Generation, Separation and HW Mapping

- use case dependent
- library of models for different type of simulations (dynamic/phasor)
- different HW/computing resources could be employed
- automatic control panel generation
- automatic data acqusition

e.g. Largo! Scenario:
- physical system runs in OPAL-RT as C-code generated from Simulink
- the containers for the Software Modules run on the RPIs

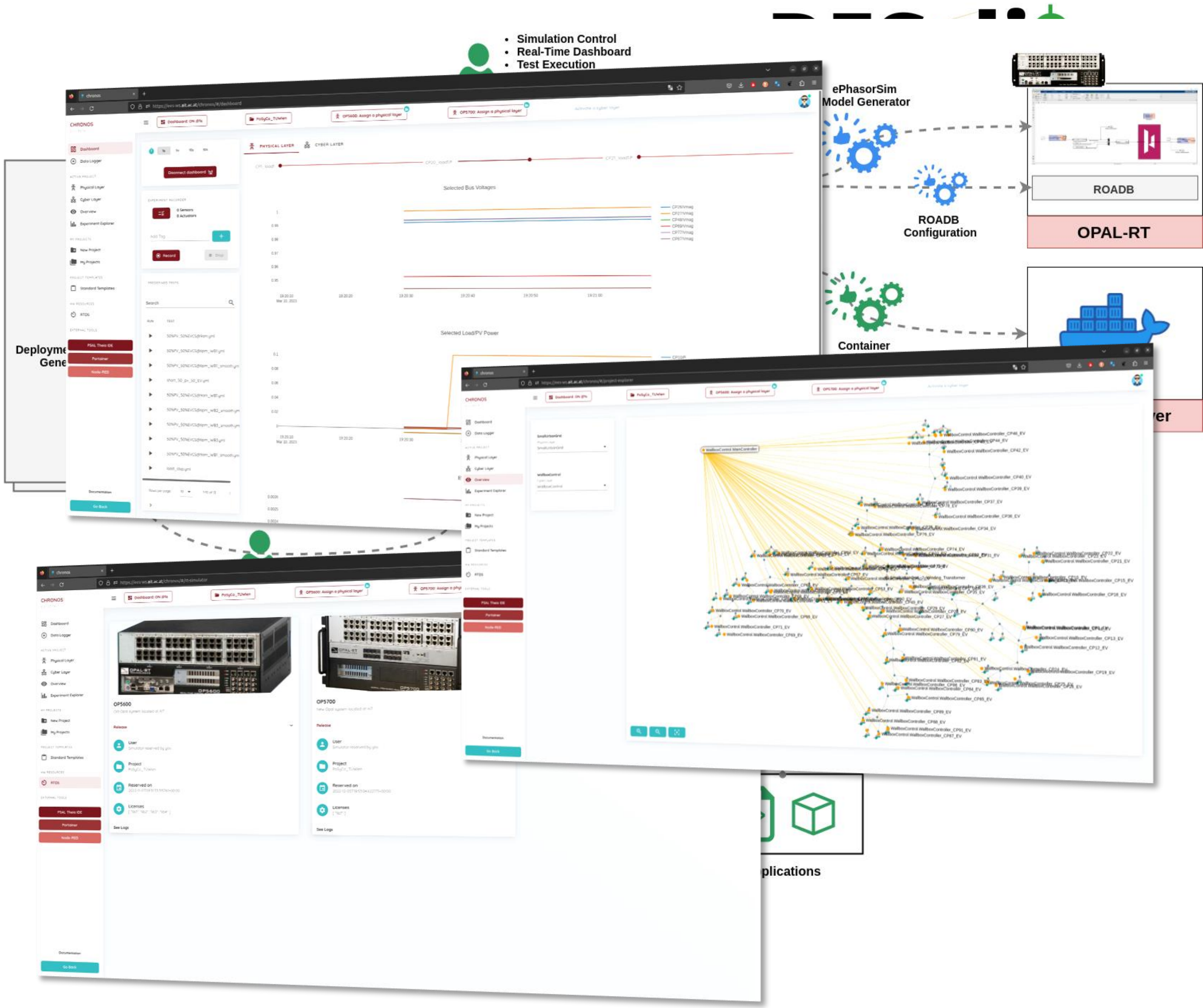
Execution and Use Case Evaluation

- simulation monitoring
- data exploration / visualisation

PREVIOUS WORK @AIT

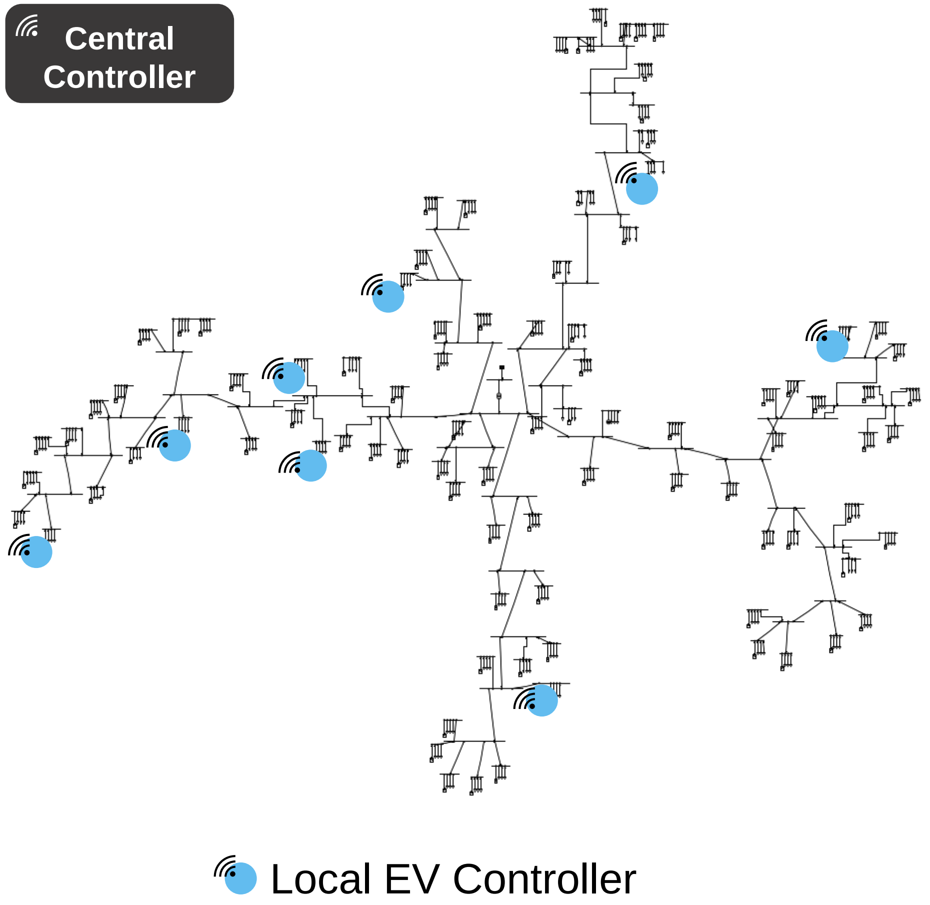
2021: PoSyCo

- Testing and Validation **as a Service**
- Generic Model Description (PSAL)
- Automatic Model Importers/Generators
- Automatic Interface Generators
- Improved RT-simulation data exchange
- **Remote Simulation Orchestration**
  - Physical layer
    - Reserve RT-simulators
    - Execute & control simulations
    - Monitor & interact with simulation
  - Cyber layer
    - Create deployment configurations
    - Docker Containers
    - Deploy application
  - Tests & Experiments
    - Execute pre-defined test scenarios
    - Record data
    - Explore results



PREVIOUS WORK @AIT

2021: PoSyCo



- Small Urban Grid:
  - 120 buses
  - PVs & EVs
- Central Controller:
  - Prevents overloading in feeders
- Local EV Controller:
  - Controls charging of EVs
  - 87 Controllers in our use case

DEVELOPMENT DIRECTIONS

Digital Network Twin

Use case:

Advanced Large-Scale Training Rooms for Network Operator Training

Interested parties:

- **DSOs:**
  - Wiener Netze
- **TSOs:**
  - Réseau de Transport d'Électricité

Smart Grid Applications Testing & Validation

Use case:

Sandbox for Evaluating Complex Software Ecosystems and Control Algorithms

Interested parties:

- **Universities:**
  - TU Wien
  - KTH
- **RTOs:**
  - Fraunhofer ISE
- **Industrial:**
  - Siemens
  - Honda

Cyber-Physical Ranges

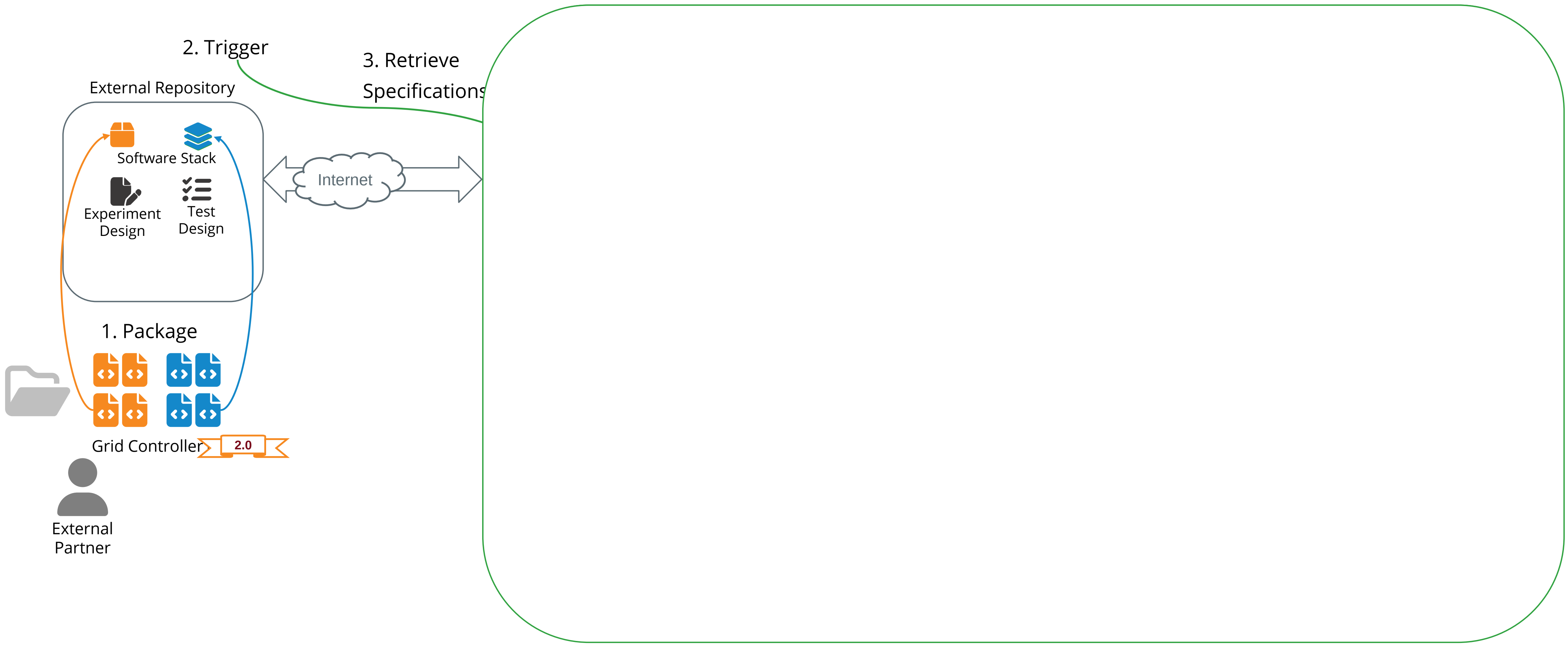
Use case:

Cyber-Physical Ranges for Cybersecurity Exercises & Training

Interested parties:

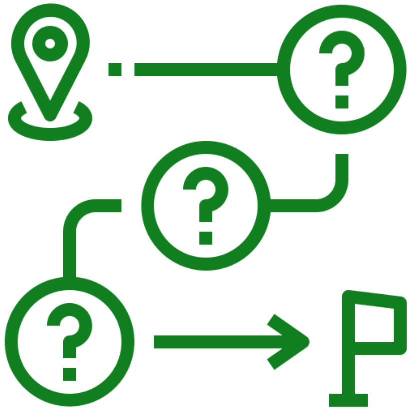
- **RTOs:**
  - AIT DSS
- **Industrial:**
  - Guardtime

Smart Grid Software Applications Testing – Workflow



Automated Cyber-Physical Testing and Validation Framework

Under the hood

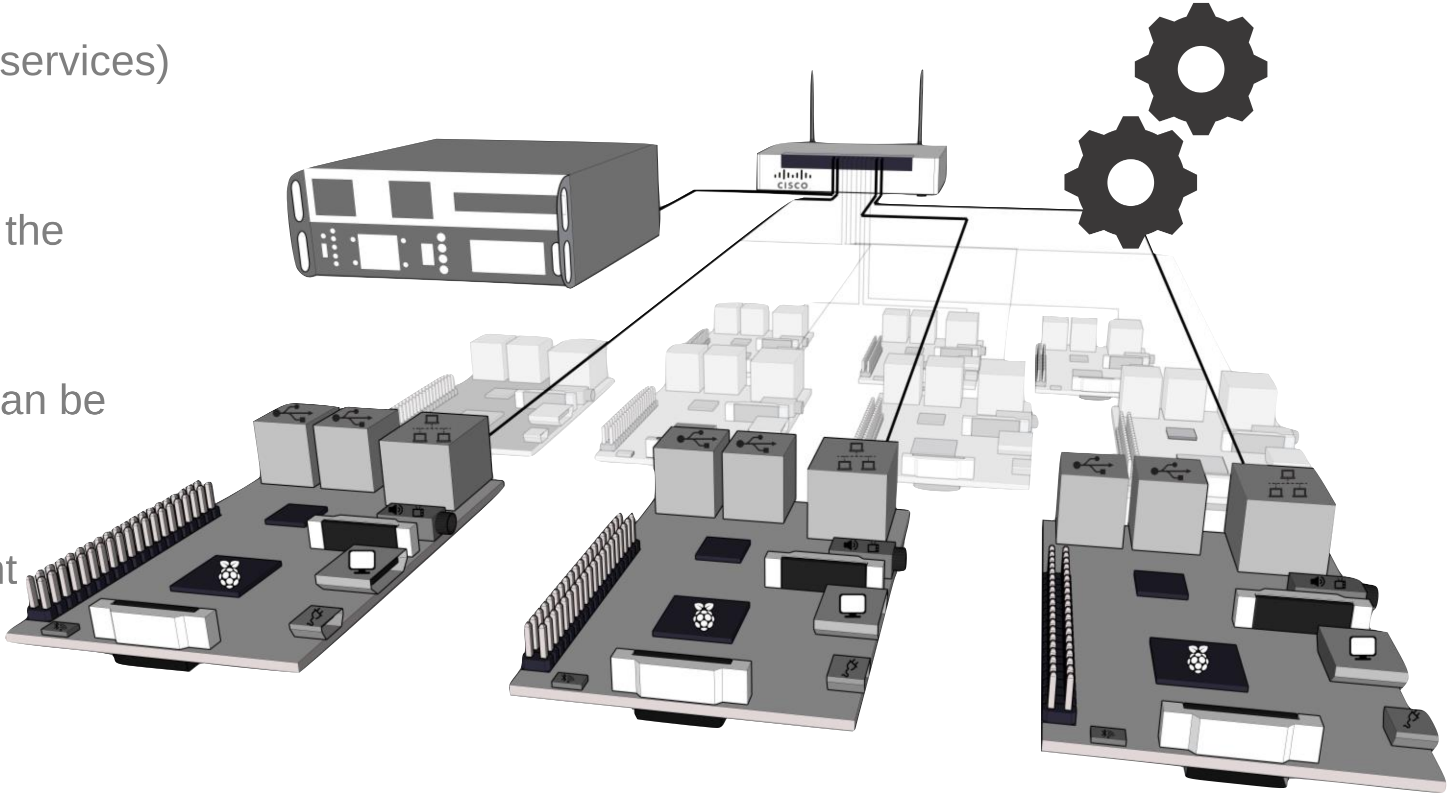


AUSTRIAN INSTITUTE OF TECHNOLOGY
TOMORROW TODAY

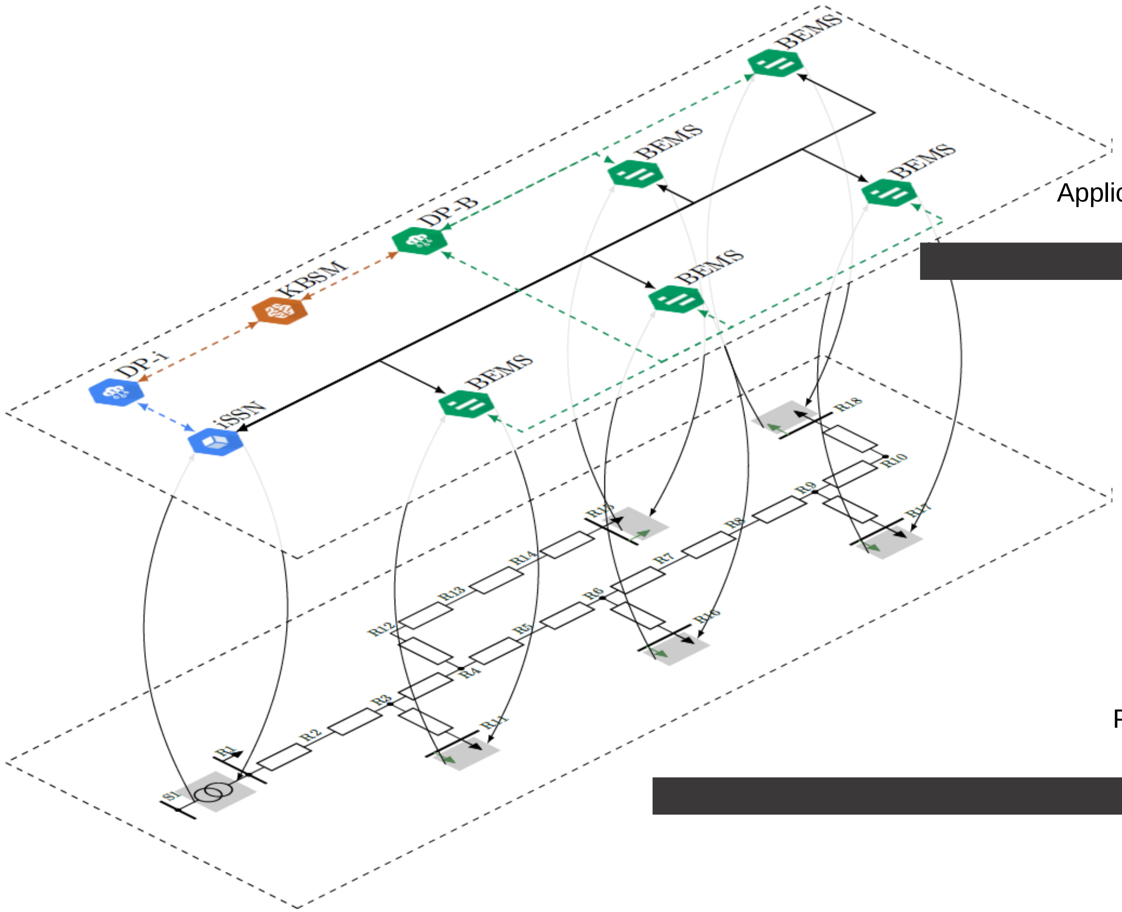
KEY CONCEPTS: DESIGN SPECIFICATION

Cyber-Physical Tests Beds for system level validation

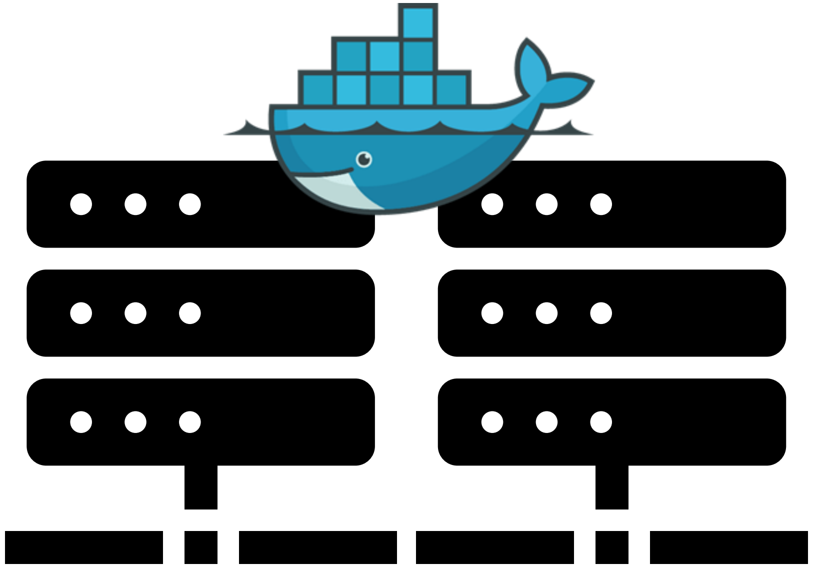
- **Modular**
  - break the functionality into modules (microservices) which are reusable
- **Reusable**
  - use the same code for simulations and for the deployment in the field
- **Reproducible**
  - each result and error is reproducible and can be debugged and analyzed offline
- **Language agnostic**
  - allow to test modules developed in different programming languages
- **Scalable**
  - capability to test large-scale systems
- **Interoperable**
  - capability to exchange information with other systems.



System architecture



Application Layer

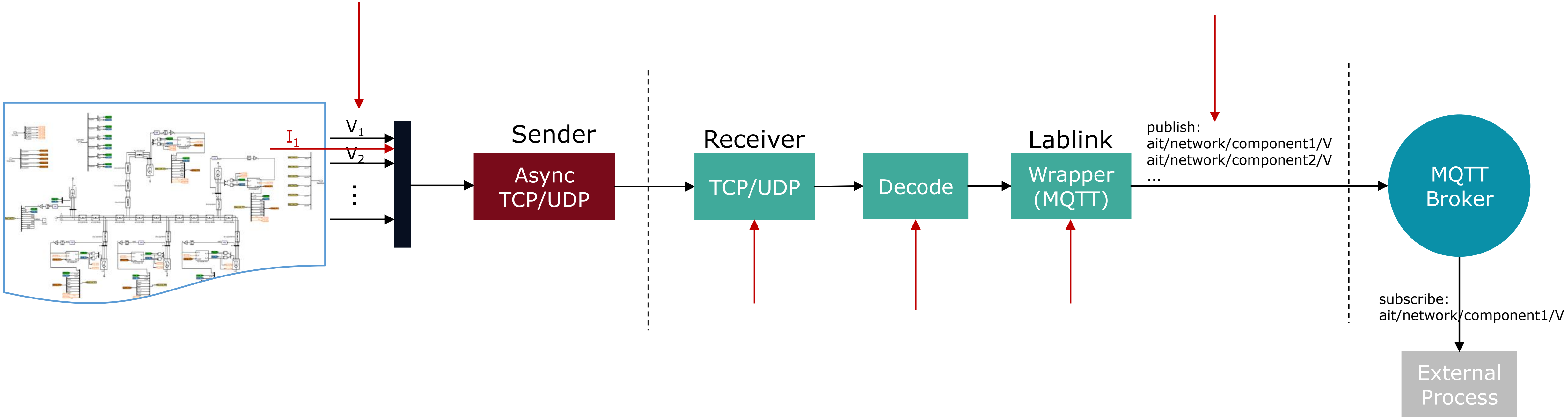


AIT Servers

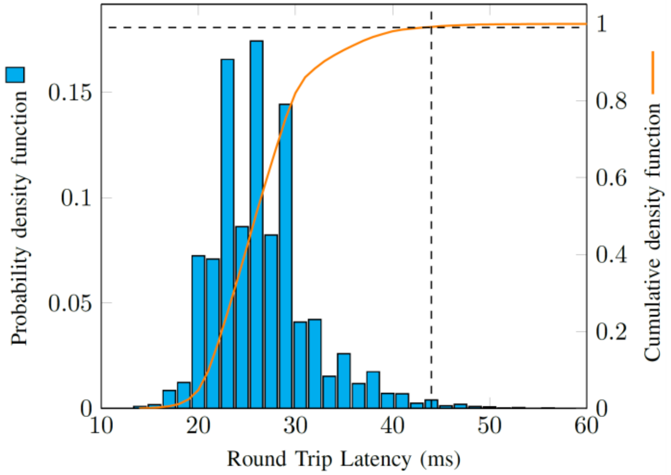
Physical Layer

Opal-RT

Exchanging data with OPAL-RT



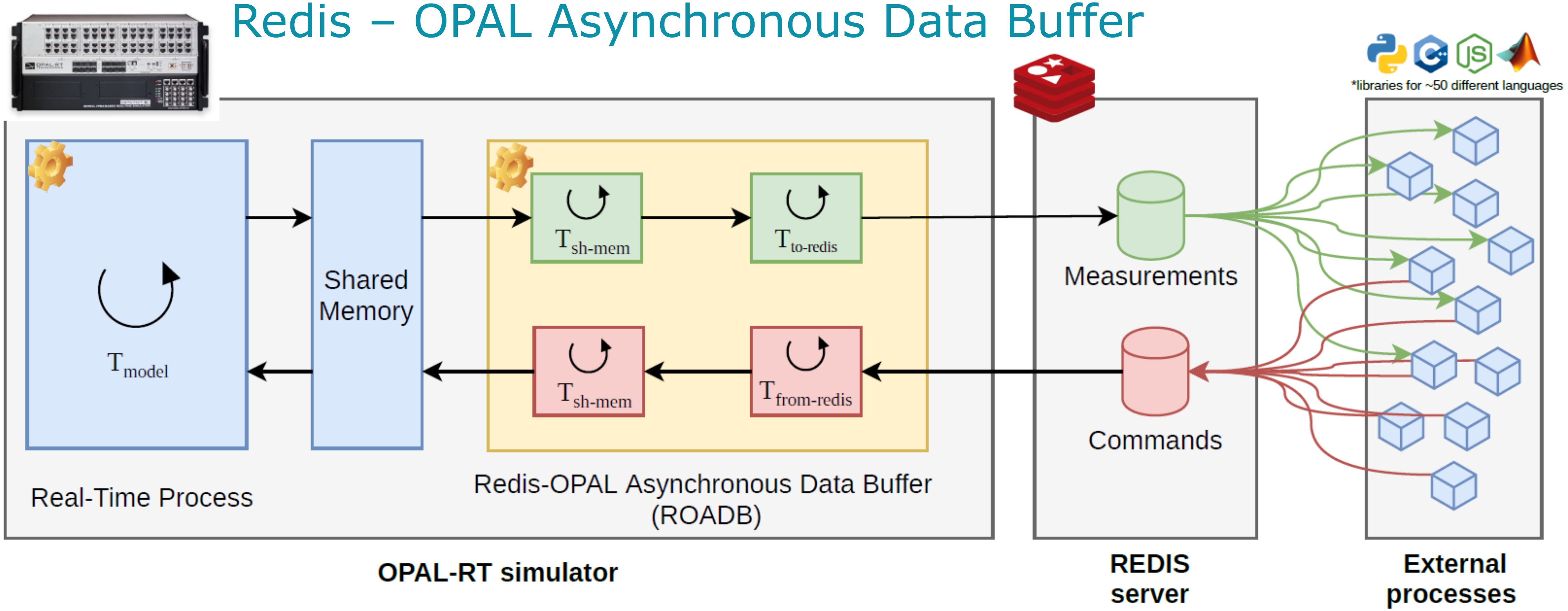
- any change in the number/order of signals being sent requires:
  - rebuild of the OPAL-RT model
  - several changes in the middle layer
- signals are sent without any identification/meta-data, therefore it has to be added to the sig (once on the OPAL-RT and once in the middle layer)
- no way of interacting with the signals at a low-level -> high latencies



Exchanging data with OPAL-RT

- improved middle-layer:
  - ☑ signals available to external processes after rebuilding the Opal-RT model
  - ☑ signal identification/metadata
  - ☑ improved latency

Redis – OPAL Asynchronous Data Buffer



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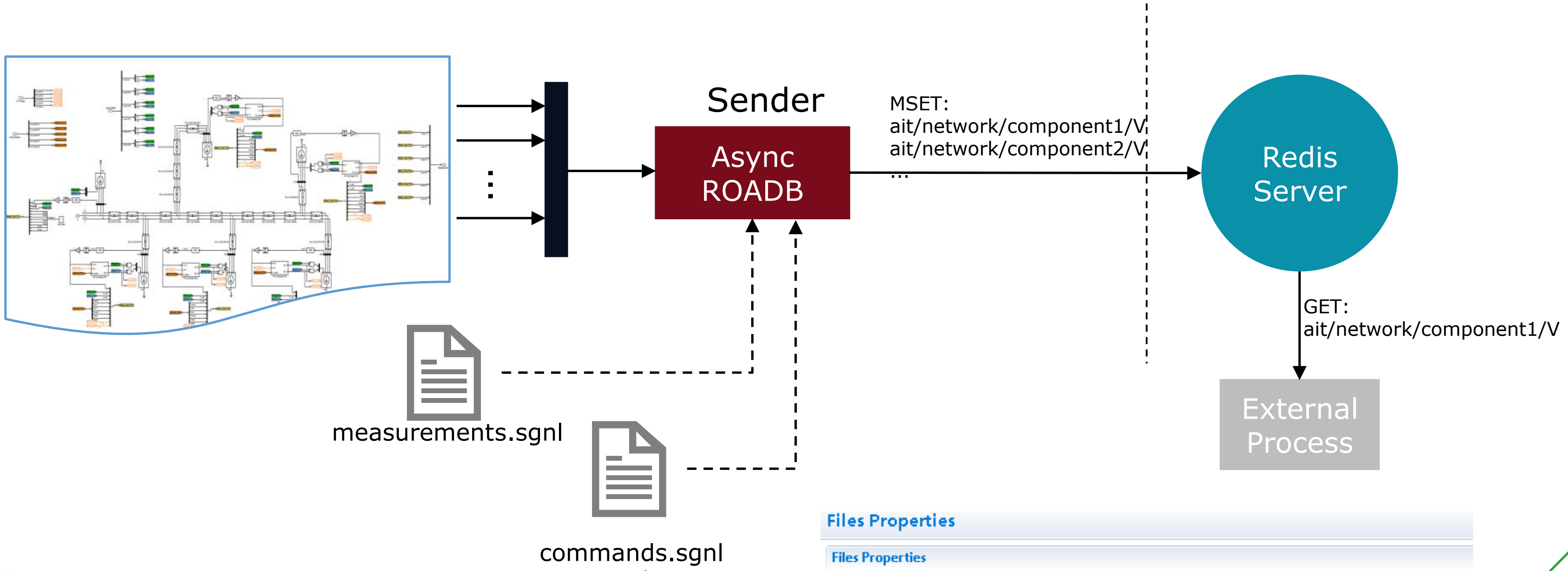

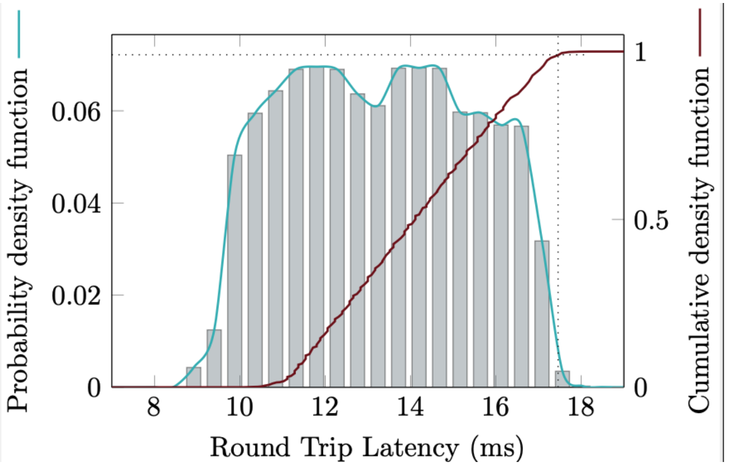

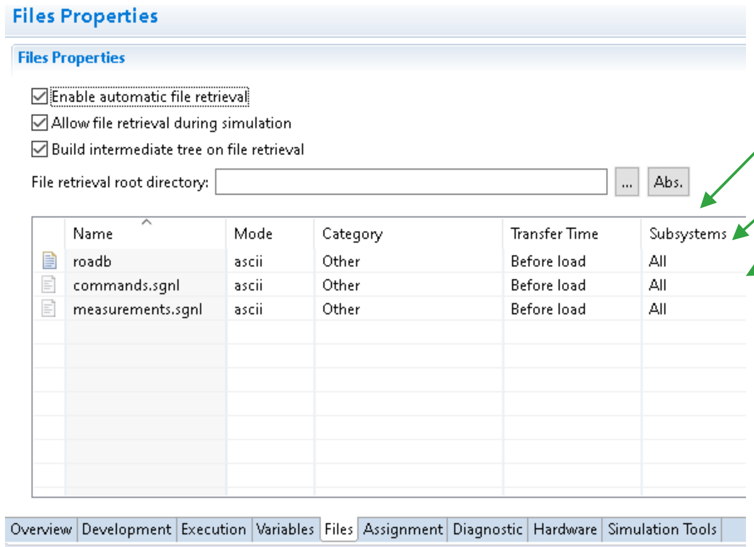

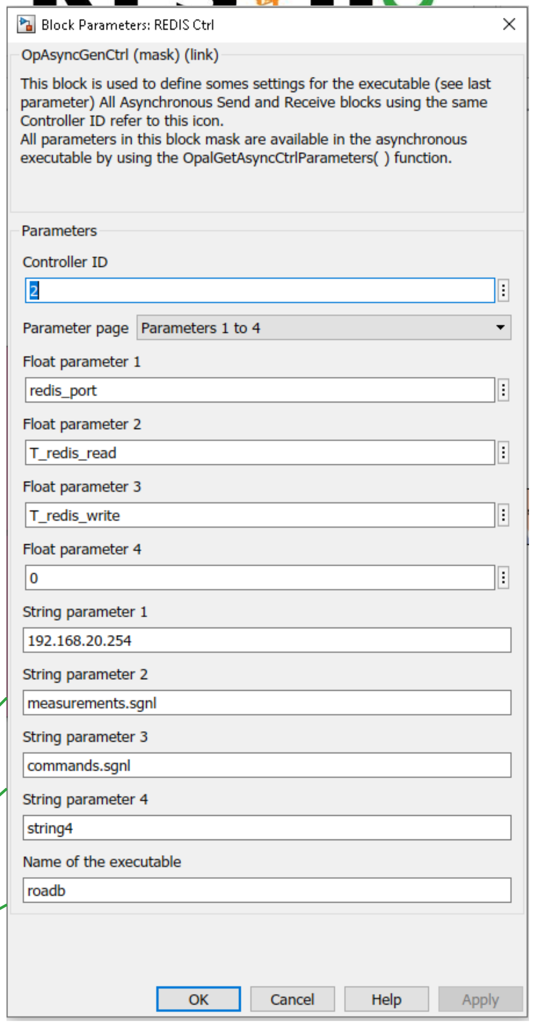

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- Automated Cyber-Physical Testing and Validation Framework
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  - Test Bed Automation
    - Model representation
    - Interlayer communication
    - Workflow
- Demo: Agent based distributed optimization - IEEE 123 buses

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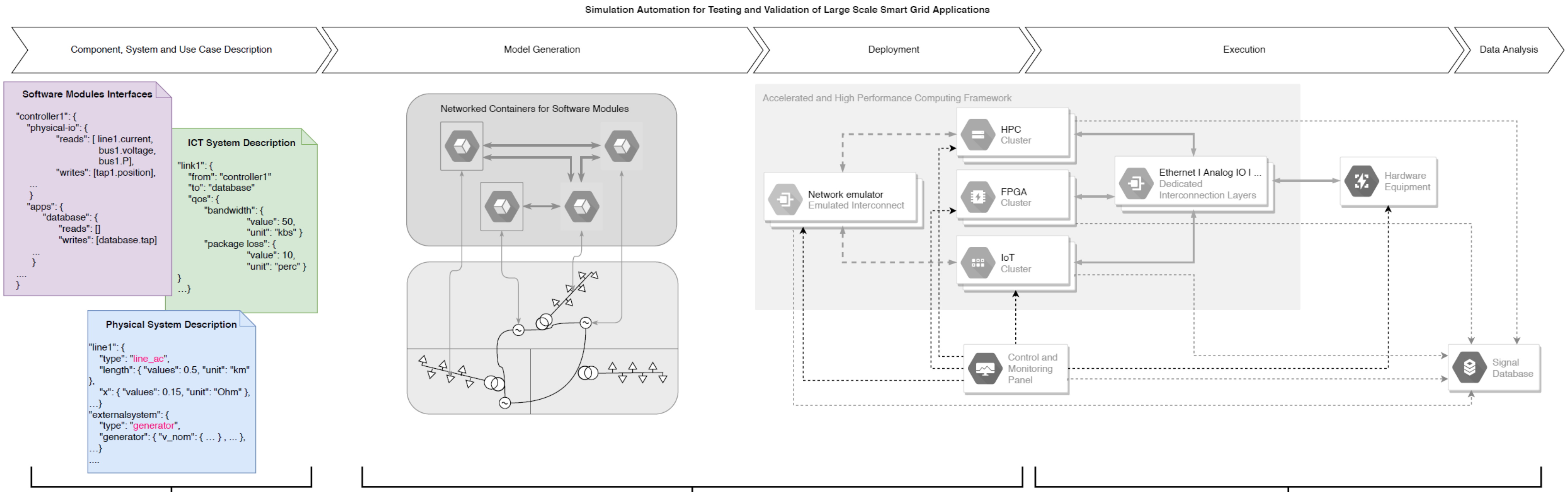
Towards automatization



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MODEL REPRESENTATION – Common Interface Model

The **CIM** for **grid model exchange** enables exchanges for the data necessary for regional or pan-European grid development studies, and for future processes related to network codes.
Grid model exchange is a complex process covering a variety of use cases, which include the exchange of:

- **Equipment information**, which contains power system equipment data; Topology information, which contains topology related information for the grid elements;

- Information on **power system state variables**, which contains the results from initial load flow simulation of the system;

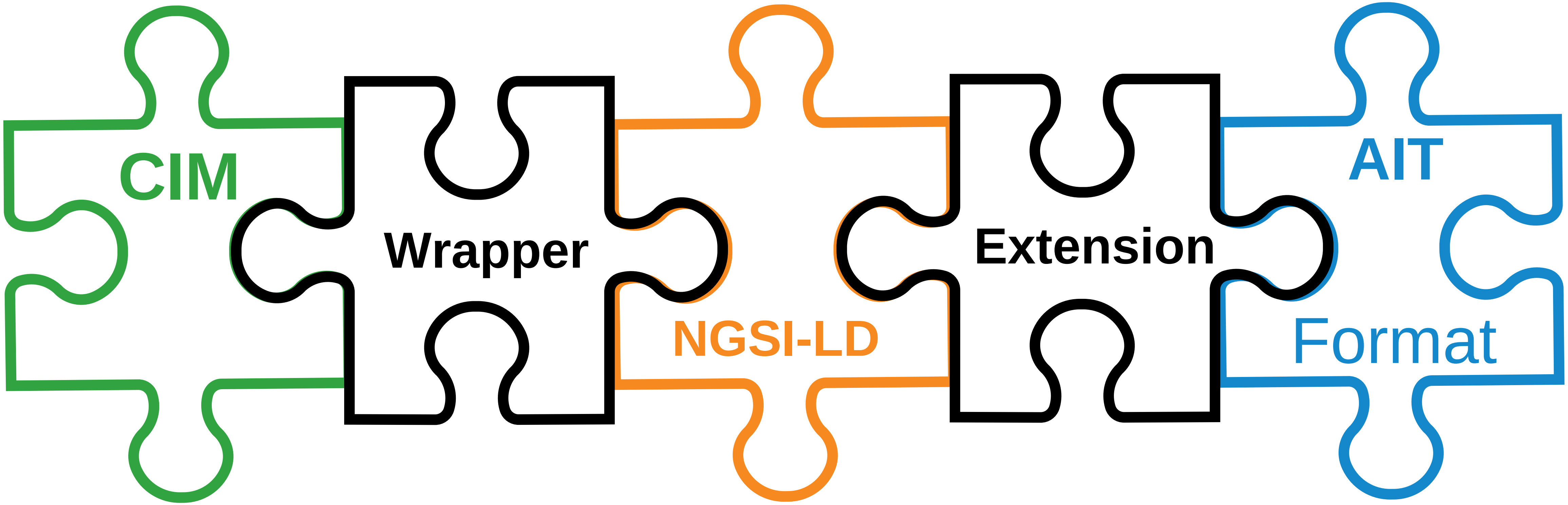
- **Steady state hypothesis information**, which is valid for newer standards and provides information on load and generation values as well as other input parameters necessary to perform load flow simulations.

Source: entso-e

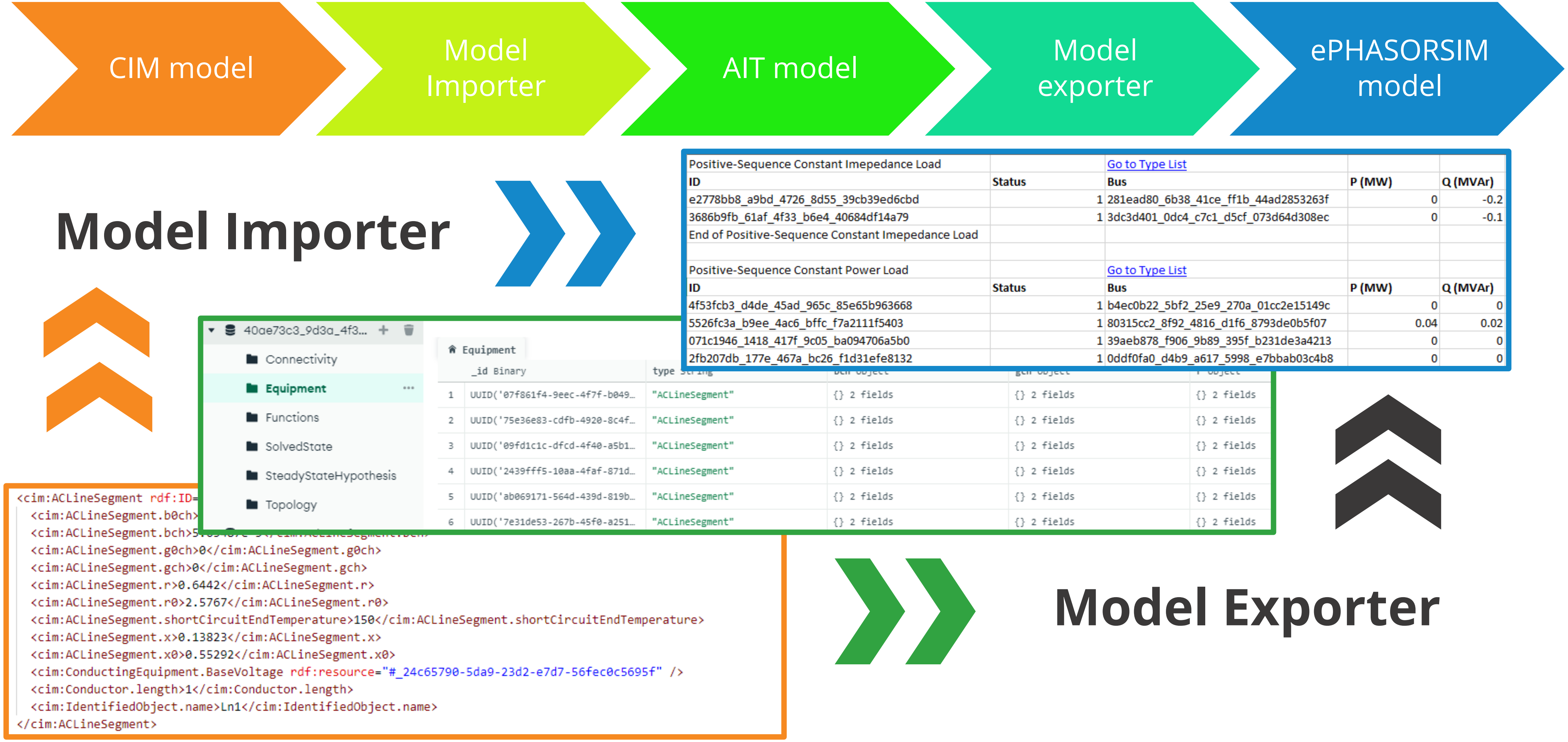
MODEL REPRESENTATION – CIM & NGSI-LD

Resources

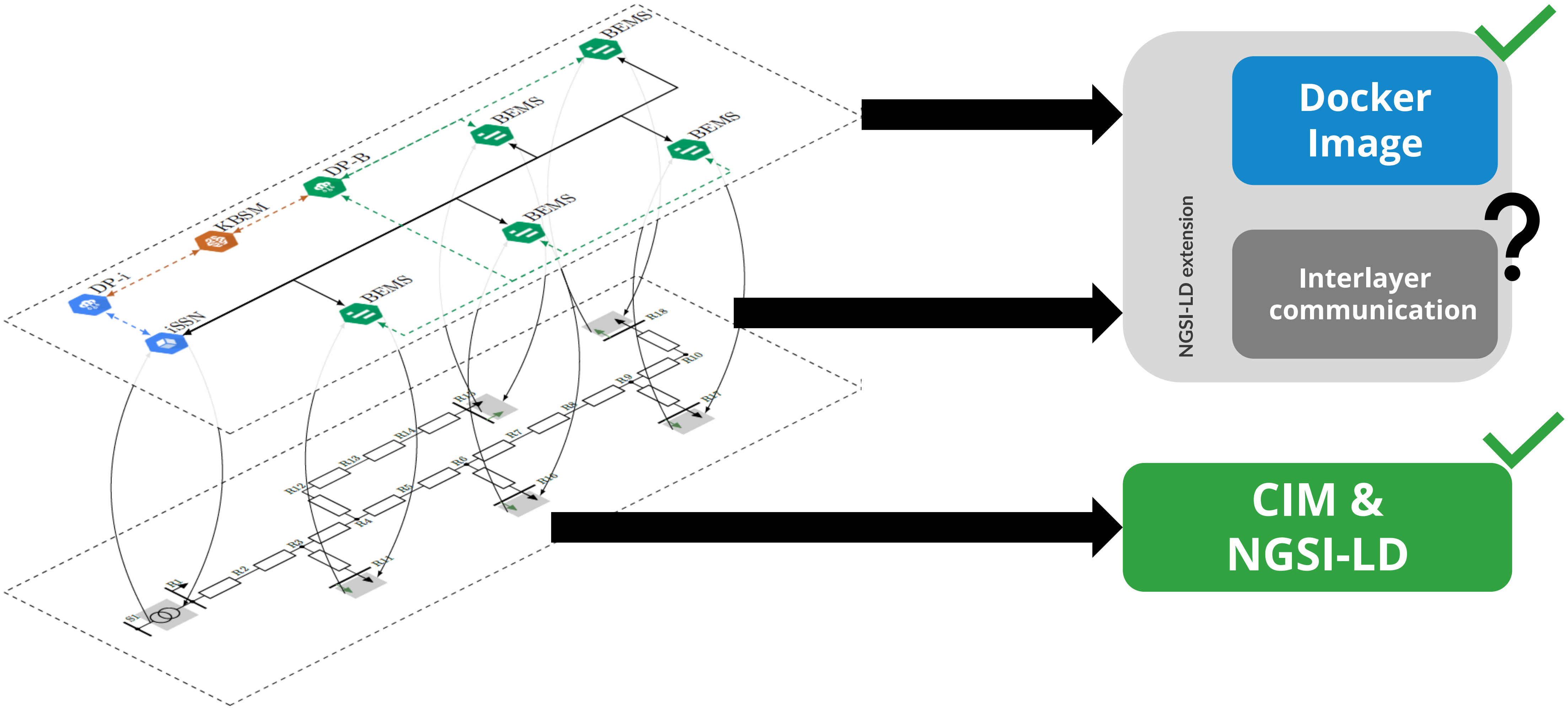
- https://fiware-datamodels.readthedocs.io/en/stable/ngsi-ld_howto/



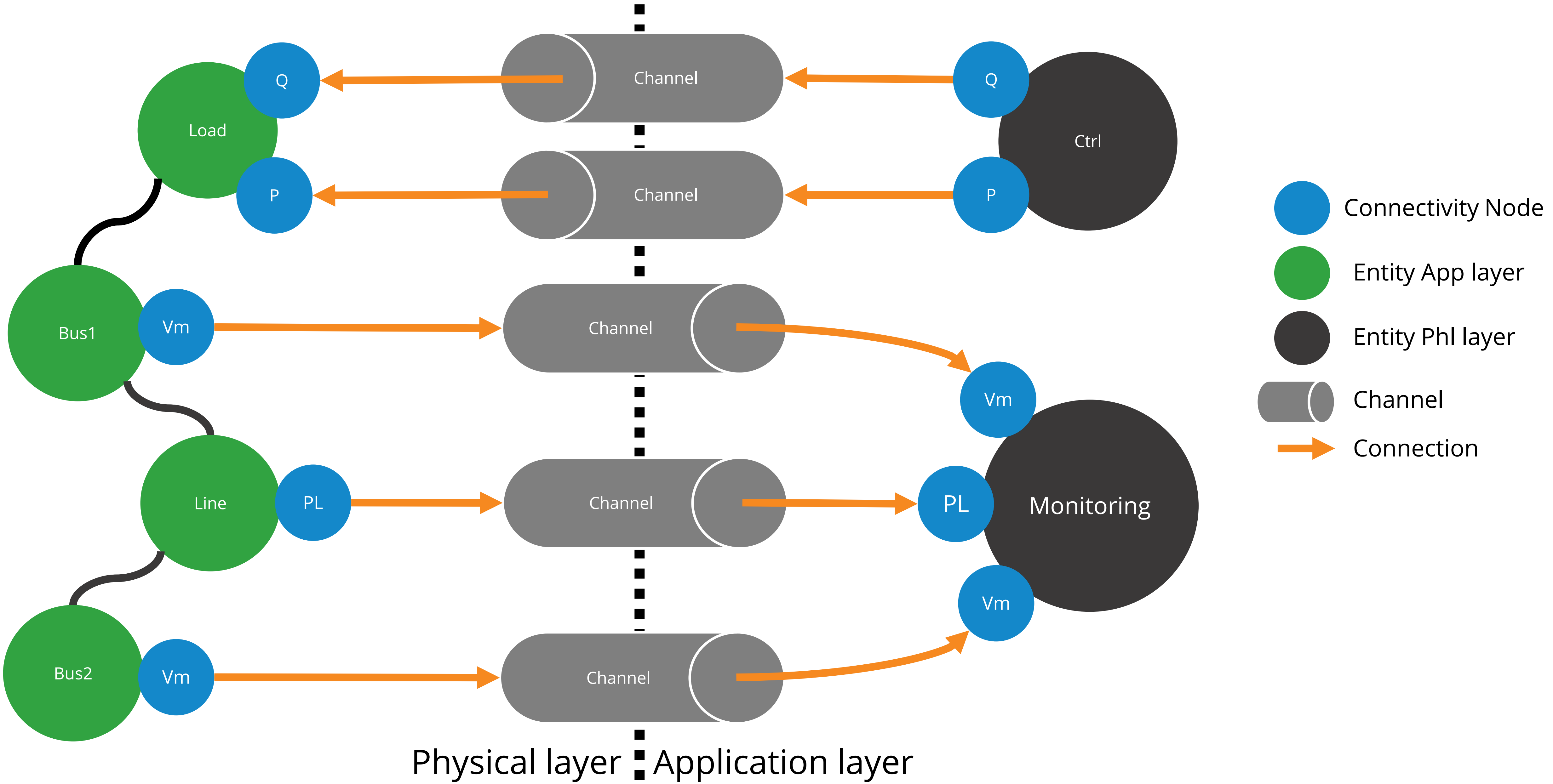
MODEL REPRESENTATION - Model converter



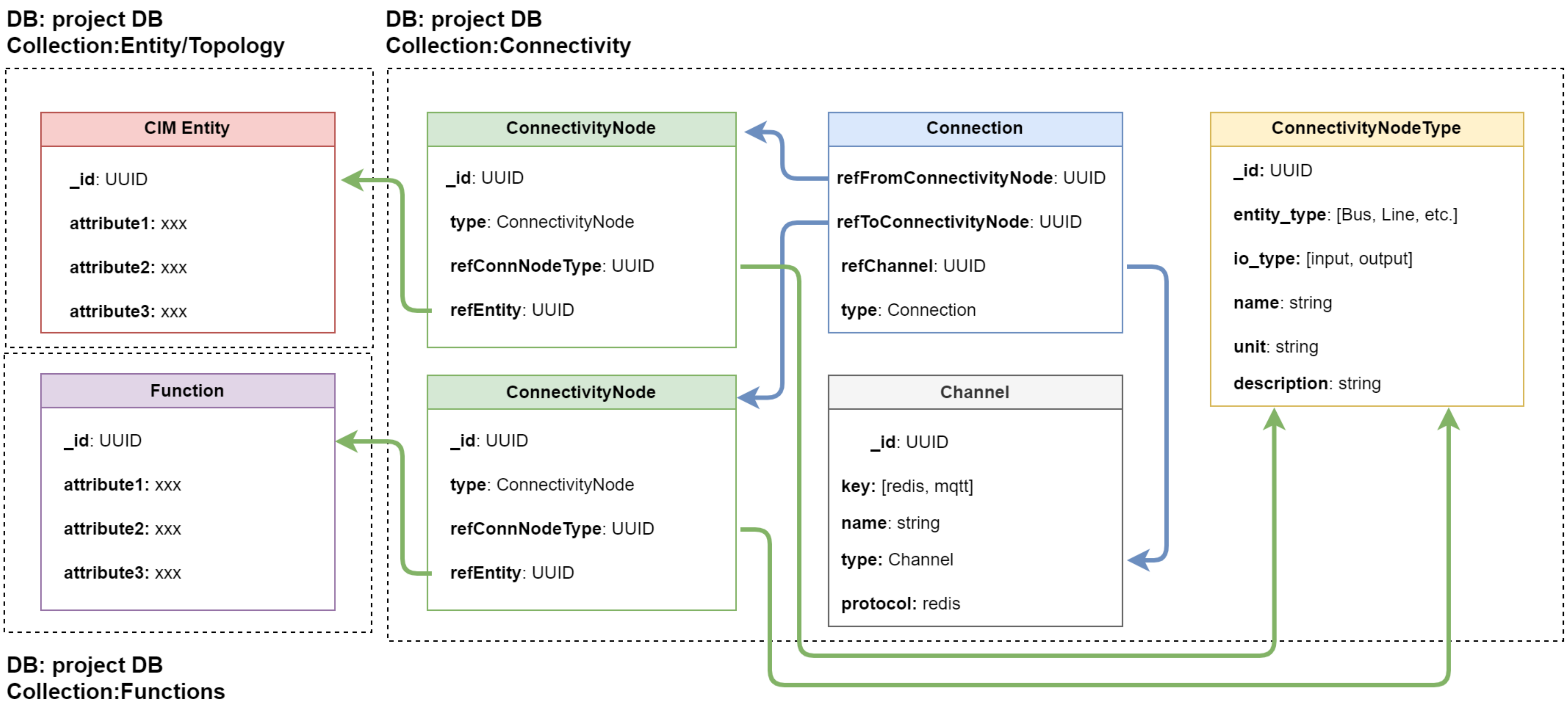
INTERLAYER COMMUNICATION



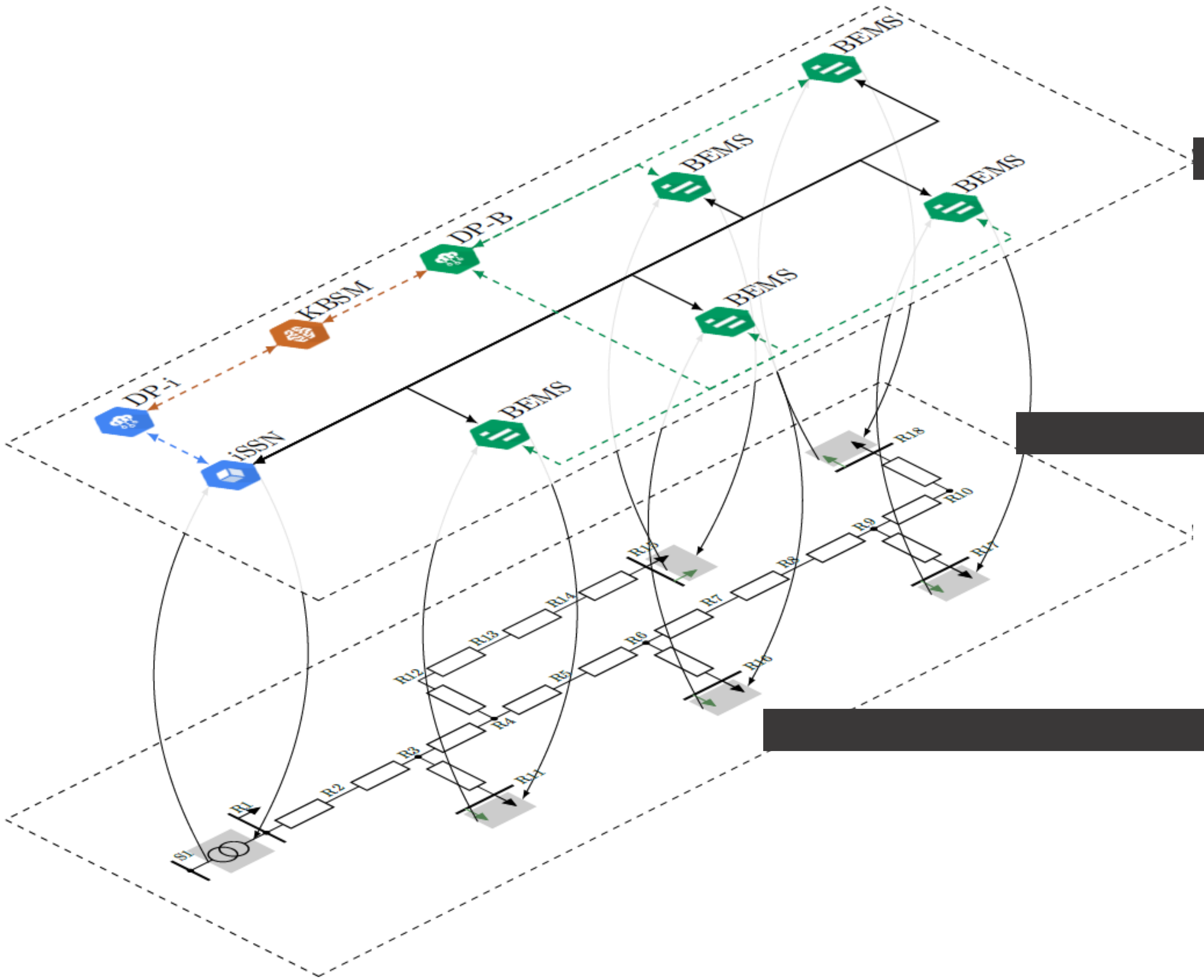
INTERLAYER COMMUNICATION– Components



INTERLAYER COMMUNICATION– Database schema



INTERLAYER COMMUNICATION



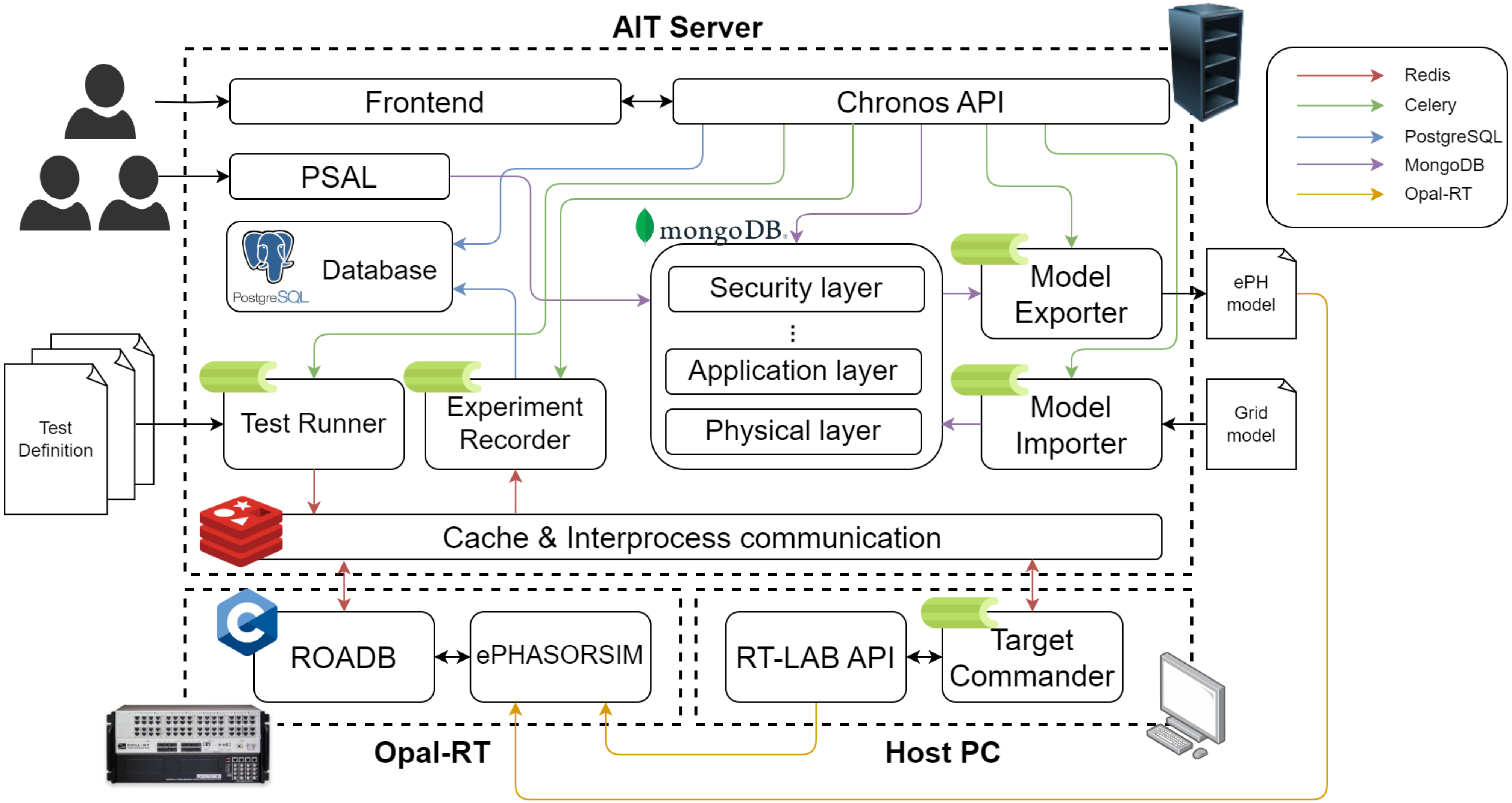
NGSI-LD extension

Docker Image

Interlayer communication

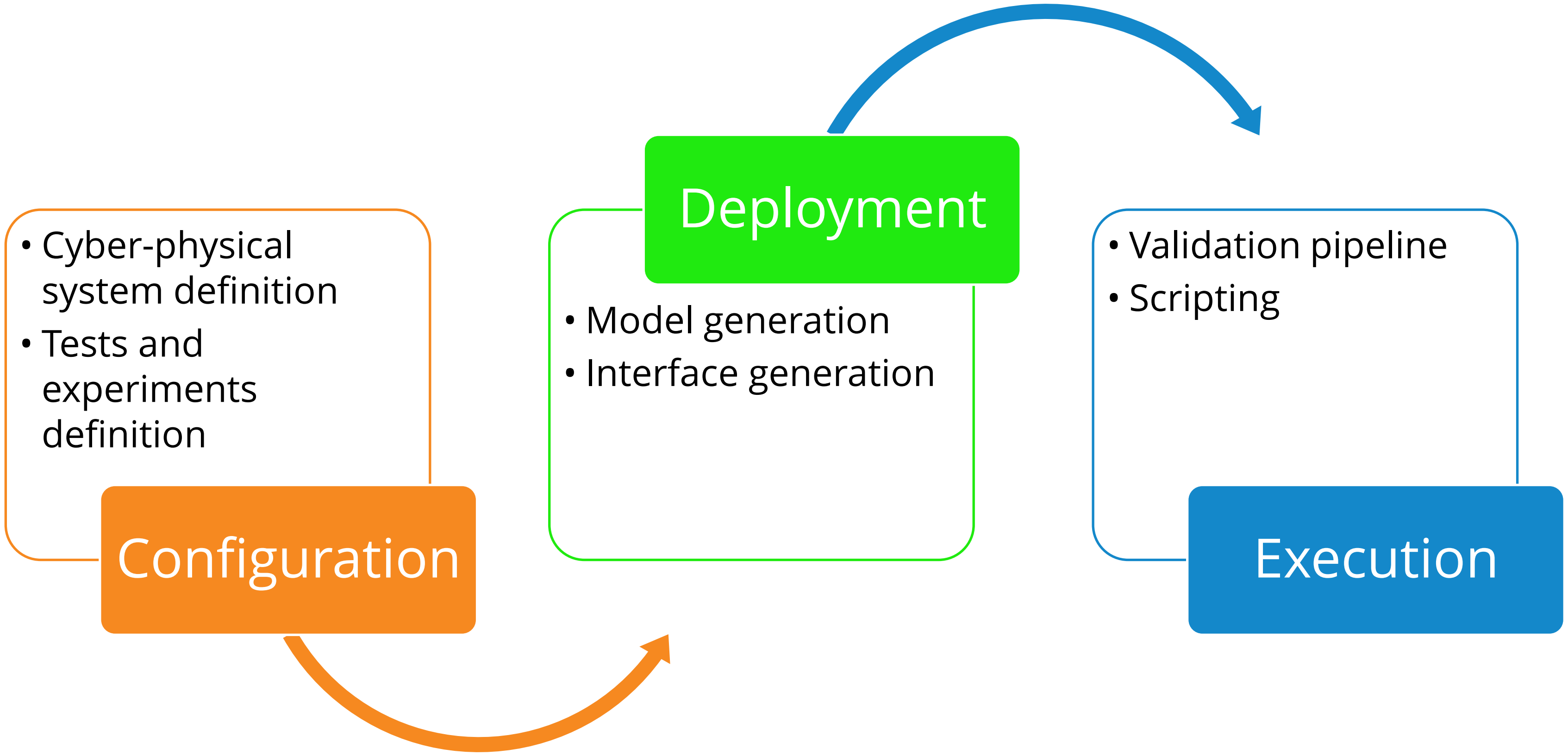
CIM & NGSI-LD

SOFTWARE ARCHITECTURE

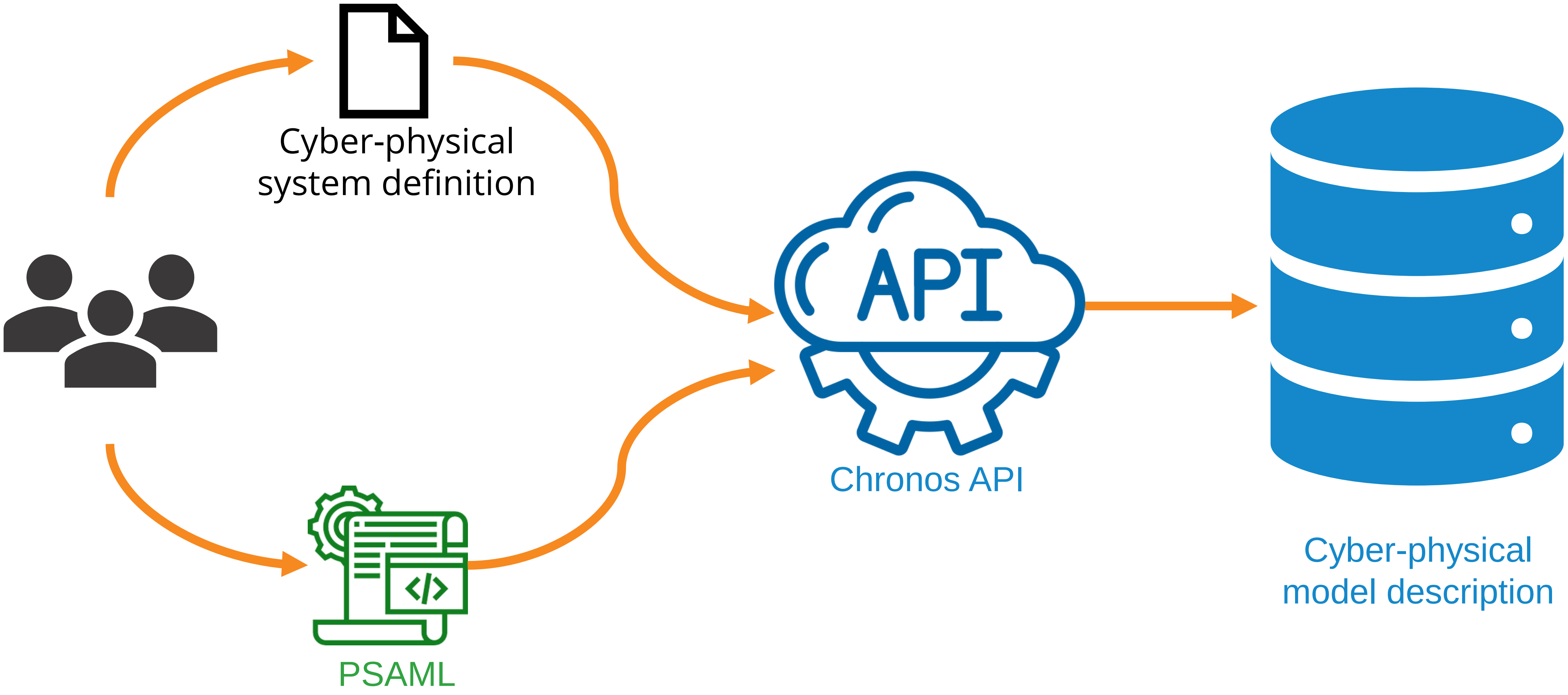


WORKFLOW

- How does a module/algorithm is integrated in the framework to be tested?
- What is the workflow to run a system level validation?



MODEL REPRESENTATION – Configuration



WORKFLOW – Configuration phase using API

https://ees-ws-dev.ait.ac.at/chronos/api/docs

Chronos API 1.0.0 OAS 3.1

/chronos/api/openapi.json

Our goal

The Chronos API are used to interact with our framework for automatically building real-time emulations of large scale cyber-physical energy systems.

The intended target application of these setups is the validation of massively distributed smart-grid software applications.

The goal is to provide a testing framework that can be integrated in modern software development toolchains.

In this manner, complex software ecosystems that act on critical infrastructure can be exhaustively evaluated and validated alongside the system they control, before being deployed in the field.

Our Center

The AIT Center for Energy is developing solutions designed to ensure a innovative energy supply for the future

Contact Denis Vettoretti

Servers

/chronos/api

Authorize

- Project
- Target
- User
- Model
- Inter-layer communication
- Chronos CI/CD
- Experiment
- Test

User interaction

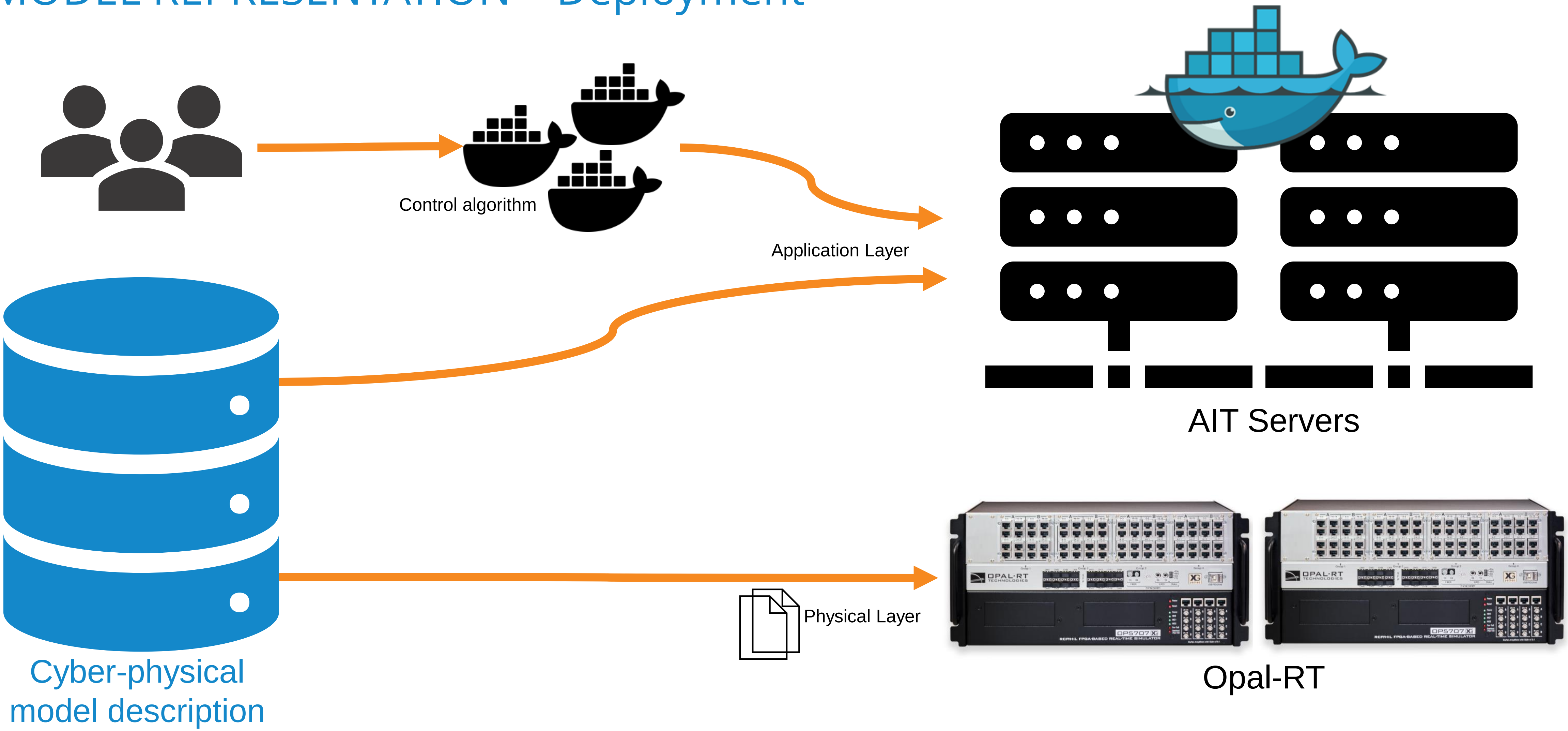
WORKFLOW – Configuration phase using PSAML

- PSAML– a scripting language based on yaml (developed by Pröstl Andren Filip)

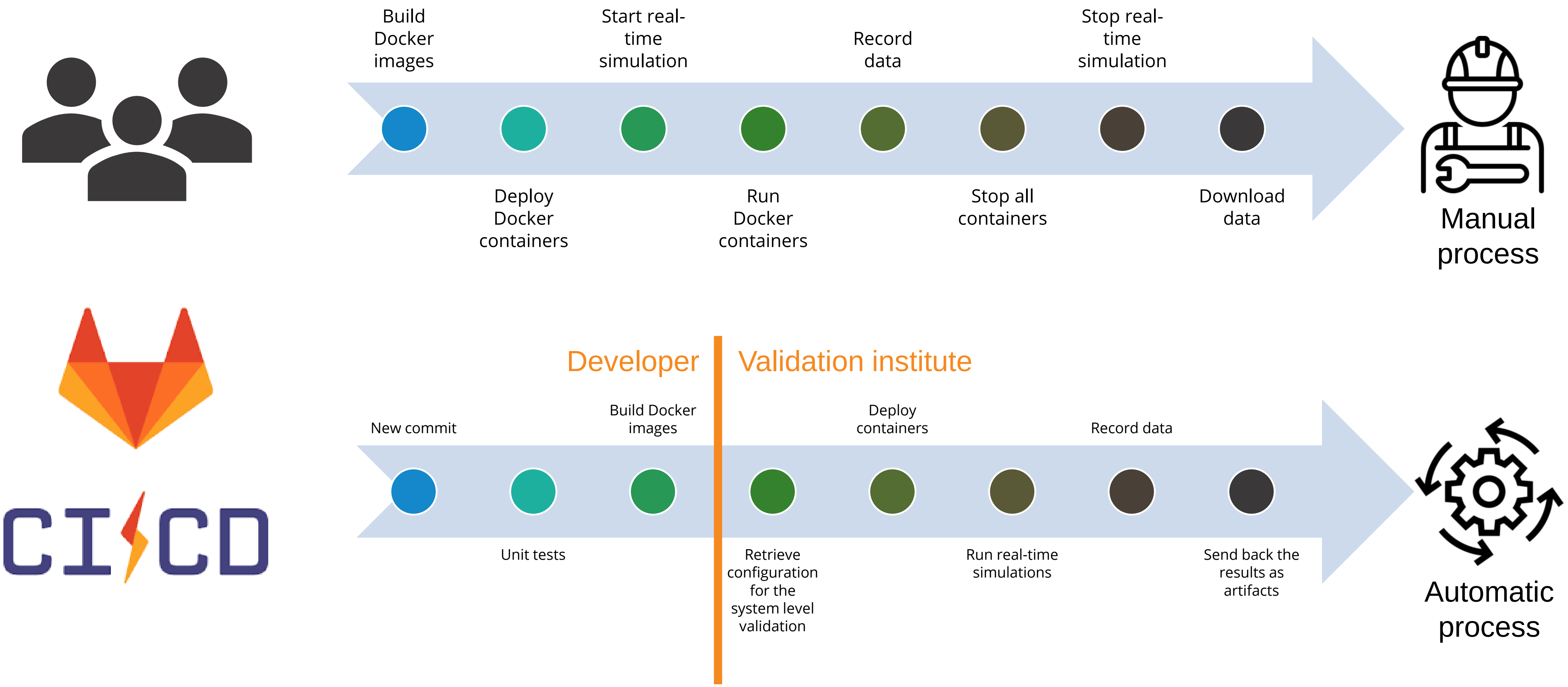
```yaml
version: 1

stages:
 - clean
 - build

when_exists: skip # [skip, replace, update]

VoltageController:
  type: Function
  name: “Voltage controller"
  nodes:
    PL: output
    Q: input
    Px:
      io_type: input
      node_type: P
      for_each: Equipment/(ElmLne_110_11[1-3])
      name: P_\1
```

```yaml
TemplateController:
  type: Function
  for_each: Equipment/(ElmLne_110_11[1-3])
  # foreach: 1..10
  name: EVController_\1

  attribute1: "Setting1"
  attribute2: $kin/refBaseVoltage/nominalVoltage

  nodes:
    P: output
    PL: input

connections:
  - from: VoltageController/Q
    to: ElmLod_32/Q

  - from: Functions/EVController_(.*)/P
    to: Equipment/\1/P
```

MODEL REPRESENTATION – Deployment



WORKFLOW – Execution

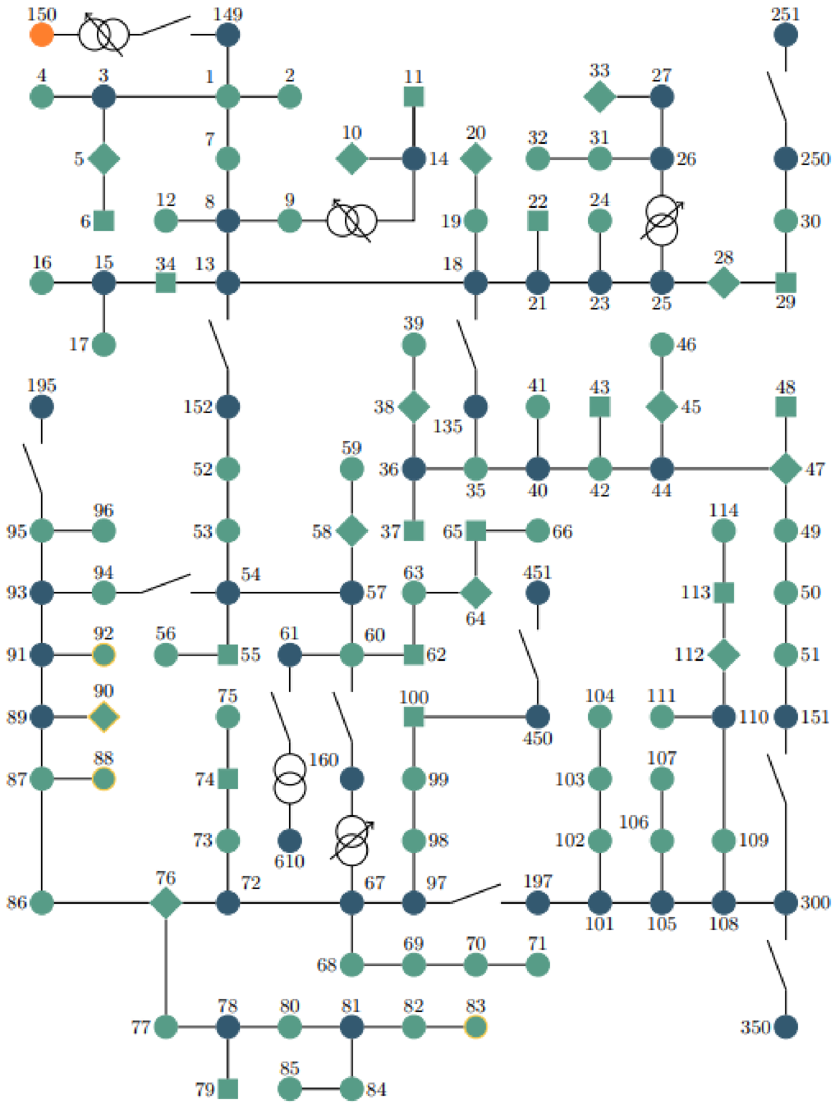


Agent based distributed optimization

DEMO IEEE123 Buses

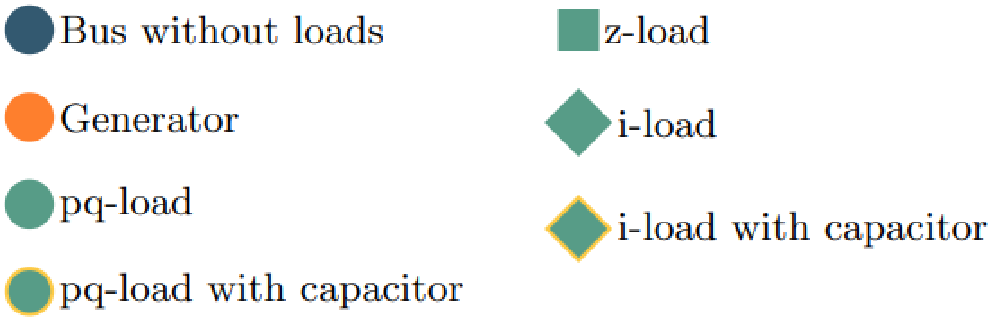
TOMORROW TODAY

IEEE123Bus - Showcase



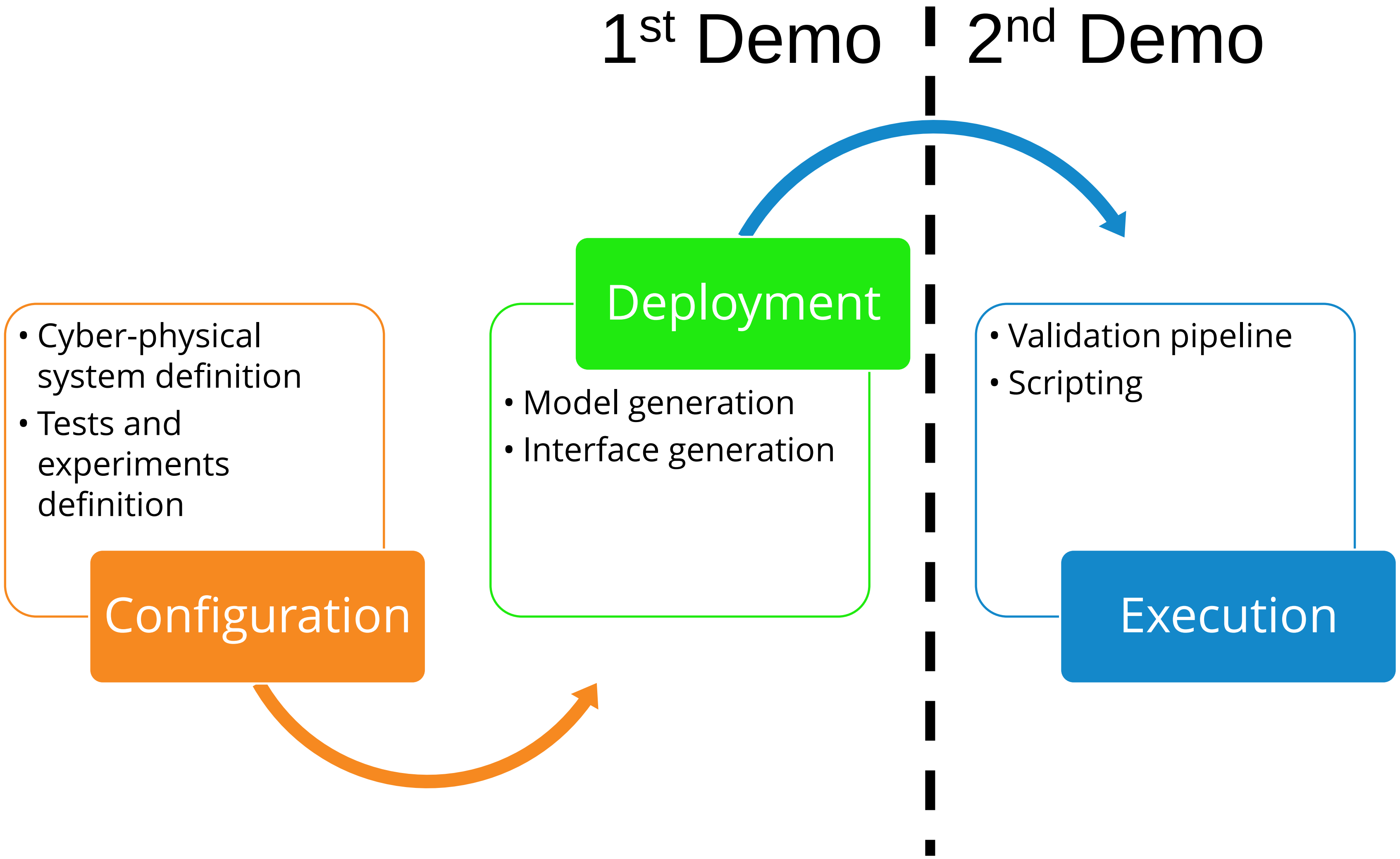
Optimization objective

Power losses minimization adjusting the local generation in the grid.



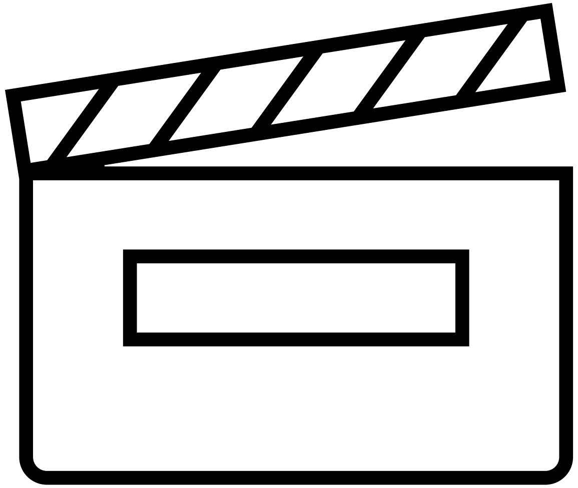
Korner, C. (2019). *Distributed optimization in electrical grids : simulation and validation* [Diploma Thesis, Technische Universität Wien]. reposiTUm. https://doi.org/10.34726/hss.2019.63821

WORKFLOW


1st Demo
2nd Demo
Cyber-physical system definition
Tests and experiments definition
Configuration
Deployment
Model generation
Interface generation
Validation pipeline
Scripting
Execution

IEEE123Bus – Model configuration and deployment

Video



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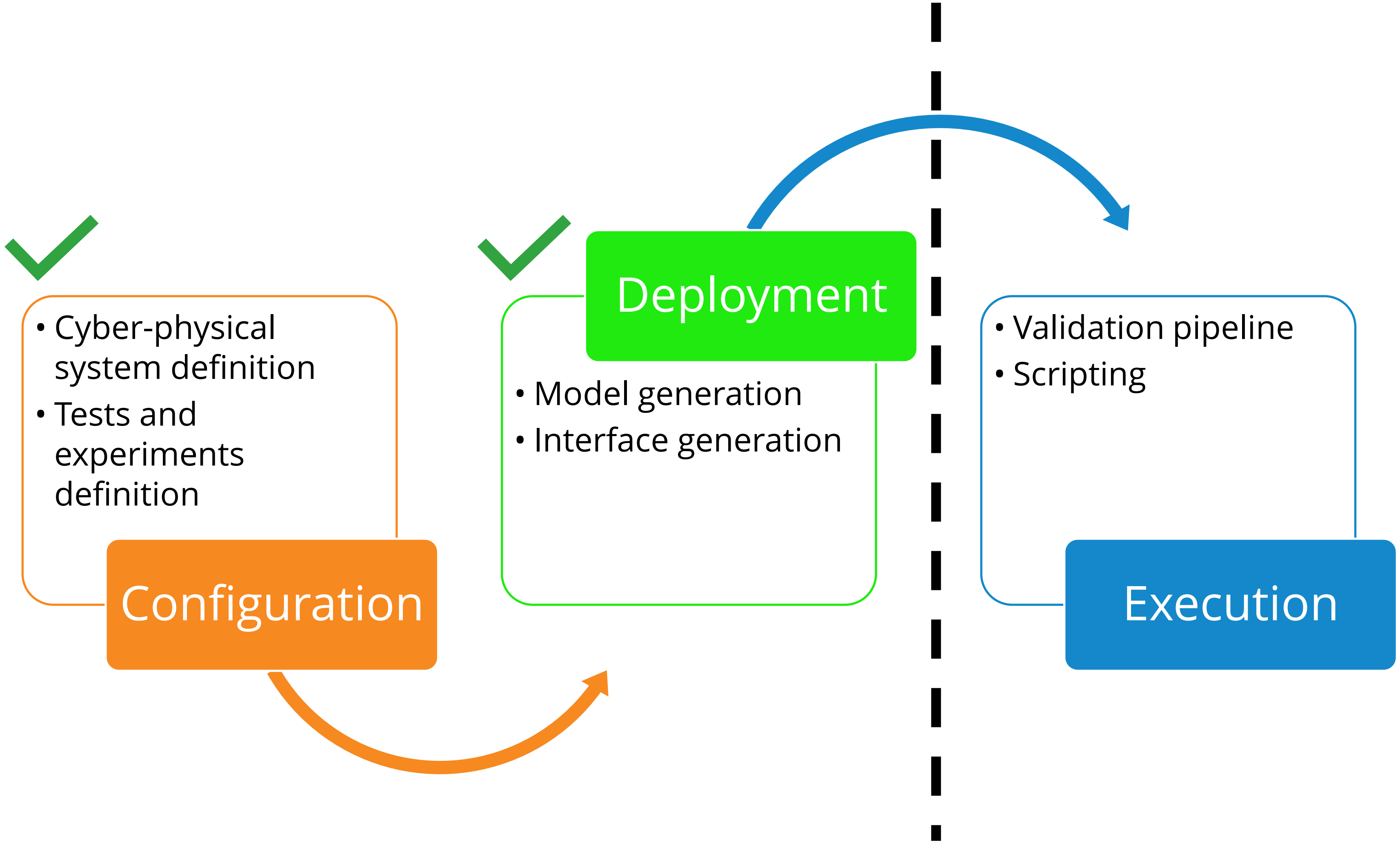
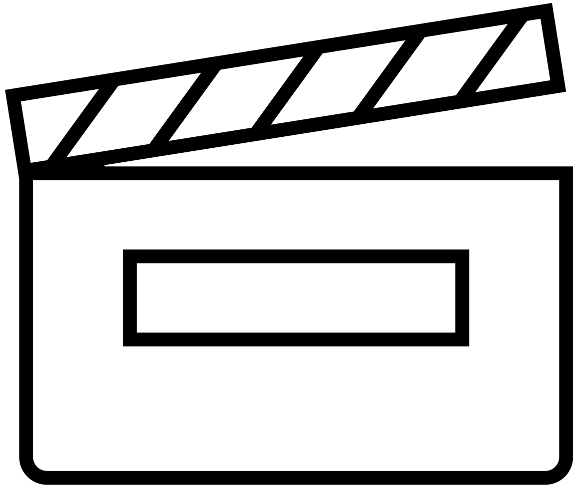


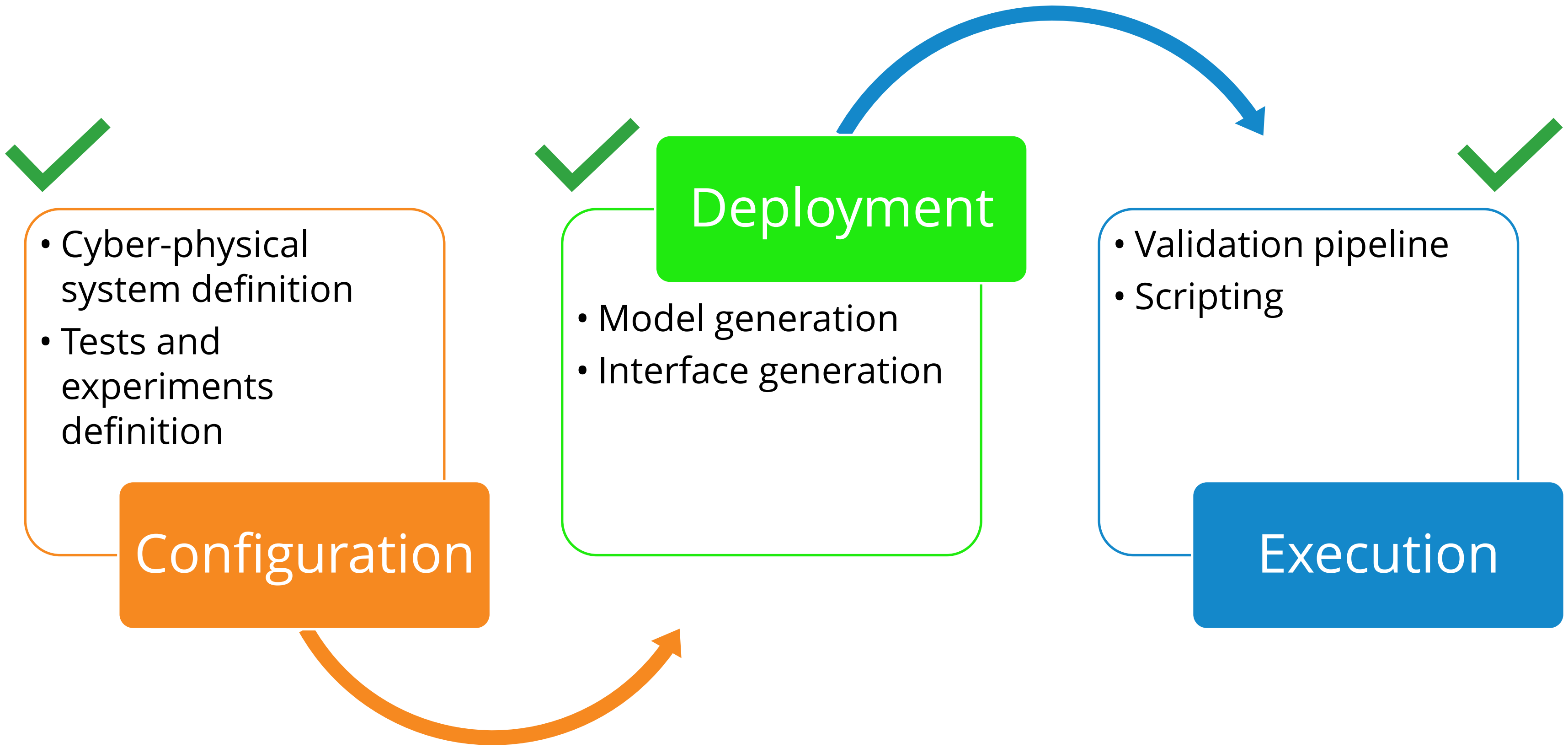
Cyber-physical system definition
Tests and experiments definition
Configuration
Deployment
Model generation
Interface generation
Validation pipeline
Scripting
Execution

IEEE123Bus – System level validation

Video



WORKFLOW



• Cyber-physical system definition
• Tests and experiments definition
Configuration
Deployment
• Model generation
• Interface generation
• Validation pipeline
• Scripting
Execution

Summary

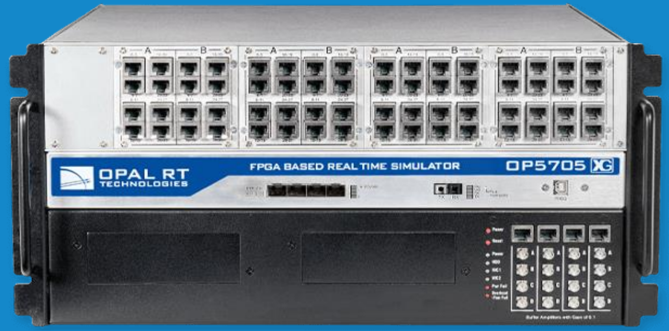
Modularity

Scripting

Fast integration

Replicability

Chronos API



Real-time simulator

Scalability

GitLab CI/CD

Interoperability

Docker

AIT's Automated Cyber-Physical Testing and Validation Framework

Q&A

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