Alessandra Somma

A Model-Driven Methodology for Architecting Digital Twins

Tutor: Prof. Alessandra De Benedictis

Cycle: XXXVII Year: Third

Candidate's information

- MSc degree: Computer Engineering
- Research group/laboratory: SECLAB
- PhD start date: November 1st 2021
- PhD end date: October 31st 2024
- Scholarship type: UNINA
- Periods abroad: February 1st to July 31st 2023 at Montimage R&D, Paris, France

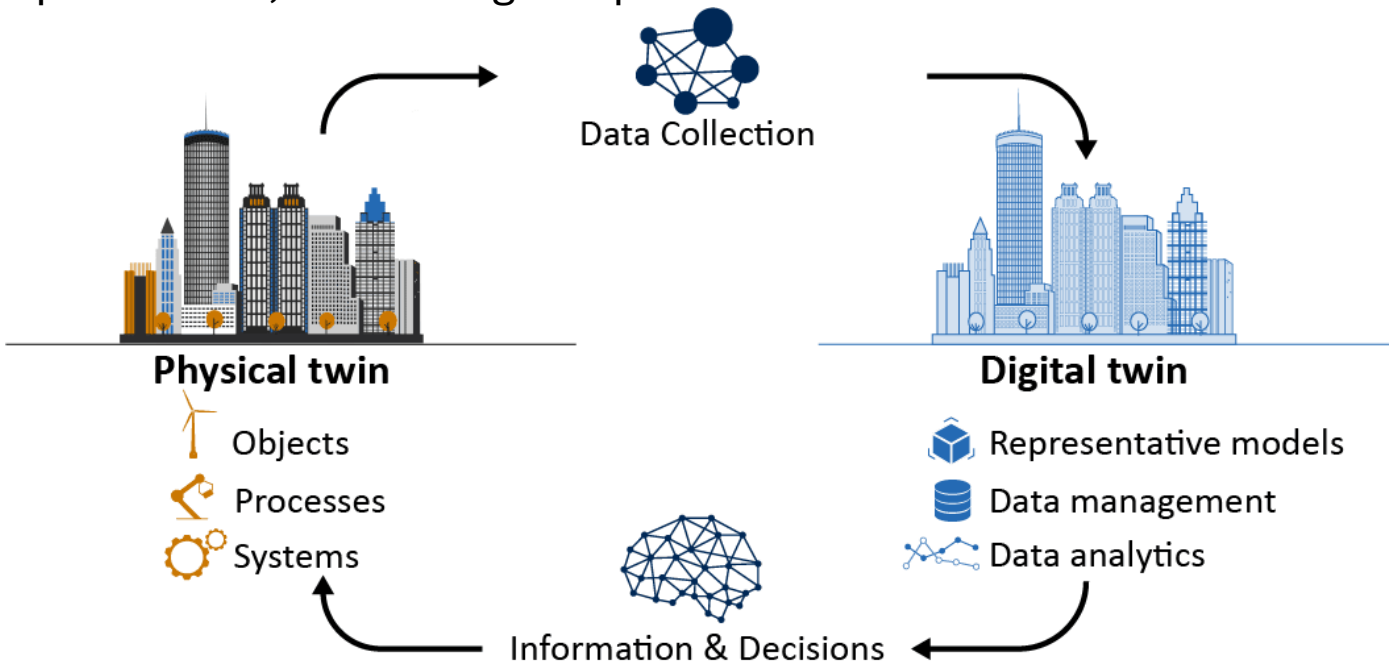
Summary of study activities

- **Ad hoc PhD courses / schools**
  - ❑ Virtualization technologies and their application
  - ❑ Imprenditorialità Accademica
  - ❑ IoT Data Analysis
  - ❑ Semantic artifacts and multimedia knowledge graphs for bio-data integration
  - ❑ Ethics and AI
  - ❑ Strategic Orientation for STEM Research & Writing
- **Conferences / events attended**
  - Training campus on “FIWARE” technologies, University of Naples Parthenope
  - 2023 IEEE International Conference on Digital Twin for presenting “A Cyber Digital Twin Framework to Support Cyber-Physical Systems Security”.
  - 2023 IEEE International Conference on Big Data for presenting “Digital Twin Space: integration of Digital Twin and Data Space concepts”.
  - International Conference on the Quality of Information and Communications Technology (QUATIC2022)

Research Area: Digital Twin

The research focuses on **Digital Twins** (DTs) technology, the virtual representation of a physical asset characterized by bidirectional seamless communication for data exchange between physical and digital worlds.

- Used for simulation, optimization, monitoring and prediction.



Challenges in DT domain:

P1. Lack of standardized Software Architecture (SA)

P2. Untrustworthy data sources

P3. Data interoperability

Research Results

P1. *Lack of standardized Software Architecture*

- ❑ A first non standardized iterative approach with validation by example.
- ❑ Three step methodology based on **software systems design best practices**.

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DYNABIC
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ICSC
Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

P2. *Untrustworthy data sources*

- ❑ **Distributed Ledger Technologies** (DLTs) for securing DT data at rest and in transit.

P3. *Data interoperability*

- ❑ **Data Space** solutions to be integrated in the overall DT architecture.
- ❑ **FIWARE** technology for context data management.

Research Results

P1. *Lack of standardized Software Architecture*

- ❑ A first non standardized iterative approach with validation by example.
- ❑ Three step methodology based on **software systems design best practices**.

PhD Thesis

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- ❑ **FIWARE** technology for context data management.

PhD Thesis

Research Products

[J1]	De Benedictis, A., Flammini, F., Mazzocca, N., Somma, A., Vitale, F., "A Digital Twin Architecture for Anomaly Detection in the Industrial Internet of Things", *IEEE Transactions on Industrial Informatics*, published.
[J2]	De Donato, L., Dirnfeld, R., Somma, A., De Benedictis, A., Flammini, F., Marrone, S., Saman Azari, M., Vittorini, V., "Towards AI-Assisted Digital Twins for Smart Railways: Preliminary Guideline and Reference Architecture", *Journal of Reliable Intelligent Environments,* published.
[J3]	De Donato, L., Dirnfeld, R., Somma, A., Flammini, F., Marrone, S., Saman Azari, M., Vittorini, V., "Integrating AI and DTs: Challenges and Opportunities in Railway Maintenance Application and Beyond", *Simulation,* published.
[J4]	Somma, A., De Benedictis, A., Esposito, C., Mazzocca, N. "The convergence of Digital Twins and Distributed Ledger Technologies: A systematic literature review and an architectural proposal", *Journal of Computer Network Applications*, published.
[J5]	De Benedictis, A., Mazzocca, N., Somma, A. and Strigaro, C. "Digital Twins in Healthcare: An Architectural Proposal and Its Application in a Social Distancing Case Study", *IEEE Journal of Biomedical and Health Informatics*, published.
[J6]	Rocco di Torrepadula, F., Somma, A., De Benedictis, A., Mazzocca, N., "Smart Ecosystems and Digital Twins: an architectural perspective and a FIWARE-based solution", *IEEE Software*, under 2nd stage review.
[C1]	Somma, A., Casola, V., Cavalli, A. R., De Benedictis, A., Mallouli, W., Valdés, V. E., "A Cyber Digital Twin Framework to Support Cyber-Physical Systems Security", *IEEE 2023 Smart World Congress,* published.
[C2]	*Somma, A.,* De Benedictis A., Longo, A., Martella, A., Martella, C., "Digital Twin Space: integration of Digital Twin and Data Space concepts", *2023 IEEE International Conference on Big Data,* published.
[C3]	De Benedictis, A., Esposito, C., Somma, A., "Toward the Adoption of Secure Cyber Digital Twins to Enhance Cyber-Physical Systems Security", in *2022 International Conference on the Quality of Information and Communications Technology (QUATIC),* published.
[C4]	De Benedictis, A., Rocco di Torrepadula, F., Somma, A. "A Digital Twin Architecture for Intelligent Public Transportation Systems: A FIWARE-Based Solution", in *2024 Web and Wireless Geographical Information Systems* (W2GIS), published.

PhD Thesis Overview: Problem

- A **Software Architecture** (SA) is the set of structures needed to reason about the system, which comprise software elements, relations among them, and properties of both.
  - Important for design and development of software-intensive systems like DTs.

- **Architecting** Digital Twins is still challenging due to the lack of standardized DT Software Architecture.

P1. Ad-hoc Architectures
- Domain-specific, non-standardized approaches limit applicability.

P2. Standardized design methodologies
- Model-Driven approaches often fail to fully comply with the MD* methodology.
- Critical DTs features remain unaddressed
  - Overemphasis on simulation modeling
  - Missing bidirectional data flow

PhD Thesis Overview: Objective

P1. Ad-hoc Architectures

- Domain-specific, non-standardized approaches limit applicability.

> **S1.** *Design and documentation* of a domain and platform independent **Digital Twin Software Architecture** (DTSA) integrating elements and relations found in literature using the Software Engineering Institute methodology. The DTSA has been evaluated by DT practitioners.

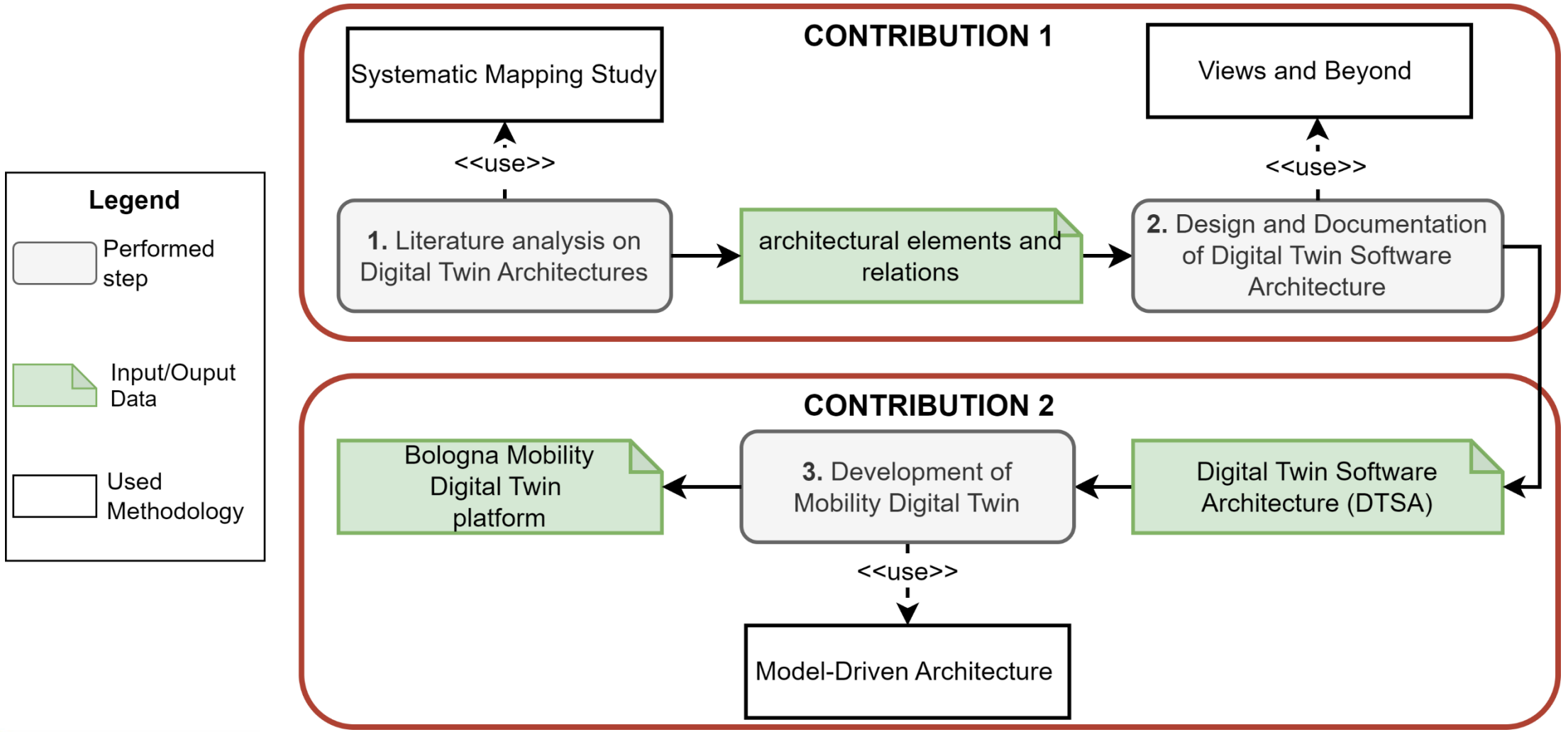
P2. Standardized design methodologies

- Model-Driven approaches often fail to fully comply with the MD* methodology.
- Critical DTs features remain unaddressed
  - Overemphasis on simulation modeling
  - Missing bidirectional data flow

> **S2.** A *Model-Driven Architecture* methodology for the development of a **Mobility Digital Twin**, based on the validated DTSA. The MDA-based approach has been used for realizing *the Bologna Mobility Digital Twin*.

PhD Thesis Overview: Methodology

The three-step approach used in the thesis to address P1, P2, P3 builds upon well-established methodologies.



Contribution 1

Digital Twin Software Architecture (DTSA)

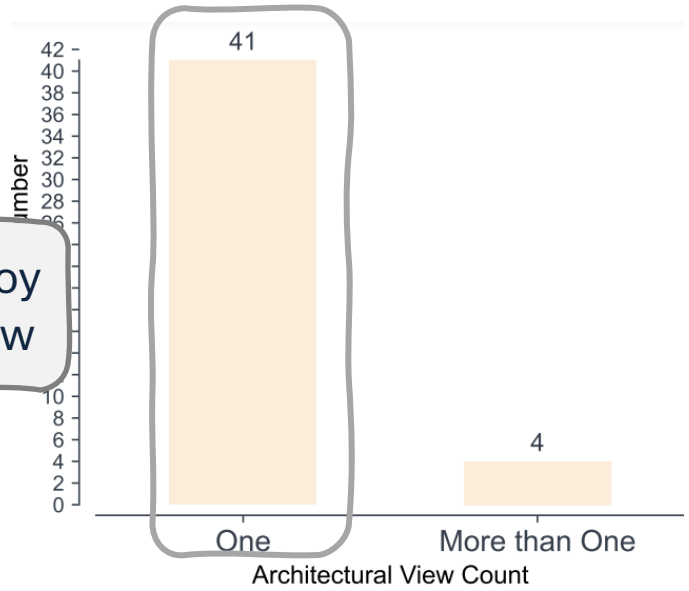
Based on architectural *elements* and *relations* found by *Systematic Mapping Study*
Designed and documented using *Views and Beyond methodology* by *Software Engineering Institute*

Systematic Mapping Study

- The Systematic Mapping Study (SMS) aims at identifying SA proposals within the DT literature and evaluate the extent to which these proposals adhere to the Software Engineering Institute (SEI) methodology based on ISO 42010 terminology.

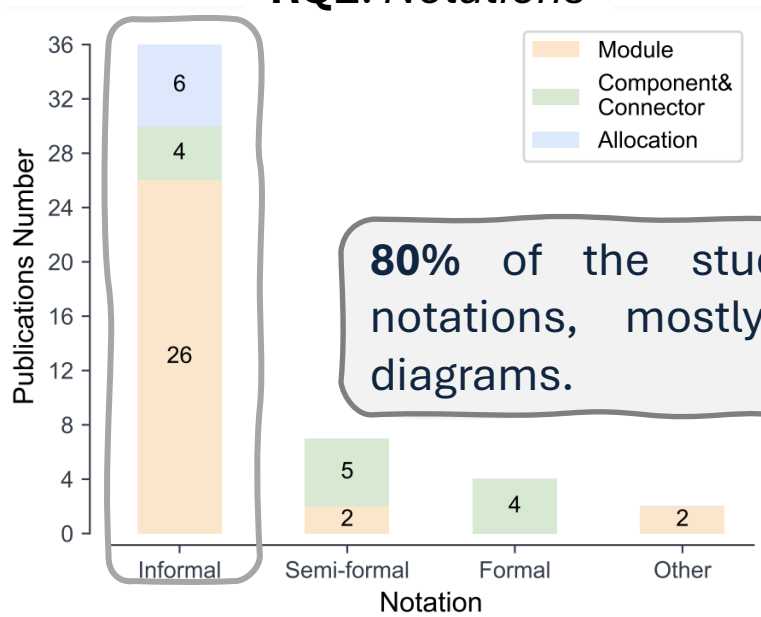
- Seven **Research Questions** (RQs) were addressed. Among them are:
  - How are the primary studies classified based on the SEI ***Architectural Views***?
  - What type of ***notation*** (informal, semi-formal, formal) is used to document DT architectures?

RQ1. *Architectural Views*



91% of the studies employ a single Architectural View

RQ2. *Notations*



80% of the studies use informal notations, mostly box and arrow diagrams.

Systematic Mapping Study

- The Systematic Mapping Study (SMS) aims at identifying SA proposals within the DT literature and evaluate the extent to which these proposals adhere to the Software Engineering Institute (SEI) methodology based on ISO 42010 terminology.
  - *Architectural View* – representation of system elements and relations.
  - Modeling Language – or *notation* used for describing AV.
- Seven Research Questions (RQs) were addressed. Among them are:
  - How are the primary studies classified based on the SEI ***Architectural Views***?
  - What type of ***notation*** (informal, semi-formal, formal) is used to document DT architectures?

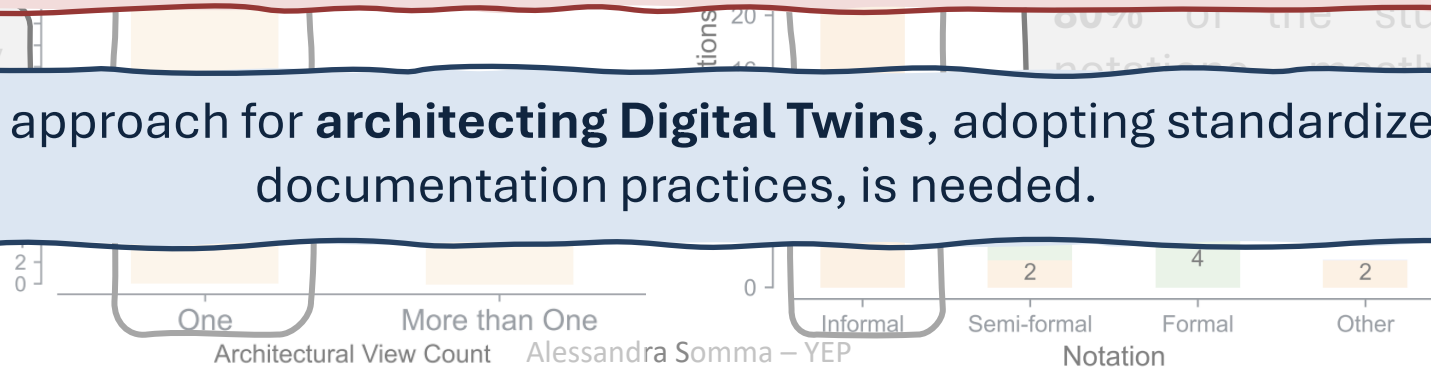
RQ1. *Architectural Views*

RQ2. *Notations*

- Lack of structured approach with distinct Architectural Views;
- Uncler architectural elements and responsibilities;
- Informal documentation

91% of the studies employ

80% of the studies use informal



A more rigorous approach for **architecting Digital Twins**, adopting standardized design and documentation practices, is needed.

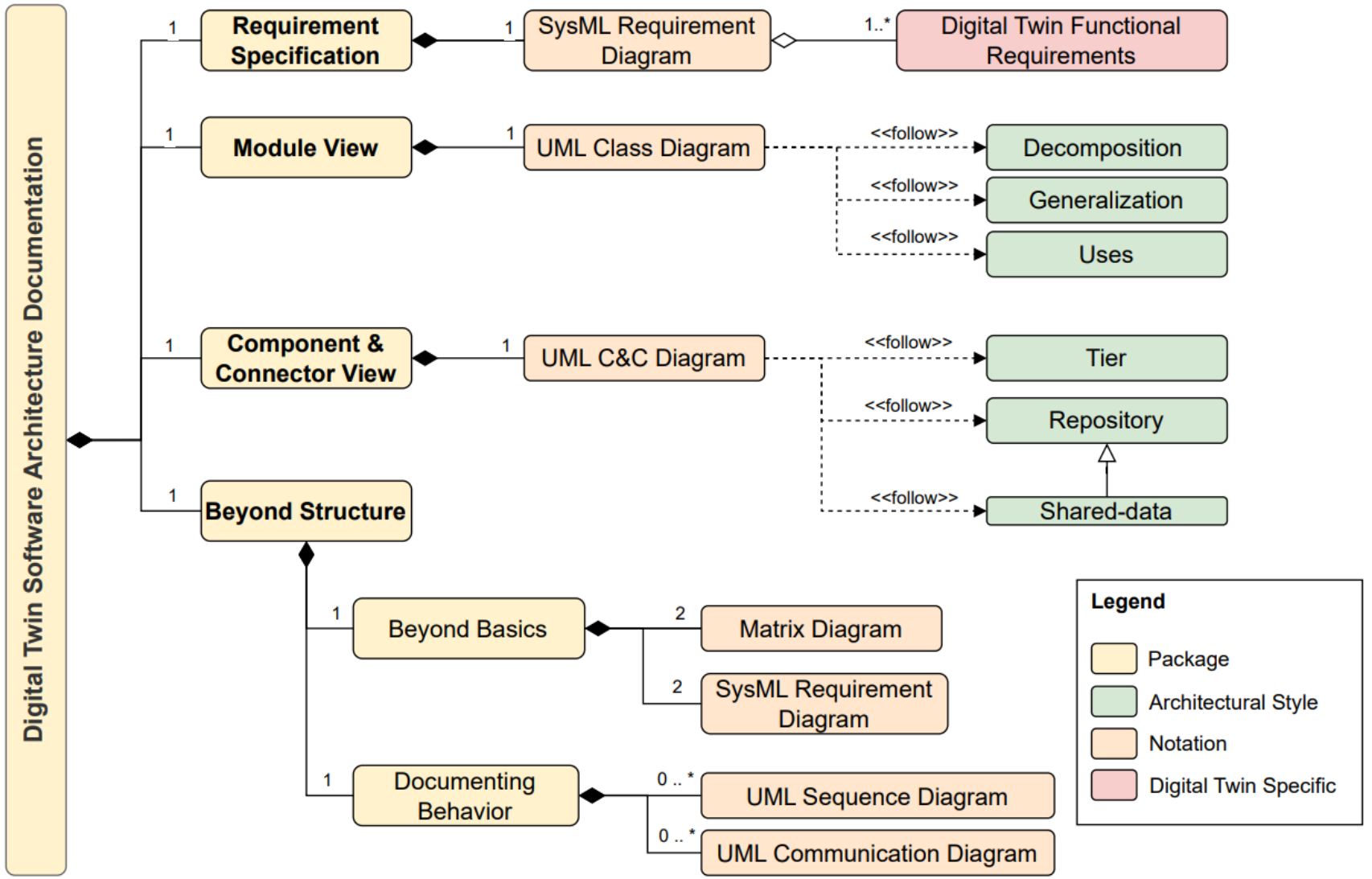
Digital Twin Software Architecture

The **Digital Twin Software Architecture** is organized into four packages, design and documented with respect to the SEI «Views and Beyond», using UML and SysML notation and the Visual Paradigm modeling tool.

Consolidating key **elements** and **relations** identified in selected primary studies

Serving as **guideline** for designers during the development of Digital Twins

Available in **public** Github repository



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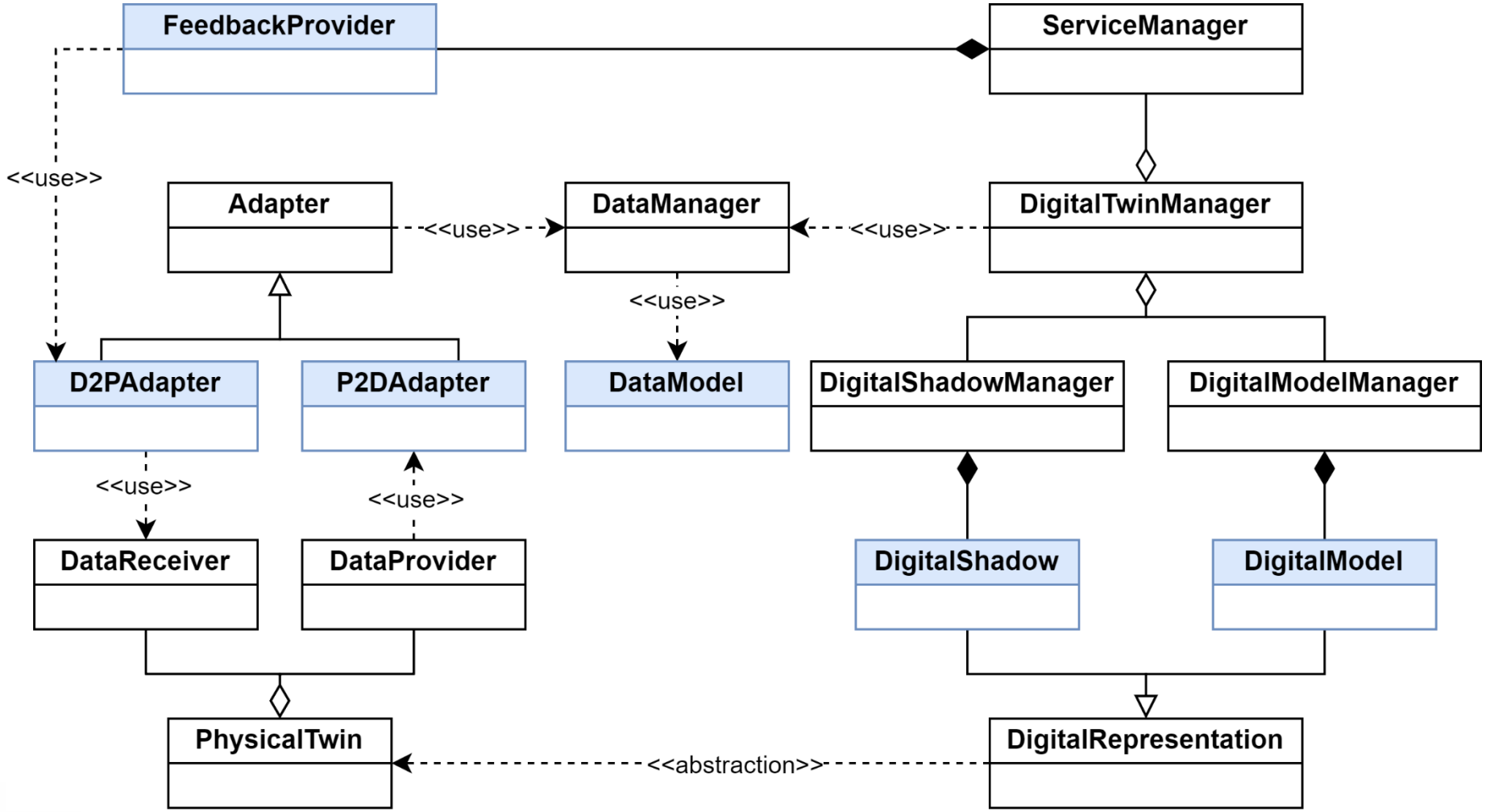
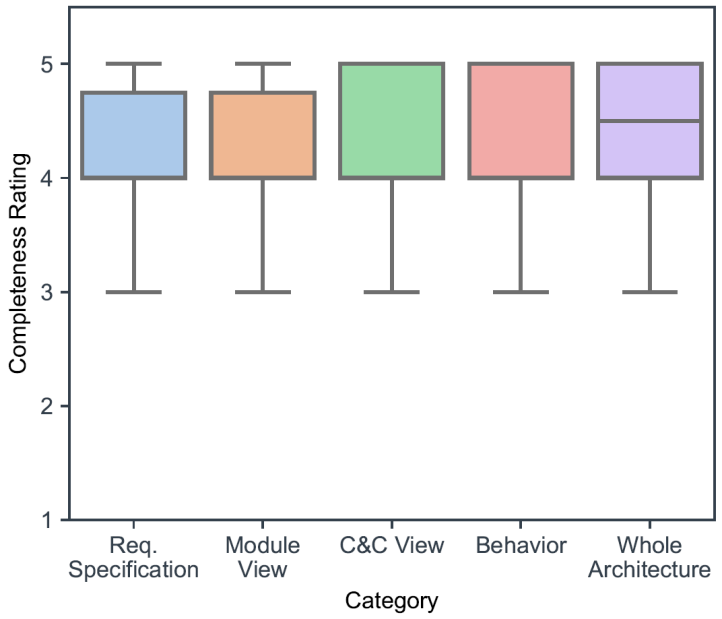
Digital Twin Software Architecture: Module View

The DT **Module View** outlines the module structures in terms of *Digital Twin Domain Entity* (DTDE) and their relations, identified from literature analysis.

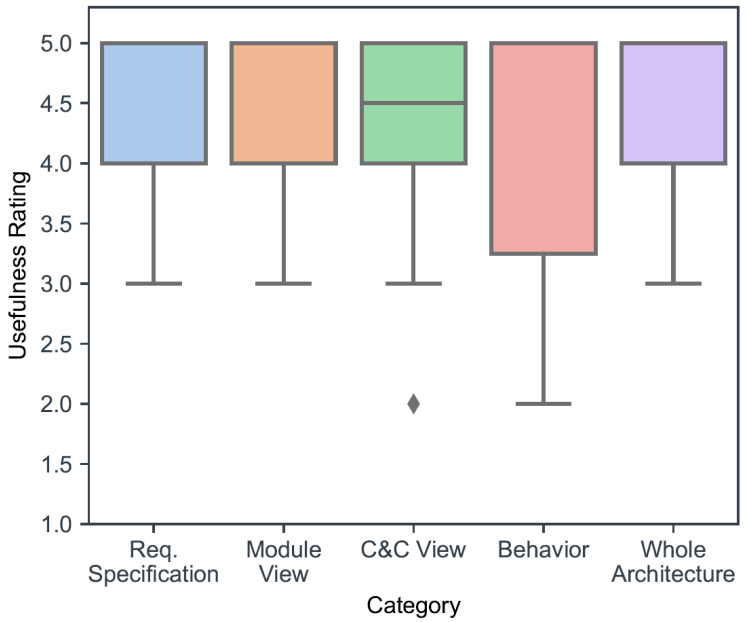


Digital Twin Software Architecture: Validation

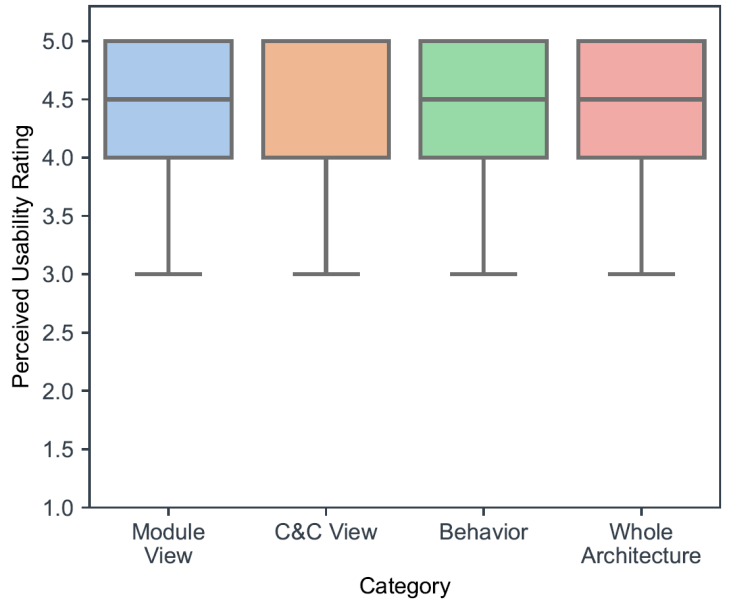
- The DTSA has been validated conducting a **validation suvery** recruiting 14 practitioners from both academia and industry. The survey aimed at evaluating the *completeness*, the *usefulness* and the *perceived usability* of the DTSA.



RQ1. *Completeness*



RQ2. *Usefulness*



RQ3. *Perceived usability*

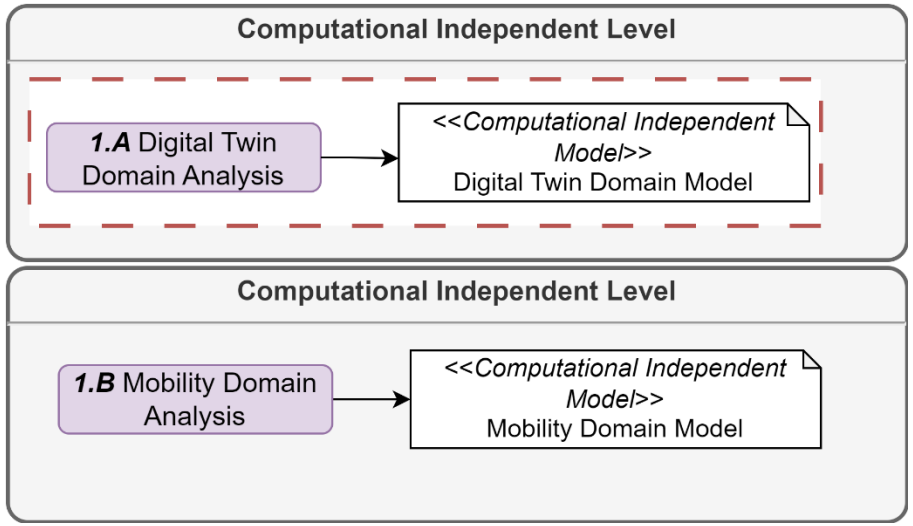
Contribution 2

Model-Driven Architecture for Mobility Digital Twin

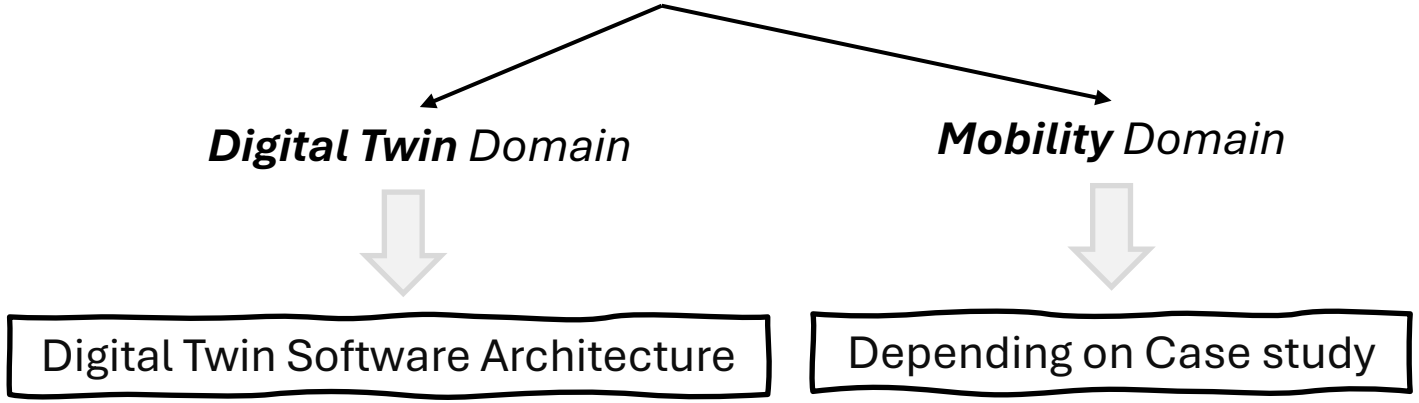
Based on OMG *Model-Driven Architecture* methodology
Development of *Bologna Mobility Digital Twin* powered by *FIWARE* and *SUMO*

Model-Driven Architecture for Mobility DTs

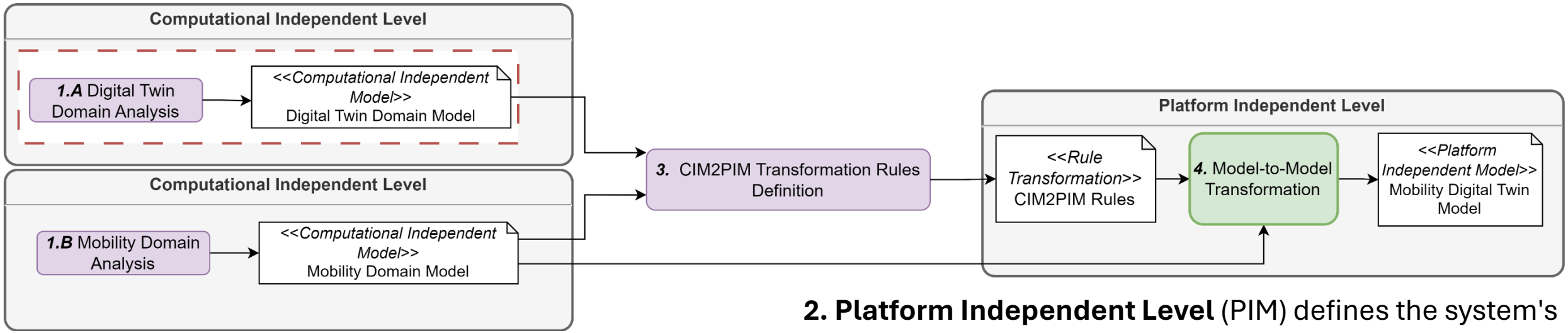
The proposed **Model-Driven Architecture** (MDA) methodology for the development of Mobility DTs consists of four modeling levels, as defined by the Object Management Group (OMG).



1. Computational Independent Level (CIM) describes the system's context without addressing the computational aspects.

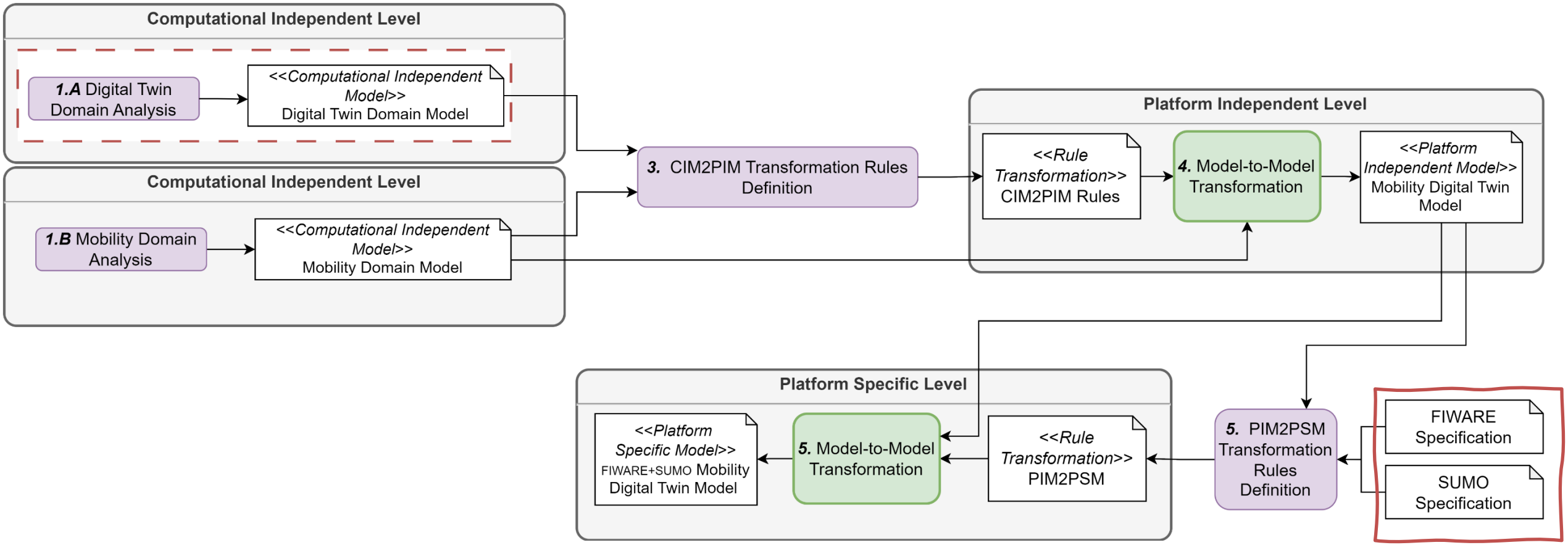


Model-Driven Architecture for Mobility DTs



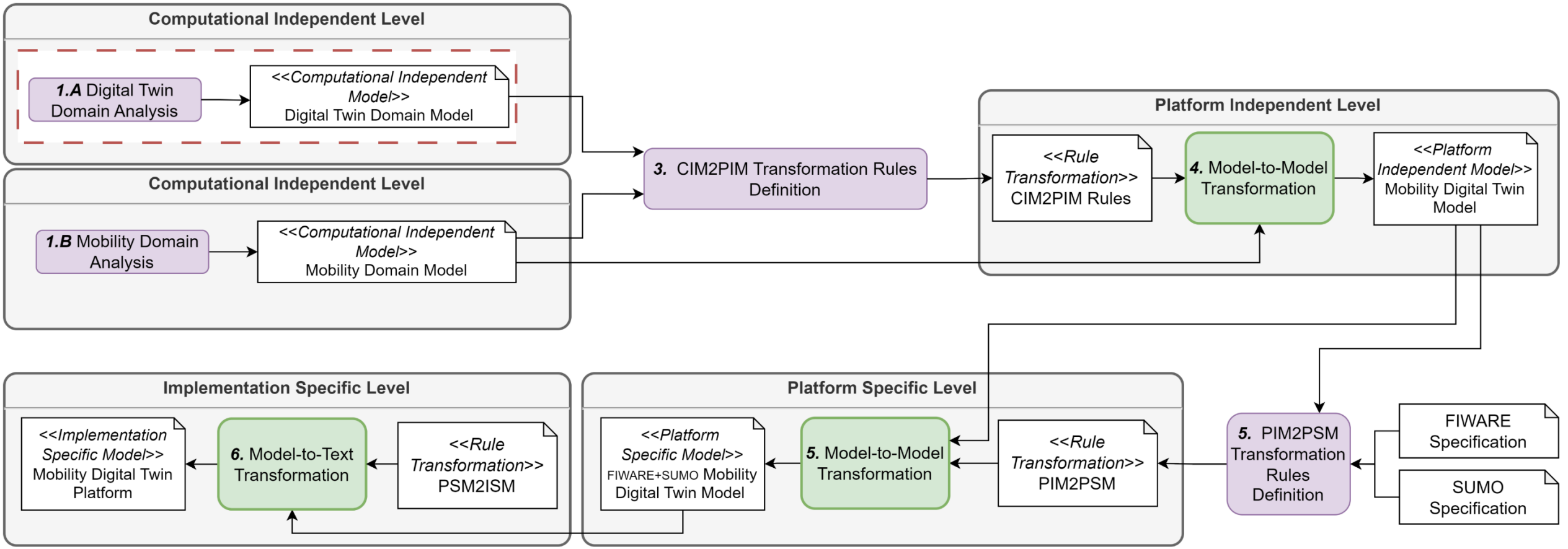
2. Platform Independent Level (PIM) defines the system's behavior and structure without referencing the implementation platform.

Model-Driven Architecture for Mobility DTs

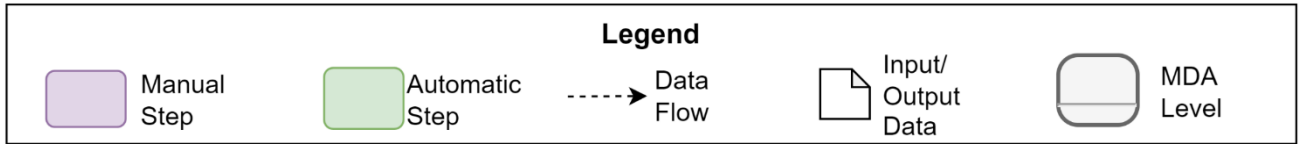


3. Platform Specific Level (PSM) details the system's structure and behavior on a specific platform.

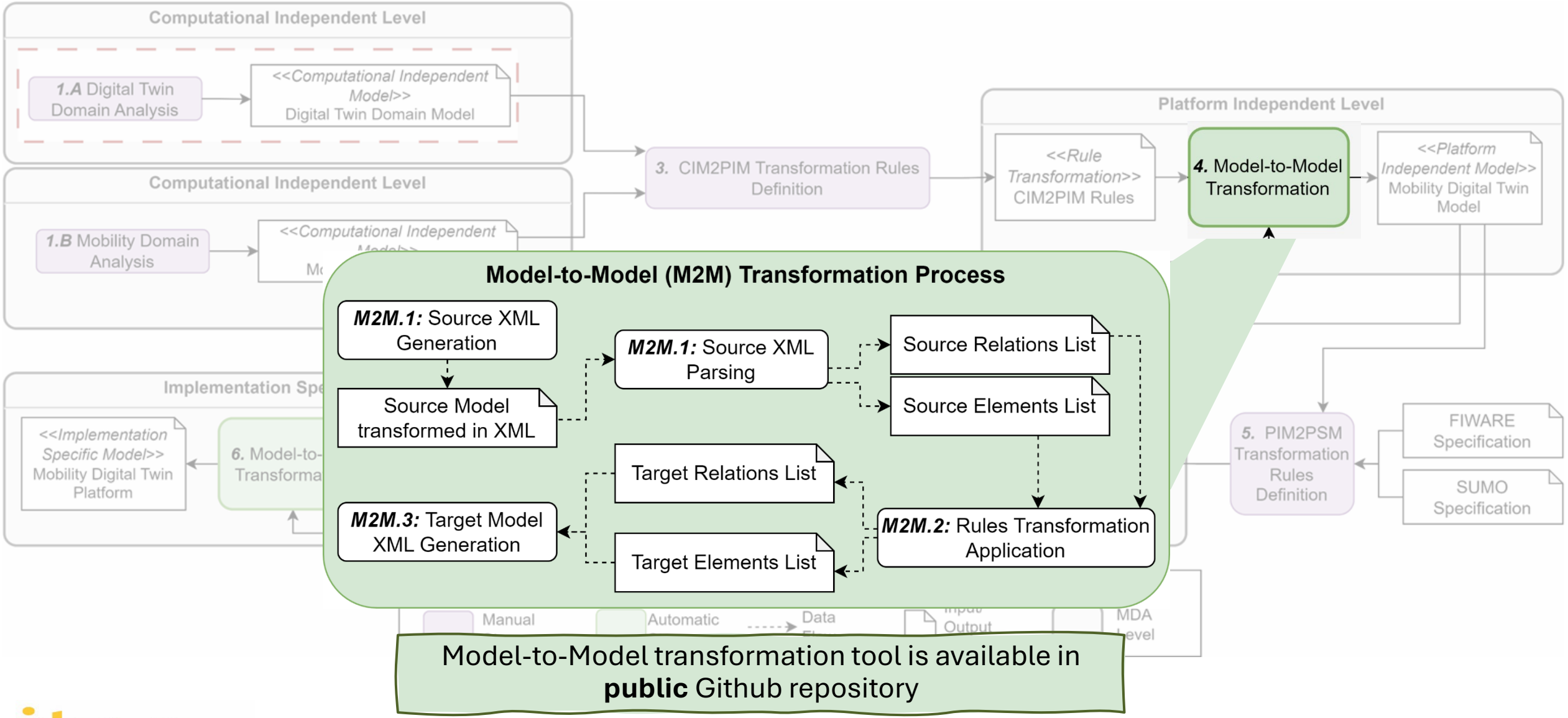
Model-Driven Architecture for Mobility DTs



4. Implementation Specific Level (ISM) details the concrete implementation to generate the executable DT system.



Model-Driven Architecture for Mobility DTs



Model-to-Model transformation tool is available in **public** Github repository

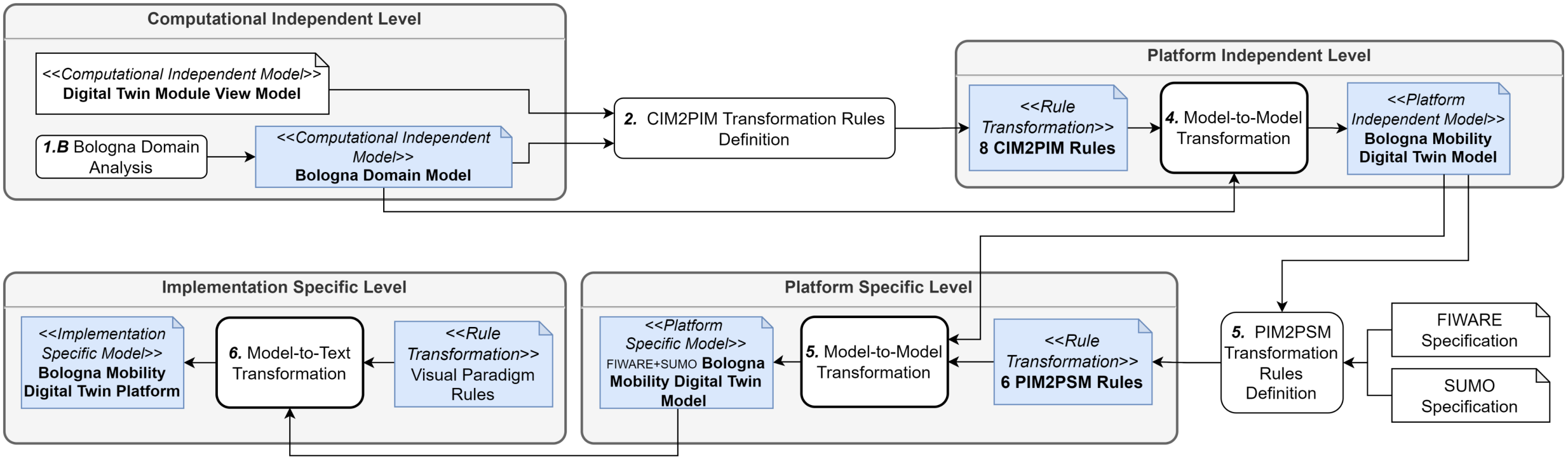
Contribution 2

Bologna Mobility Digital Twin

Based on MDA methodology for Mobility Digital Twins
Powered by FIWARE and Simulator of Urban MObility (SUMO)

Bologna Mobility Digital Twin

The **Bologna Mobility Digital Twin** is developed using the MDA methodology previously discussed. The Model are represented using UML class diagram notation, Visual Paradigm is the modeling tool.



Bologna Mobility Digital Twin

The Bologna Mobility Digital Twin virtualizes two neighborhoods of Italian city to simulate and monitor current (private) traffic flow within the selected area.

- *Real world traffic data* measured by traffic loop sensors, *traffic lights positions* and their working logic are retrieved from Bologna Open Data.
- *No access* to real environment is provided. → realization of a **Bologna Virtual Environment.**

traffic flow data

traffic light logic

Bologna Mobility **Virtual Environment**

real world data

Traffic light control

SUMO

FIWARE

Bologna Mobility **Digital Twin Platform**

MDA artifacts

Bologna Mobility Digital Twin Platform is available in **public** Github repository

Bologna Mobility Digital Twin powered by FIWARE and SUMO

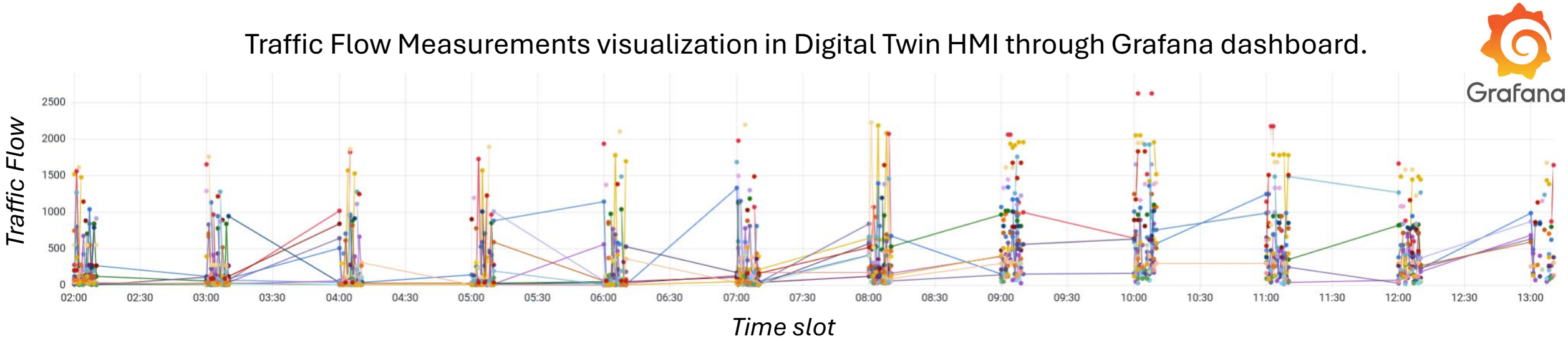
- **FIWARE** is an *open-source* and *standard based* initiative that facilitates the development of smart solutions such as Smart Cities.
  - FIWARE architecture is very extensive and is based on components known as **Generic Enablers** (GEs), reusable and configurable tools across multiple domains.
  - The **Context Broker, Connecting Europe Facility (CEF)** building block, is the only mandatory FIWARE GEs for realizing solutions «*powered by FIWARE*».

- **Eclipse SUMO** is an open-source, multimodal, highly-portable traffic simulator designed for simulating real-world traffic scenarios.

Bologna Mobility Digital Twin: Monitoring Scenario

- The deployed Bologna Mobility Digital Twin platform allows for:
  - **monitoring** current state of the traffic flow

Traffic Flow Measurements visualization in Digital Twin HMI through Grafana dashboard.

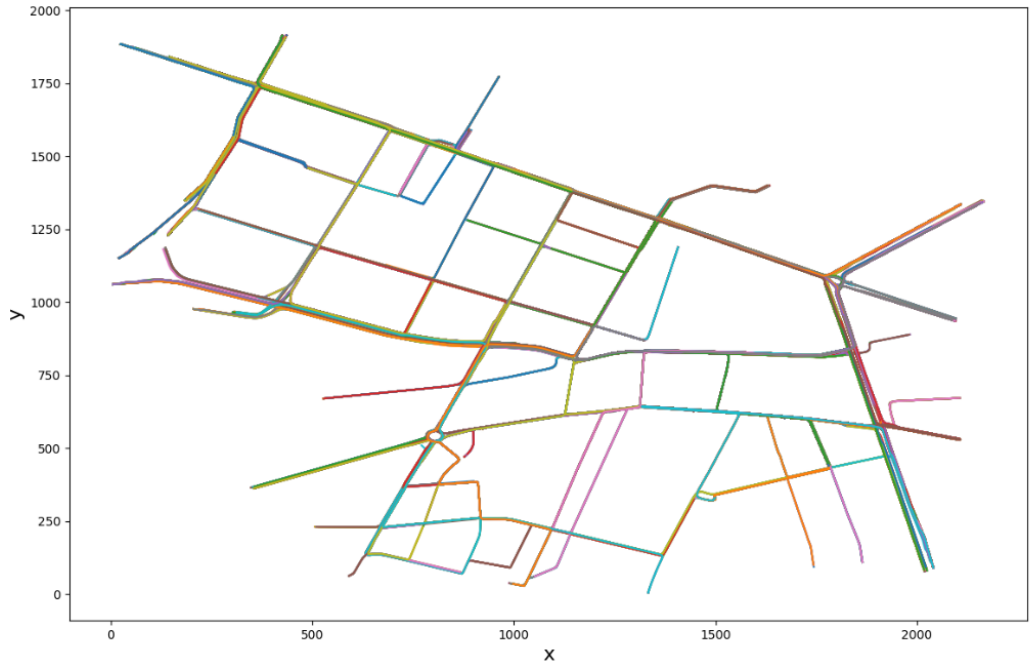


The traffic flow measurements depict the traffic volume across different time slots, with each color representing data from a specific traffic loop sensor. A noticeable increase in traffic intensity can be observed during the 7-10 AM time slots.

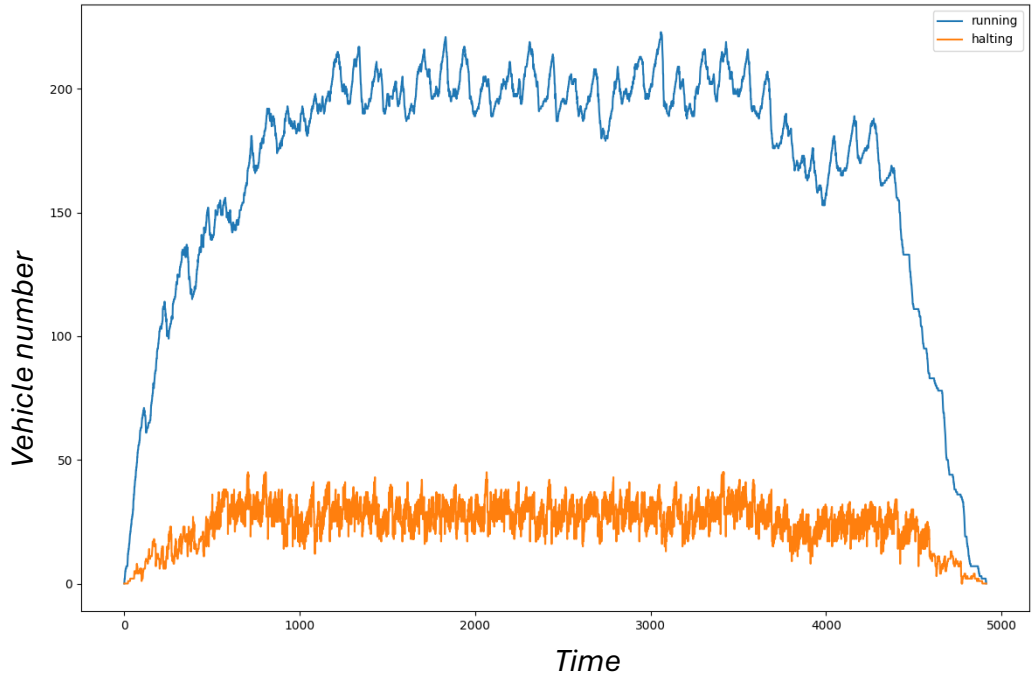
Bologna Mobility Digital Twin: Simulation Scenario

- The deployed Bologna Mobility Digital Twin platform allows for:
  - **monitoring** current state of the traffic flow
  - **simulation** of traffic flow in defined time slot while the entire system remains operational
  - **simulation results visualization** for each scenario (locally or in Digital Twin HMI).

Trajectories coverage graph



Running and halted vehicles during the simulation



The simulation results show an almost complete utilization of the network (left), and no peaks for stopped cars are highlighted in the number of running cars compared to those that are halted (right).

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Conclusion and Future Work

The thesis aims at solving the **software architecting** of Digital Twins by utilizing established practices in software system design and development methodologies, along with two key technologies: *FIWARE* for data management and *SUMO* for mobility simulations.

Research products available in *public Github repositories*:

Digital Twin Software Architecture	Model-to-Model Transformation tool	Bologna Mobility Digital Twin Platform

Future work:

- ❑ Apply the DTSA and MDA-based approach to **different domains** to evaluate their applicability across a wide range of scenarios where Digital Twins could provide significant benefits.
- ❑ **Extension of MDA approach** to fulfill the DT requirements related to detection of deviations from expected behavior and identification of potential future failures.
- ❑ Extension of MDA approach to **Urban Digital Twins** to be realized as sytems-of-systems**.**