Scalable Framework for Behavior Execution of Mobility and Transport Digital Twins

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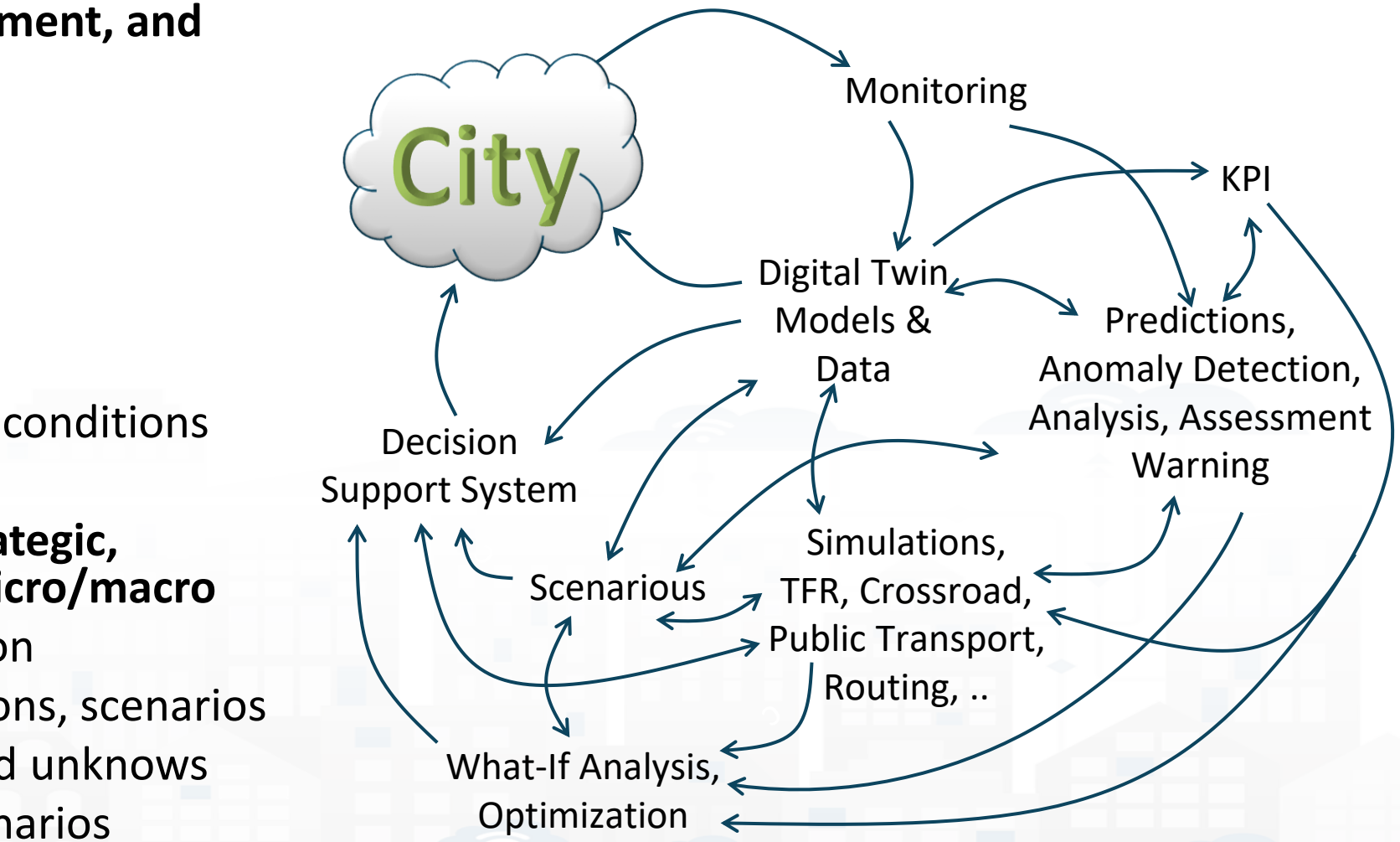
DISIT lab, https://www.disit.org, https://www.snap4city.org

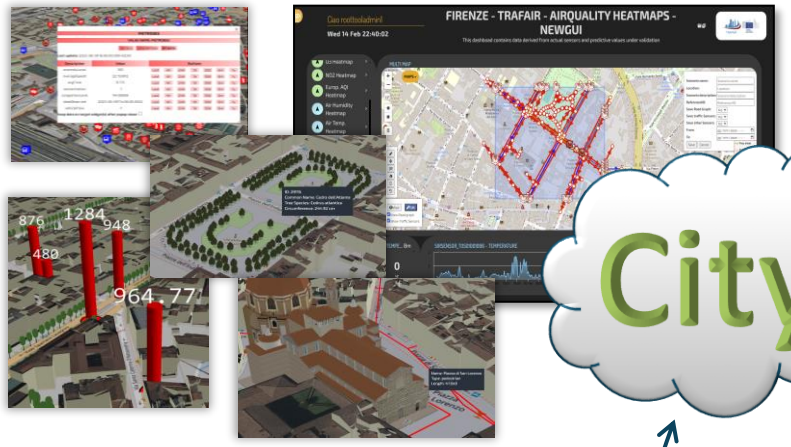
CN MOST flagship projects OPTIFaaS and scalability project SASUAM

CISOSE 2025, IEEE BigDataService 21 - 24 July 2025 Tucson, Arizona, United States

Main tasks

- **Controlling Status: management, and operational**
  - Monitoring via KPI
  - Predictions vs KPI
  - Anomaly detection
  - Neuro-Symbolic analysis
  - Risk assessment
  - Early warning on critical conditions
  - Fast What-if analysis
- **Making plan: tactic and strategic, medium and long range, micro/macro**
  - Simulation & optimization
  - Generative AI Prescriptions, scenarios
  - Resilience to Unexpected unknows
  - What-if analysis wrt scenarios
  - Collaboration with stakeholders





City

Monitoring

KPI

Digital Twin Models & Data

Predictions, Anomaly Detection, Analysis, Assessment Warning

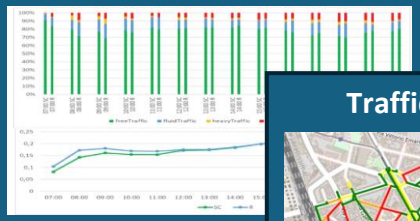
Decision Support System

Scenarious

Simulations, TFR, Crossroad, Public Transport, Routing, ..

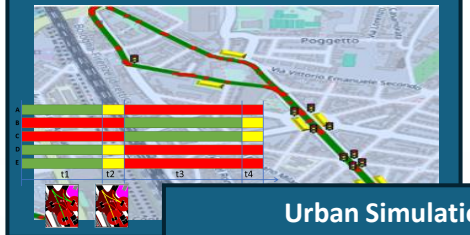
What-If Analysis, Optimization

KPI, Predictions, ...



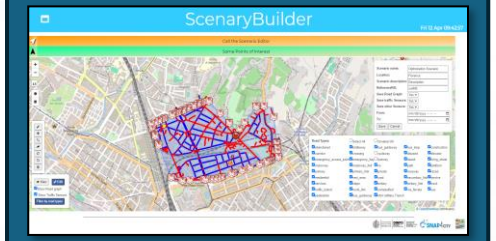
Traffic Reconstruction

Traffic Light Plan optimization

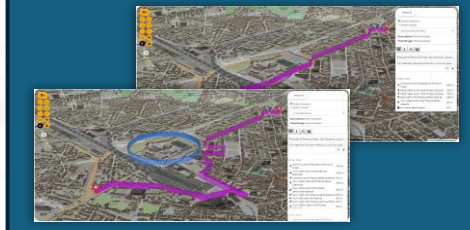


Urban Simulation

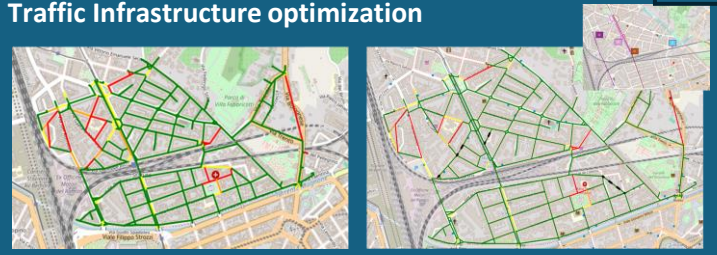
Scenario Editor



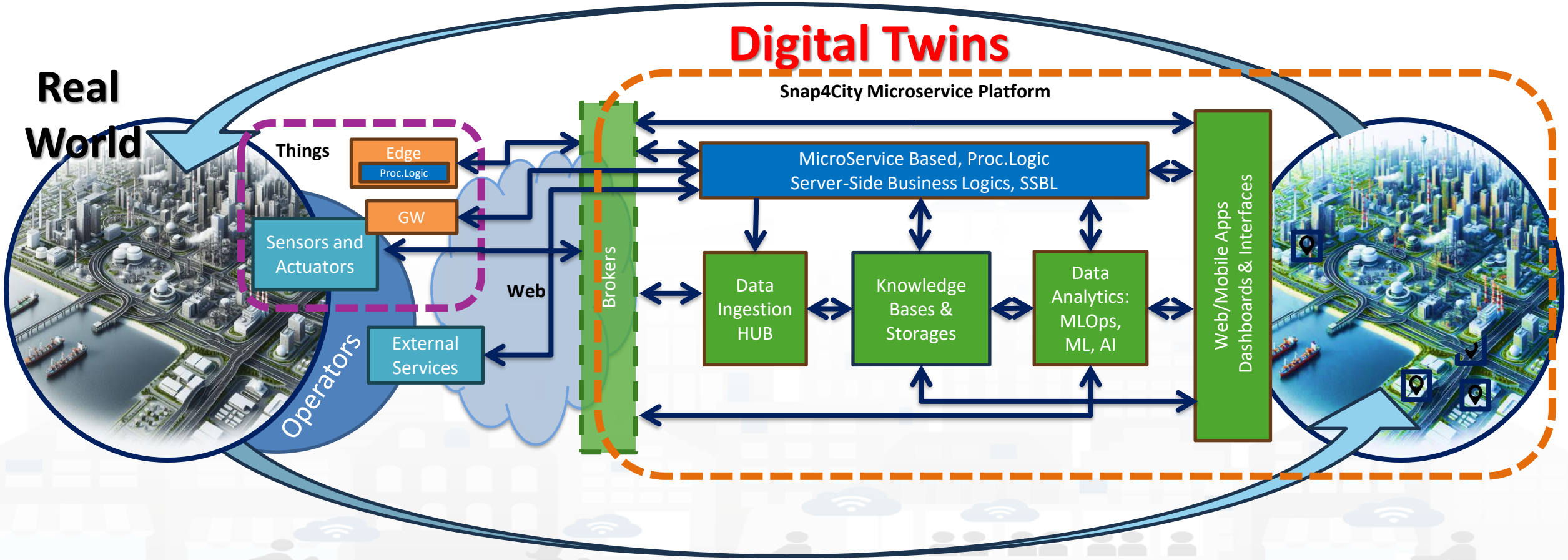
Routing / Dynamic Routing



Traffic Infrastructure optimization



Digital Twin Development Platform



The Challenge: Complex Smart Cities

Increasing complexity of smart city systems, especially mobility and transport

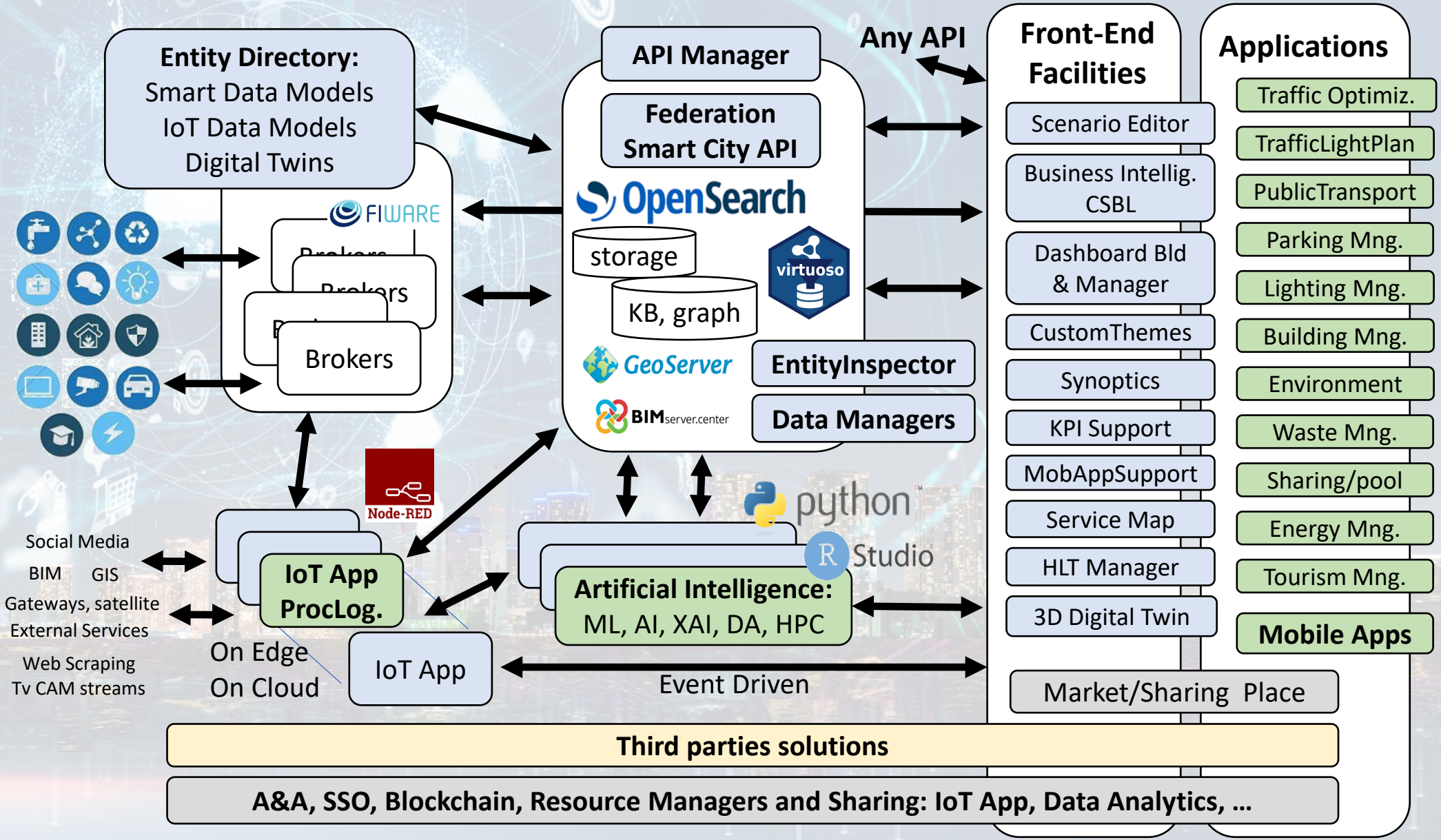
Traditional what-if analysis:

- Human-driven, "try-n-error" process
  - Low automation
  - Limited scalability; cannot fully exploit cloud/container capabilities for large trials

Heterogeneity of processes: Simulations, Optimizations, predictions, …

- Multiple behavioral aspects (vehicle agents, routing, routing, pollutant diffusion, traffic light optimization) optimization)
- Different paradigms (discrete-event, agent-based, based, reinforced learning, LLM, GA, …)
- Various spatial and temporal scales (micro-, meso-, meso-, macro)
- scalability of executions of the processes
- accountability of resource consumption, allocation allocation

Technical Architecture



100% OPEN SOURCE

Powered by FIWARE

FREE TRIAL

PEN Test Passed

EU GDPR COMPLIANT

SNAP4 Appliances and Dockers Installations

EUROPEAN OPEN SCIENCE CLOUD

Node-RED

JS Foundation

EØ15 digital ecosystem

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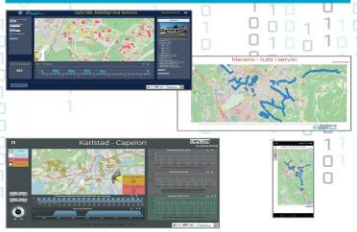
OPERATION AND PLAN - CONTROL ROOMS - DECISION SUPPORT SYSTEMS - WHAT-IF ANALYSIS - OPTIMIZATION - APPLICATIONS

HORIZONTAL AI PLATFORM

MOBILITY AND TRANSPORT

SMART ENERGY AND SMART BUILDING



ENVIRONMENT AND WASTE MANAGEMENT

CITY USER'S SERVICES AND TOURISM MANAGEMENT

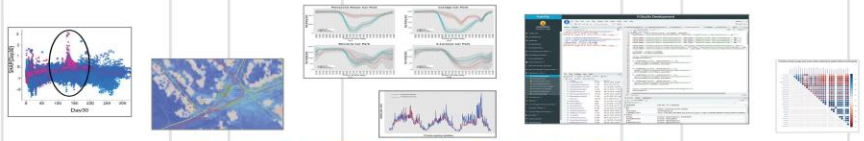
BUSINESS INTELLIGENCE - SIMULATIONS - VISUAL ANALYTICS - SYNOPTICS - GRAPHICAL WIDGETS - ANALYTICS

DASHBOARDS, WIDGETS TEMPLATES

PREDICTION - ANOMALY DETECTION - CLUSTERING - ROUTING - SENTIMENT NLP - TRAFFIC FLOW - PEOPLE FLOWS - SDG
15 MIN CITY INDEX - KPI - HEATMAPS - ORIGIN DESTINATION - MAPS - VECTOR FIELD - ETC...

API - MICROSERVICES - GIS - BPM
VIDEO - REPORTS - MAPS - 3D ...

EXPERT SYSTEM, KNOWLEDGE BASE
SEMANTIC REASONING
SMART DATA MODEL
IOT DEVICE MODELS, DATA SPACES



BIG DATA ANALYTICS, ARTIFICIAL INTELLIGENCE
EXPLAINABLE AI, MACHINE LEARNING, GENERATIVE AI
OPERATIVE RESEARCH, STATISTICS

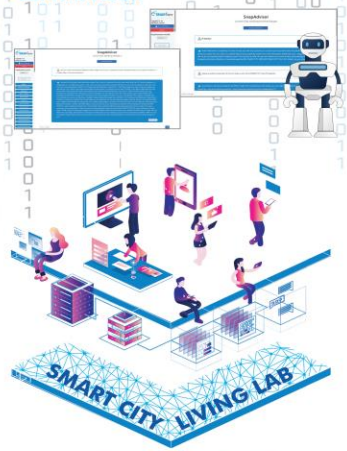
VISUAL PROGRAMMING, ADAPTERS
DATA FLOWS, WORKFLOWS
PARALLEL DISTRIBUTED PROCESSING
DATA DRIVEN

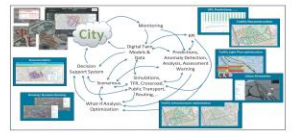
FULL INTEROPERABILITY, ANY: DATA, BROKERS, NETWORKS AND VERTICALS

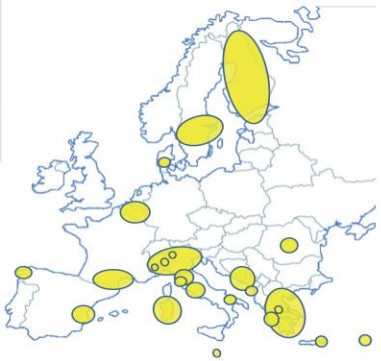
NATIVE AND EXTERNAL APPLICATIONS

- Smart Parking
- Smart Light
- Smart Waste
- Smart Energy
- Smart Building
- Smart Tourism
- ...

- DEVELOMENT ENVIRONMENT AND METHODOLOGY
- VISUAL PROGRAMMING, ML, AI, HPC
- TRAINING COURSES
- LLM ADVISOR

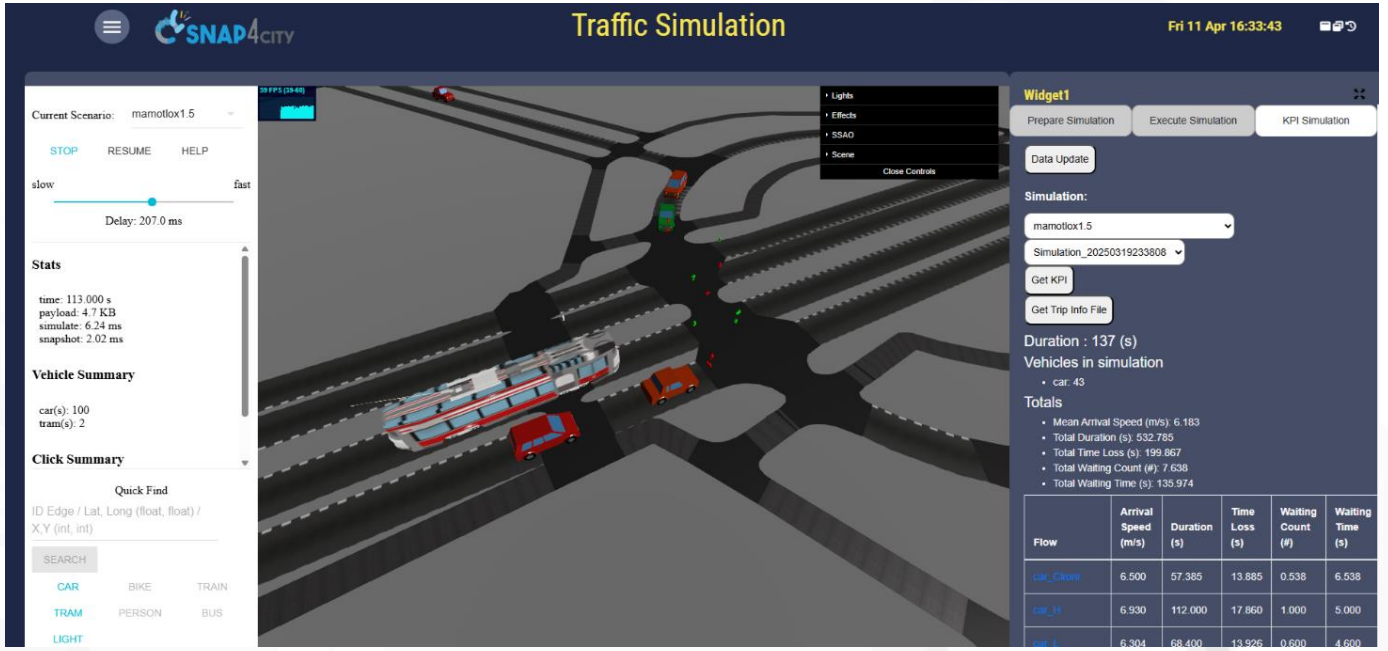




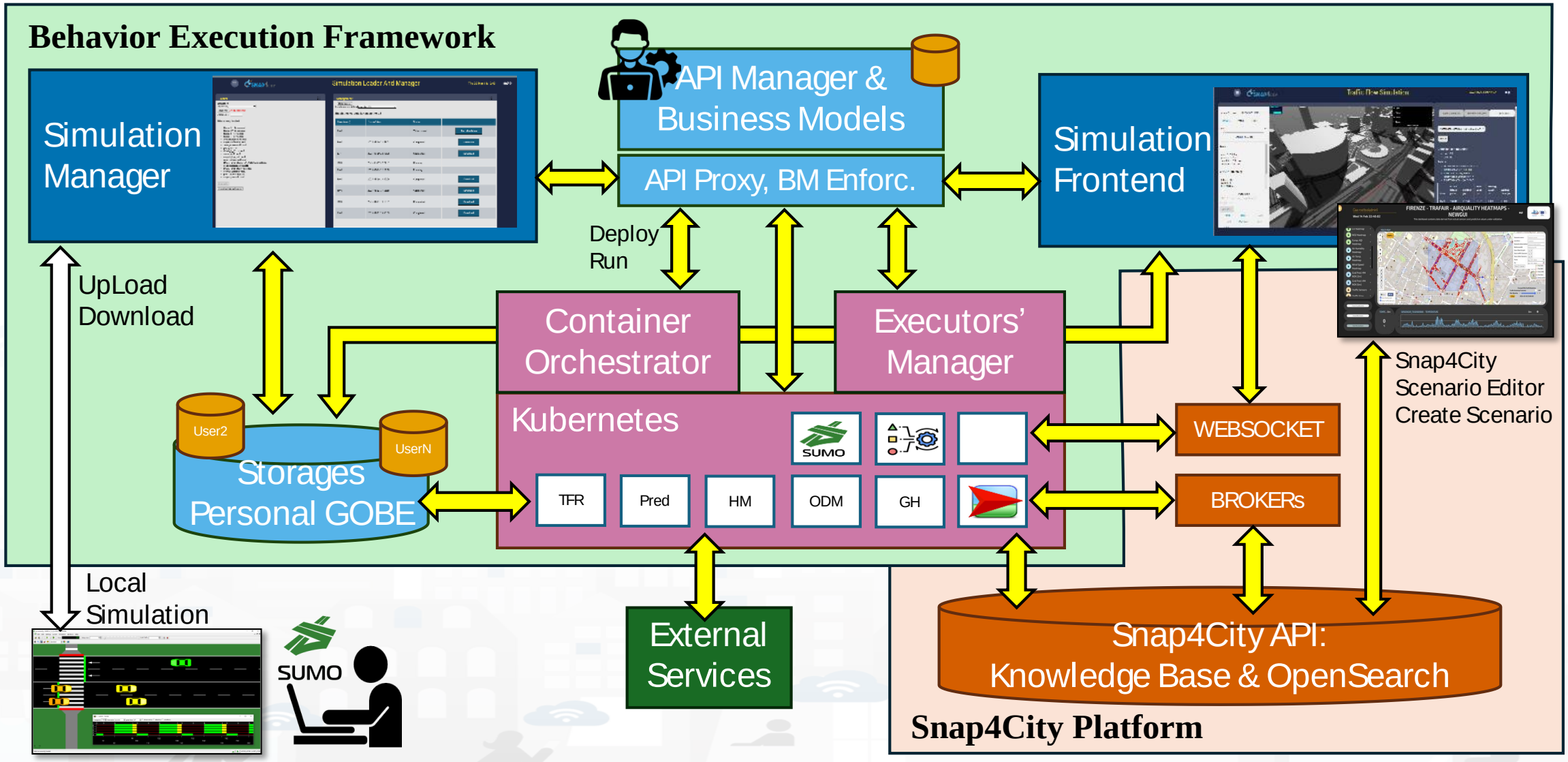


BEFDIT Behavior Execution Framework for Digital Twins

- Orchestrates heterogeneous behavioral Simulations, predictions, reconstruction, classification, causality, anomaly detection, Routing, ODM prod., ..
- Supports co-simulation and co-execution of multiple tools, multiple instances (open-source & proprietary)
- Leverages cloud/container-based infrastructures
- Optimization ready and not only What-If Ready
- Facilitates real-time and offline management of simulations, executions
- Integrated into Snap4City Open-Source platform.



BEFDIT Architecture



BEFDIT – Core Contributions & Requirements

- **R.1: Support for Various Behavioral Executors (BEXs):** Modular architecture for diverse algorithms (statistical, ML/AI, operational research), Supports BEXs in different languages from various providers, Examples: vehicle agents, routing, pollutant diffusion, traffic predictions
- **R.2: Groups of Behavioral Executions (GOBE):** Multiple BEXs towards a shared goal within a "Scenario“, Activated programmatically or via web GUI
- **R.3: Support for Independent BEXs:** Concurrent execution of multiple instances of same or different BEXs, Each BEX deployed as a container on cloud, by diff. users, diff. contexts, etc..
- **R.4: Interoperable BEXs:** Supports various communication protocols (API, Web Services, files) for data exchange
- **R.5: Web-Based Support** for GOBE: GUI for setup, monitoring, monitoring, results. Dashboards for real-time visualization and parameter adjustments. Dashboards results for decision-makers makers
- **R.6: GOBE as a Service with Scalable Resource Allocation: Allocation:** Dynamically allocates computational resources (CPU, GPU, (CPU, GPU, memory, storage, API) Optimizes performance via load load balancing and adaptive scaling
- **R.7: Persistent Simulation Data Model:** Cloud-based storage for storage for Scenarios, GOBE setups, and results. Version control and and rollback options; allows resume/replay/analysis of past runs runs
- **R.8: Users' Management: Supports multiple users with different roles (admin, operators, users):** Manages access and usage

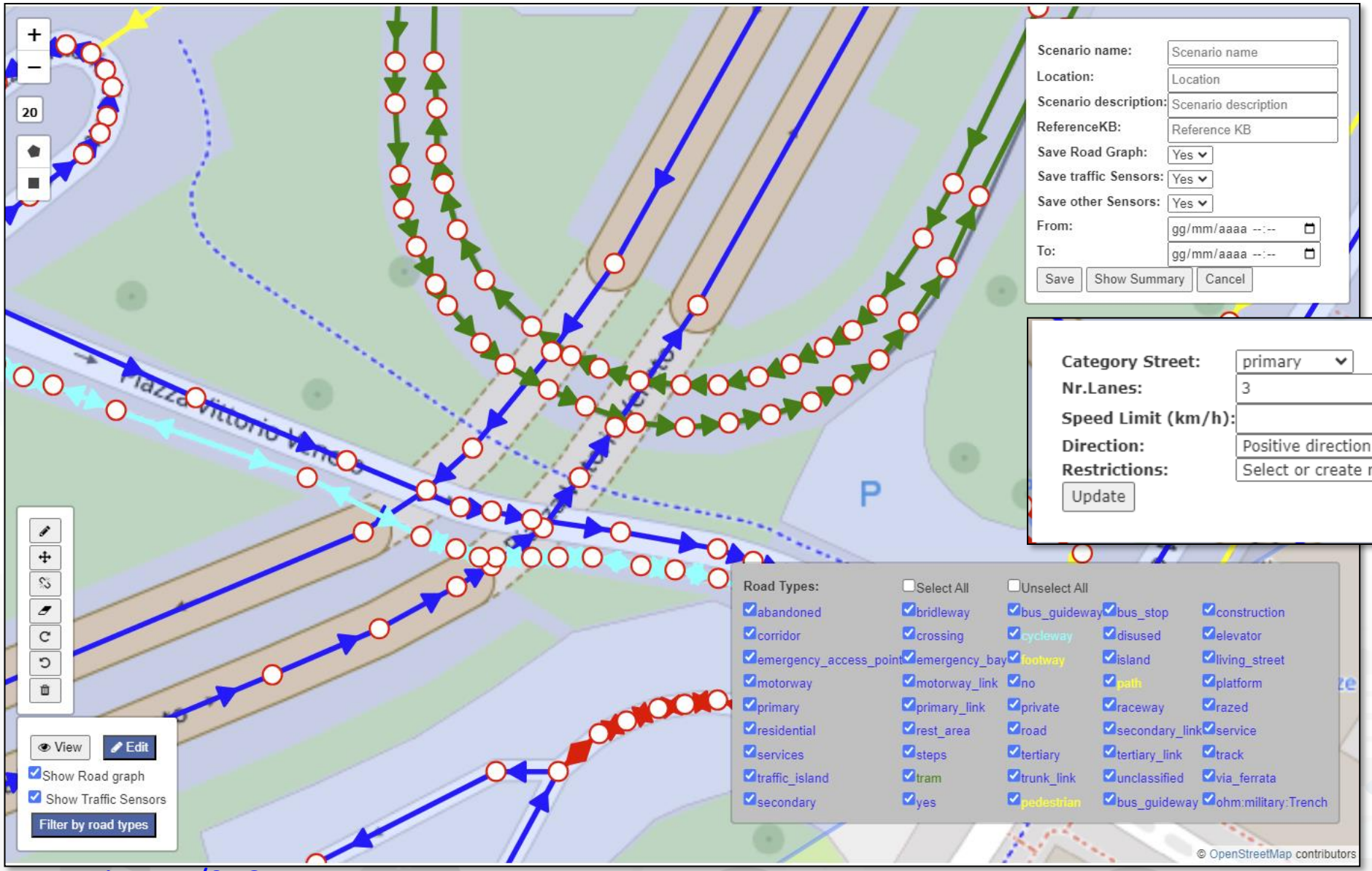
Scenario Editor

Select map

Zoom

New Scenario

Editing
Drag & drop
Split & Join
Delete
Do and Undo



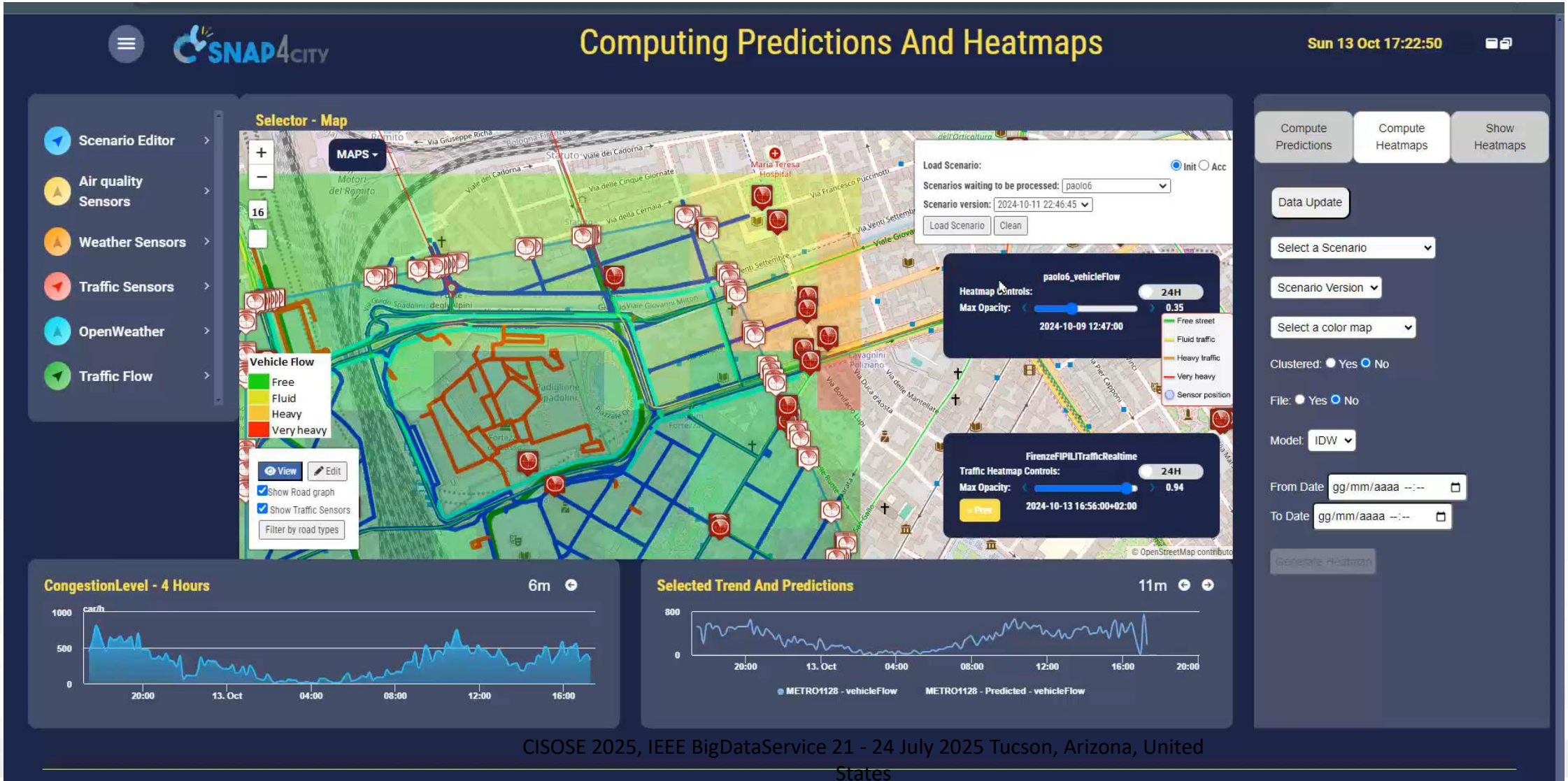
Edit Road Segment

- identifier
- composition
- elemLocation
- elementClass
- elementType
- length
- operatingStatus
- speedLimit
- trafficDir
- width
- highwayType
- route

Properties of Road Elements

https://www.snap4city.org/976

Predictions and Heatmaps in Real Time



BEFDIT & SUMO – Urban Mobility Simulation

SUMO (Simulation of Urban Mobility) example

Two main modes:

Local Setup, Cloud Execution

- Prepare SUMO scenarios locally (e.g., NetEditor)
- Upload to BEFDIT/Snap4City for execution in the cloud
- Results available via download or real-time (SUMO Web3D via WebSocket)

Full Snap4City Workflow

- Scenario creation via Snap4City tools (e.g., Scenario Editor)
- Automatic versioning, cloud conversion to SUMO input (via Kubernetes microservice)
- Easy integration of real-time data

Simulation Workflow & Co-Simulation

Define/upload scenario

- Area → bounding box
- Timespan → datetime range
- Demand → ODMs

Convert to SUMO input (network, routes)

Run (offline/online with Web3D)

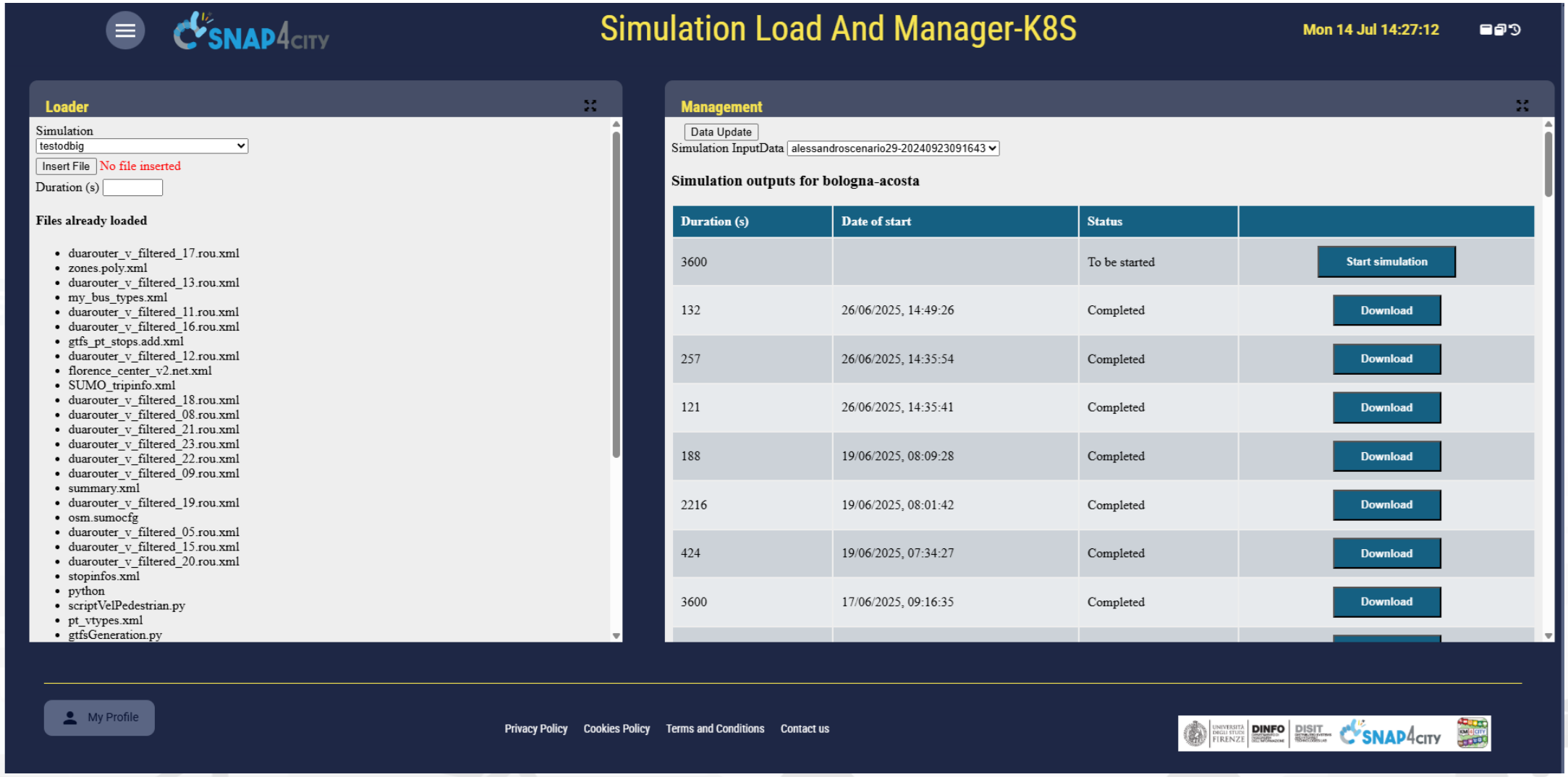
Analyze results via KPIs (e.g., speed, time loss, waiting time)

Co-Simulation

- Integrates SUMO with other BEXs (e.g., GraphHopper for dynamic routing)
- Enables congestion avoidance, road closures, smart infrastructure tests
- Managed via Kubernetes clusters and scalable microservices

BEFDIT & SUMO Integration – Urban Mobility Simulation

BEFDIT & SUMO Integration – Urban Mobility Simulation



From Simple Simulation to scalability

SUMO produces real-time outputs (e.g., traffic status, traffic light plans)
Data injected into Snap4City via virtual sensors

Supports:

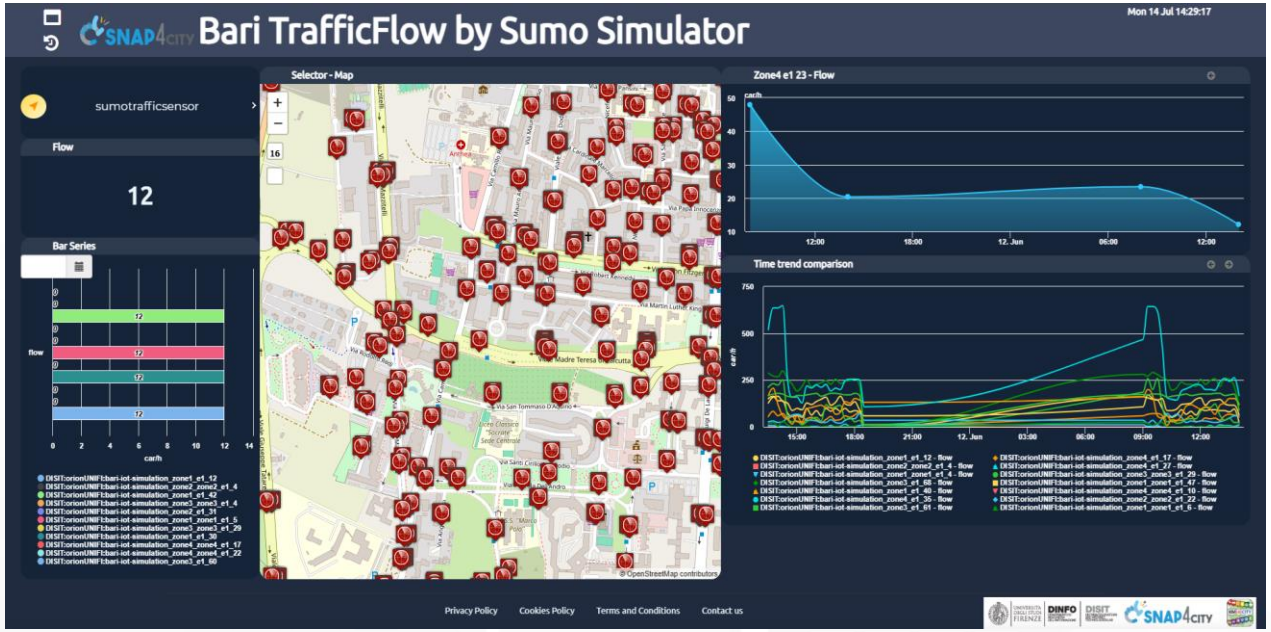
- Dashboards & analytics
- Smart city service testing
- Predictive model validation
- Backup during sensor failures

Scalability & Performance

- 3,351 simulation operations/month
- 200,000+ routing requests (e.g., Florence) via GraphHopper
- 10,000+ flows for RL training

Complex spatial scenarios supported:

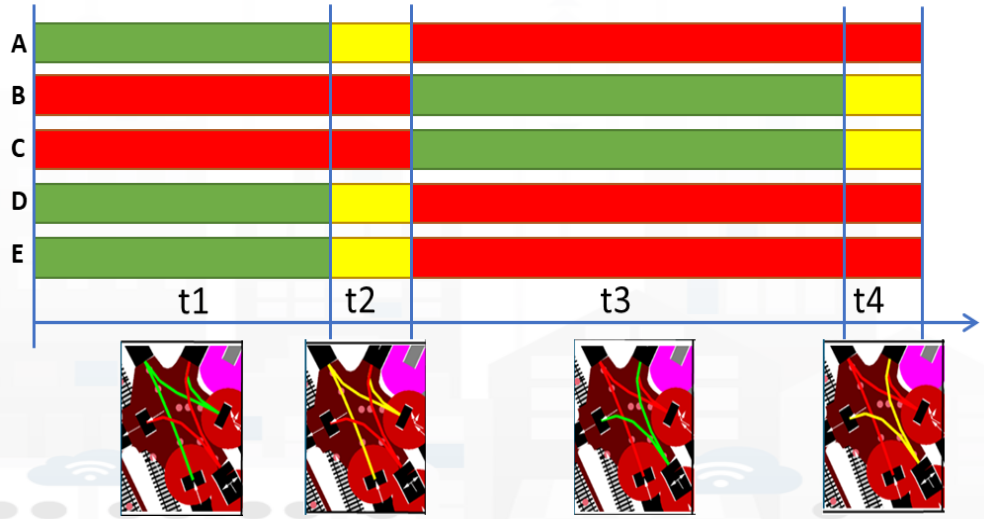
- Helsinki/Antwerp: 5.3M roads
- Greece: 6.7M roads
- Other areas: up to 13M roads



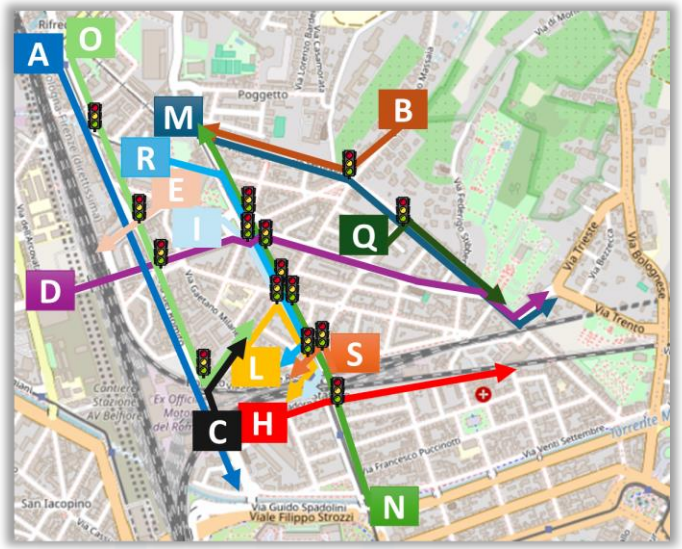
Traffic Light Plan Optimisation, Digital Twin

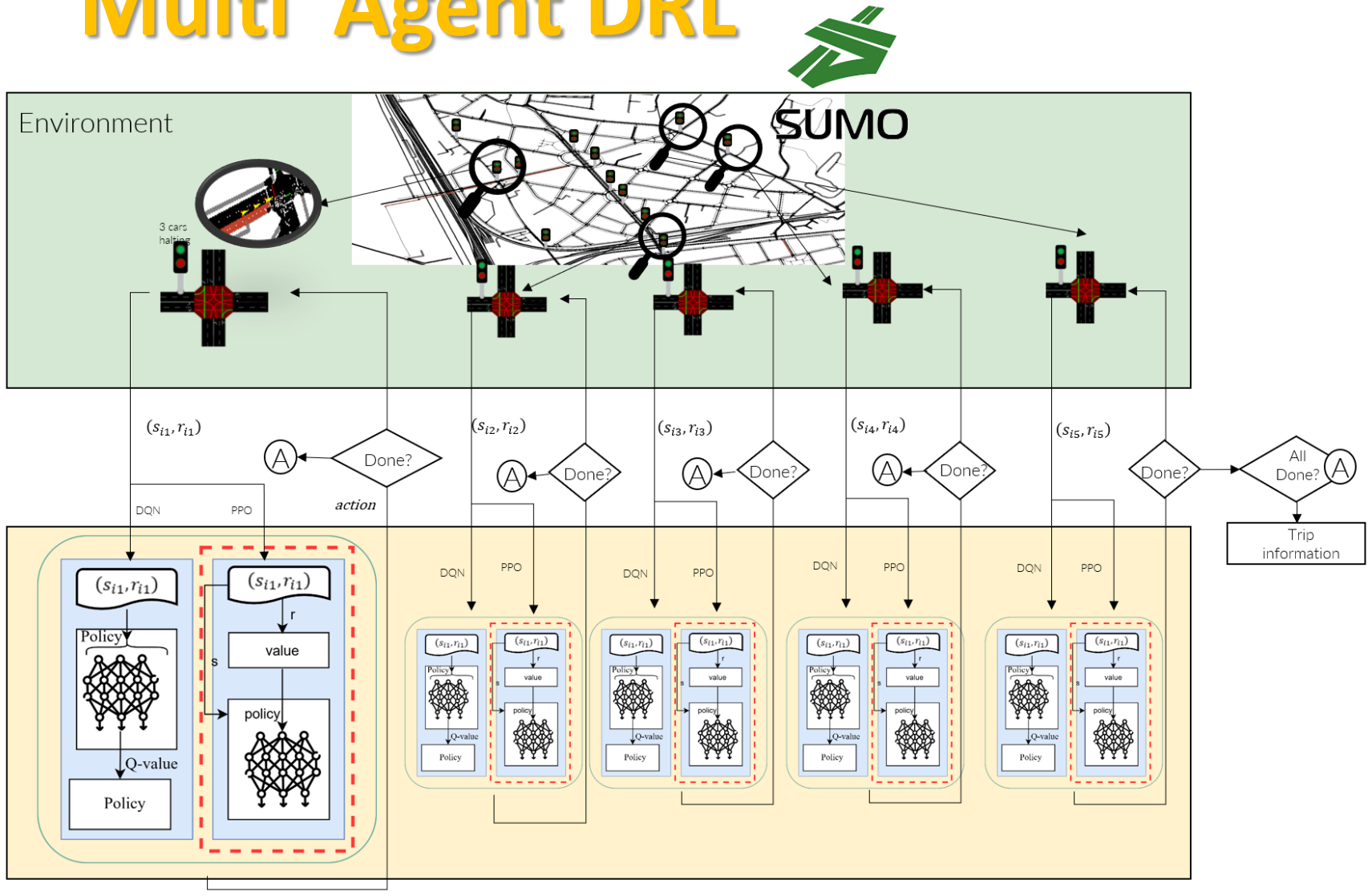
- **Match Multiple Objectives and Synchronization:**
  - public and private traffic, tramway priority
  - Micro and Macro Scales
  - **AI: Genetic Algorithms, Deep Reinforced Learning**
    - Fixed and Actuated Cycles
    - Adjusted on Demand
- **Validation/integ.** with ***SUMO*** simulation
  - Travel Time, waiting time, waiting count
  - Specific travel time on directions
  - CO2 emissions, etc.
- **Reductions from 5% to 15%**

MOST CENTRO NAZIONALE PER LA MOBILITÀ SOSTENIBILE

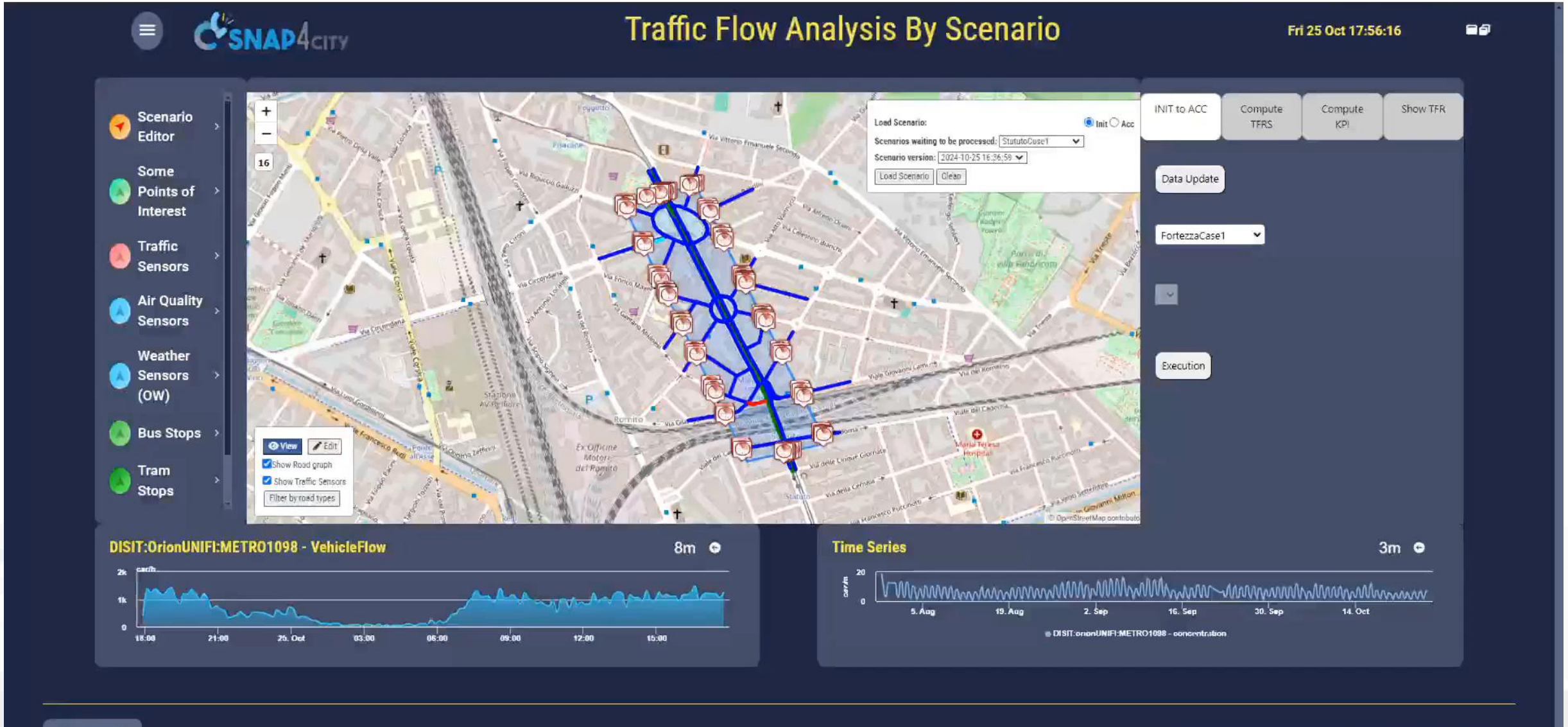


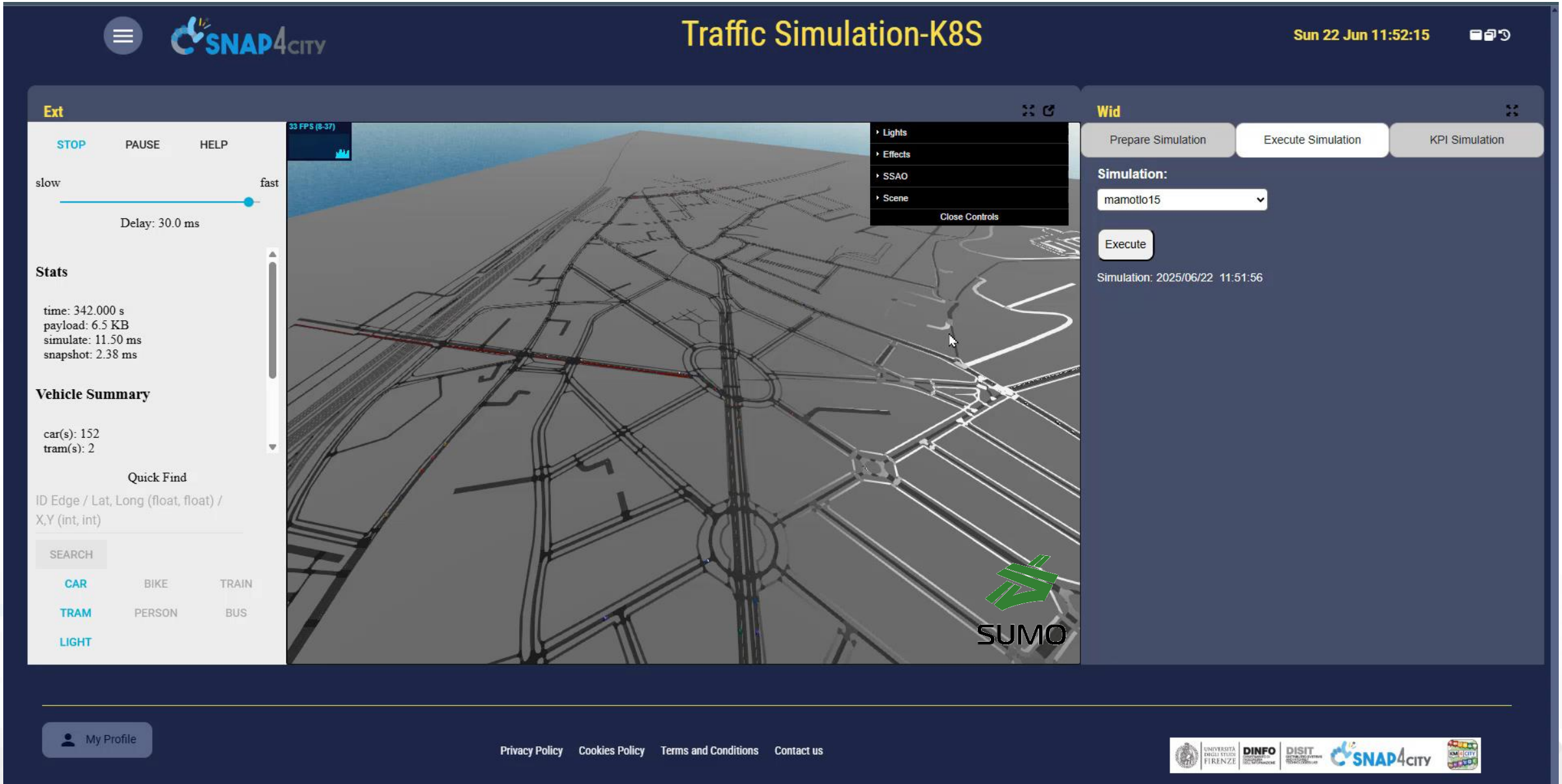
Multi Agent DRL





Optimization of Traffic Light Plan




Traffic Simulation-K8S
Sun 22 Jun 11:52:15
Ext
STOP
PAUSE
HELP
slow
fast
Delay: 30.0 ms
Stats
time: 342.000 s
payload: 6.5 KB
simulate: 11.50 ms
snapshot: 2.38 ms
Vehicle Summary
car(s): 152
tram(s): 2
Quick Find
ID Edge / Lat, Long (float, float) / X,Y (int, int)
SEARCH
CAR
BIKE
TRAIN
TRAM
PERSON
BUS
LIGHT
33 FPS (8-37)
Lights
Effects
SSAO
Scene
Close Controls
SUMO
Wid
Prepare Simulation
Execute Simulation
KPI Simulation
Simulation:
mamotlo15
Execute
Simulation: 2025/06/22 11:51:56
My Profile
Privacy Policy
Cookies Policy
Terms and Conditions
Contact us

MTT for Multi Agent DRL for TLP

Model	TL	all	dir_N	dir_M	dir_A	dir_D	Careggi	Costanza
4TWD-NTNS-MWD-A	1	3013.85	176.93	233.75	194.46	237.65	436.00	427.00
4TWD-NTNS-MWD-P-A	1	3013.85	176.93	233.75	194.46	237.65	436.00	427.00
SUMO Actuated	1	2935.41	249.60	209.77	202.42	270.86	486.73	478.36
Webster	1	5188.87	211.66	242.32	205.46	562.31	984.00	427.00
Webster A	1	2968.90	183.50	242.67	201.27	251.76	482.27	427.00
SARL-FC DQN	1	2834.93	206.68	244.78	199.21	243.26	486.72	485.00
SARL-FC DQN A	1	2760.12	206.35	244.63	198.00	244.76	436.00	427.00
MADRL-FC DQN	1	3089.20	188.29	220.91	205.07	248.06	485.00	445.00
MADRL-FC DQN A	1	2983.69	189.11	220.70	187.00	248.79	436.00	427.00
MARL-FC PPO	1	2910.76	200.38	235.41	198.14	237.78	547.00	445.00
MARL-FC PPO A	1	2855.12	200.93	235.53	196.39	237.97	436.00	427.00
SMART A	1	2599.13	182.14	200	188.28	235.11	436.00	427.00

Conclusions & Future Work

Key Findings

BEFDIT enables scalable, modular, and interoperable simulation ecosystems

- MLOps support for stable and one shot API calls
- API-based interoperability
- Containerized BEXs ("Behavior Execution as a Service")
- Persistent versioned simulation management
- Privacy-aware multi-user collaboration

Future Directions

- More simulators & BEXs
- Smarter AI optimization loops
- Automated multi-domain optimization

Thanks for your attention

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CN MOST flagship projects OPTIFaaS and scalability project SASUAM