Architecting IoT Systems

The journey and challenges

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Acknowledgements

The materials used in this presentation have been adapted/generated from various sources as well as based on my own research experiences and knowledge — Karthik Vaidhyanathan

Sources:

1. Presentation on Architecting CPS, Henry Muccini, Mohammad Sharaf, Karthik Vaidhyanathan

2. CAPS Modeling Framework - caps.disim.univaq.it

3. Personal experiences with the Uffizi and VASARI Projects (VASARI OR2.2)

Global IoT market size: USD 714.48 billion in 2024; projected to reach USD 4,062.34 billion by 2032

https://www.fortunebusinessinsights.com/industry-reports/internet-of-things-iot-market-100307

What is IoT?

The internet of Things (IoT) is the network of **physical objects** that contain **embedded technology** to communicate and sense or interact with their internal states or the **external environment**

—— Gartner

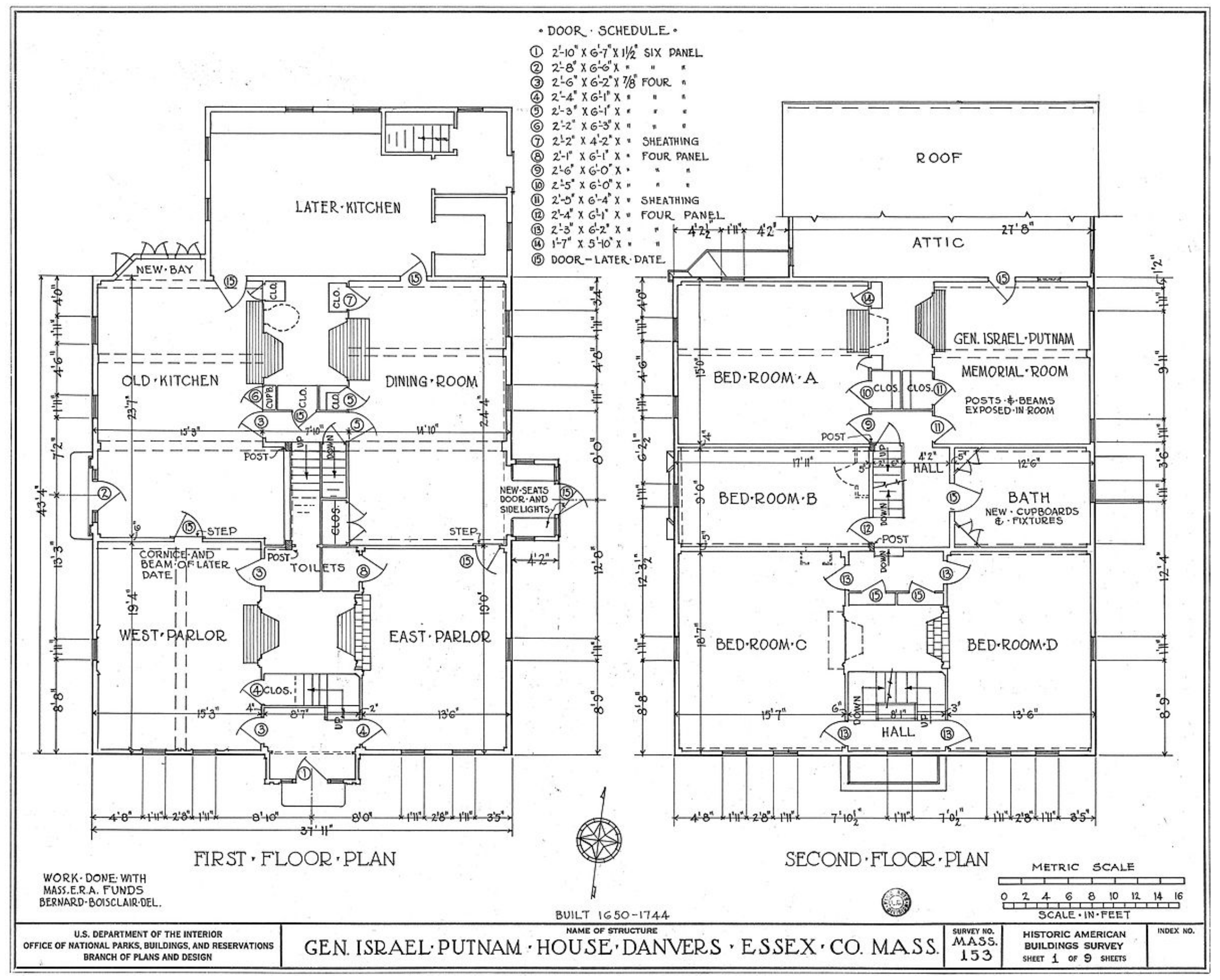
75% of self-initiated IoT projects from the companies were considered as a **failure !!**
— Cisco

https://newsroom.cisco.com/press-release-content?articleId=1847422

Software Architecture: The Foundation

What you do if you want to build a house?

1. You will have a set of needs/requirements
2. You will meet a civil engineer/architect and list your requirements
3. Civil Engineer/Architect comes with a building plan with different views
4. Once you are convinced with the plan, you start the construction

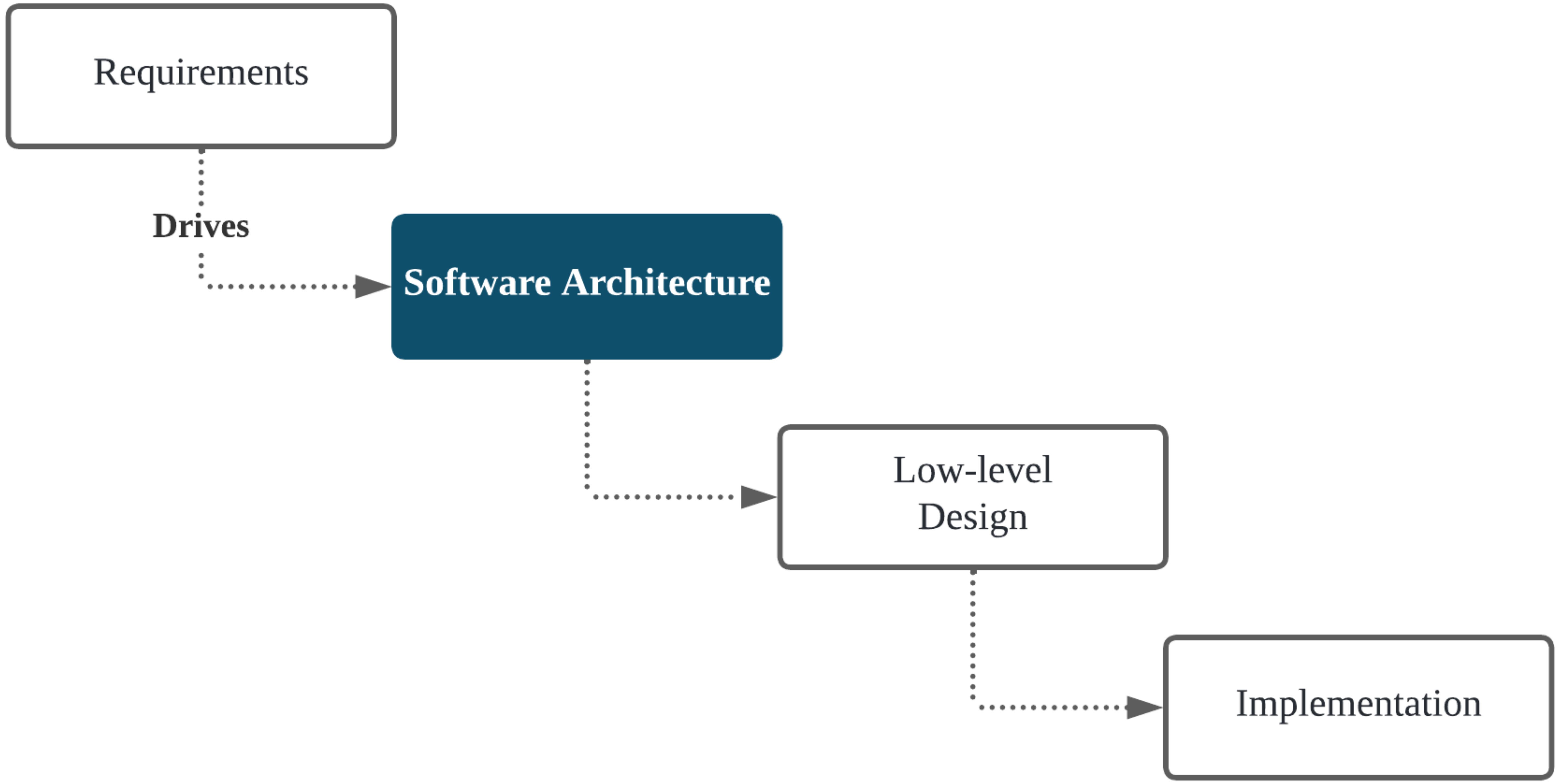


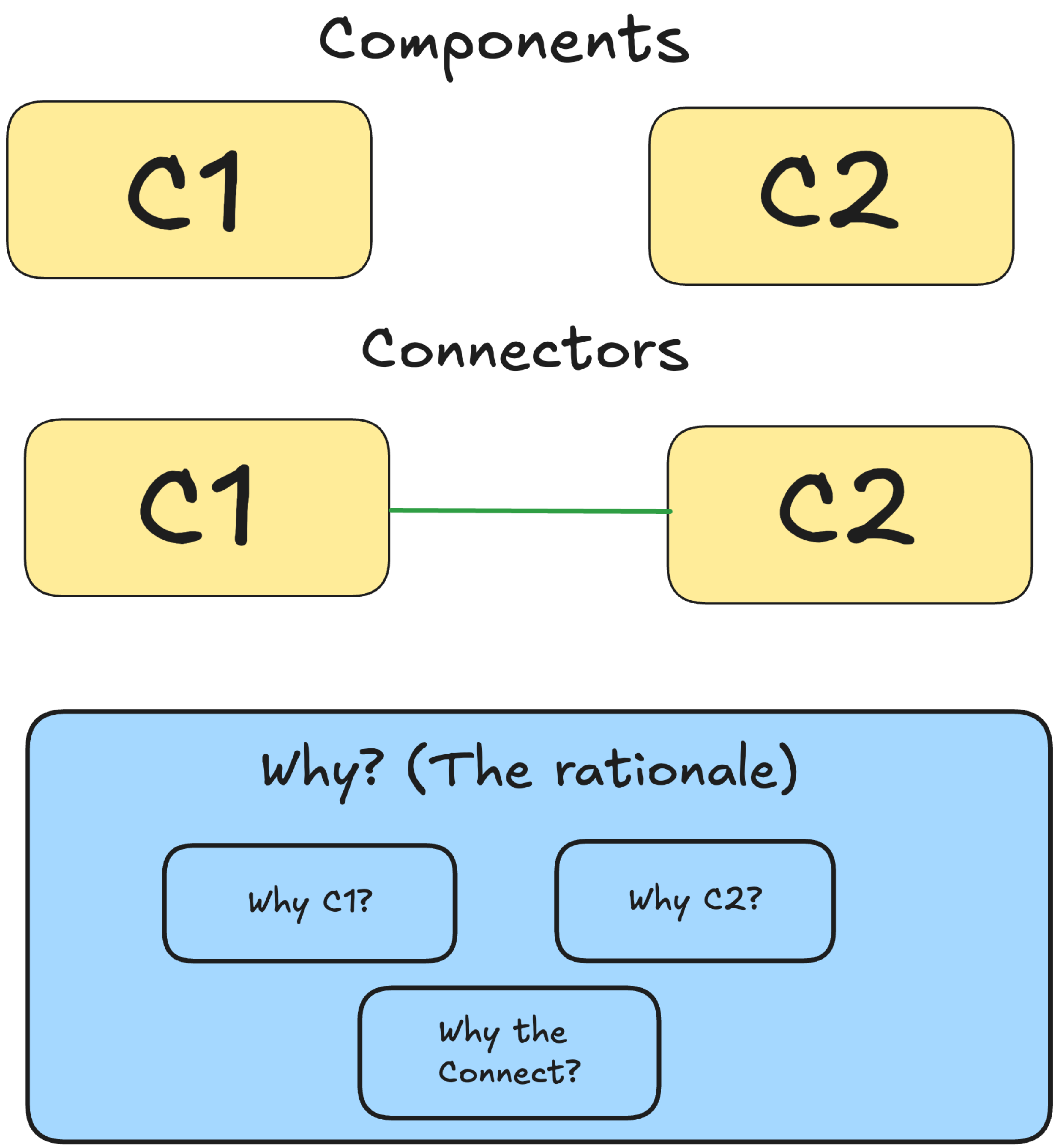
2D Plan

3D Plan

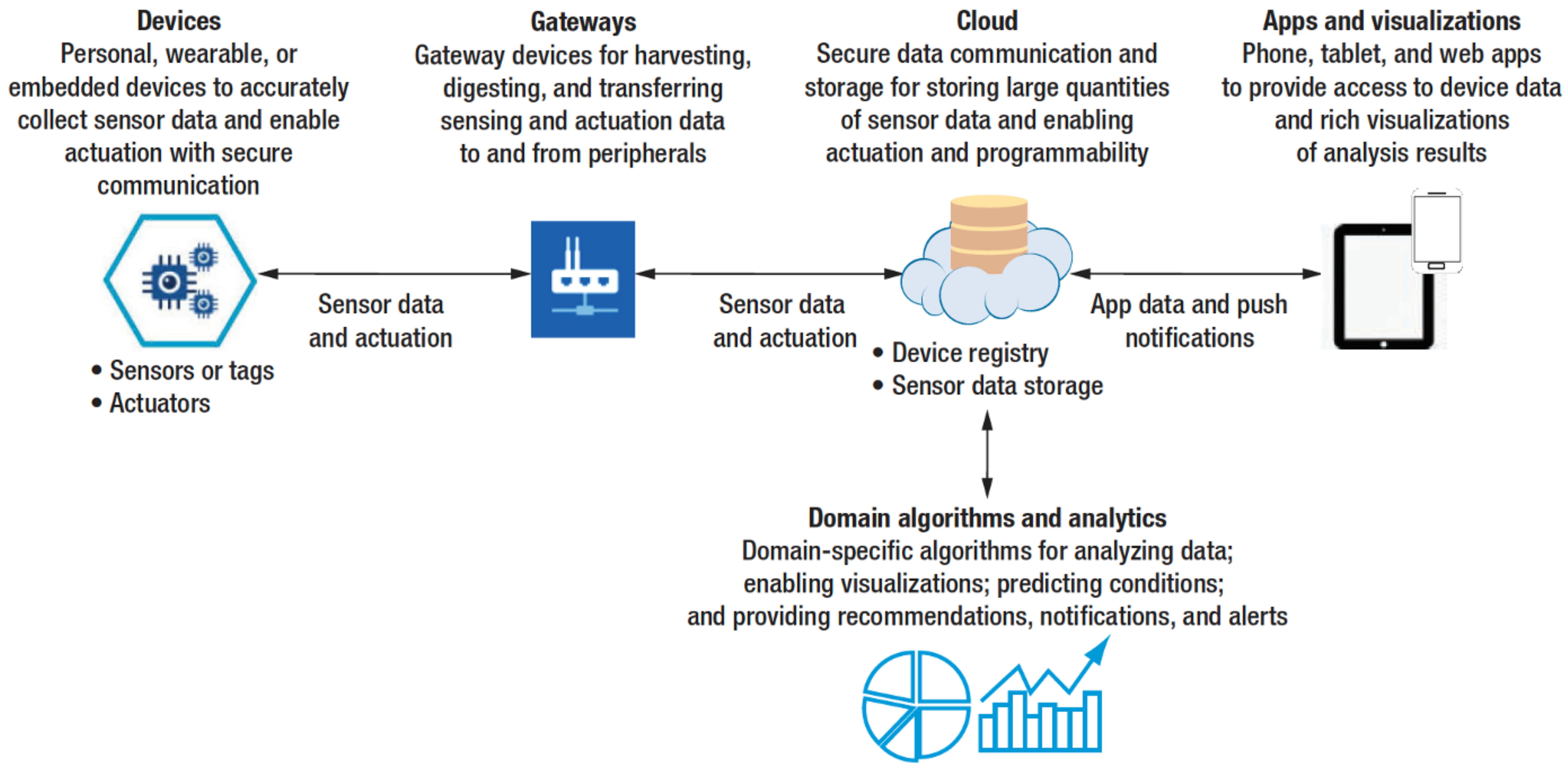
Image Source: Google Images

What is Software Architecture?





IoT Architecture: At a High Level



A. Taivalsaari and T. Mikkonen, "**A roadmap to the programmable world: software challenges in the iot era,**" IEEE Software, vol. 34, no. 1, pp. 72–80, 2017.

Architecting IoT systems: The case of Uffizi Gallery

- 3rd most visited museum in Italy in 2018
- More than 2.200.000 visitors per year
- Limited contemporary access forsafety reasons
- Waiting time can go upto **4 hours!!**

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Scenarios on Free Sundays

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Florence's Uffizi Galleries to reduce four-hour queues to five minutes with new ticketing algorithm

THE FLORENTINE | NEWS | THINGS TO DO | COMMUNITY | ART + CULTURE | FOOD + WINE | SHOP | CLASSIFIEDS

ART + CULTURE

An Uffizi without lineups

A new algorithm developed by Henry Muccini at the University of L'Aquila resolves the historic problem of the Uffizi l

BY Alexandra Korey | Share | bookmark

Fri 26 Oct 2018 2:22 PM

As soon as he was nominated as **director of the Uffizi Galleries, Eike Schmidt** said he hoped to address some of the museum's biggest problems. Speaking on TV, he said that by the end of his mandate he hoped to eliminate the historically long lineups, unquestionably the source of much frustration for visitors to the city who often found themselves spending three good hours under the portico for their chance to see paintings by Botticelli, Leonardo and Michelangelo amongst others.

1. https://www.traveller.com.au/uffizi-gallery-florence-queuing-times-cut-from-hours-to-minutes-with-new-system-h16fx
2. https://www.telegraph.co.uk/news/2018/10/09/florences-uffizi-galleries-reduce-four-hour-queues-five-minutes/
3. https://www.theflorentine.net/2018/10/26/uffizi-lineup/

Key Requirements and Concerns

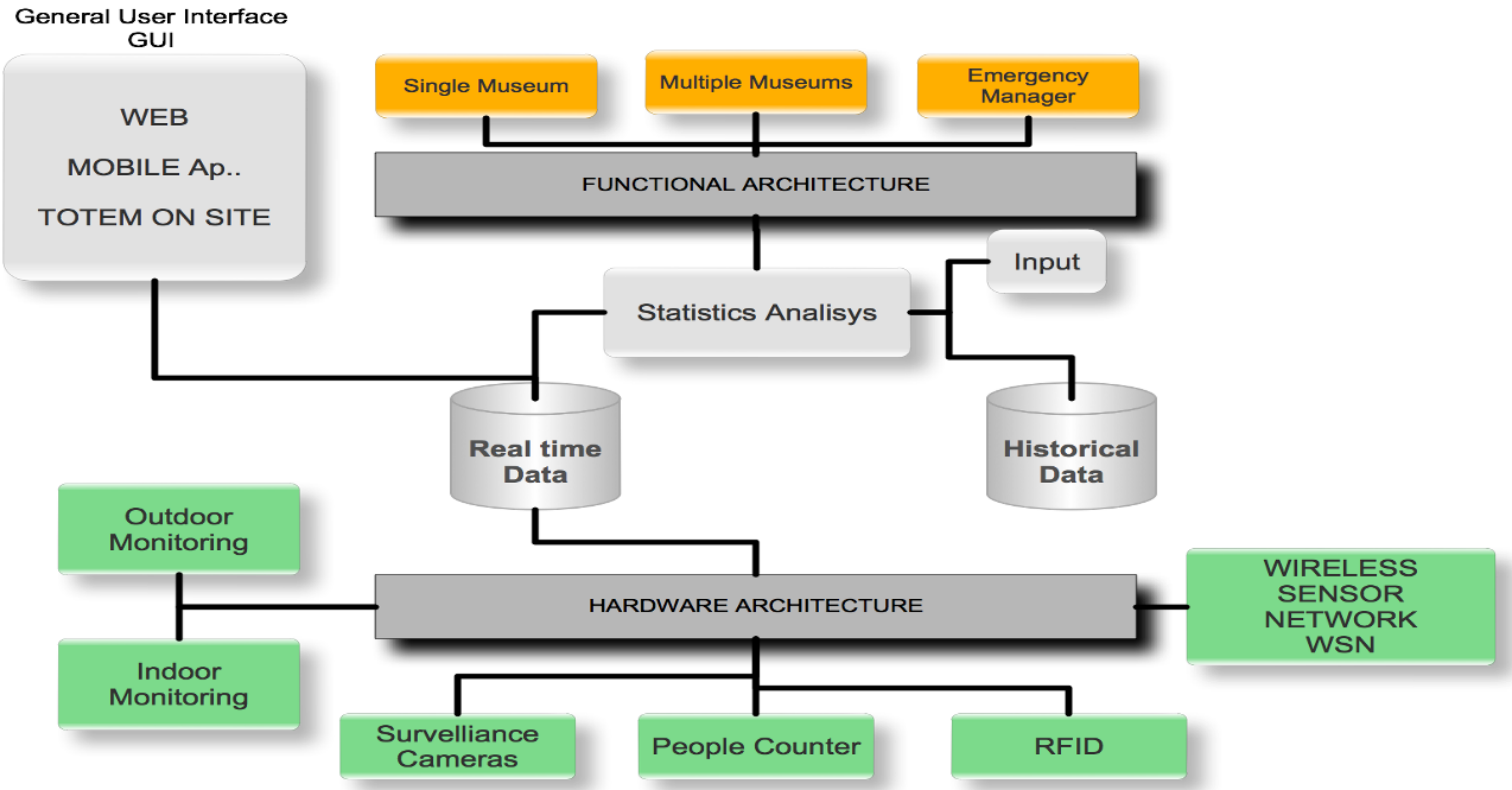
Indoor and Outdoor Crowd Management

- Reduce Waiting time to get in!
- Optimize internal human flow
- Multi-museum Load Balancing

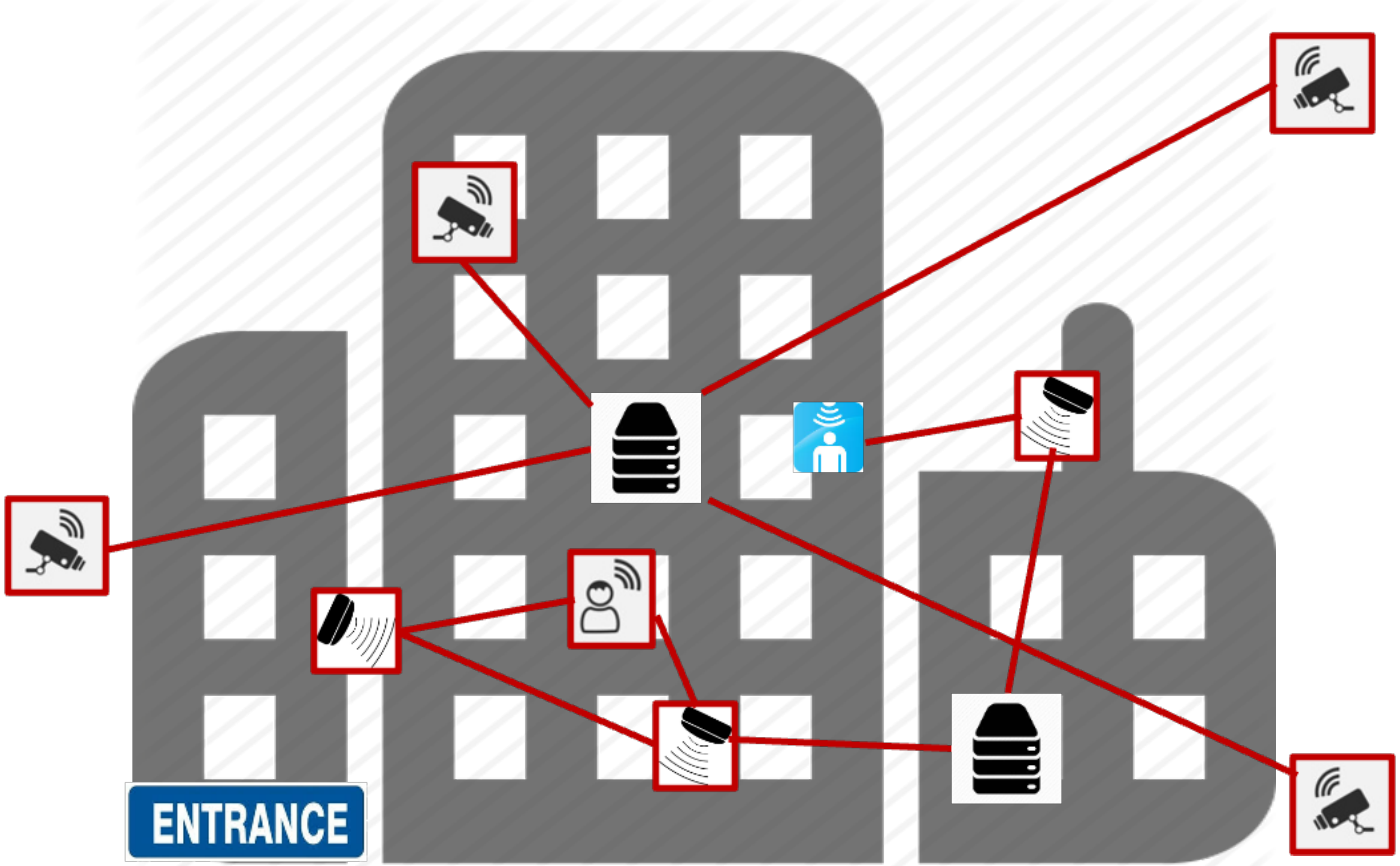
Key Constraints

- Slots divided into 15 minutes - Max capacity limit
- Extremely high arrival rate - 2000 people in 60 mins
- Visitors may stay as long as they wish - 45 mins to 4 hours
- Limited ICT infrastructure - No wifi

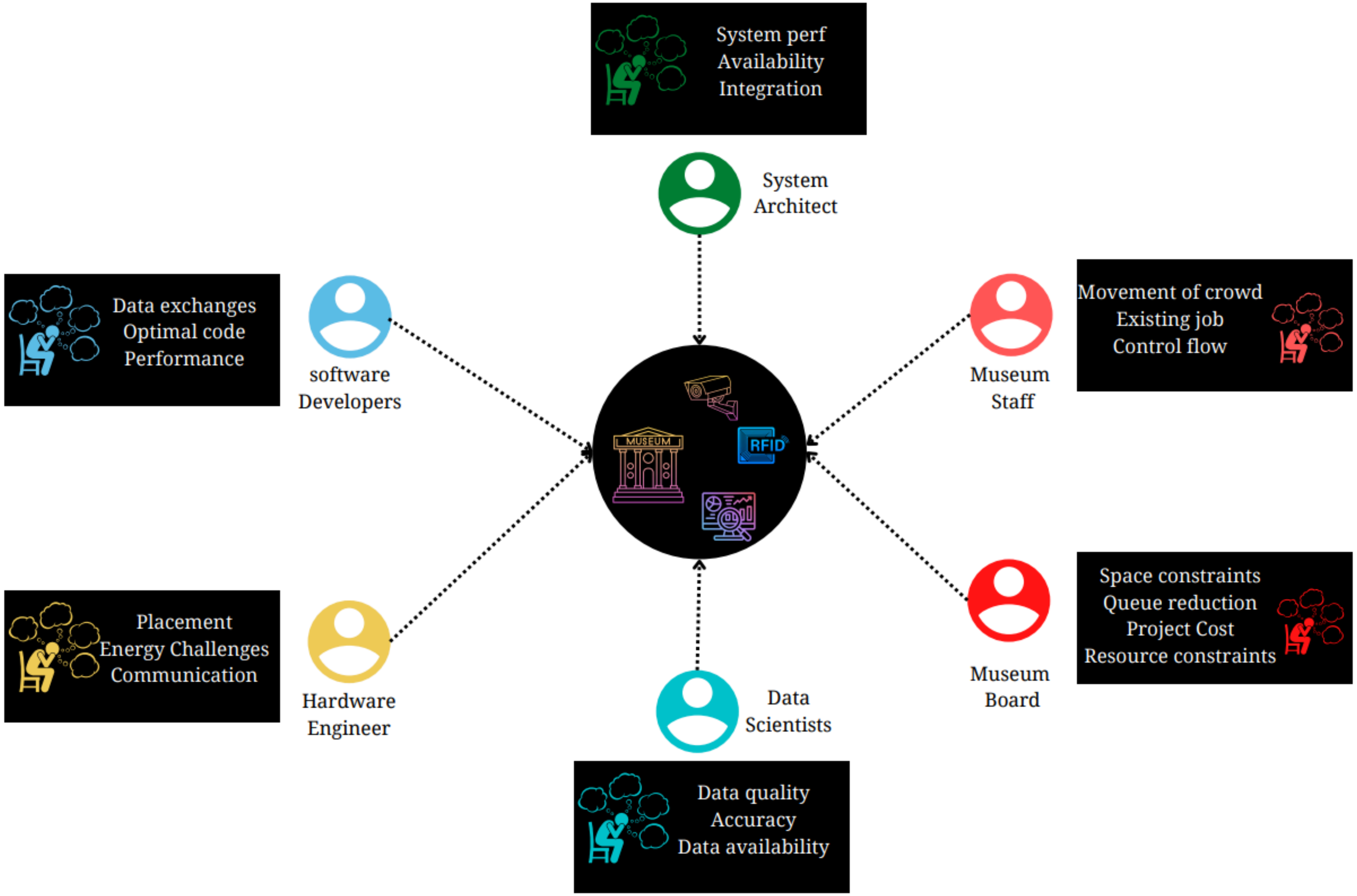
What can be a high level architecture?



Overall: Technical



Overall: Conceptual

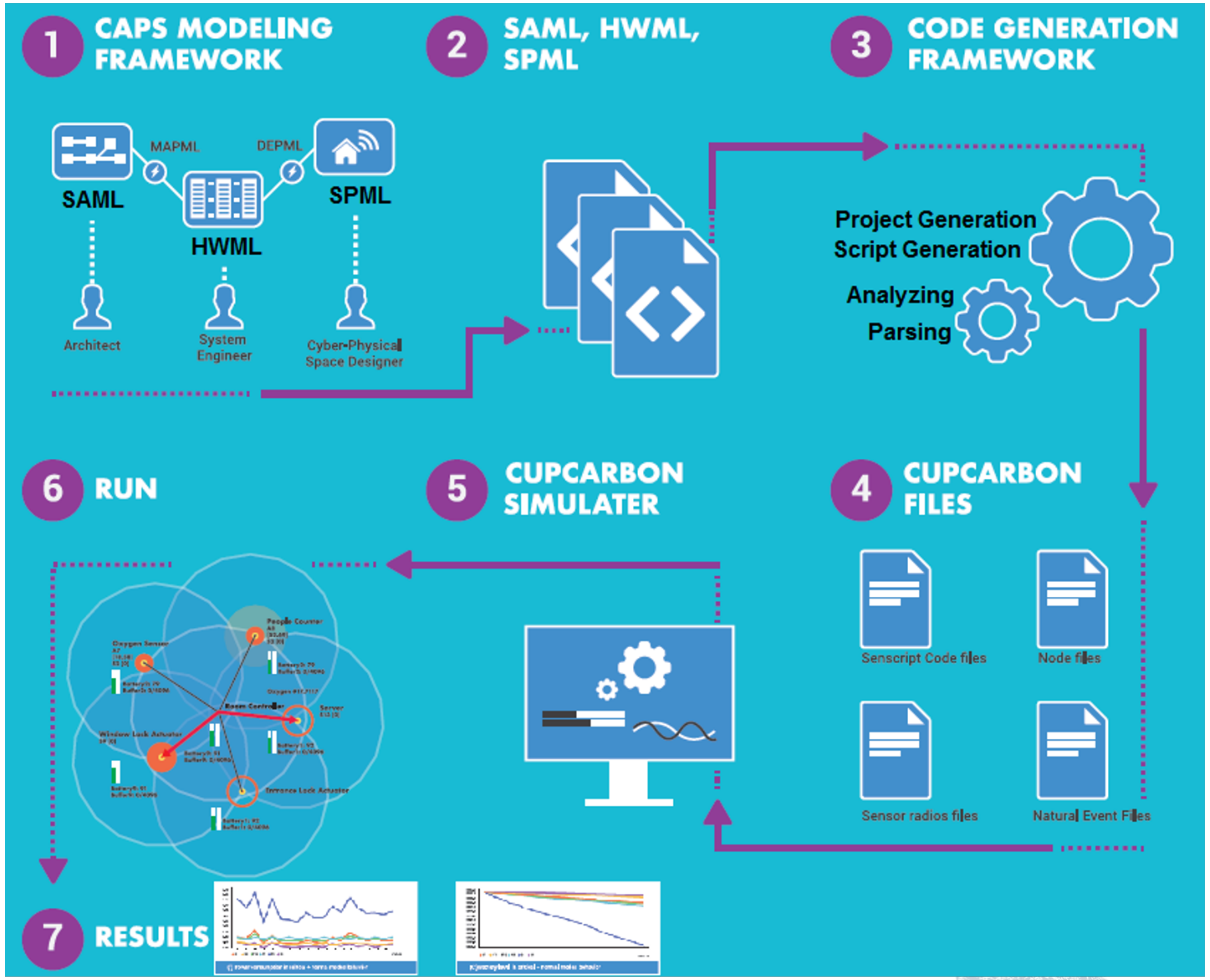


Overall: Decision Making

- Which solution is more e.g. **energy** efficient?
- Which architecture decisions may limit the **amount of data** created, transferred, and analyzed?
- What kind of **communication protocol** to be used?
- Which communication **topology** to use?
- What **technology stack** to be used?
- ....

Using Modeling as the Backbone: The CAPS Perspective

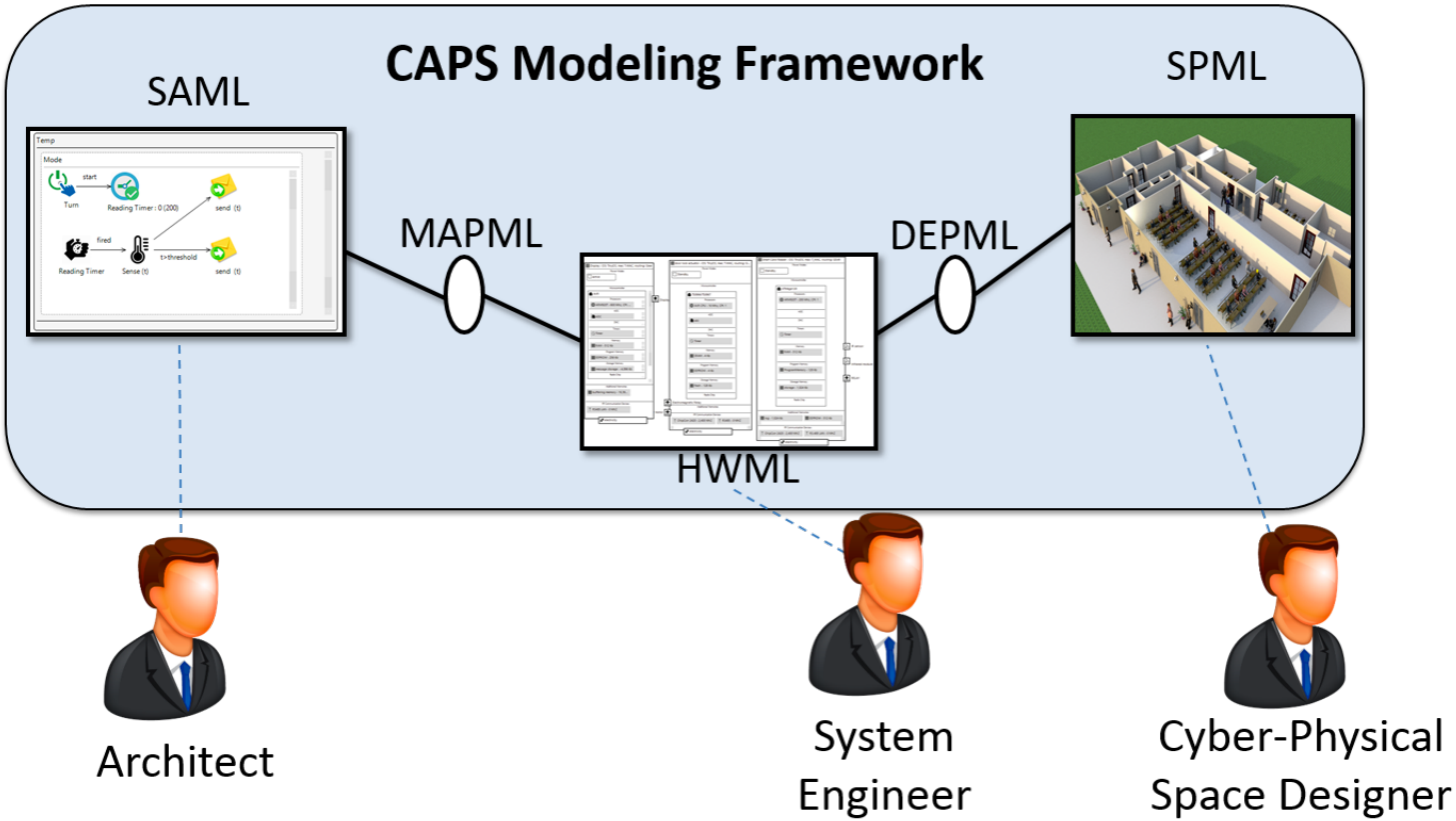
- Create model of the system (low/no code)
- Generate simulatable instance of the system
  - Data for simulation can be from real-world
  - CupCarbon is a simulator for smart city applications
- Once verification is done, generate code



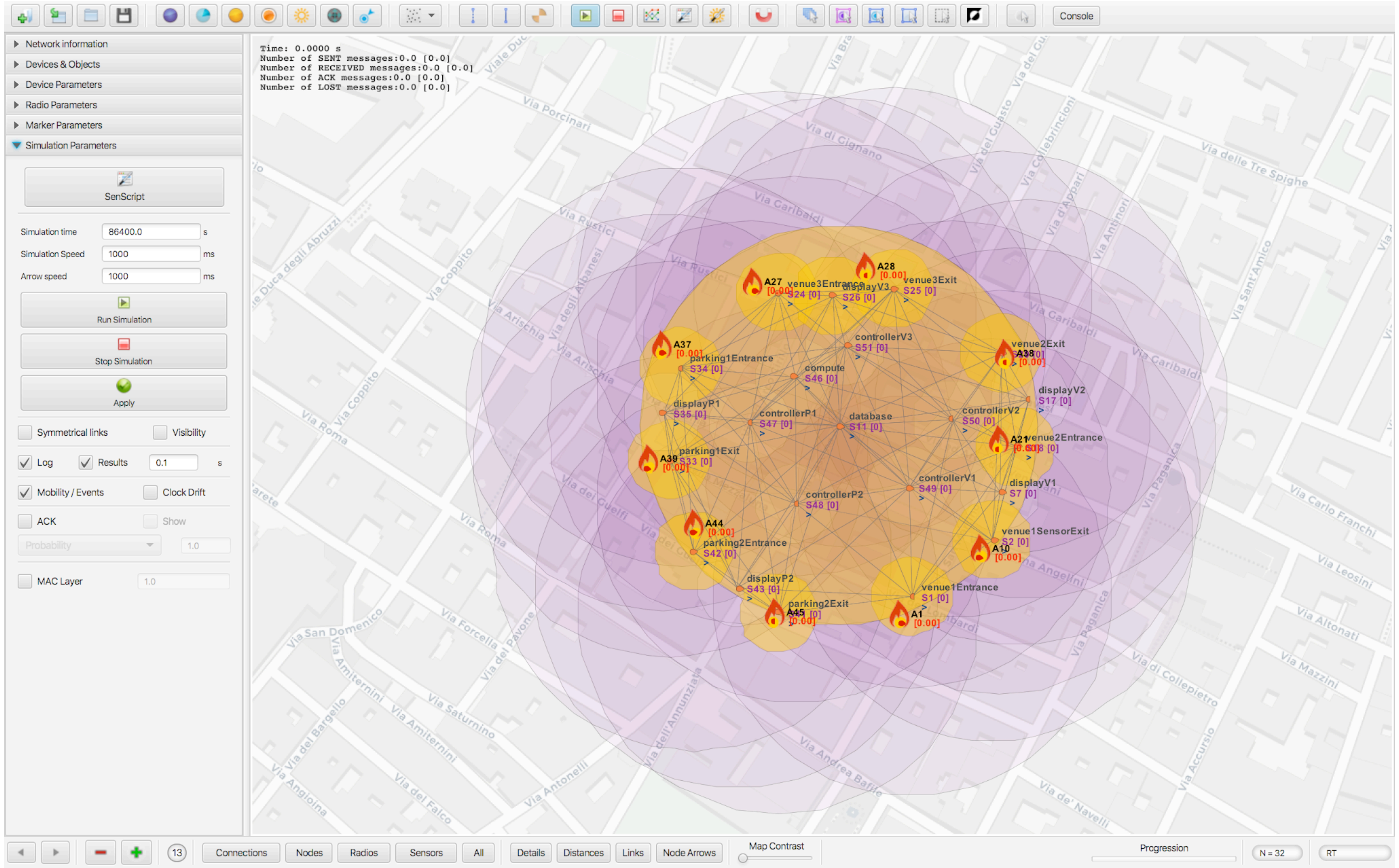
https://cupcarbon.com

What Kind of Modeling?

Multi-view Modeling Framework - IEEE 42010



View from CupCarbon Simulator



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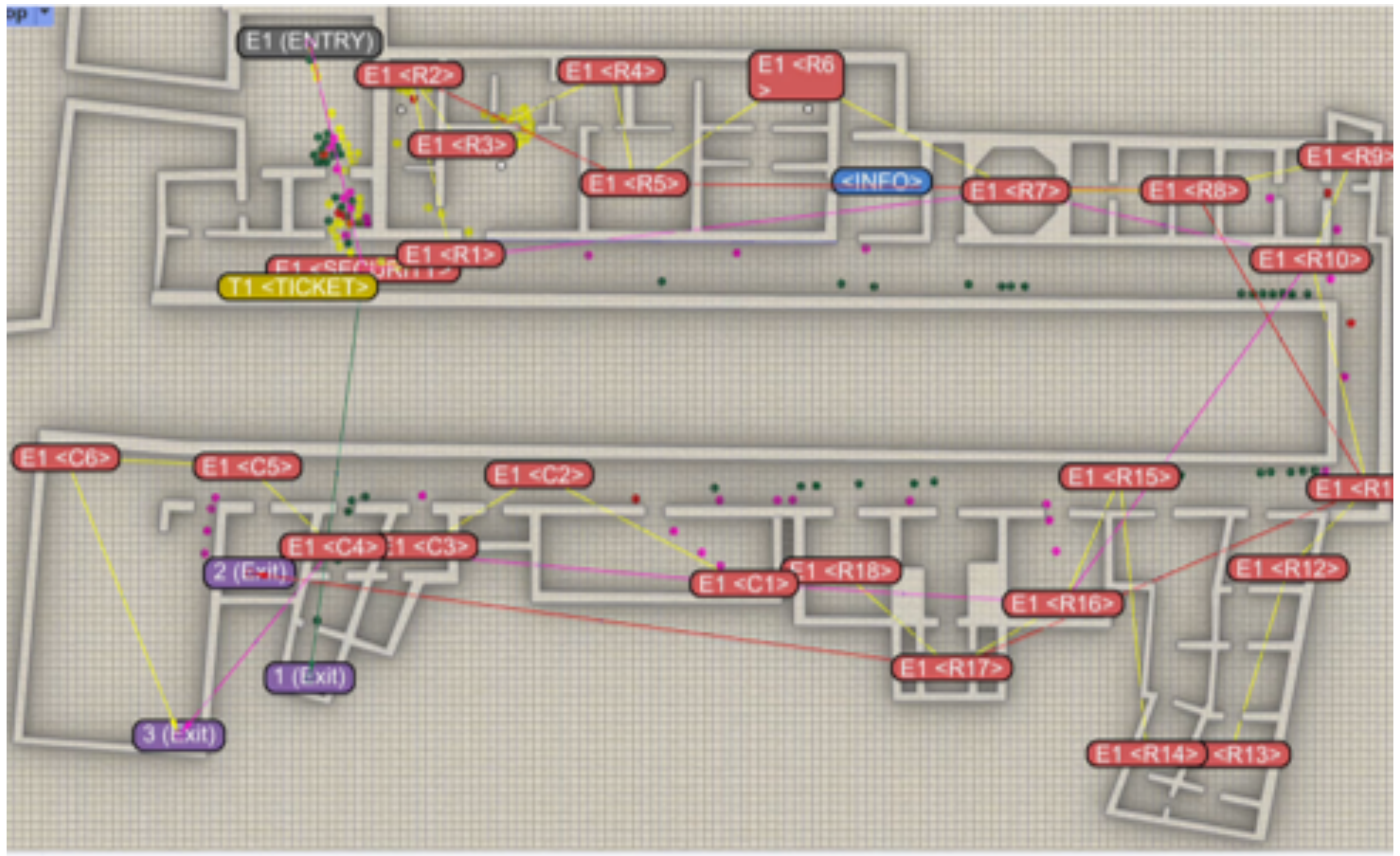
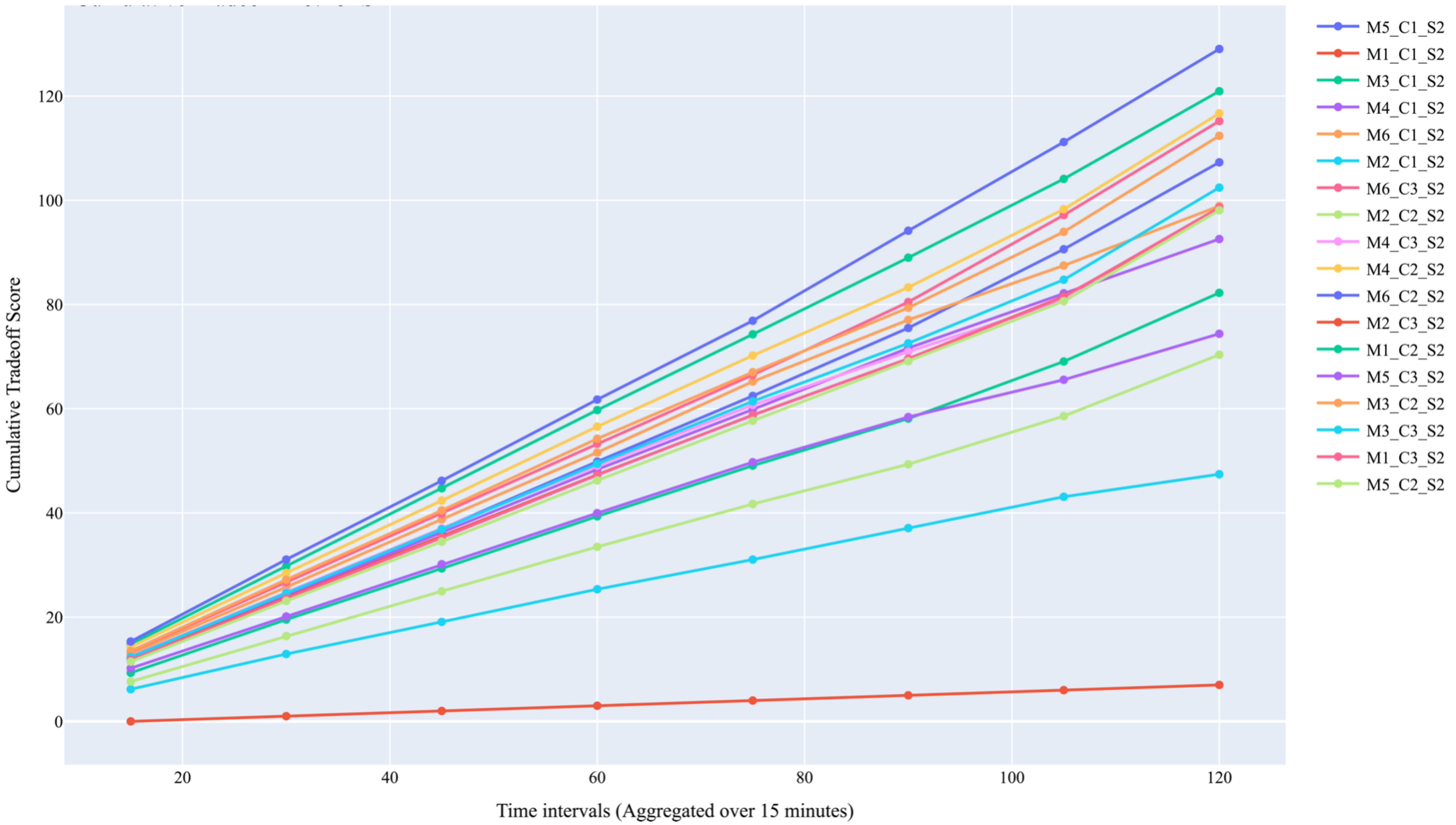
Consider Human Behaviour



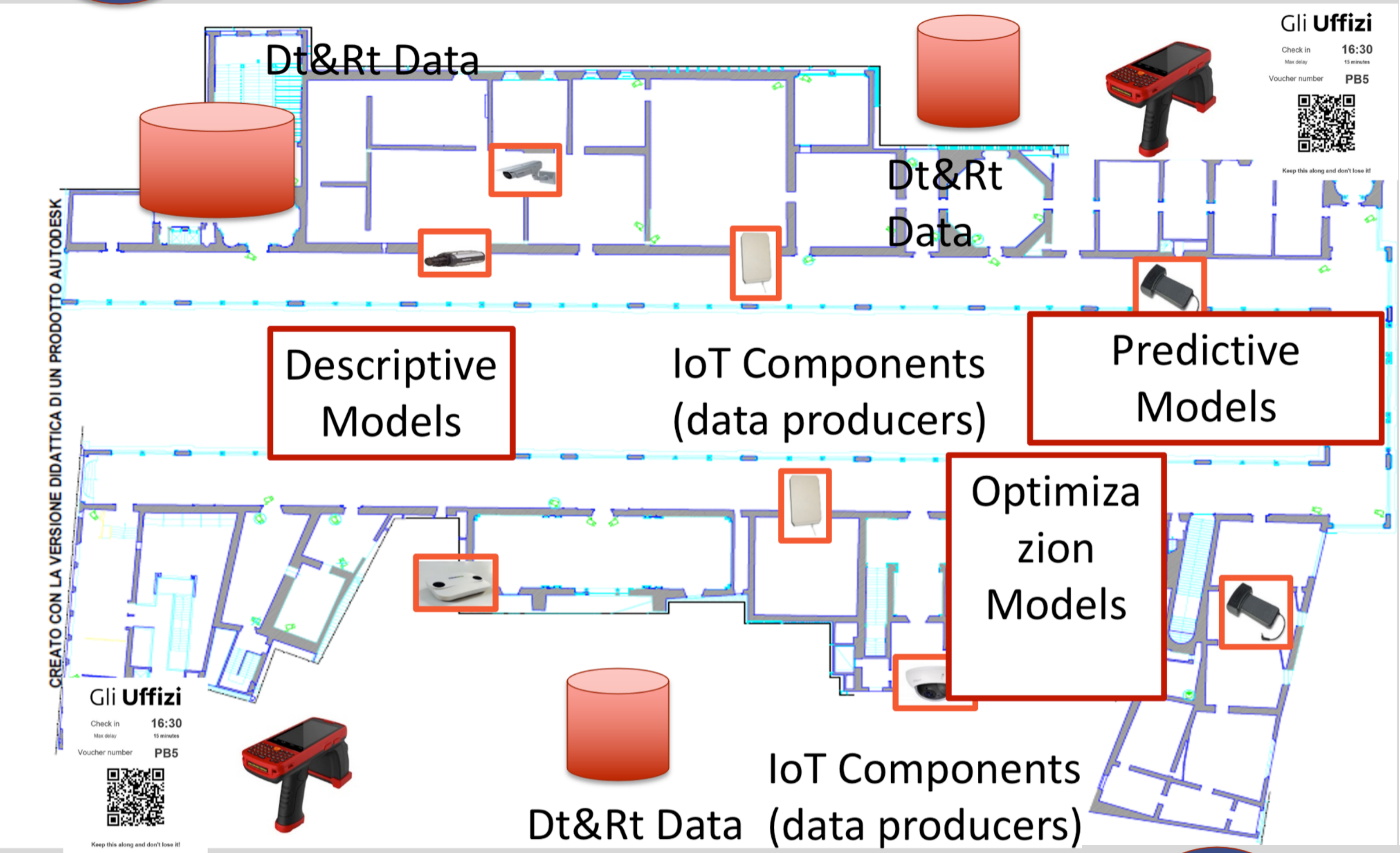
Human behaviour simulation in PedSim



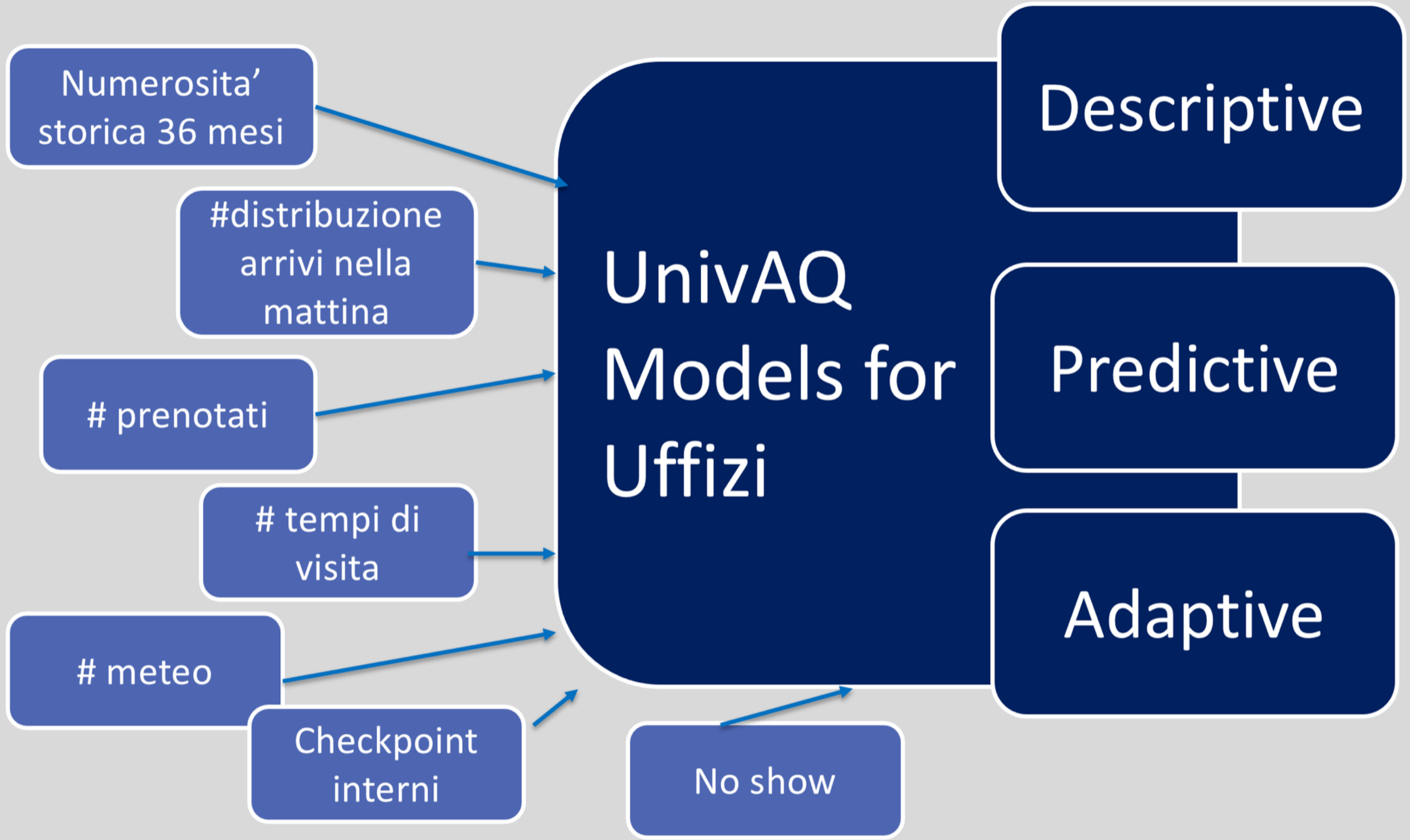
Which model and configuration to be used?

Abughazala, Moamin B., Mahyar T. Moghaddam, Henry Muccini, and Karthik Vaidhyanathan. **Human behavior-oriented architectural design** In *European Conference on Software Architecture*, pp. 134-143. Springer, Cham, 2021.

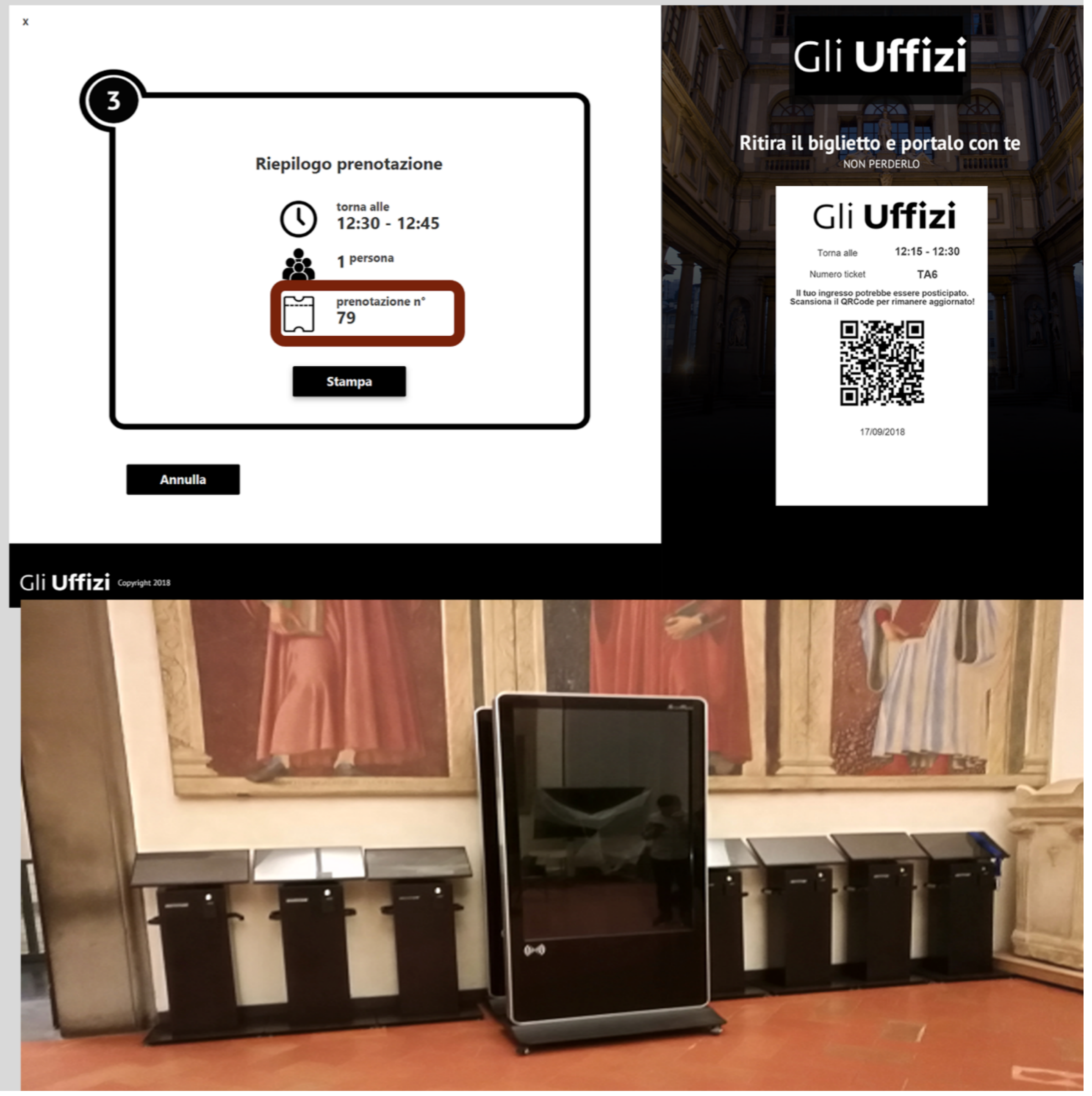
1 Infrastructure (big data)



2 Models



3 Human Factors



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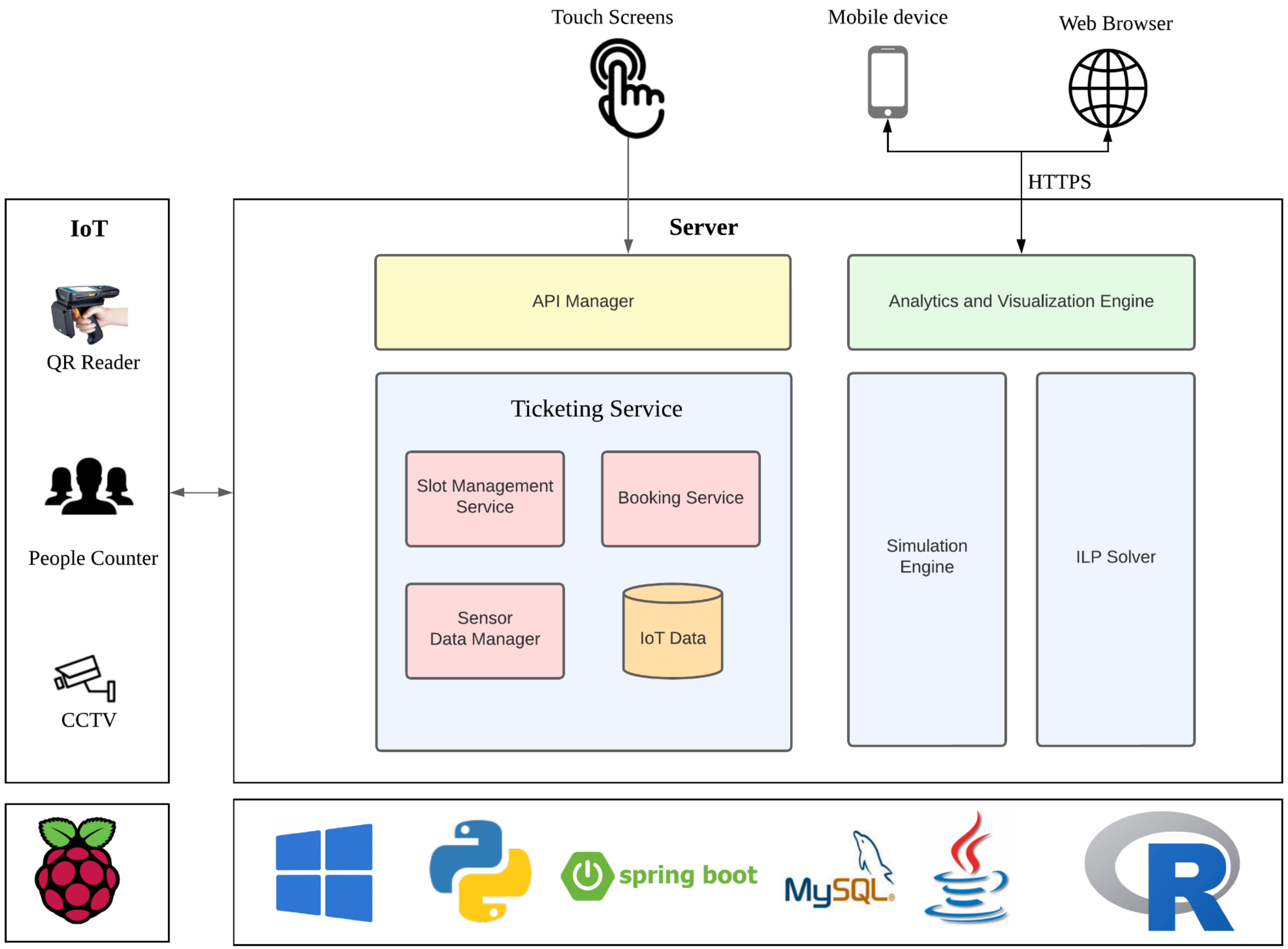
High-level Technical Architecture



Glimpse from the VASARI Project

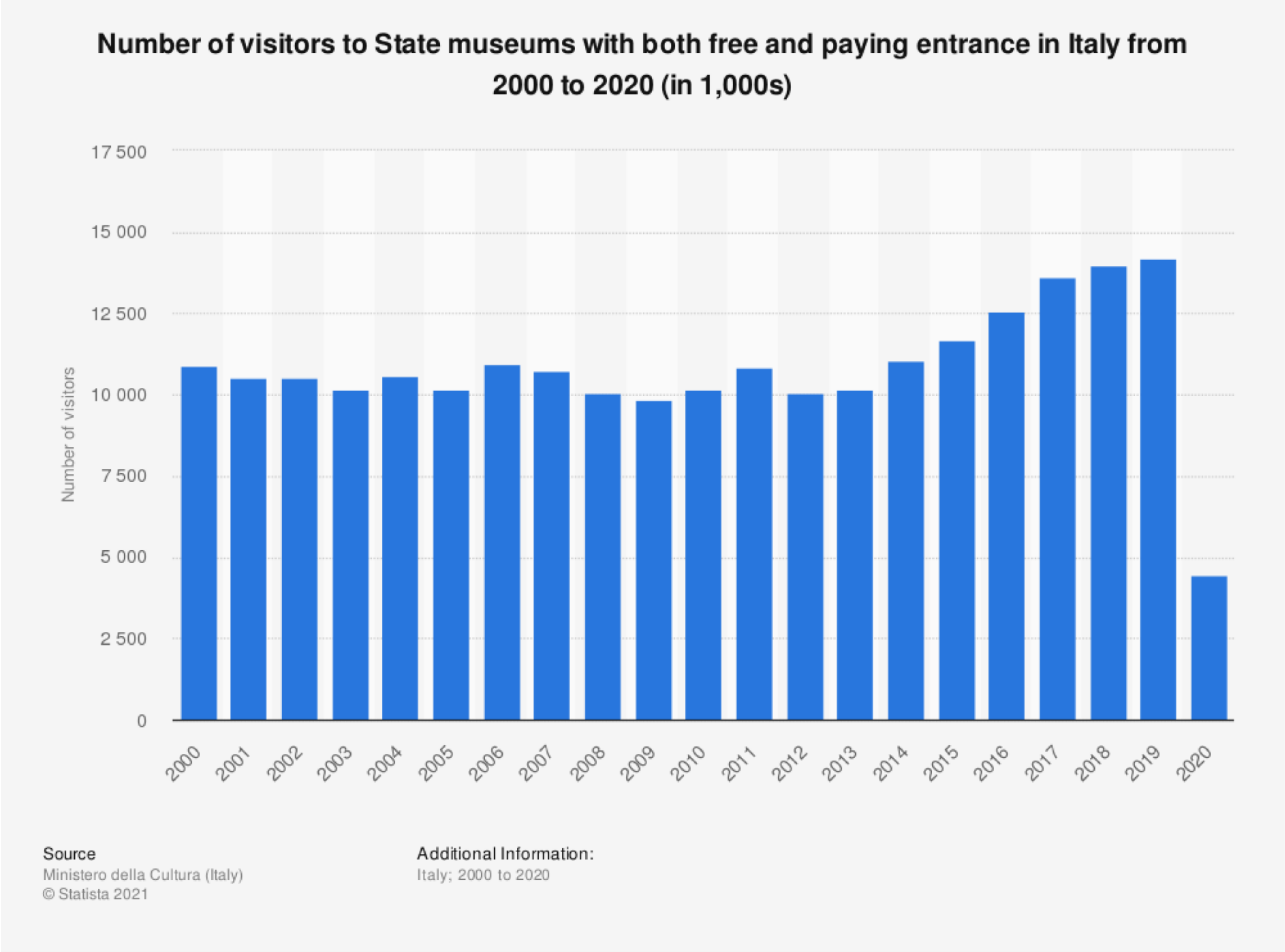


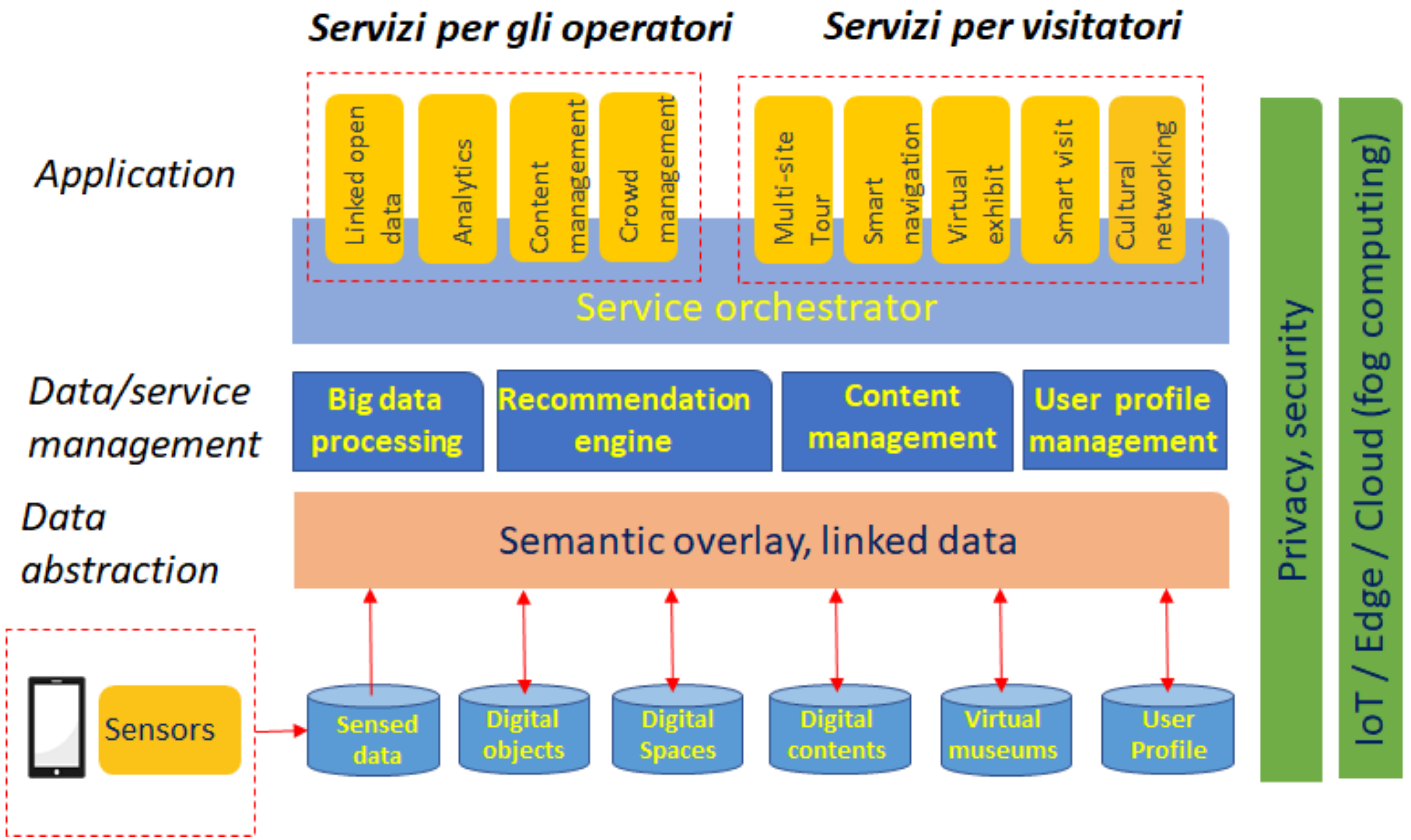
Image source: statista.com

Image source: mithsonianmag.com

Improving **visiting experience** is gaining more and more importance

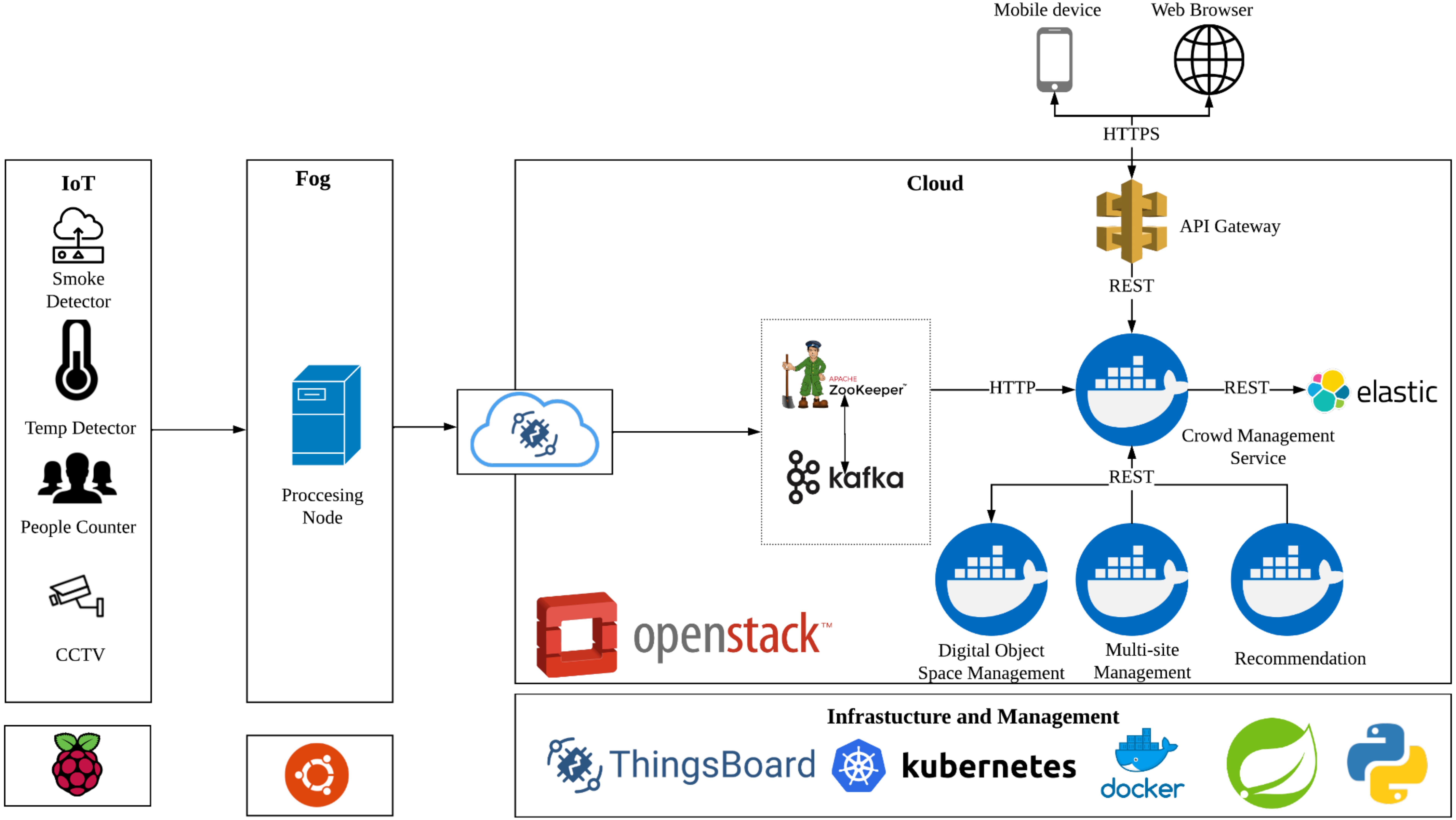
The VASARI Project

- 6 Million Euro project with 18 partners - Academia and Industry
- Providing visitors with immersive inclusive & contextualized experience
- Technologies: IoT, Fog, Cloud, Microservices Big data, ML, VR and AR



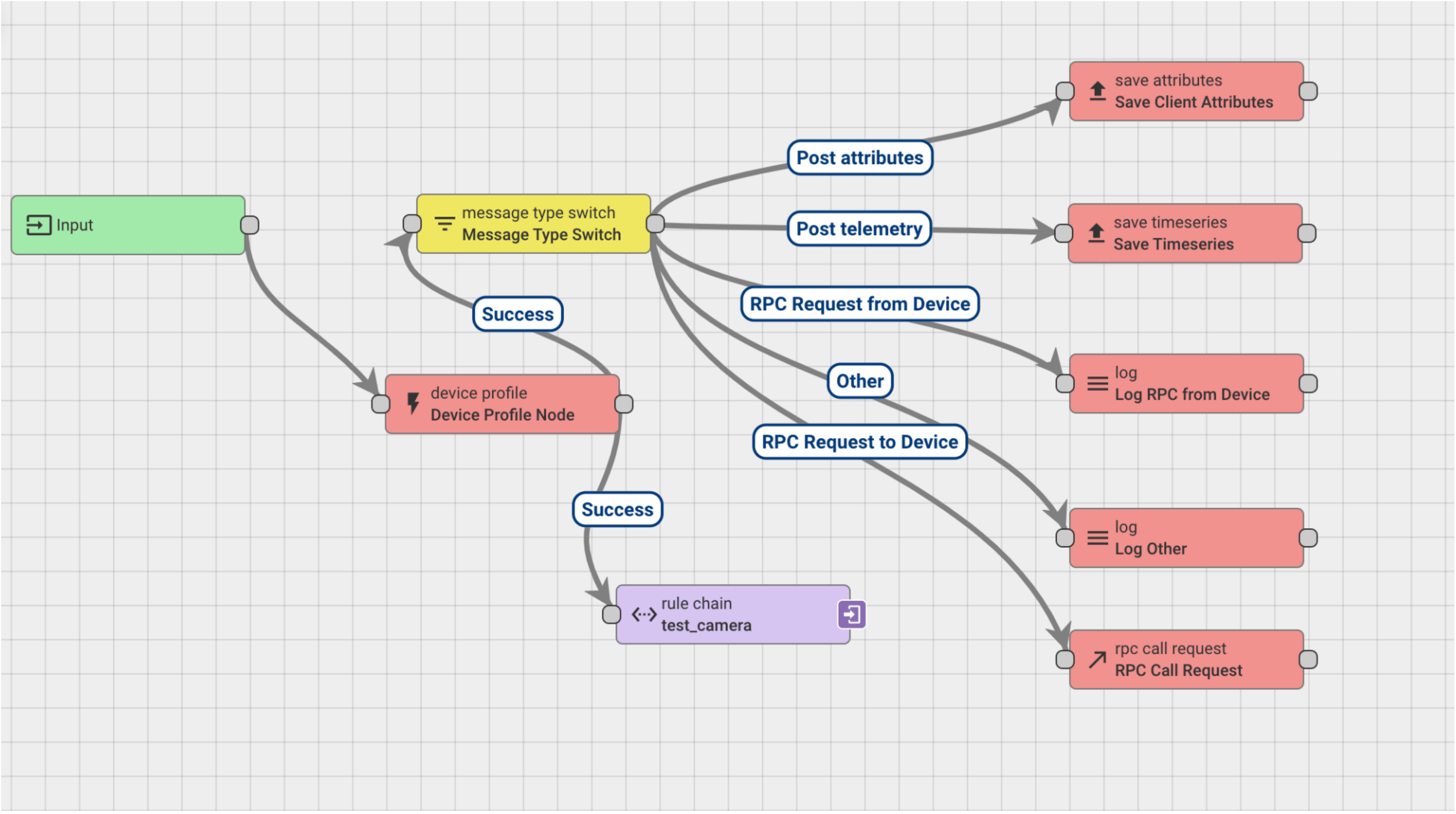
https://www.vasariartexperience.it/

View of a Subsystem in VASARI



https://www.vasariartexperience.it/progetto/

Implementation View



Challenges in IoT Systems

The Smart City Living Lab Case@IIITH

Weather

Air Quality

Water Quality and Quantity

Energy Monitoring

Smart House

Crowd Monitoring

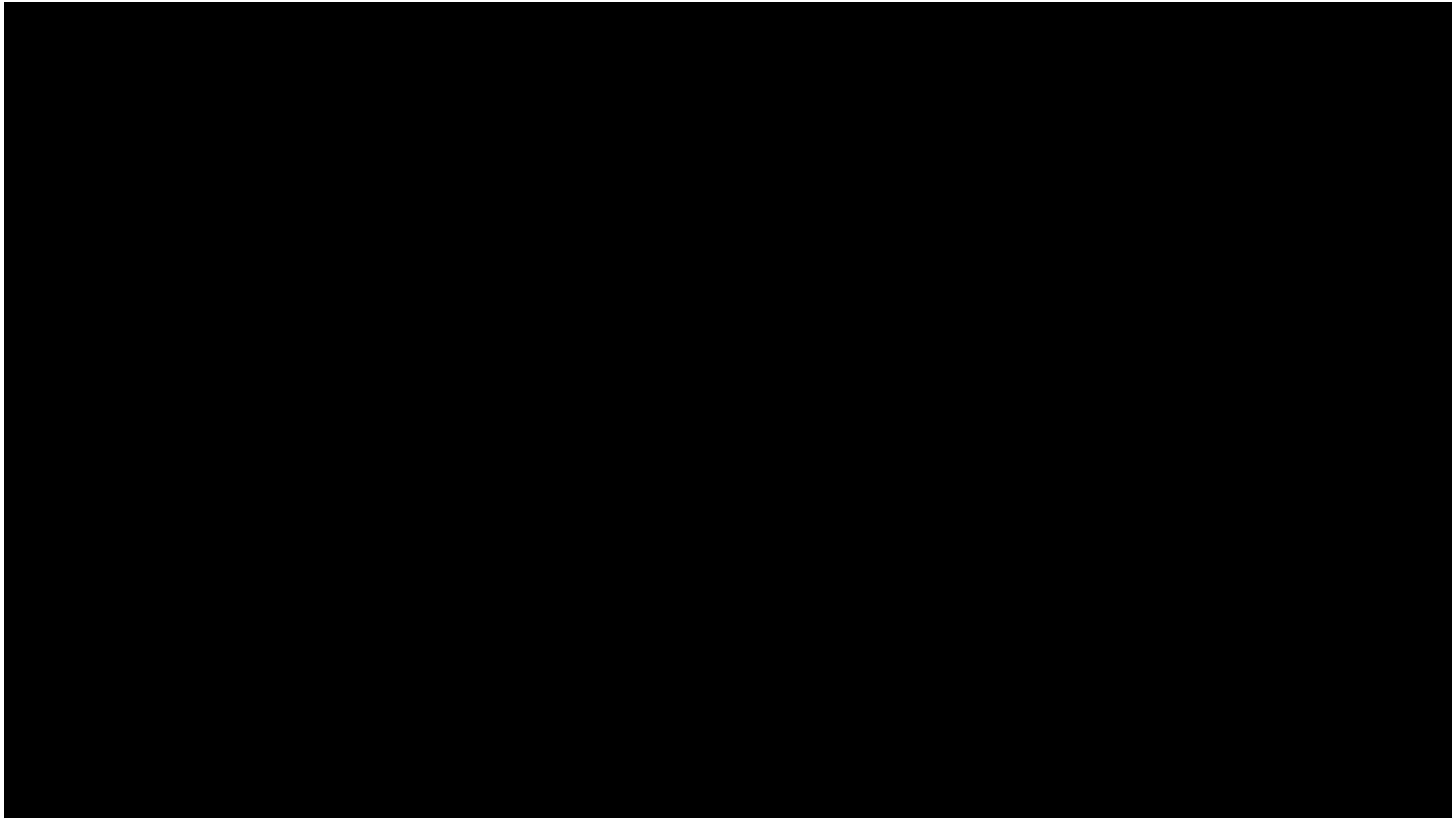
Smart Lamp

350+ IoT nodes deployed across the campus

Some Key Challenges

- Each Sensor nodes may use different protocol – MQTT, HTTP, COAP,..
- Support for different communication channels – Wifi, 4G, LoRA, etc.
- Nodes may fail - Hardware issues or software issues
- Adding new node should be a hassle-free process
- Near-real time visualizations, data also needs to be sent to multiple stakeholders

The need for an Interop Framework



onem2m.org

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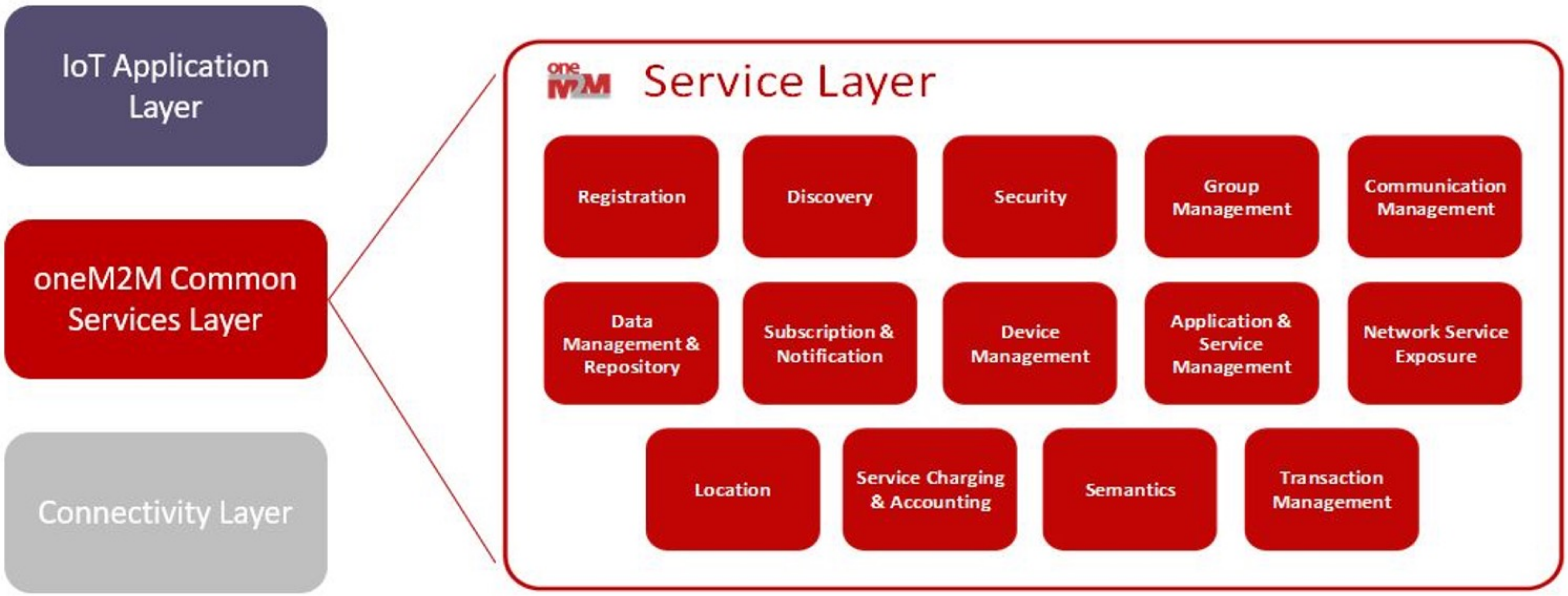
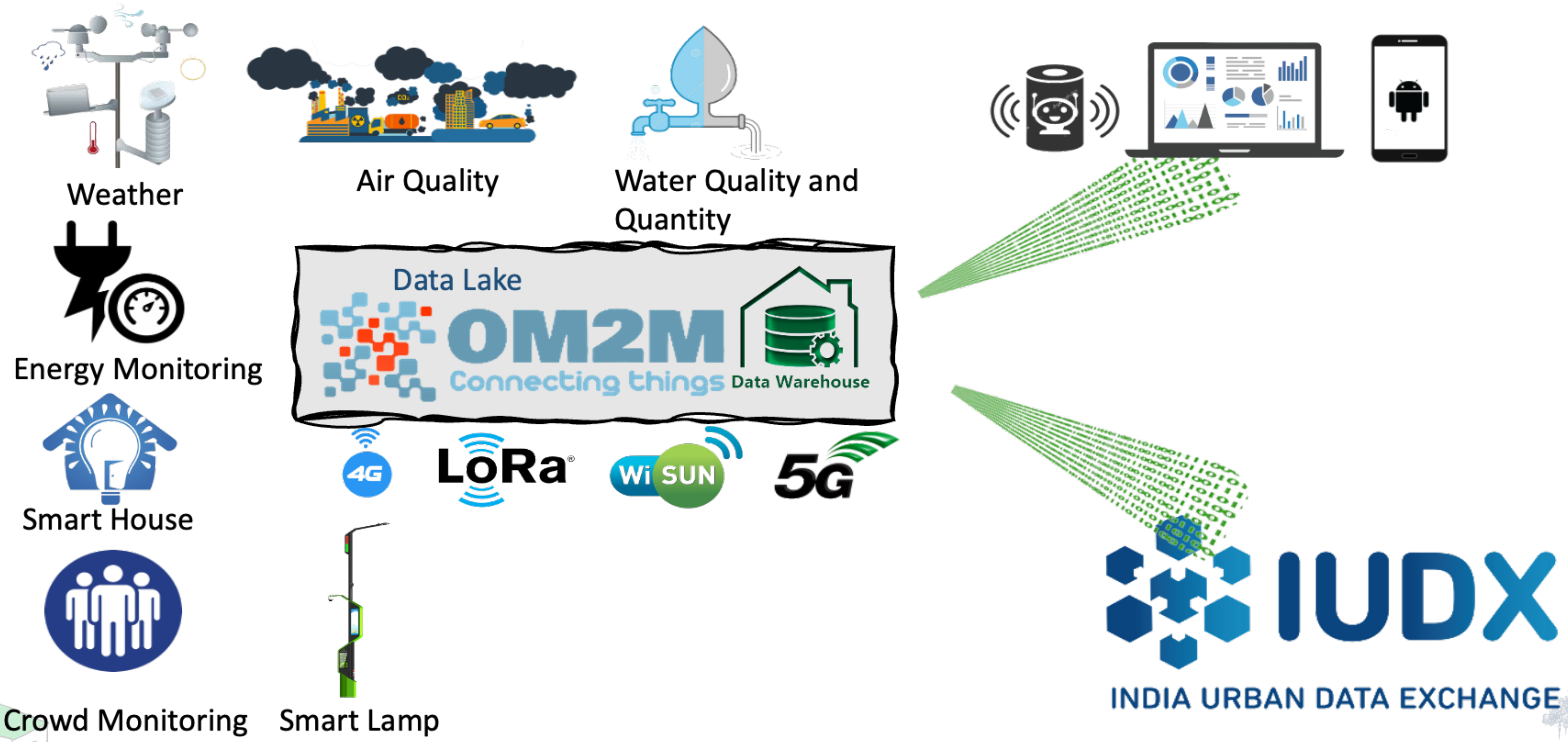
The OneM2M Standard



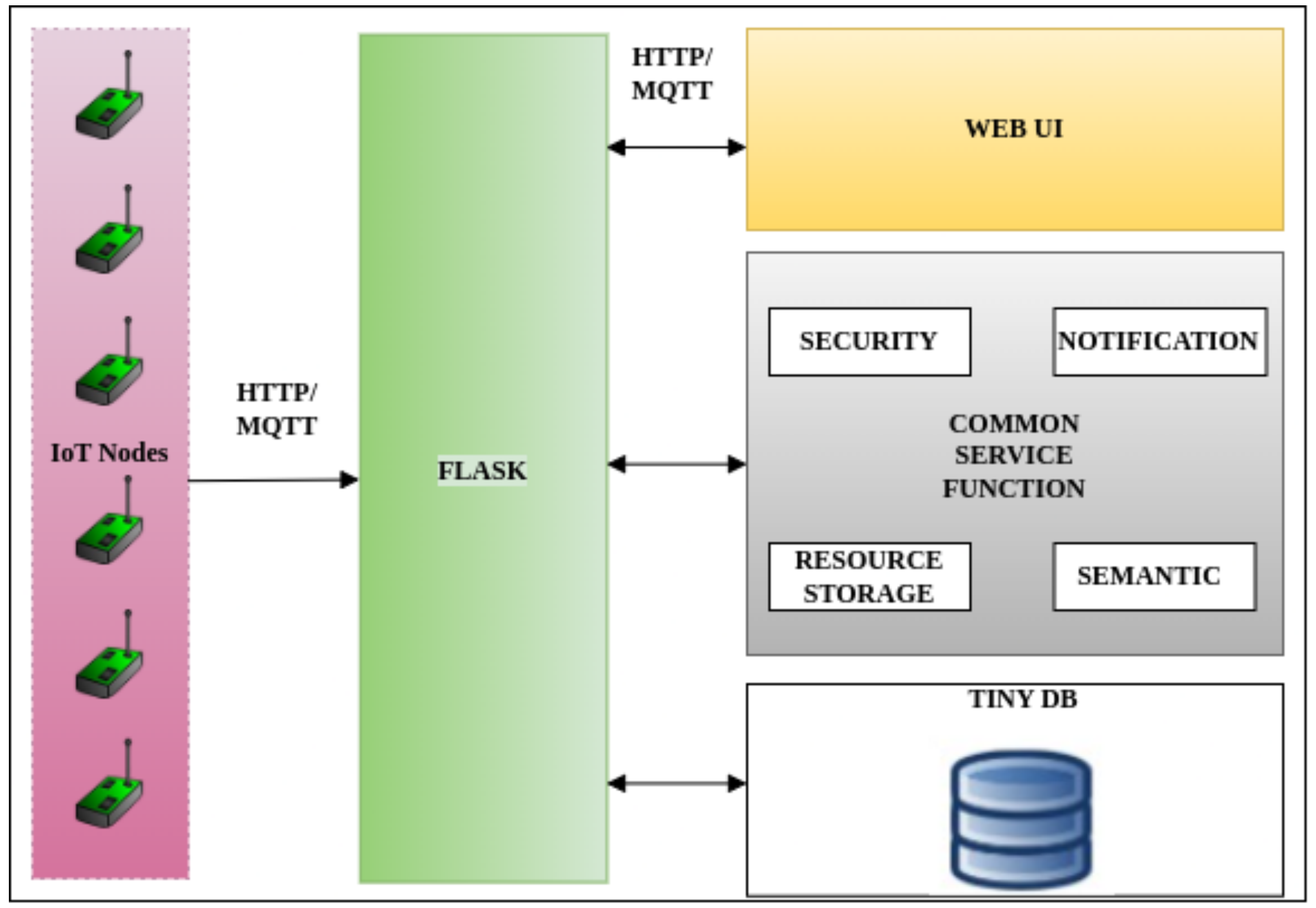
Standard defined and maintained by body consisting of members from US, Japan, Europe, India, Korea, China, etc

Putting it Together

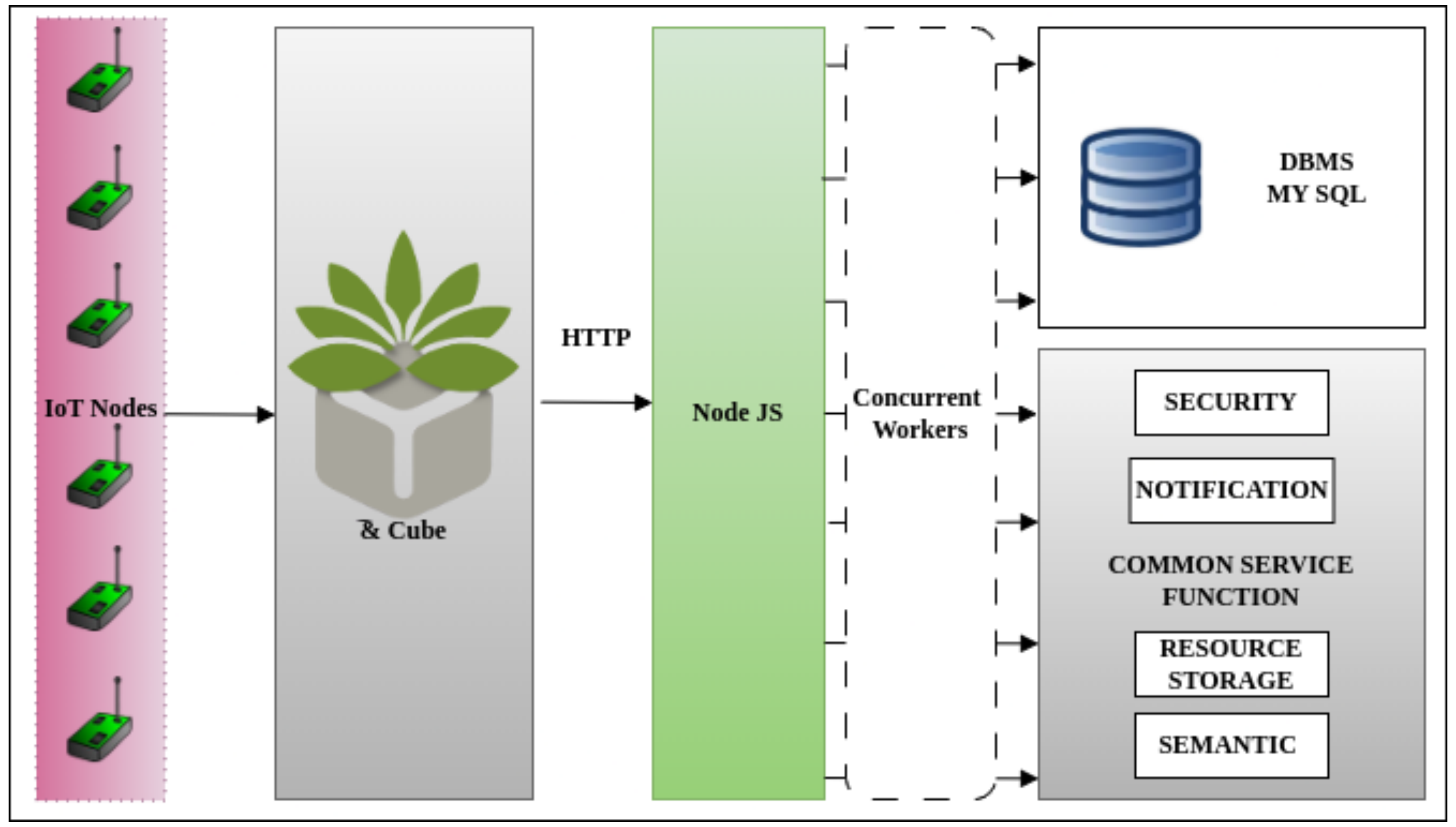


Multiple Providers

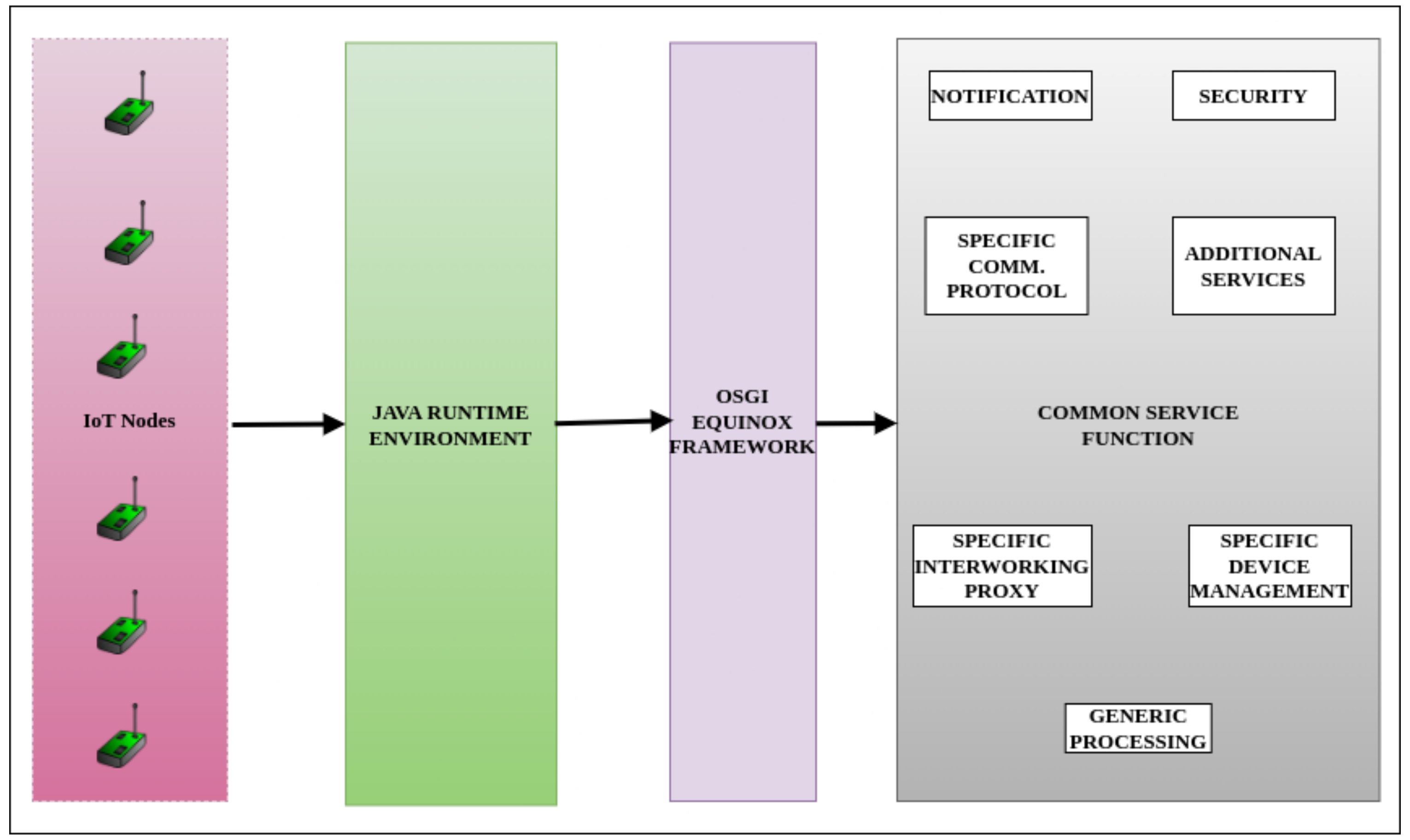
Which to choose?



ACME



Mobius



OM2M

Grounded in Research

- **RQ1:** What are the key characteristics and components of each interoperability architecture based on OneM2M standards?
- **RQ2:** How do different interoperability frameworks compare with respect to metrics such as latency, throughput and resource utilization?
- **RQ3:** What are the scalability and adaptability aspects of each architecture to accommodate large-scale IoT deployments?

Exploratory Study of oneM2M-based Interoperability Architectures for IoT: A Smart City Perspective

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***Abstract*—The advent of the Internet of Things (IoT) has ushered in transformative possibilities for smart cities, with the potential to revolutionize urban living through enhanced connectivity and data-driven decision-making. However, the effective realization of IoT in smart cities hinges upon the seamless interoperability of diverse devices and systems. To address this critical need, the oneM2M standards initiative has emerged as a foundational framework for IoT interoperability. In this research paper, we perform an exploratory analysis of three prominent open-source oneM2M based interoperability systems—Mobius, OM2M, and ACME. We leverage an existing large-scale system provided by our Smart City Living Lab deployed at IIIT Hyderabad, sprawling a 66-acre campus featuring over 370 nodes across eight verticals. We investigate the architectural characteristics of each solution, considering their strengths and limitations in facilitating IoT interoperability. Through this analysis, our paper aims to provide valuable insights for stakeholders seeking to implement IoT interoperability solutions in the context of smart cities. By evaluating the strengths and limitations of Mobius, OM2M, and ACME, we seek to offer guidance for selecting the most suitable solution. Our analysis reveals that the optimal framework choice depends on specific quality constraints: Mobius excels in performance, while ACME offers advantages in ease of setup for smaller-scale implementations.**

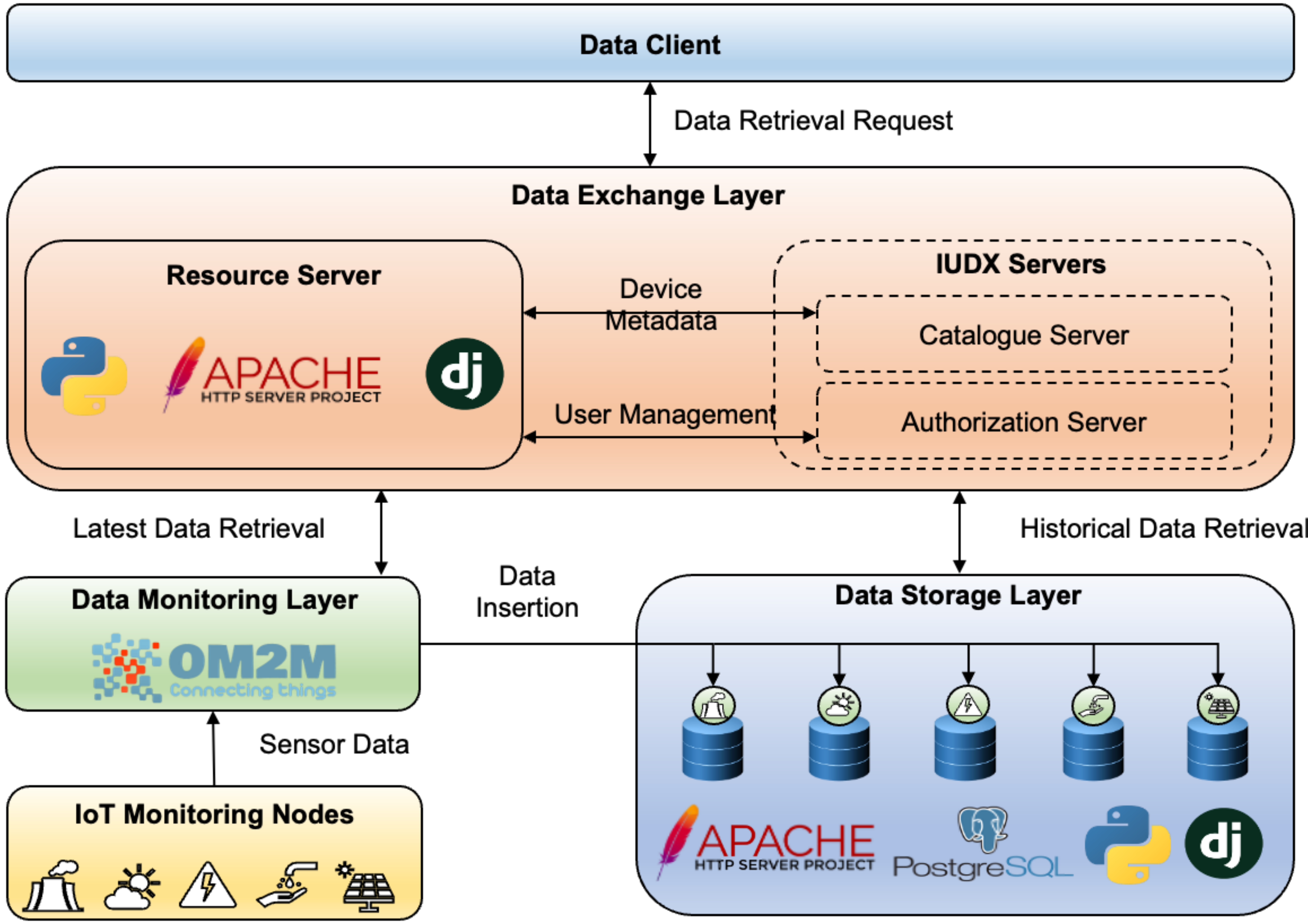
***Index Terms*—interoperability, software architecture, smartcity, data platform architecture, oneM2M, IoT, performance**

and implementation of these interoperability frameworks play a crucial role in determining the overall performance and quality of services in smart city applications. The rapid growth of IoT devices within these smart urban ecosystems underscores the necessity for a robust interoperability layer. Such a layer is indispensable for facilitating the smooth operation of smart city applications by enabling diverse IoT devices and systems to interact without barriers, thereby supporting the scalability, security, and reliability of the smart city network.

Popular interoperability solutions for smart cities include Mobius [4], OM2M [5], and ACME [6]. Each of these solutions, notably open-source, differ in their technology stacks and approaches. We focus on open-source options for transparency and accessibility, enabling stakeholders to make informed decisions when selecting an interoperability solution for their smart city deployment. Real-world deployments are considered key for evaluation. We use a large-scale Smart City Living Lab at IIIT Hyderabad to test these solutions and explore their architectures thoroughly and gain practical insights.

This paper is the first to explore state-of-the-art oneM2M-based interoperability solutions. Our evaluation shows Mobius

Zooming in Further to the Architecture



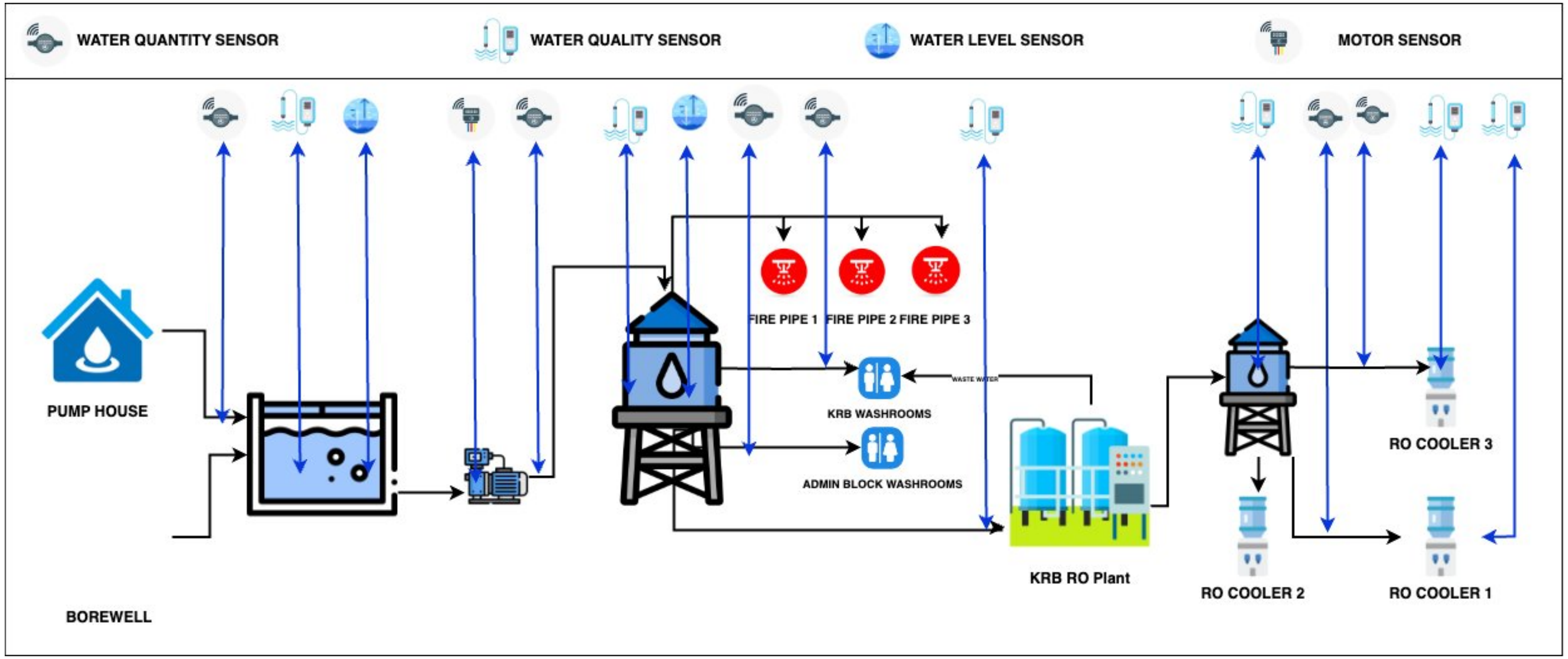
Applying all to solve challenge in Water Domain

Why not use Digital Twins?

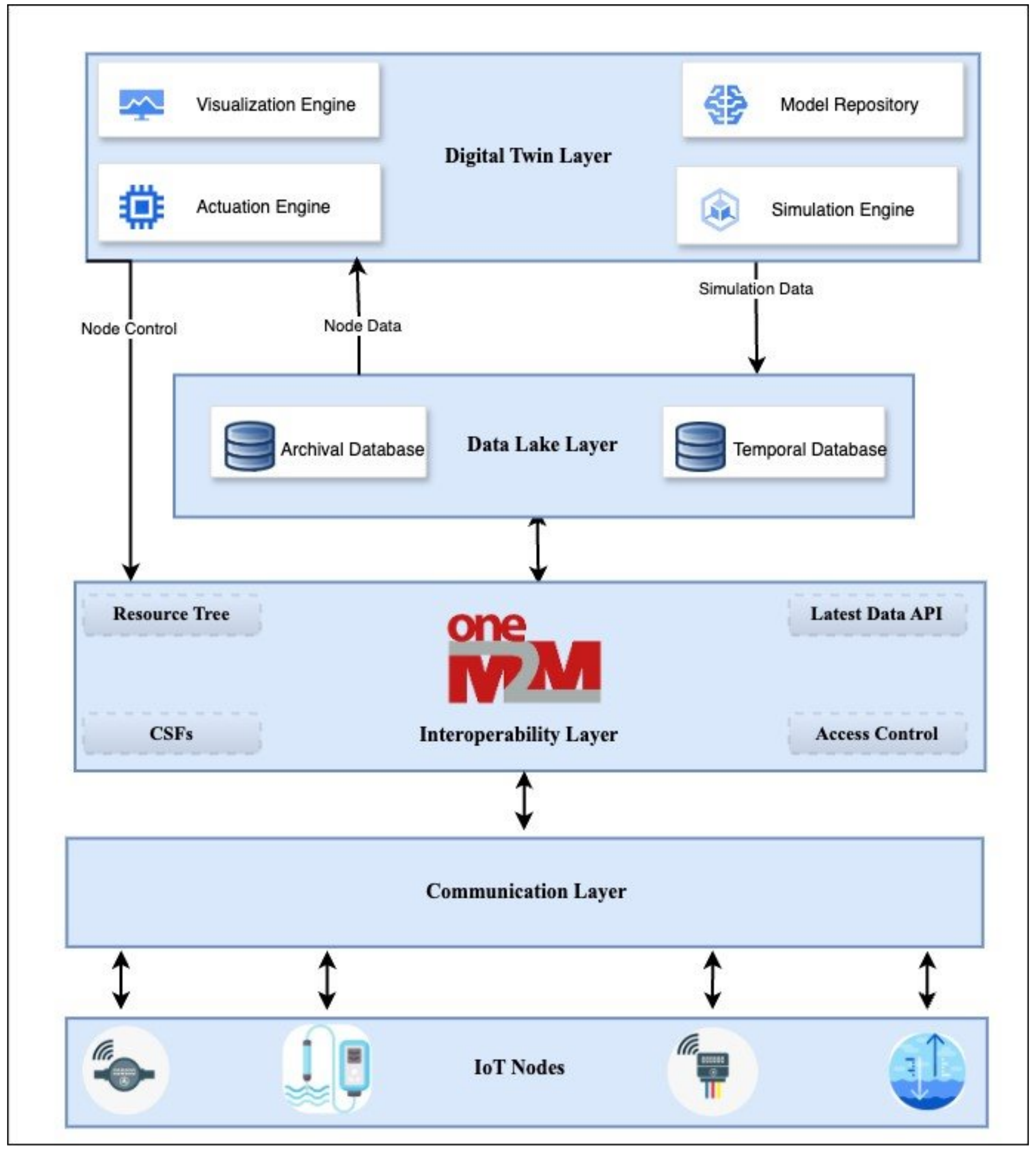
A digital twin is an integrated ***data-driven virtual representation*** *of* ***real-world entities and processes****, with* ***synchronized interaction*** *at a specified frequency and fidelity* - Digital Twin Consortium

- Create a twin of water network: **Visualise, Simulate and Actuate**
- Advantages were clear but:
    - State-of-the art is not established as such
    - Area is new and lot of uncertainties

Development From Scratch



Representation of a live water network



- Meetings with ZF team on gathering feedbacks
- **Scenarios supported:** impurities effect, water leakages, node failure

Digital Twin

Username:

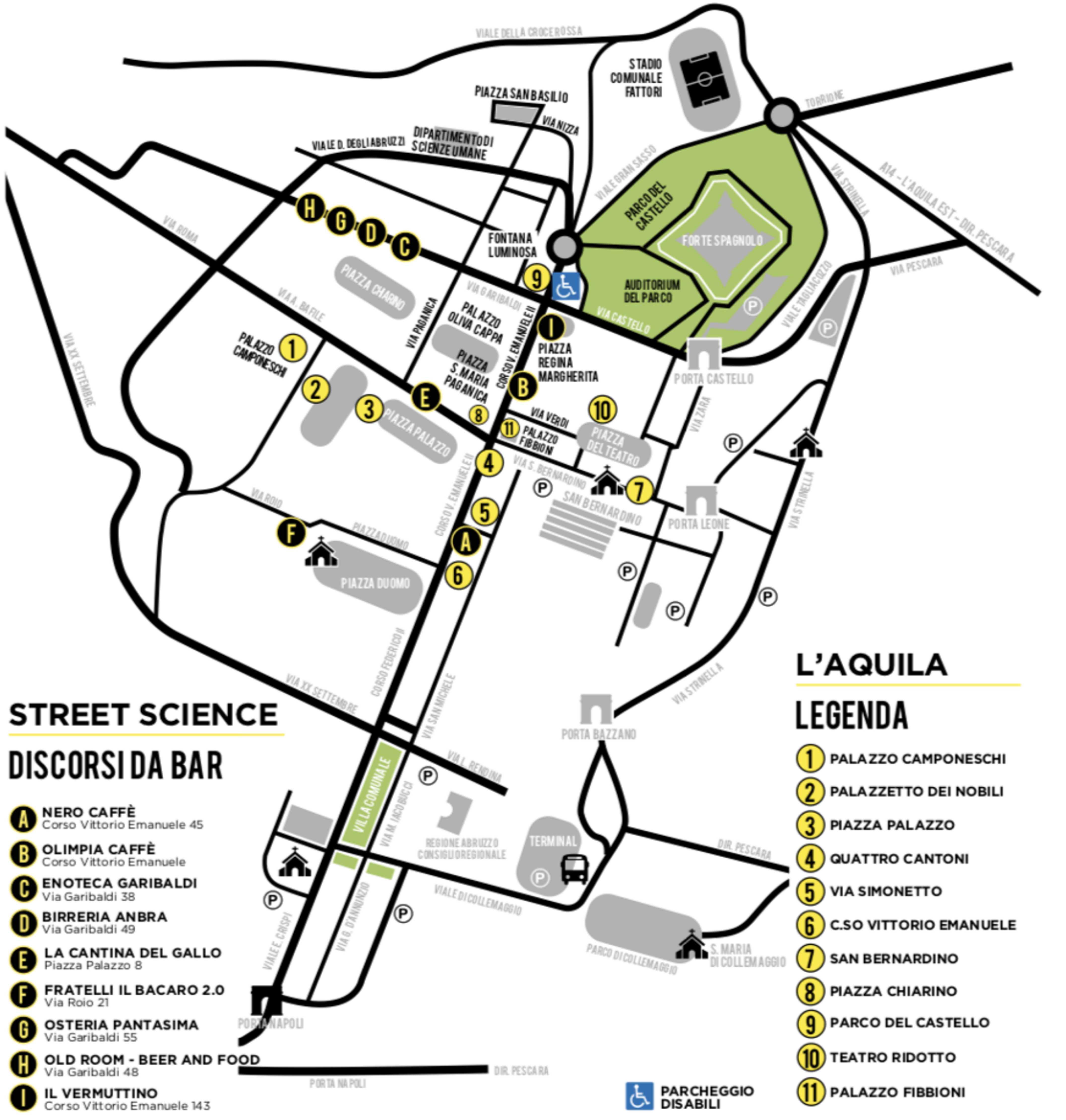
admin

Password:

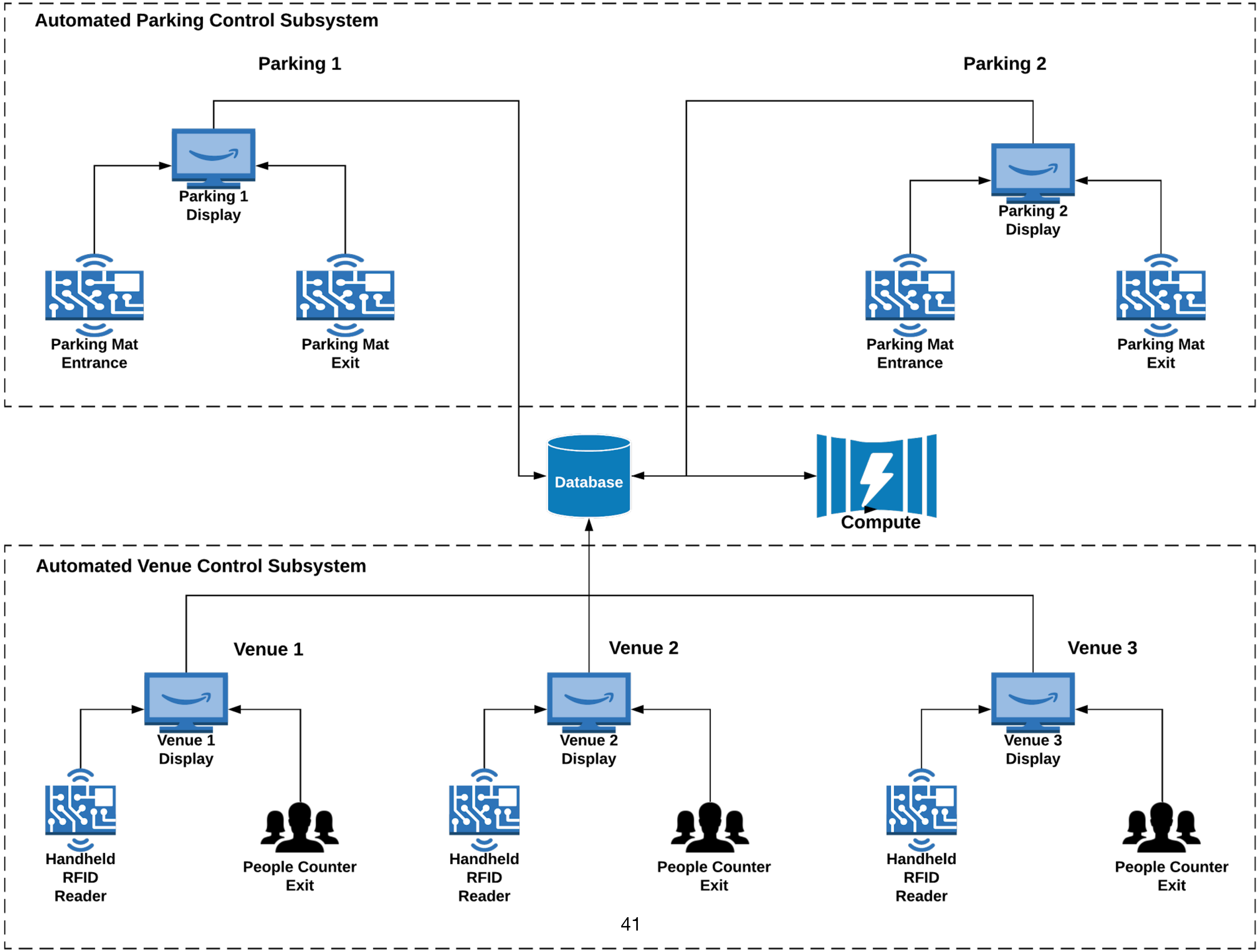
••••••••••••••••

Login

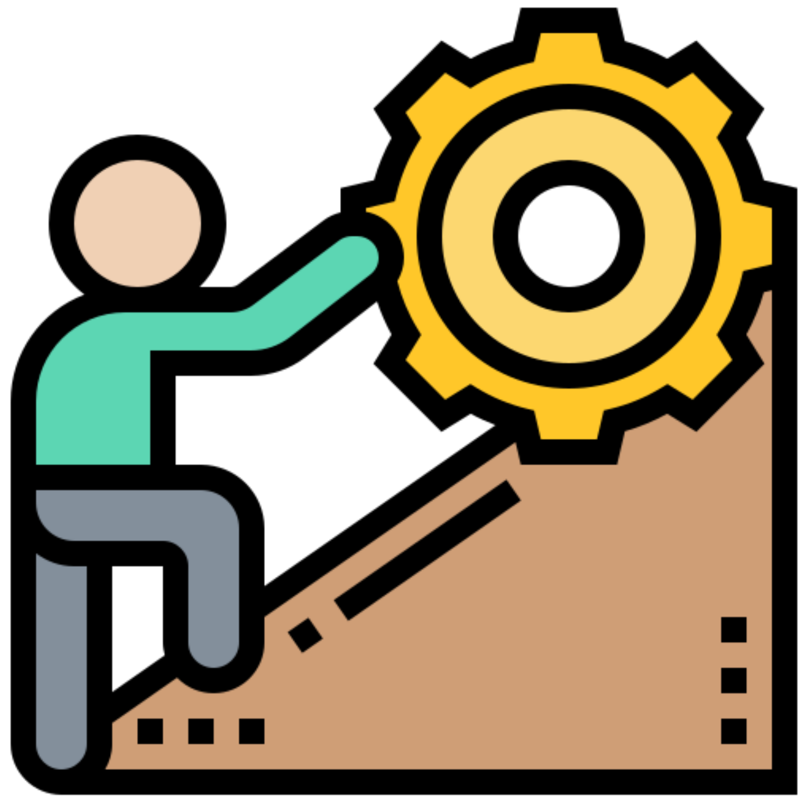
What about the Architecture itself: Glimpse from the NdR Case



High Level View of NdR System



Constraints in NdR System



- More than **35000 visitors** - City center is very small
- Late hours are more crowded than early hours!
- Limited availability of parking lots
- Limited availability of external power source - **Battery powered sensors!**
- Need for accurate and near-real time information

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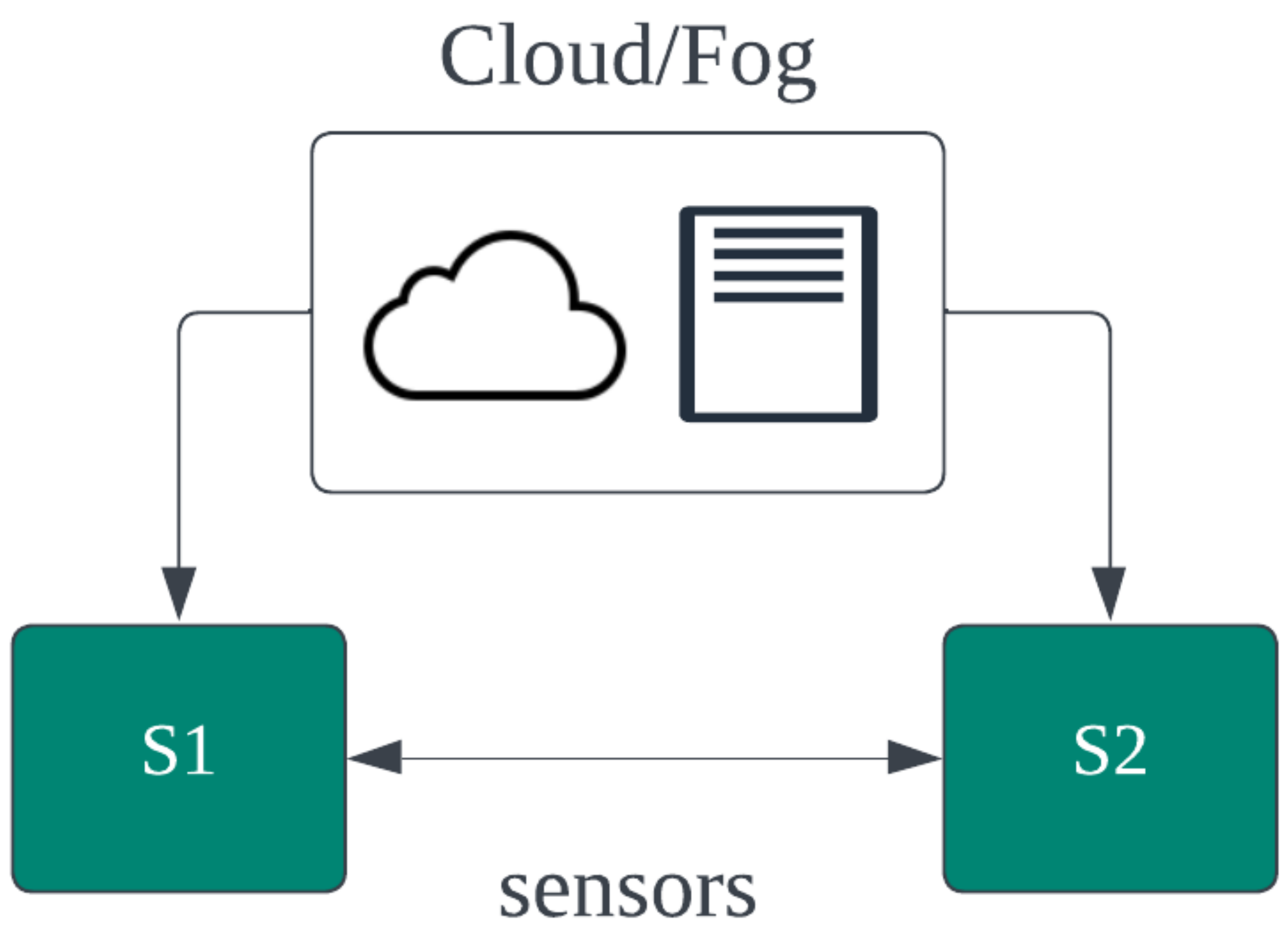
Leveraging IoT Deployment Patterns

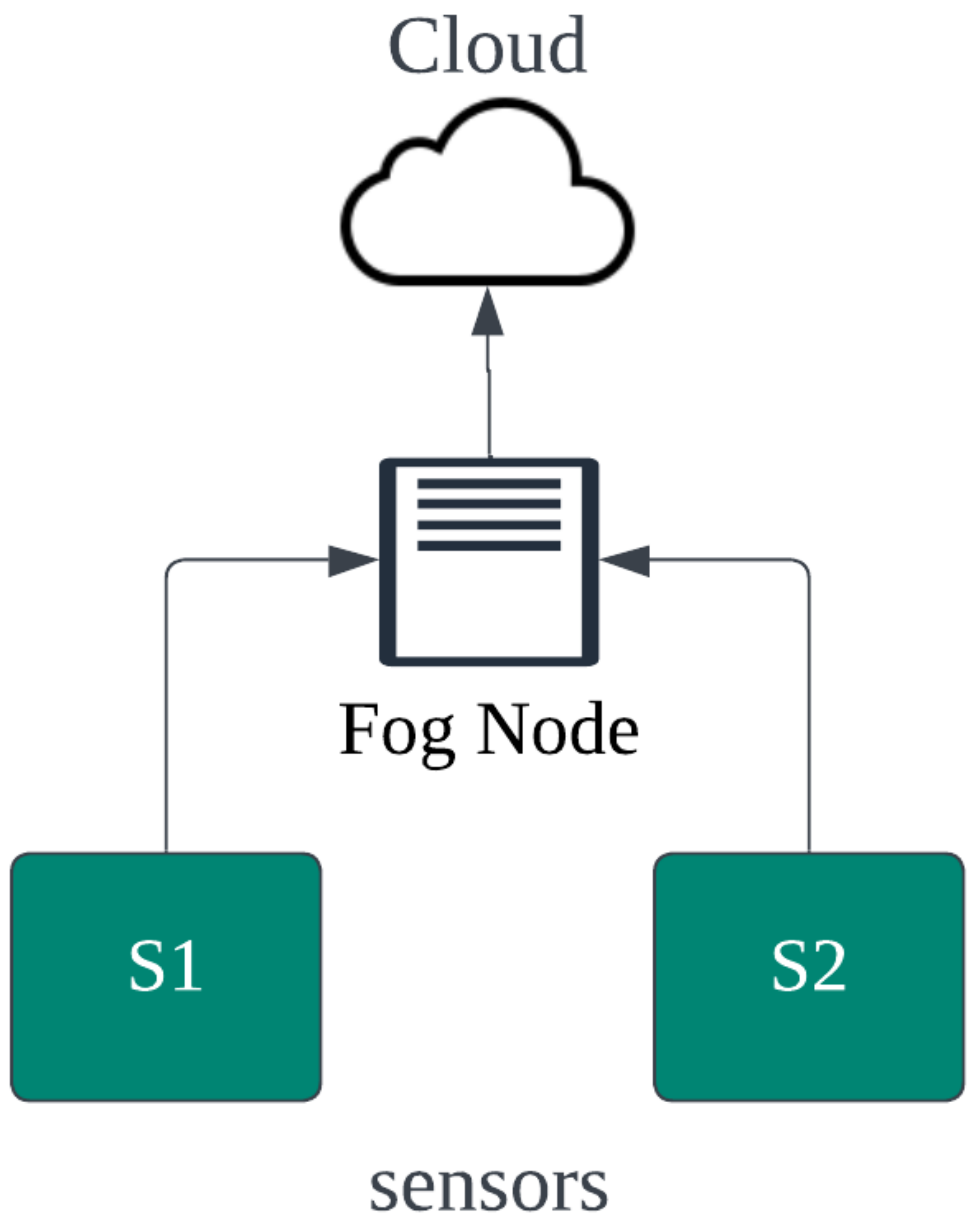


Edge

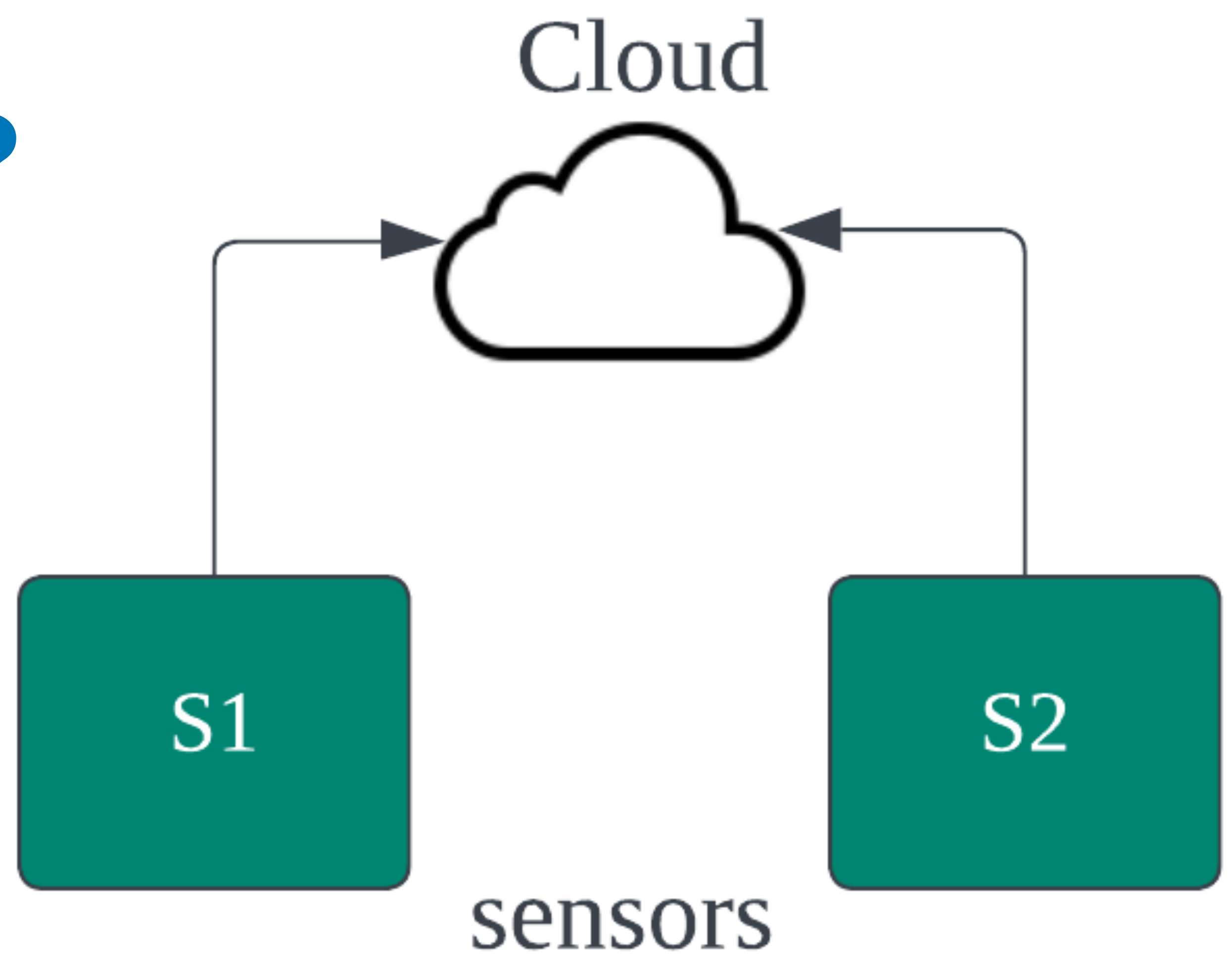
Low latency, high battery

Can we dynamically adapt?

Fog



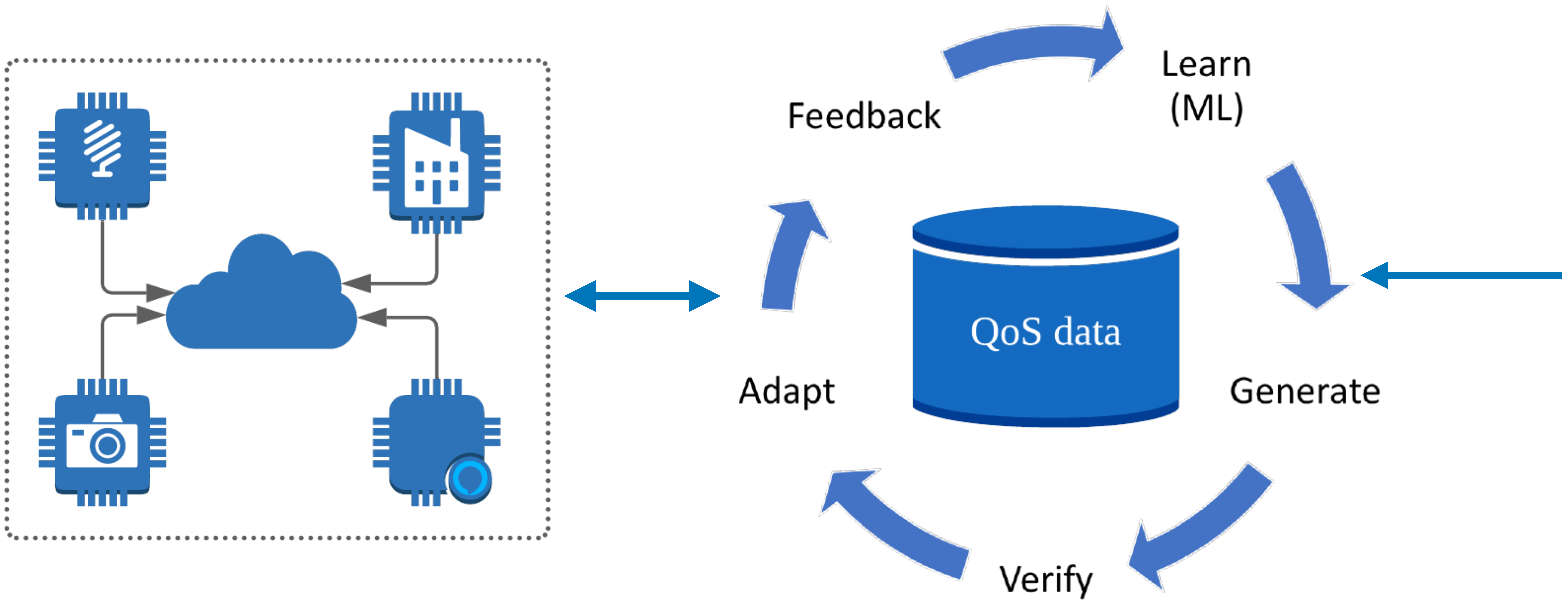
Higher latency, less energy, setup cost



Cloud

Highest latency, less energy

The overall Goal!

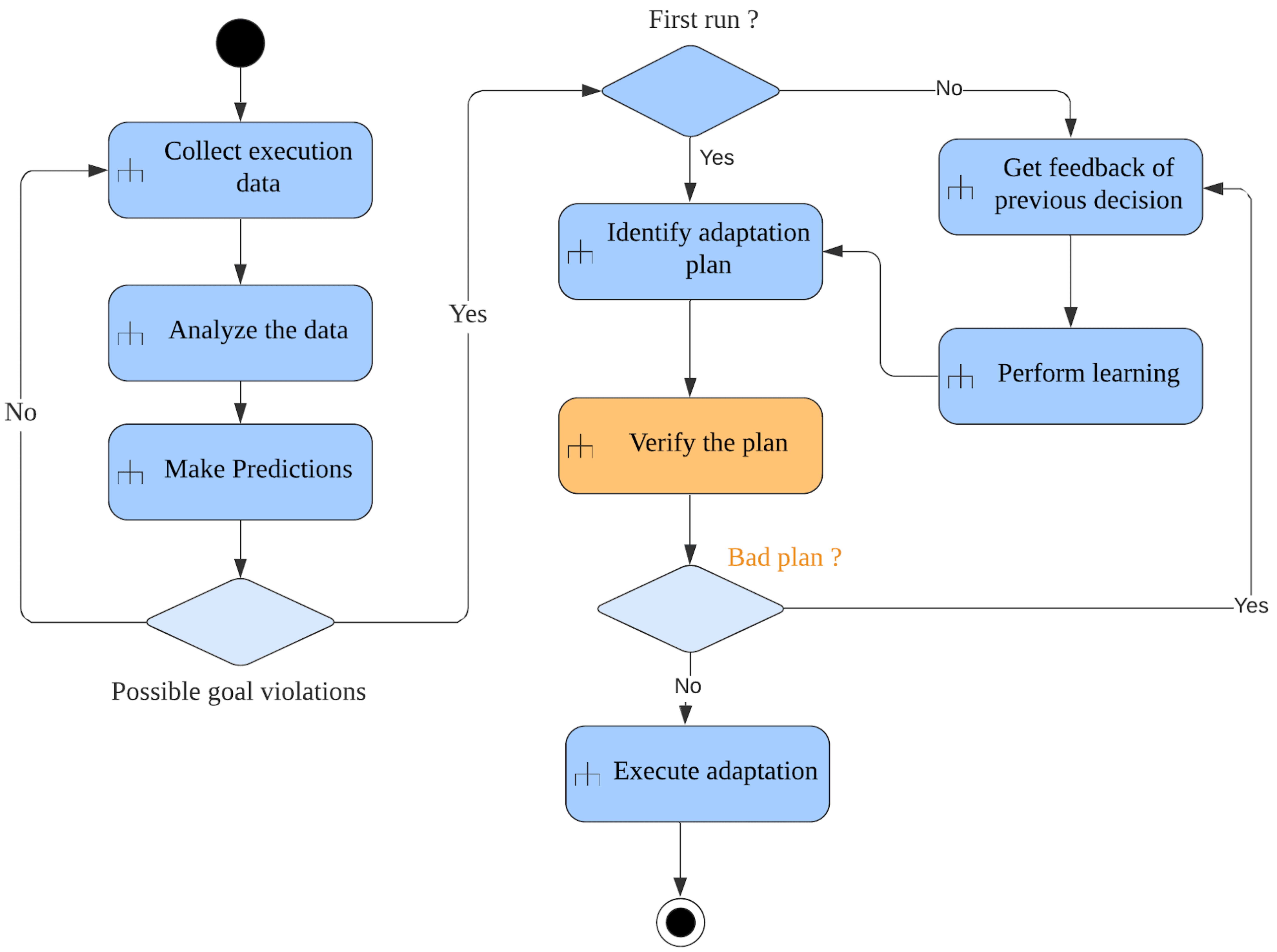


Goals

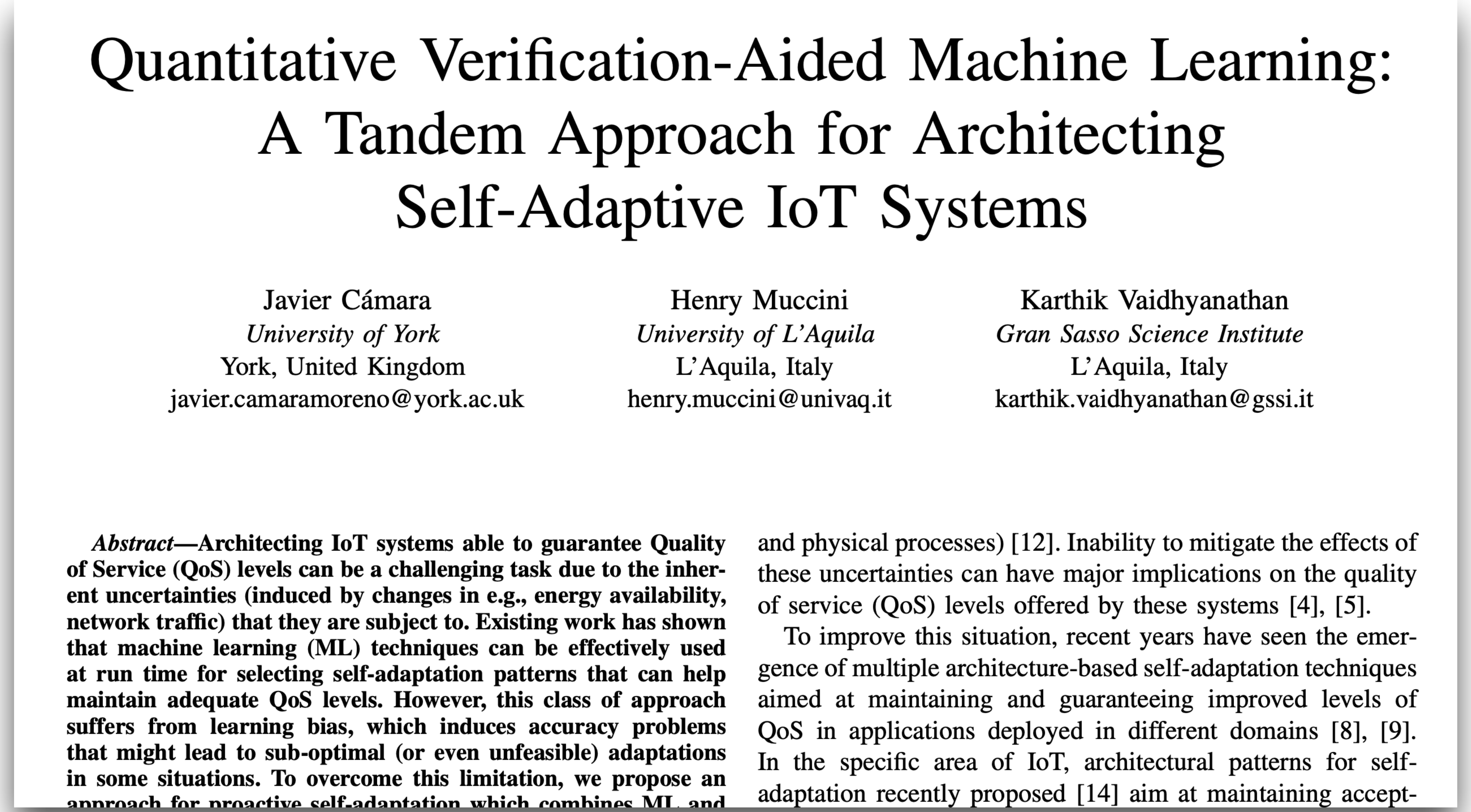
1. energy < 10 joules
2. packet loss < 3
3. CPU <= 40%
4. ....

How to develop an approach?

Learning to Verification-aided Learning



Verification-aided Learning Approach



Quantitative Verification-Aided Machine Learning: A Tandem Approach for Architecting Self-Adaptive IoT Systems

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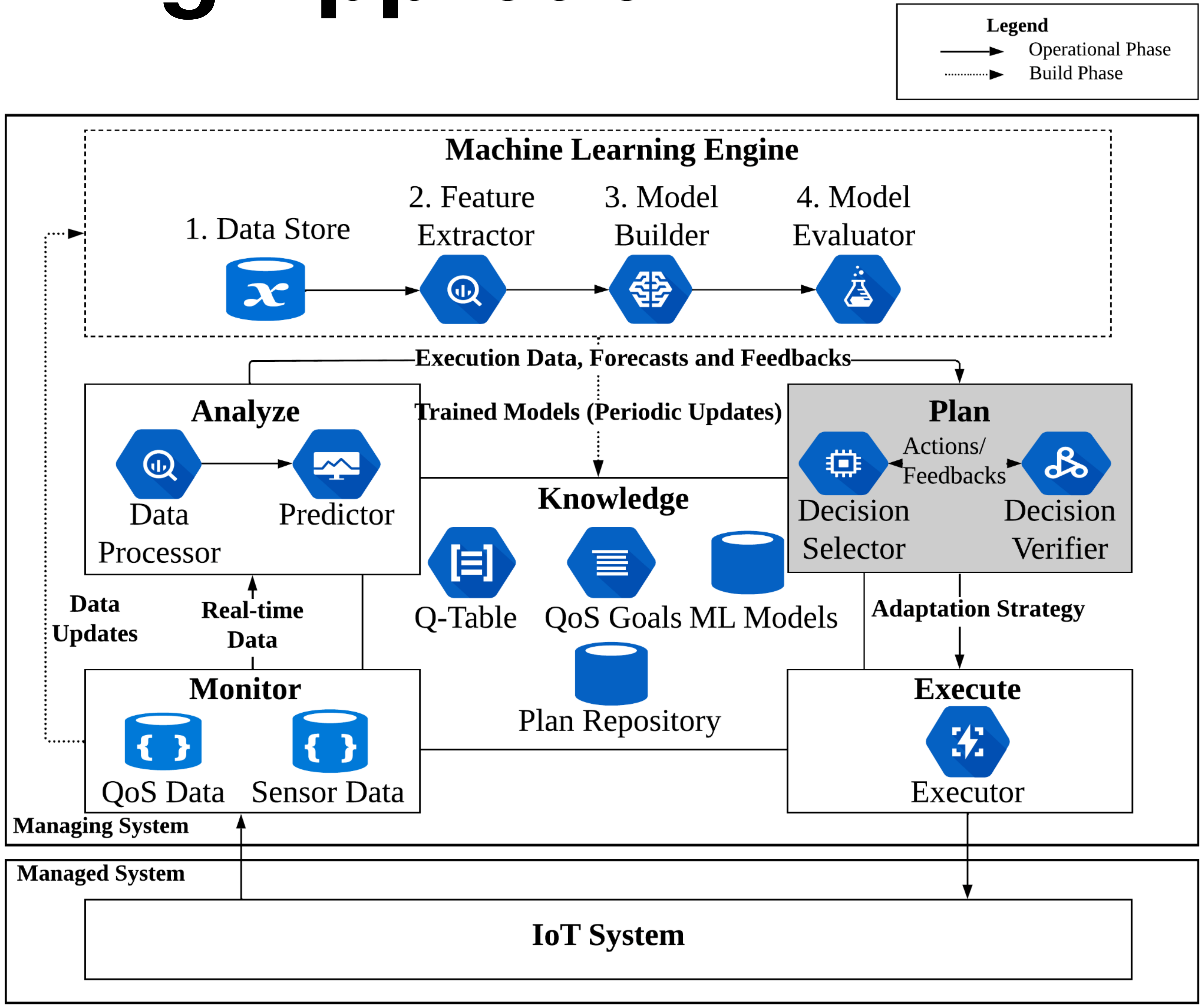
Henry Muccini, *University of L'Aquila*, L'Aquila, Italy, henry.muccini@univaq.it
Karthik Vaidhyanathan, *Gran Sasso Science Institute*, L'Aquila, Italy, karthik.vaidhyanathan@gssi.it

***Abstract*—Architecting IoT systems able to guarantee Quality of Service (QoS) levels can be a challenging task due to the inherent uncertainties (induced by changes in e.g., energy availability, network traffic) that they are subject to. Existing work has shown that machine learning (ML) techniques can be effectively used at run time for selecting self-adaptation patterns that can help maintain adequate QoS levels. However, this class of approach suffers from learning bias, which induces accuracy problems that might lead to sub-optimal (or even unfeasible) adaptations in some situations. To overcome this limitation, we propose an approach for proactive self-adaptation which combines ML and**

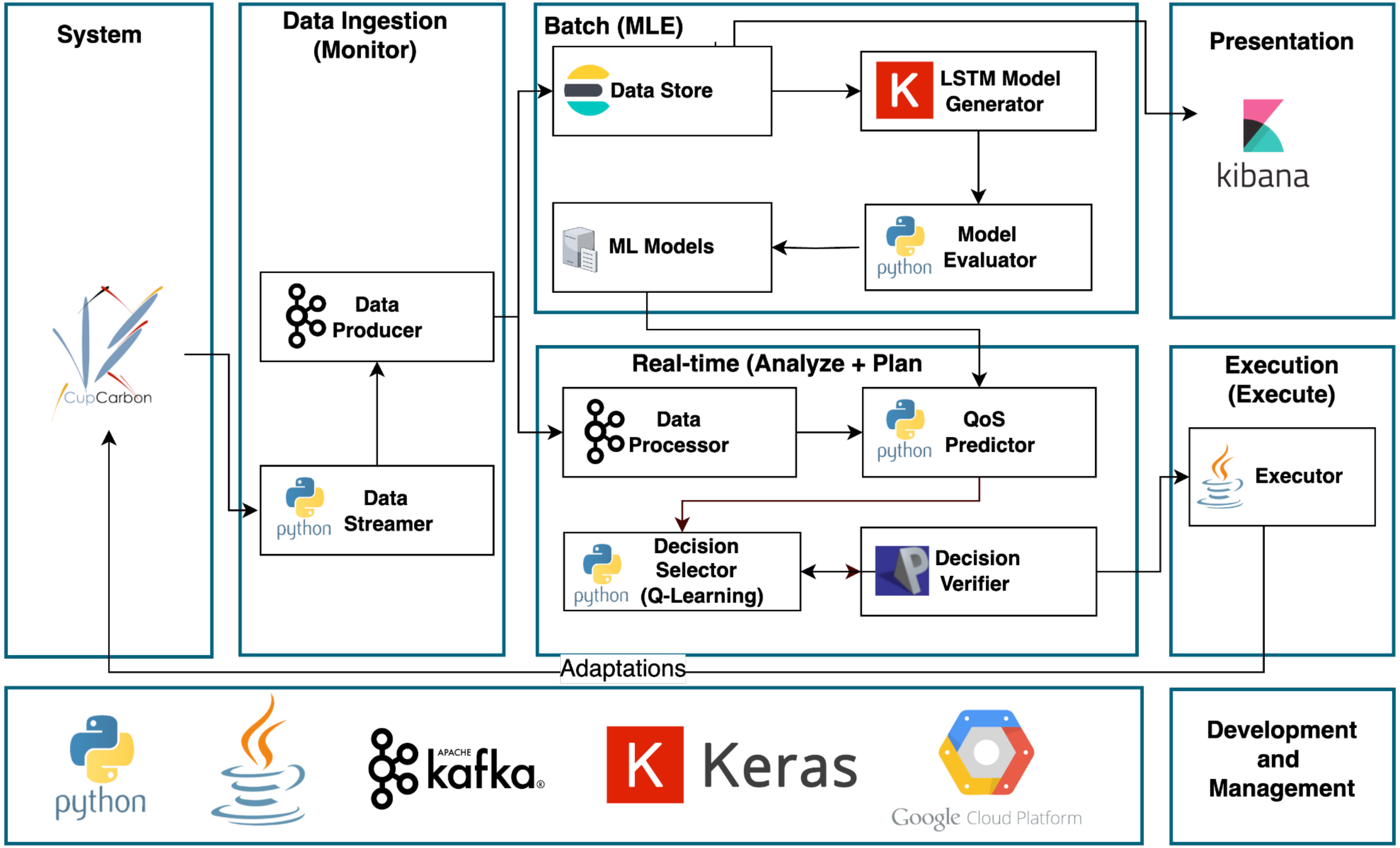
and physical processes) [12]. Inability to mitigate the effects of these uncertainties can have major implications on the quality of service (QoS) levels offered by these systems [4], [5].

To improve this situation, recent years have seen the emergence of multiple architecture-based self-adaptation techniques aimed at maintaining and guaranteeing improved levels of QoS in applications deployed in different domains [8], [9]. In the specific area of IoT, architectural patterns for self-adaptation recently proposed [14] aim at maintaining accept-

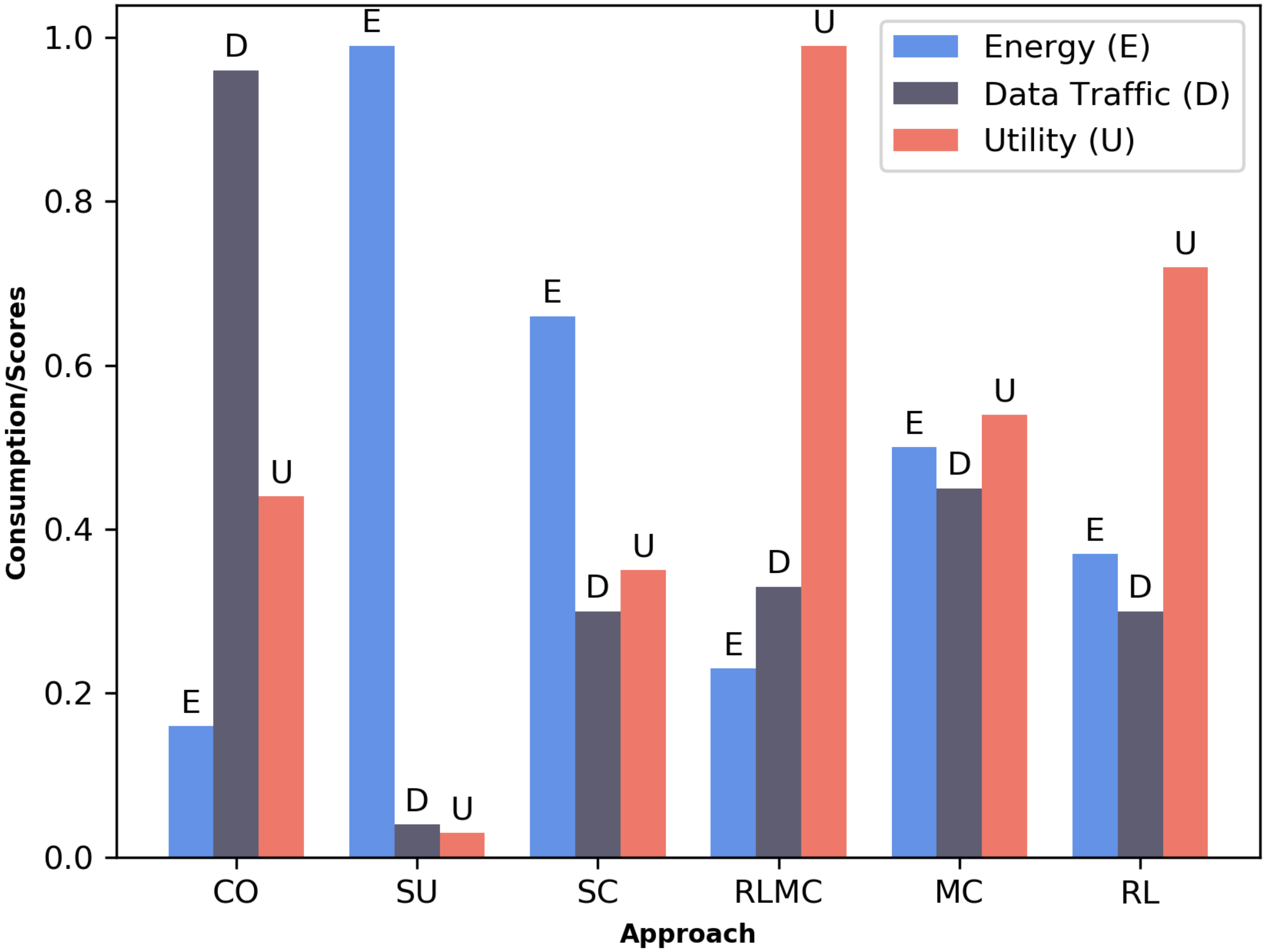


Javier Camara, Henry Muccini, Karthik Vaidhyanathan. Quantitative Verification-Aided Machine Learning: A Tandem Approach for Architecting Self-Adaptive IoT Systems. Proceedings of the IEEE International Conference on Software Architecture (ICSA 2020) - https://mysat.gitlab.io/archlearner-web/

Implementation Overview



Effectiveness - Energy and Traffic Goals



Chain of Multi-level Adaptation

User goal:
«first check the <u>weather conditions</u> and then check for <u>parking lots</u>»

Application level: dynamically combine the weather and parking microservices to accomplish the user's goal.

Microservices level: combine the instances of weather and parking microservices that offer the least response time (to minimize the overall response time perceived by the user).

IoT devices level: reduce the data transfer frequency of IoT devices except parking mats to save more power.

M. De Sanctis, H. Muccini, K. Vaidhyanathan: **Data-drivenAdaptation in Microservice-based IoT Architectures.** IEEE ICSA 2020 - NEMI Track
M. De Sanctis, H. Muccini, K. Vaidhyanathan: **A User-driven Adaptation approach for Microservice-based IoT Applications**, IoT 2021

Applying to IoT Systems

Dynamically generate services

TOURIST
Hi! I have 3 hours to explore Hyderabad's old charm. What do you recommend?

TRAVEL GUIDE
You can visit Laad Bazaar, it offers traditional markets . The adjacent Charminar area combines historical architecture with Hyderabadi cuisine options.

Possible Services and Parameters:
Historical Information
- **Sites: Charminar, Laad Bazaar**

Suggests sites based on user constraint of three hours and static data available

TOURIST
That sounds good, I am famished. Something to eat along the way would be great as well

TRAVEL GUIDE
Laad Bazaar has several local street food vendors serving regional specialties while Charminar has authentic Hyderabadi cuisine options. Would you preffer having veg or non-veg?

Possible Services and Parameters:
Restaurant Finder
- **Location - Laad Bazaar, Charminar**

Historical Information
- **Sites: Charminar, Laad Bazaar**

Asks additional preferences for Goal Refinement

TOURIST
I am in the mood for non-veg today!

TRAVEL GUIDE
Great! Here's your plan: Charminar (1.5h) → Laad Bazaar (1h) → Local Eatery (0.5h) for cuisines (nearby). Based on your prefferences I suggest you use these services:
Restaurant Finder: non-veg
Historical Info: Laad Bazaar,Charminar

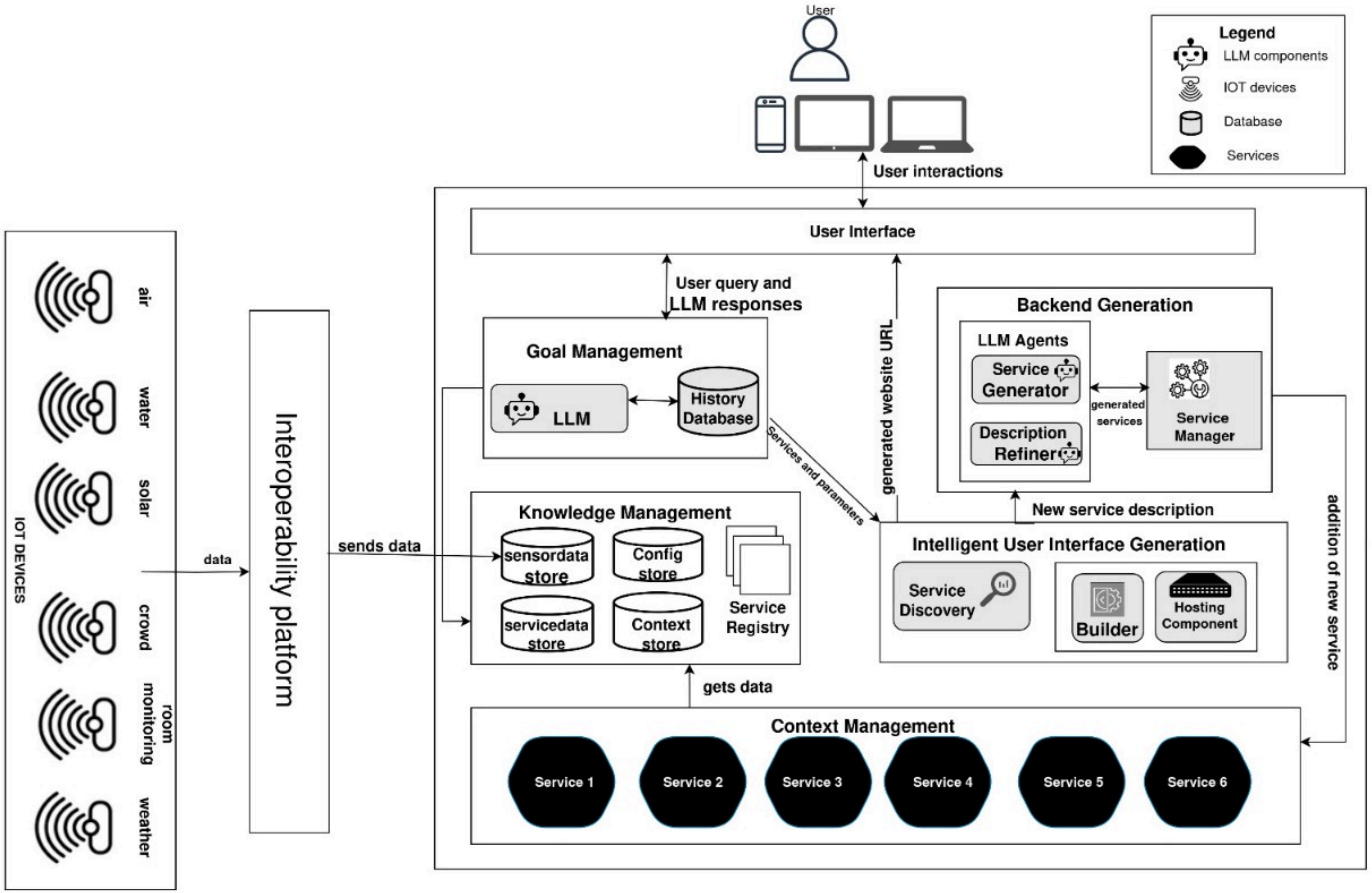
TOURIST
This sounds good!

Final Services and Parameters
Restaurant Finder-
- **Location: Laad Bazaar**
- **Diet: Non-Veg**
- **Cuisine: Any**

Historical Information-
- **Sites: Charminar, Laad Bazaar**

Lays out a plan, recieves confirmation and proceeds to build the application

IoT-Together: Mixed Initiative Interactions



Adnan, B., Miryala, S., Sambu, A., Vaidhyanathan, K., De Sanctis, M. and Spalazzese, R., 2025. **Leveraging LLMs for Dynamic IoT Systems Generation through Mixed-Initiative Interaction**.ICSA 2025 Companion, ICSA 2024 Companion

Demo


INTERNATIONAL INSTITUTE OF
INFORMATION TECHNOLOGY
HYDERABAD
R&D
2025
showcase
Leveraging LLMs for Dynamic IoT Systems Generation through Mixed-Initiative Interaction
Aneesh Sambu
Bassam Adnan
Sathvika Miryala | Karthik Vaidyanathan
SERC
Tech for
Sustainable
Futures

Edge-Cloud Continuum

- Edge Cloud Continuum for Self-adaptation
  - Intelligently switch AI processing between edge and cloud
  - Switch could also be between options in edge
  - Proactive approaches for pre-fetch of resources
- Sustainable EdgeAIOps
  - Effective management of AIOps on edge
  - Model versioning, governance, automated pipelines

DECCAN Chronicle

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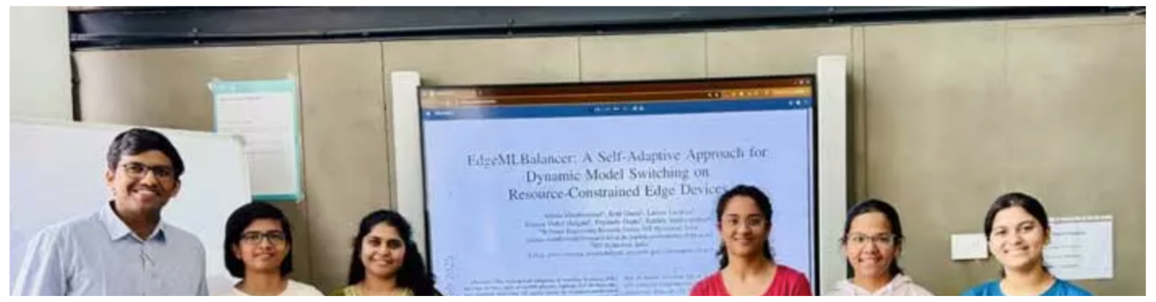
IIIT-Hyderabad demonstrates ML model-switching approach on smart phones for real-time traffic monitoring

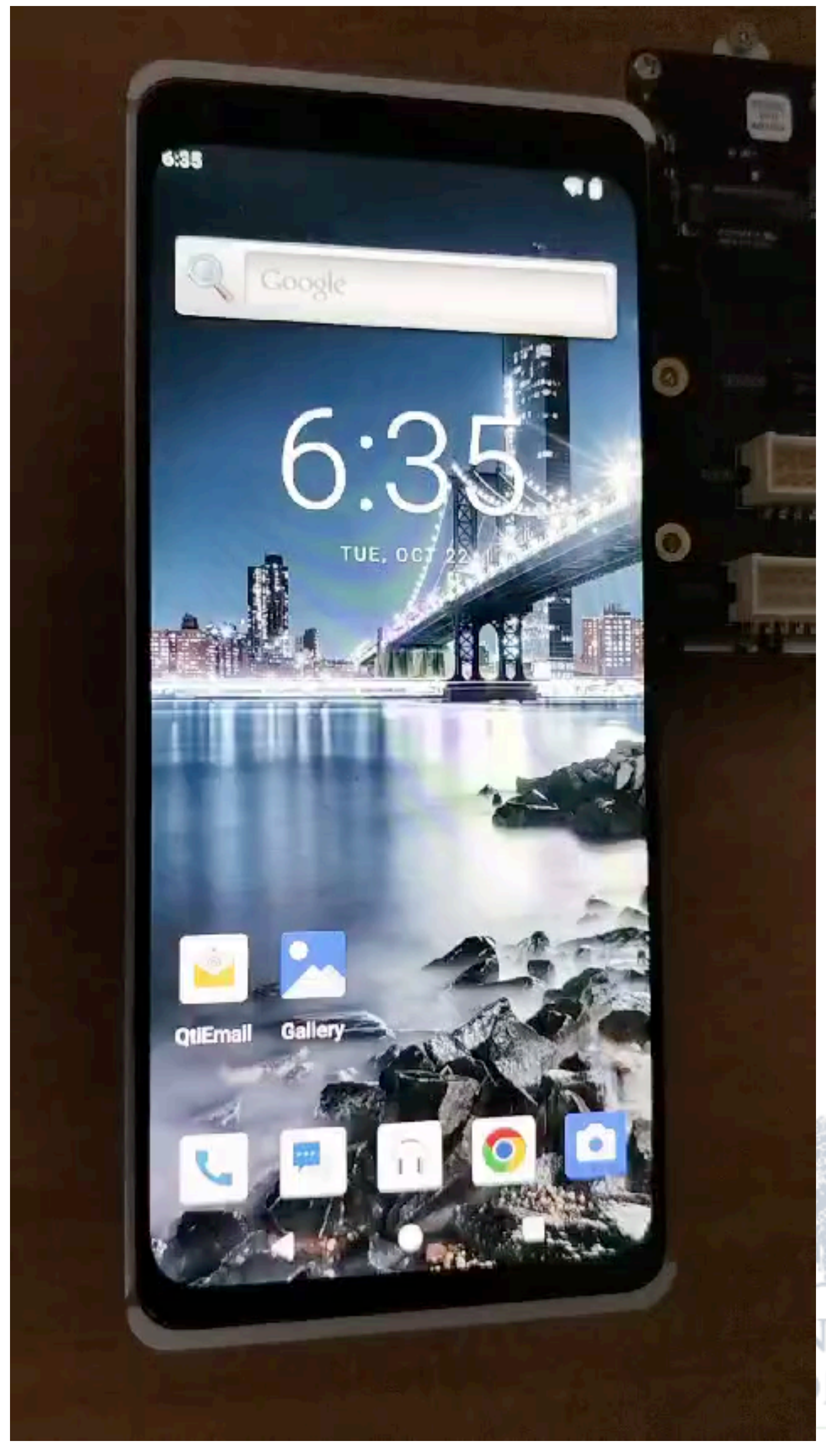
Telangana

M Srinivas

27 February 2025 2:55 PM

Second year CSE students of IIIT-Hyderabad unveiled ML model





Qualcomm

https://www.qualcomm.com/videos/dynamic-ml-model-switching

Key Takeaways

- Architecting IoT systems requires a holistic approach
- A combination of hardware, software, environment and human behaviour makes it challenging and interesting
- Digital Twins are becoming the need of the hour to manage some of the challenges - Need for better engineering practices
- Generative and in particular, Agentic AI are opening up a lot of possibilities in autonomous adaptation

IEEE Software Magazine

SCAN ME

SE Radio Podcasts

Thank you

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