# SOLEA -
# SOLAR ENERGY AUTOPILOT

## A Digital Twin Framework for Autonomous Solar Thermal Plants

09/16/2026, Inga Miadowicz, Deutsches Zentrum für Luft- und Raumfahrt (DLR)

# Presentation Context

**Solar Energy Autopilot [1]**

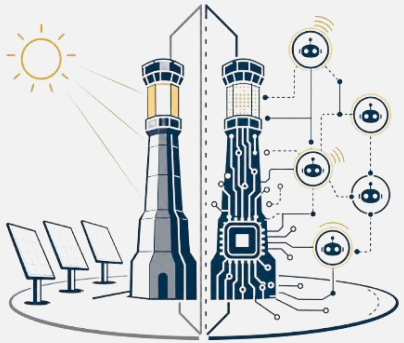
4 Automation
Software Assets

3 Data & Communication

2 Measurement & Control

1 Industrial Facility
Physical Assets

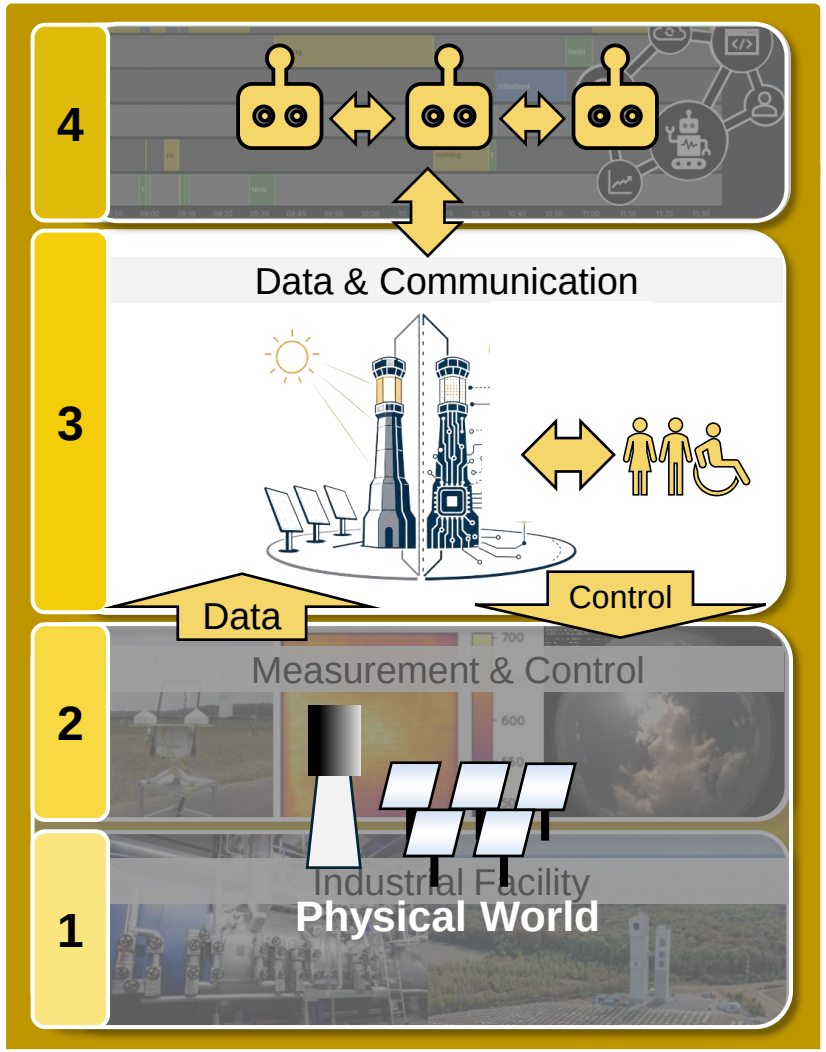
**Digital Twin Framework [2]**
Represents physical & software assets



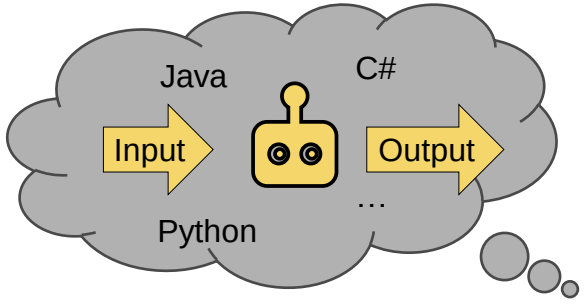
# Background

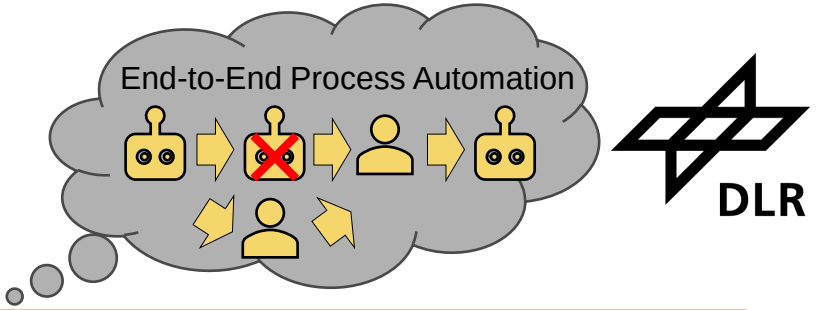
- Digital Twin
  - Bi-directionally synchronized representation of the physical world [3]
    a) …to access a virtual representation of plant components based on measurement data
    b) …to control plant components based on control systems
  - Enables monitoring, plant control, intelligent decision-making, simulation, prediction, …
  - A lot of publications and commercial products

Middleware platform for the Jülich solar tower, featuring an digital twin for physical assets as described in [4]



# Motivation




## 1. Research Gap: Transparency

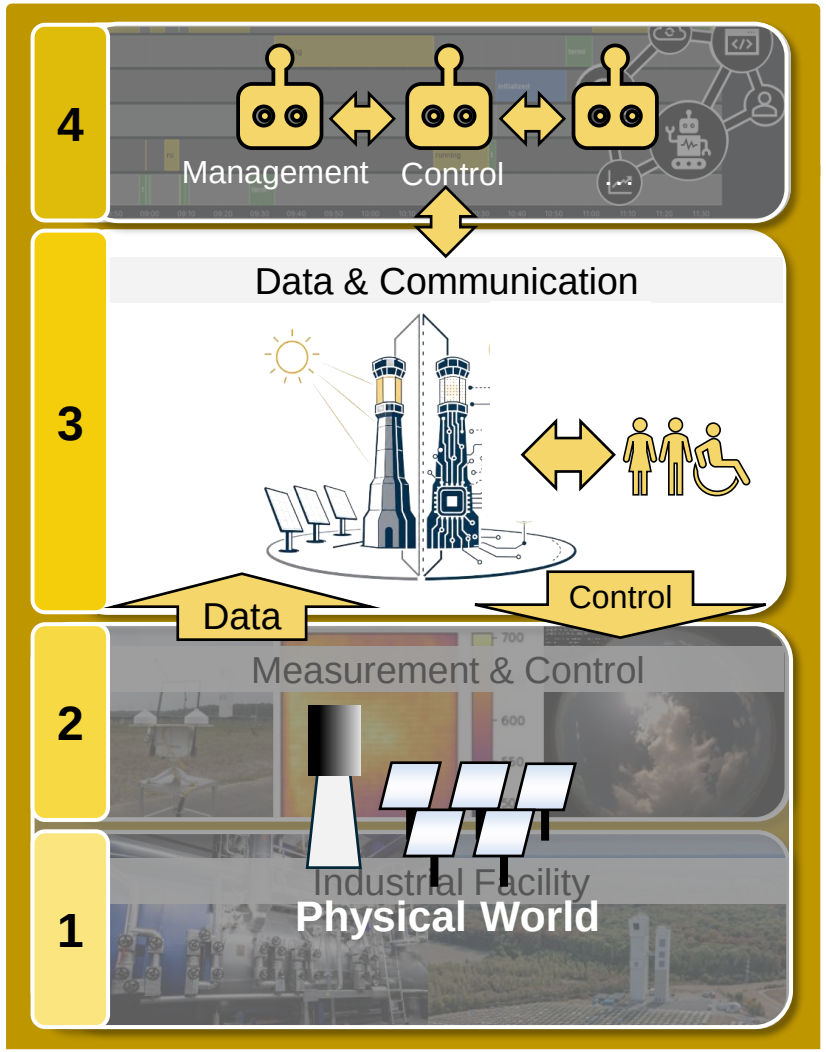
- Physical digital twin only shows effects of decision-making
- “Black Box” nature of distributed, heterogeneous software agents

Objective 1: Transparent supervision & monitoring of agent-based process execution

## 2. Research Gap: Collaboration

- Mixed systems with human-in-the-loop
- Changing multi-agent system structure during the gradual evolution towards autonomy

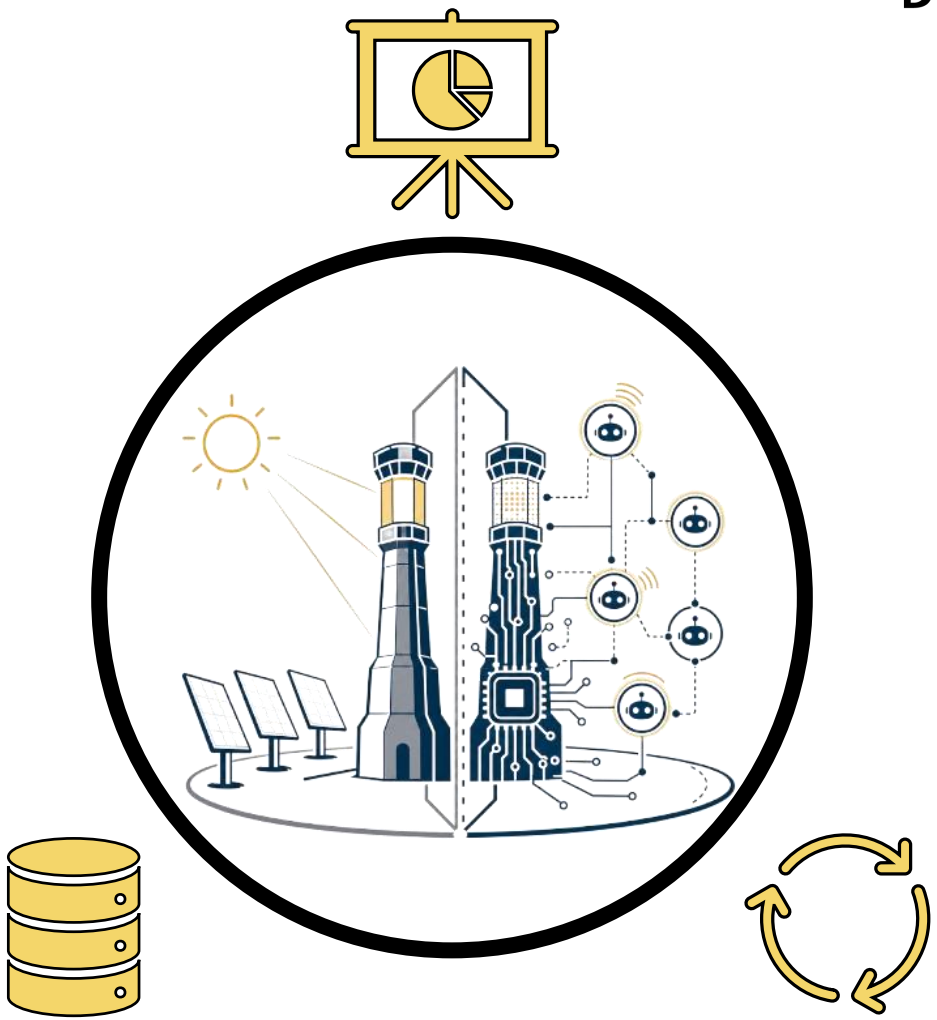
Objective 2: Flexible inter-agent and human-agent collaboration for end-to-end process automation



# Results

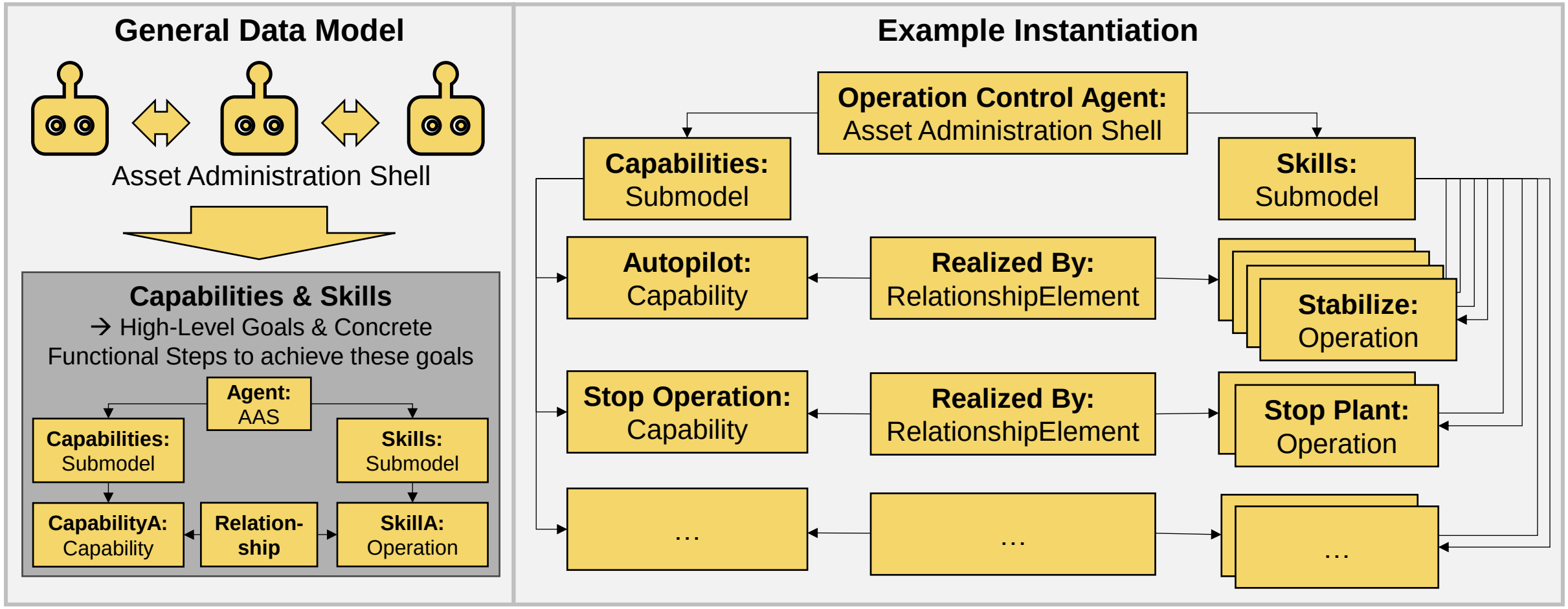
- SOLEA digital twin framework for physical plant and multi-agent system representation [2]
- Overview

1. **Part: Standards-based data model**
   - Baseline for representing physical and software assets in the virtual space
2. **Part: Digital twin infrastructure**
   - Collect, manage and provide access to digital twin data for agents and humans
3. **Part: Interaction workflows**
   - Define rules that describe how agents and humans transparently collaborate



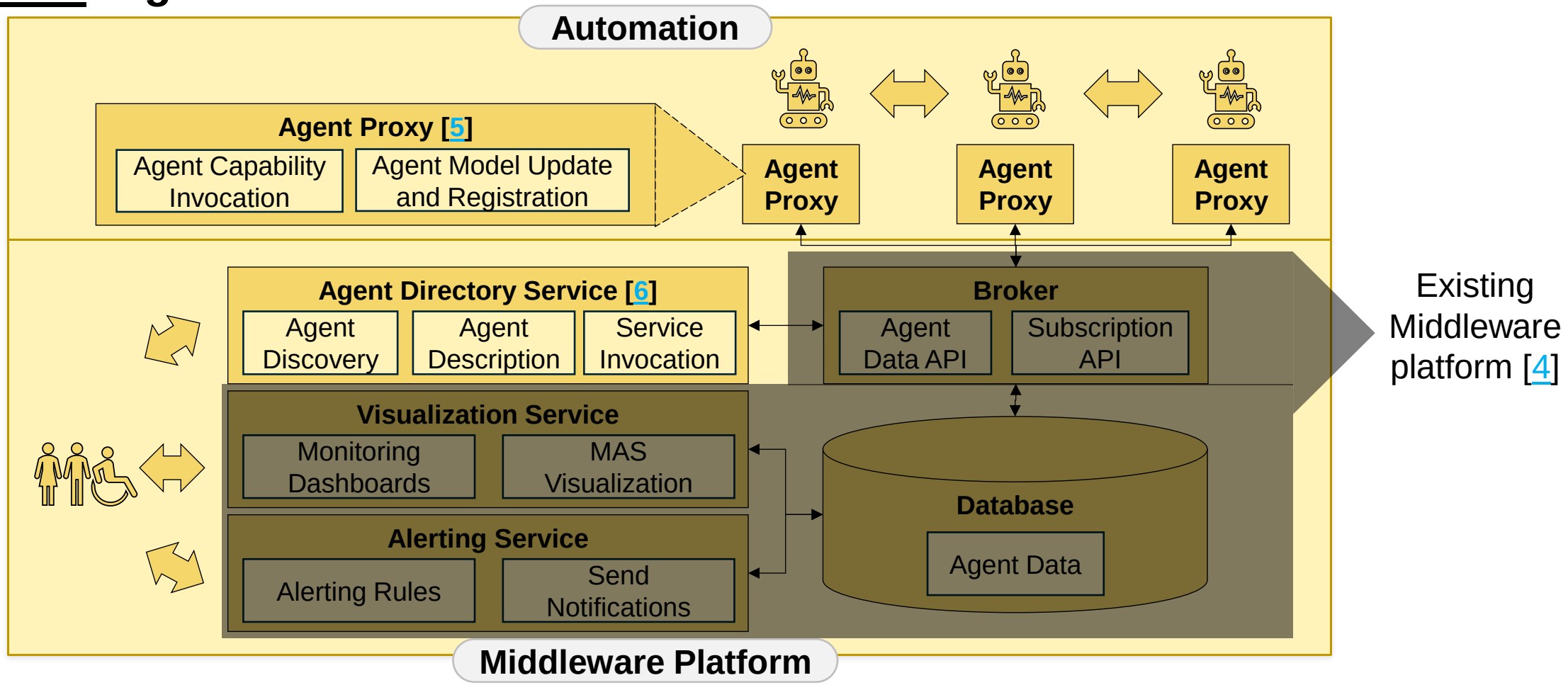
# Results

- **<u>Part 1:</u> Standards-Based Data Model**



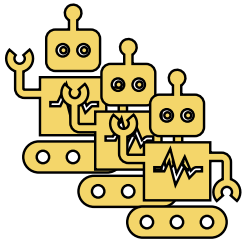
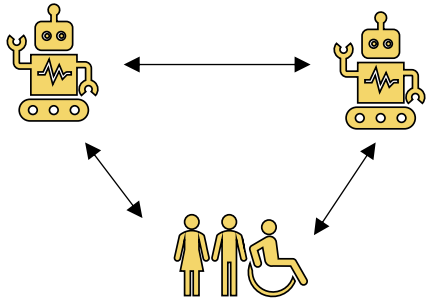
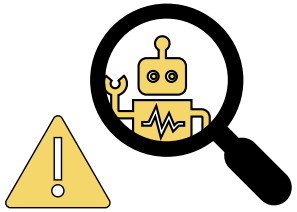
# Results

- **Part 2: Digital Twin Infrastructure**



# Results

- **<u>Part 3:</u> Interaction Workflows**

| Agent Registration | Agent Collaboration | Agent Supervision |
|---|---|---|
|  |  |  |
| Add, update, remove **agents** from the system by creating, patching or deleting their **entity in the digital twin** | **Find** agents in the system, **explore** their AAS self-description, and **invoke their capabilities** using different mechanisms | **Synchronize agent states** with the digital twin as a baseline for **monitoring** and their **automatic notification** on events |

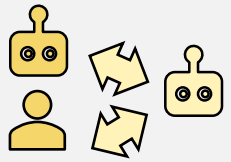
# Conclusion

These are my capabilities, skills, interfaces, runtime states, …

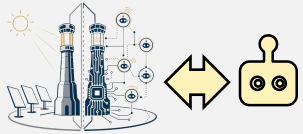
## Agent Perspective

- Self-Registration
- Self-Description
- Self-Discovery
- Self-Collaboration

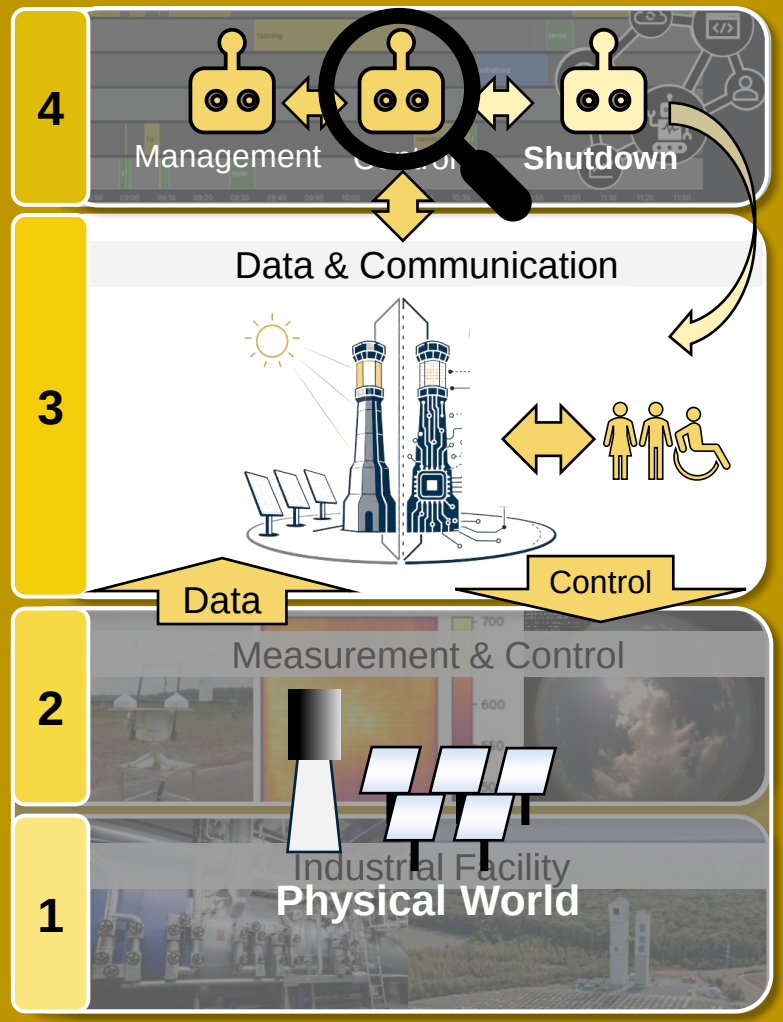
Peer-to-Peer



Event-Based



- Self-Monitoring




## Human Perspective

- Agent Monitoring

# Conclusion

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Peer-to-Pee

Self-Monitoring

Perspective

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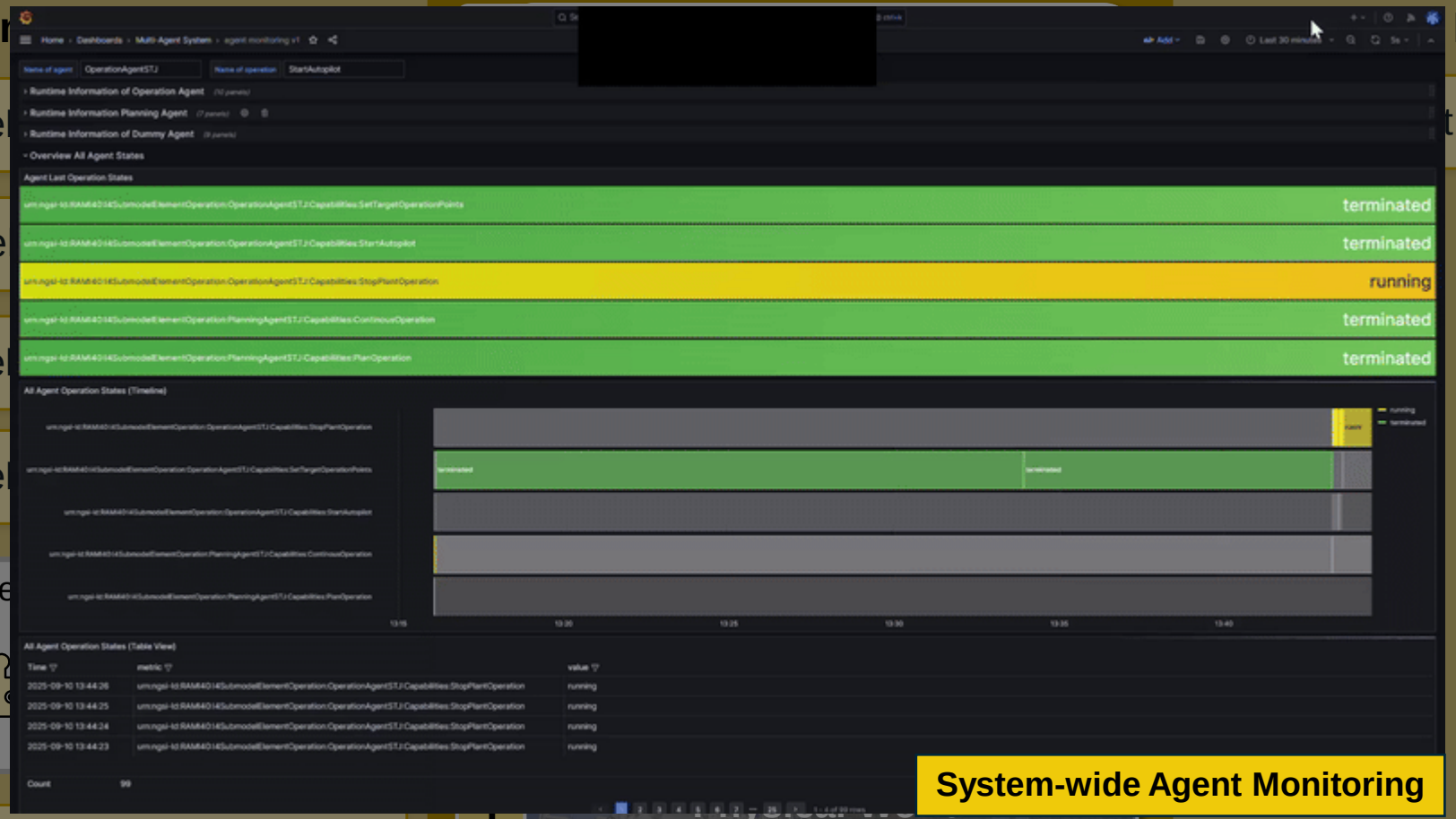


System-wide Agent Monitoring

# Conclusion

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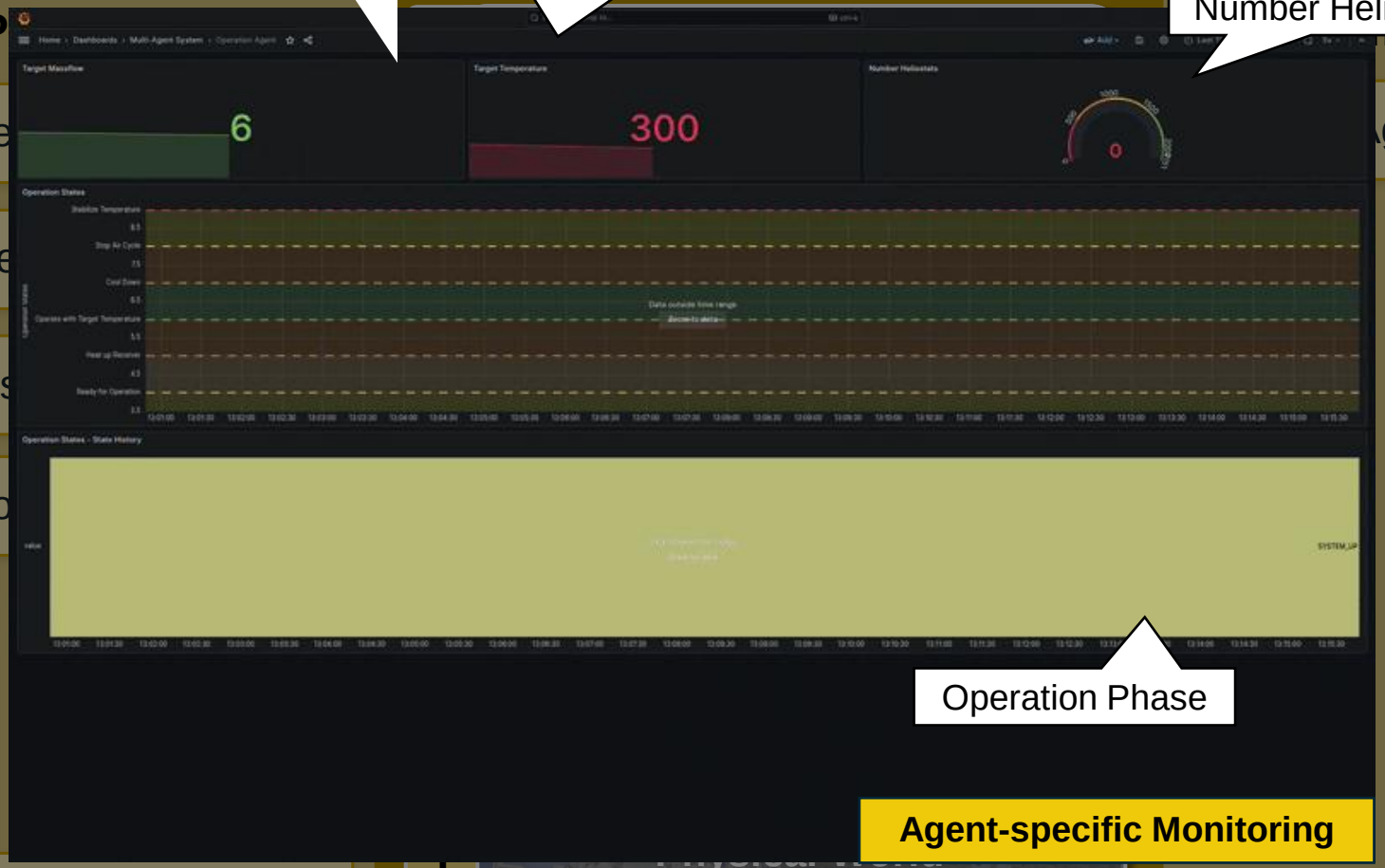
Peer-to-Peer

Self-Monitoring

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gent Monitoring

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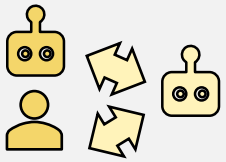

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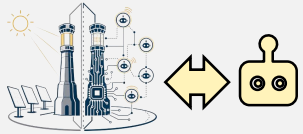

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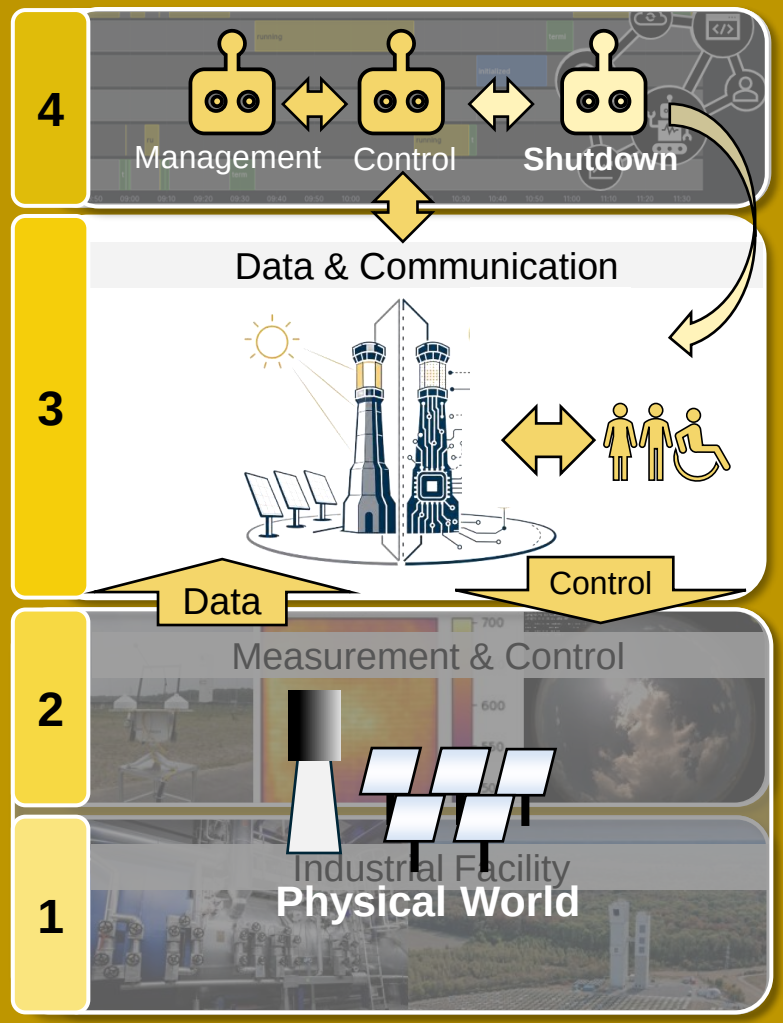
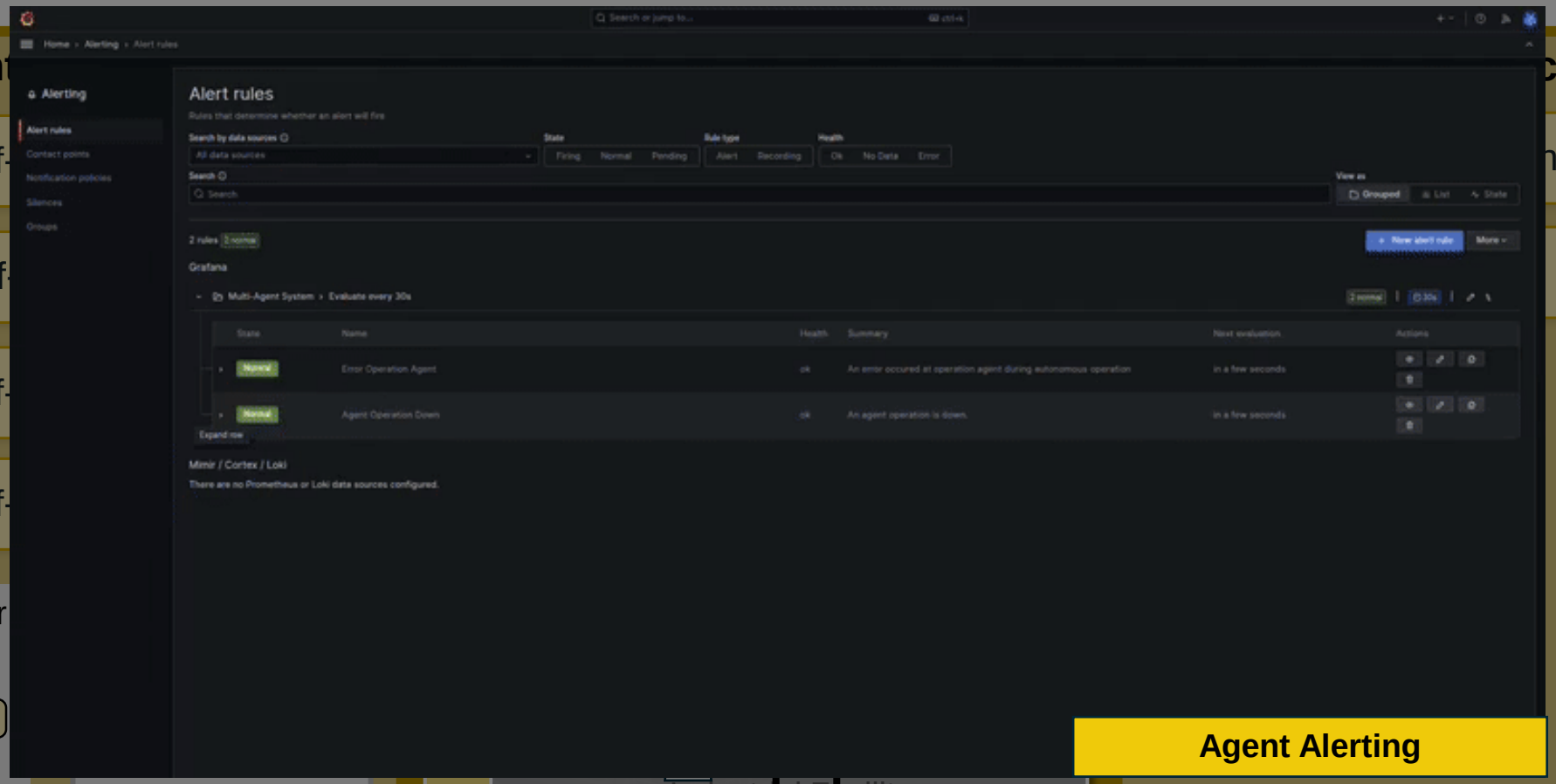



## Human Perspective

- Agent Monitoring
- Agent Alerting

# Conclusion




Peer-to-Peer

Self-Monitoring

1

Industrial Facility

Physical World

# Conclusion

## Agent Perspective

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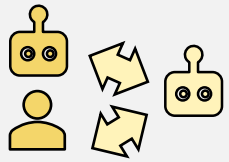
Peer-to-Peer



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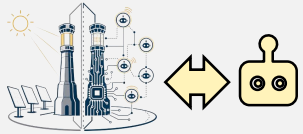
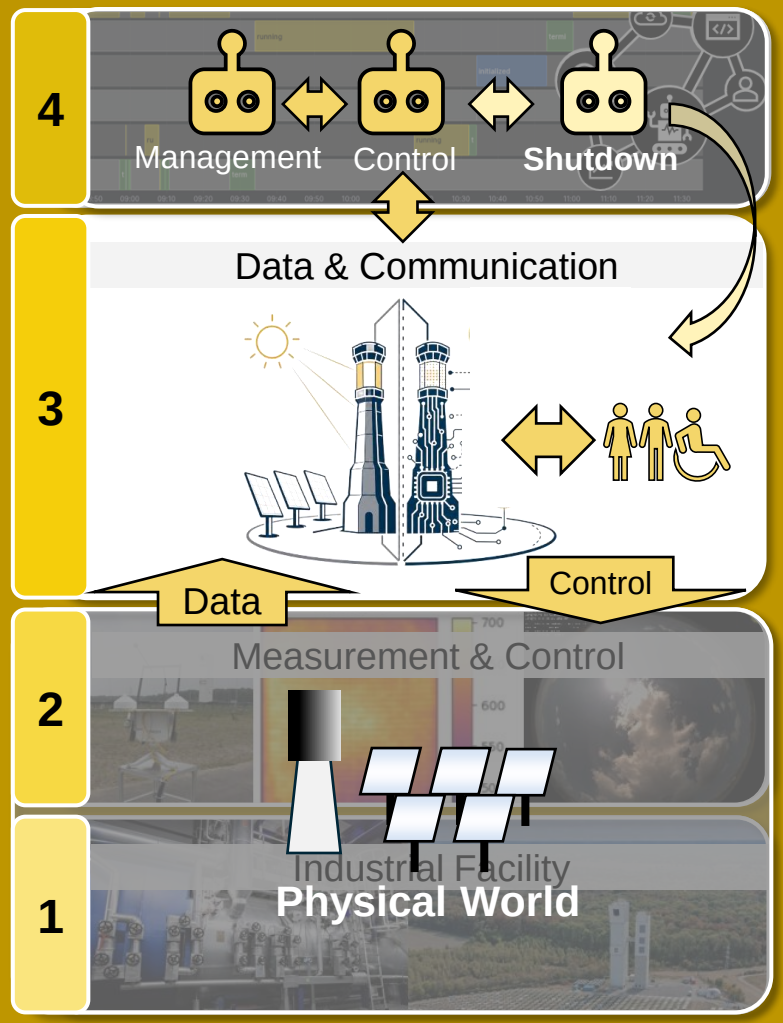


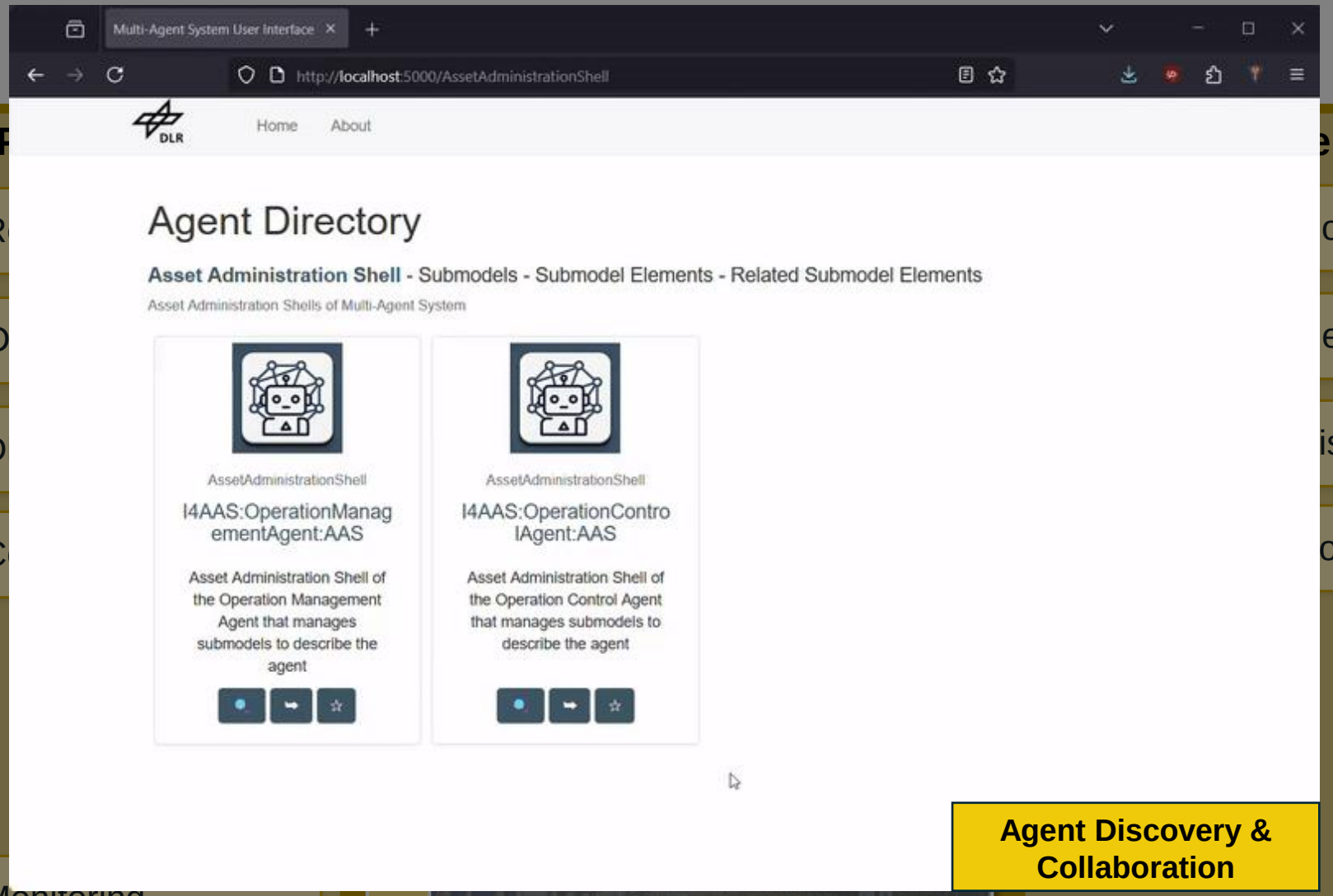
- Self-Monitoring




## Human Perspective

- Agent Monitoring
- Agent Alerting
- Agent Discovery
- Agent Collaboration

# Conclusion




**Agent Discovery & Collaboration**

# Conclusion

## Agent Perspective

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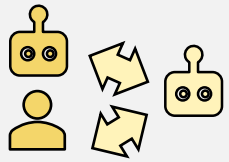
Peer-to-Peer



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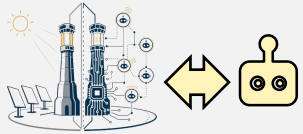

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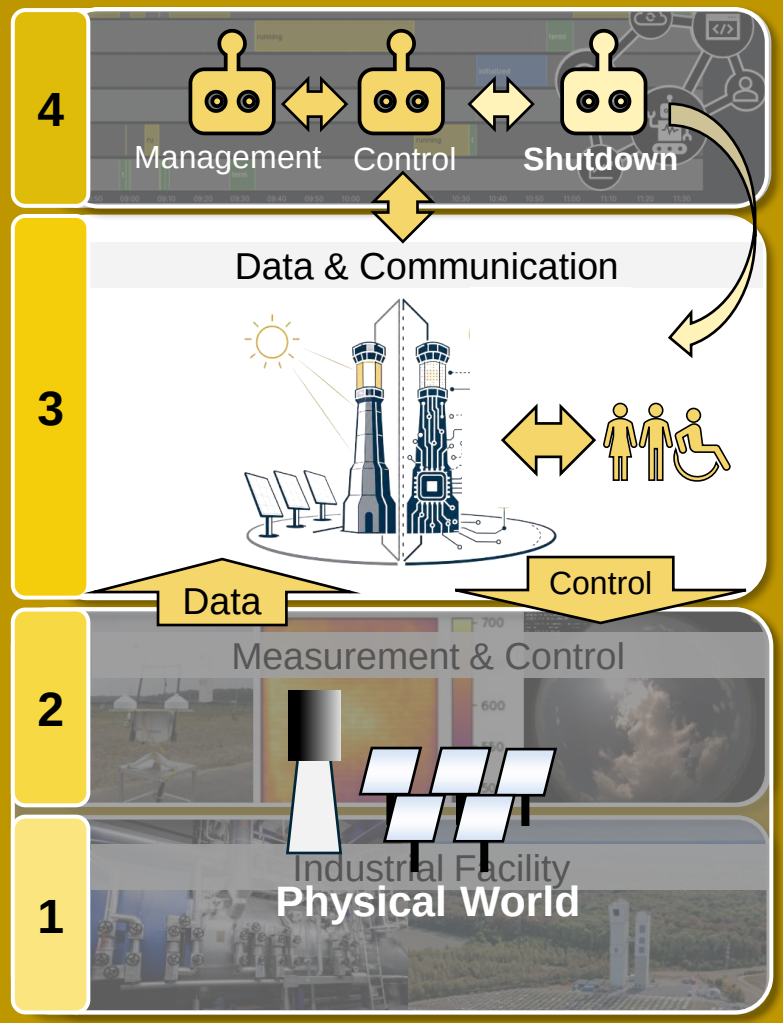



## Human Perspective

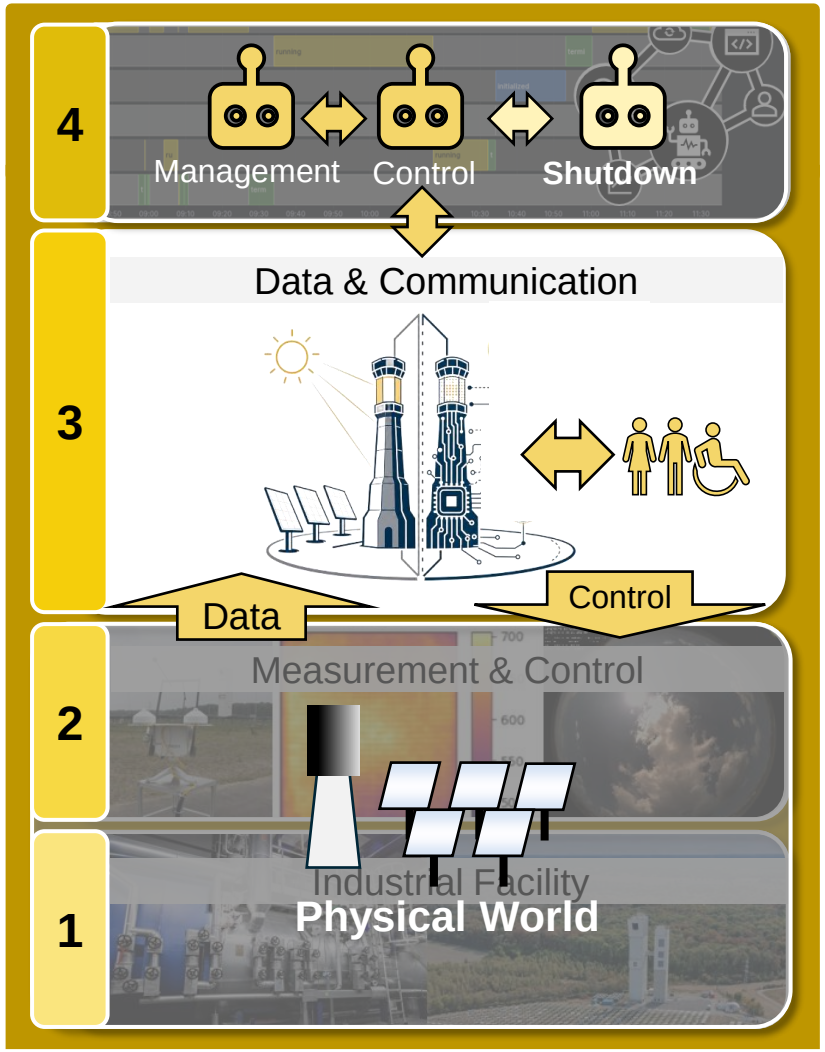
- Agent Monitoring
- Agent Alerting
- Agent Discovery
- Agent Collaboration

# Summary

**Goal:** Close connectivity and transparency gaps between agents & humans

**Approach:** Enhance the digital twin concept to represent physical entities and software agents

**Solution:** SOLEA digital twin framework for full-stack connectivity between physical components, multi-agent system, and human operators





# Thank you for your attention.

→ I am happy to answer additional Questions in person or via E-Mail: Inga.Miadowicz@dlr.de

# References


**[1]** „*Solar Energy Autopilot (SOLEA): A Holistic System Architecture for Autonomous Concentrated Solar Thermal Plants and Its Evaluation in an Operational Power Tower Facility*“ - Miadowicz, I., Kuhl, M., Maldonado Quinto, D., Dürr, N., Schwarzbözl, P., Sibum, M., ... & Pitz-Paal, R., Felderer, M.; Pre-Print submitted to Solar Energy (2026). https://dx.doi.org/10.2139/ssrn.5788942

**[2]** „*From Automation to Autonomy: A Digital Twin Framework for Transparent Agent and Human Collaboration in Industrial Multi-Agent Systems*“ - Miadowicz, I., Kuhl, M., Maldonado Quinto, D., Pitz-Paal, R., & Felderer, M. (2026). Systems, 14(1), 76. https://doi.org/10.3390/systems14010076

**[3]** „*Digital Twin in manufacturing: A categorical literature review and classification*” - Kritzinger, W., Karner, M., Traar, G., Henjes, J., Sihn, W (2018). IFAC-PapersOnLine, 51, 1016–1022. https://doi.org/10.1016/j.ifacol.2018.08.474

**[4]** “*An action research study on the digital transformation of concentrated solar thermal plants*” - Miadowicz, I., Quinto, D. M., Pitz-Paal, R., & Felderer, M. (2025). Solar Energy Advances, 5, 100102. https://doi.org/10.1016/j.seja.2025.100102

**[5]** Agent-Proxy, Available as Open-Source Software: https://github.com/DLR-SF/Agent-Proxy (07.07.2026)

**[6]** Agent-Directory, Available as Open-Source Software: https://github.com/DLR-SF/Agent-Directory (07.07.2026)