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Confidence-Based Maintenance Optimization in Digital Twins for Aging Sensor Networks

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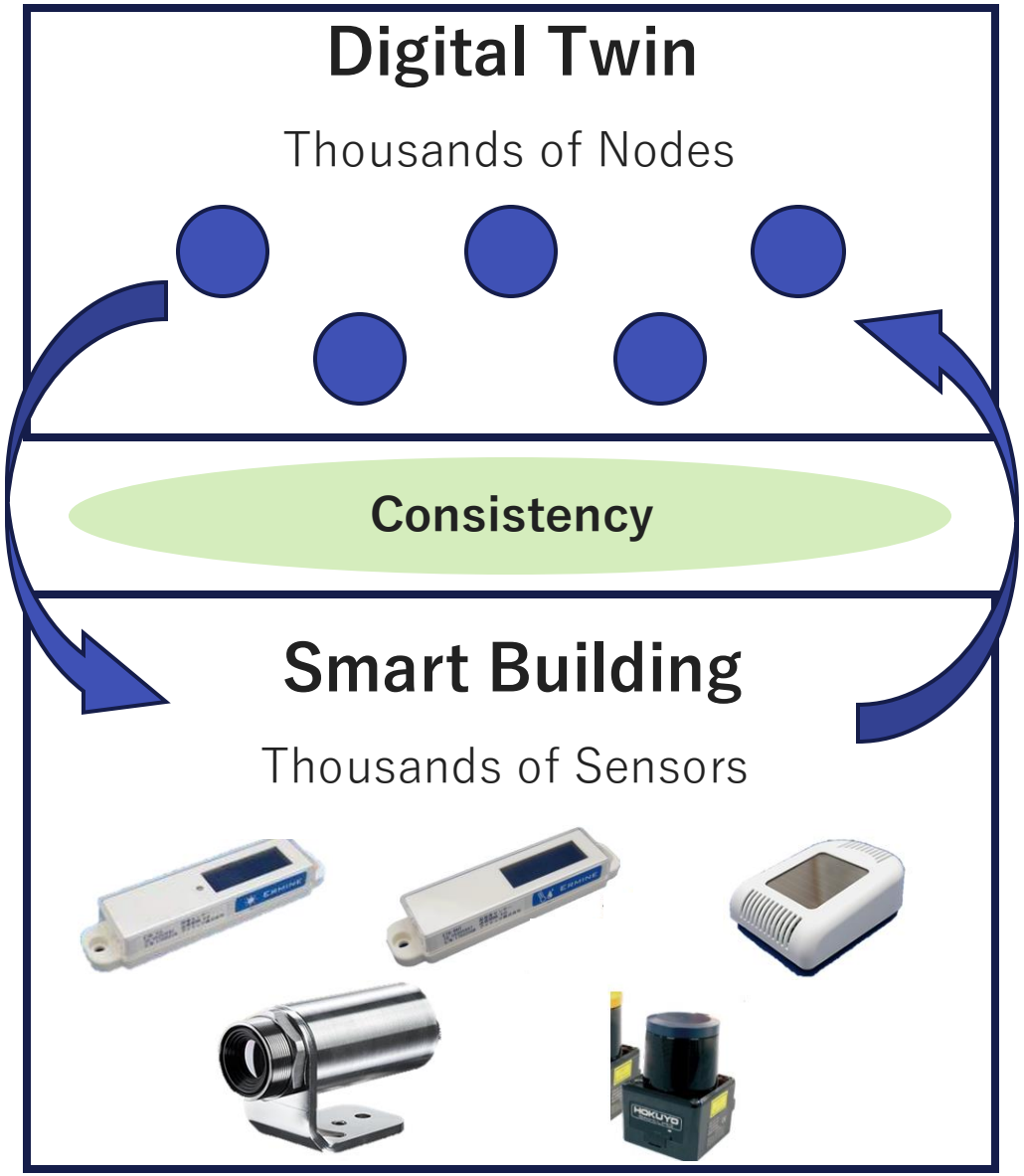
Massive Sensor Deployments

- Hundreds to thousands of IoT sensors in smart buildings.
- Extremely limited maintenance resources.

Essential for Digital Twins

- **Spatial and operational consistency** of these massive networks.



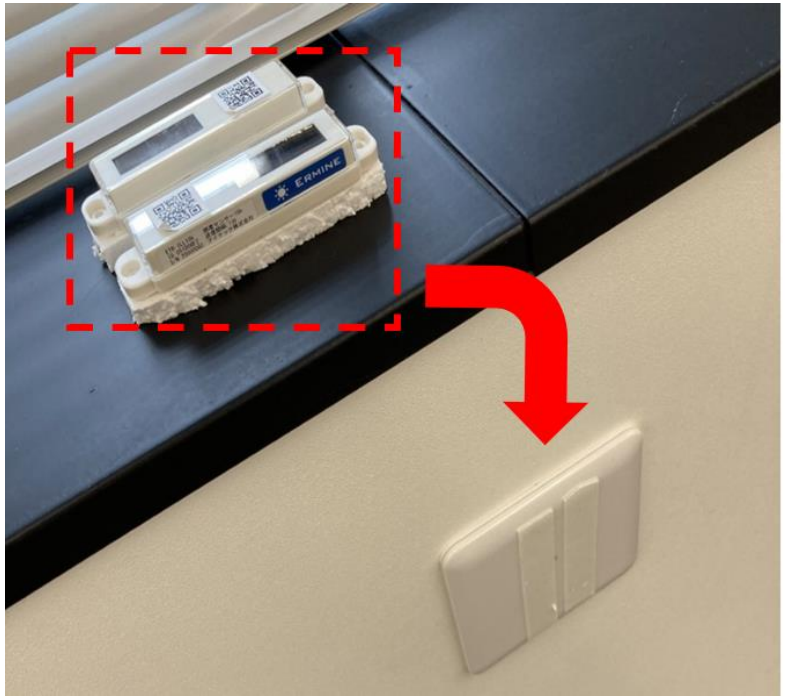
Network Aging over Time

Long-term operation leads to:

- **Sensor degradation**
  - Performance decline
- **Relocation errors**
  - Misplaced or detached due to human/environmental interference

The Consistency Gap:

A silent mismatch where the Digital Twin assumes a sensor is correct, while it has physically detached in the real world.



e.g., Sensor detached due to environmental interference

Limitations of Current Approaches

Time-based (TBM): Unrealistic cost and time for large-scale deployments.
Condition-based (CBM): Misses physical degradation if data appears normal.

Key Concept

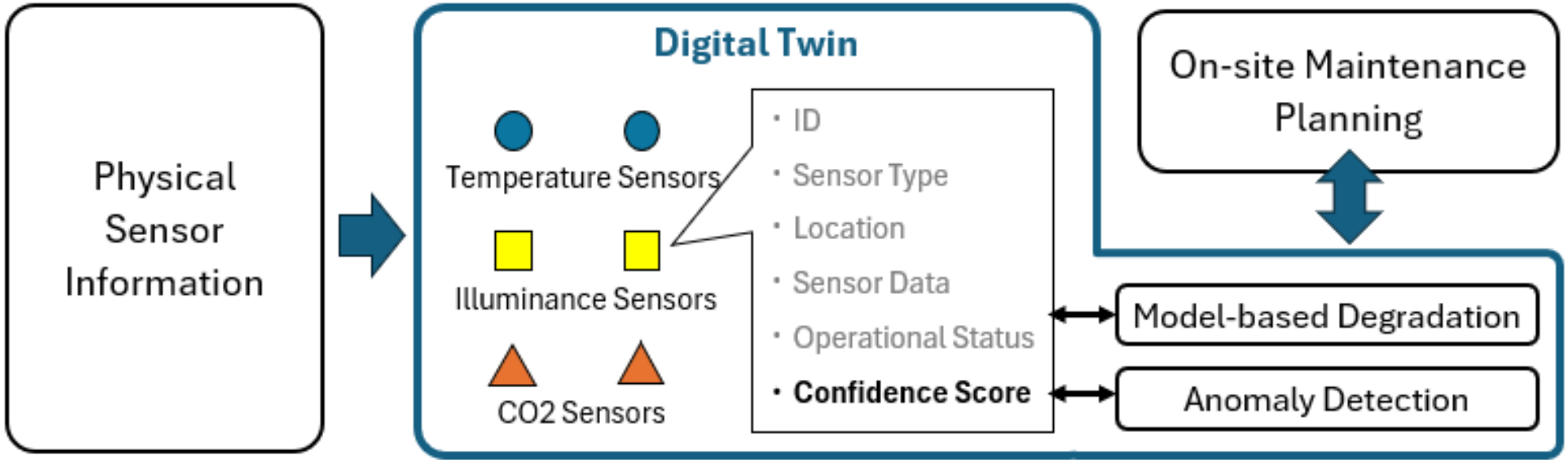
We assign each sensor property a **Confidence Score**:

Confidence = Probability that the sensor is still correct

- **Probabilistic Decay Modeling**: Quantifies hidden physical and operational decay as a Confidence Score.
- **Route Optimization**: Minimizes costs by planning paths only for sensors with low scores.

Workflow of the Proposed Maintenance Process

1. Assign Confidence Score:
Each sensor maintains a dynamic confidence value.
2. Dynamic Update:
Score decreases over time or upon anomaly detection.
3. Maintenance Optimization:
Prioritizes low-score sensors to plan cost-effective inspection routes.



Overall Confidence (S^d):

Joint probability that all $\mathbf{n}$ properties are consistent.
(In this study, n=2: **Placement** ($\mathrm{s_{loc}}^{\mathrm{d}}$) & **Operation**($\mathrm{s_{op}}^{\mathrm{d}}$))

$$S^d = \prod_{i=1}^{n} {s_i}^d$$

1. Placement Consistency ($\mathrm{s_{loc}}$)

- Models rare, independent misplacement events.
- Modeled as a **Poisson process** (rate λ).

$$\mathrm{s_{loc}}^{d} = \exp(-\lambda\,(t - t_0))$$

2. Operation Consistency ($\mathrm{s_{op}}$)

- Models hardware degradation and failure over time.
- Modeled via **Weibull distribution** (scale η, shape k)

$$\mathrm{s_{op}}^{d} = \exp(-\left((t - t_0)/\eta\right)^k)$$

Route Optimization and Score Update

1. Target Selection (Thresholding)

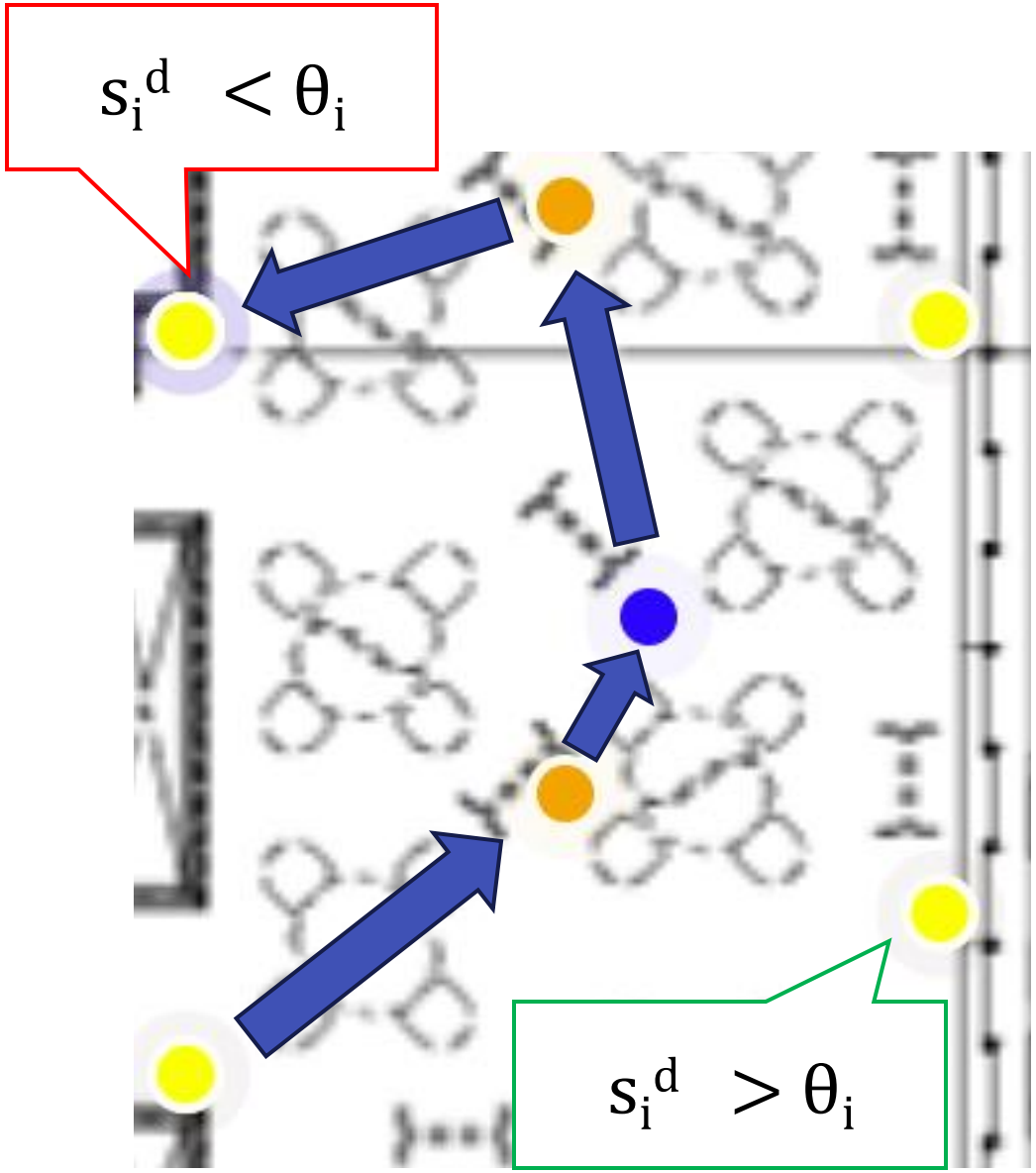
- Select property **i** of device **d** if $s_i^d < \theta_i$.
- Eliminates unnecessary inspections.

2. Route Optimization

- Minimizes movement cost between selected devices.
- Approximated using a greedy algorithm.

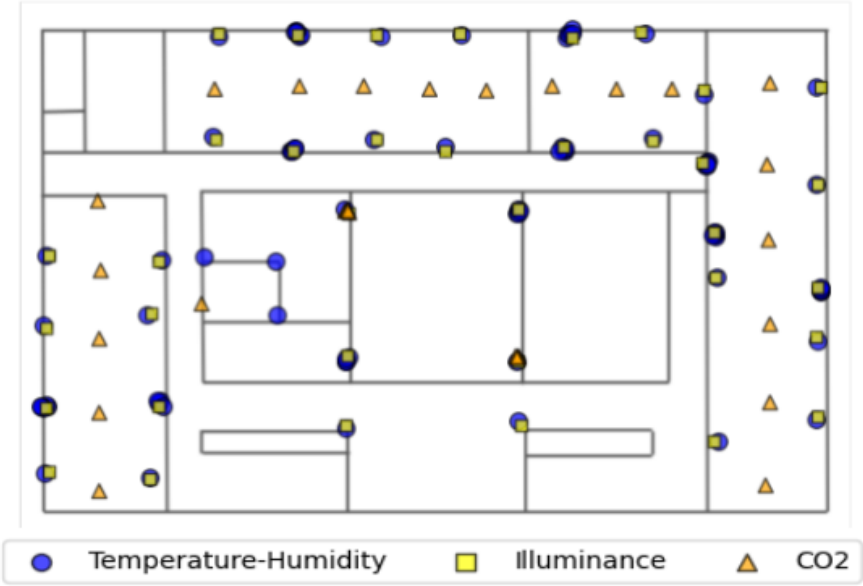
3. Confidence Score Update

- If property is verified/fixed: $s_i^d \leftarrow 1.0$ (Reset t_0 to t_{now}).
- Ensures the digital registry accurately reflects physical reality.



Target Environment

- Smart-campus digital twin (54m × 32.4m floor).
- 147 sensors: Temperature/Humidity, Illuminance, and CO_2.
- 1-year continuous operation simulation.



Evaluation Metrics

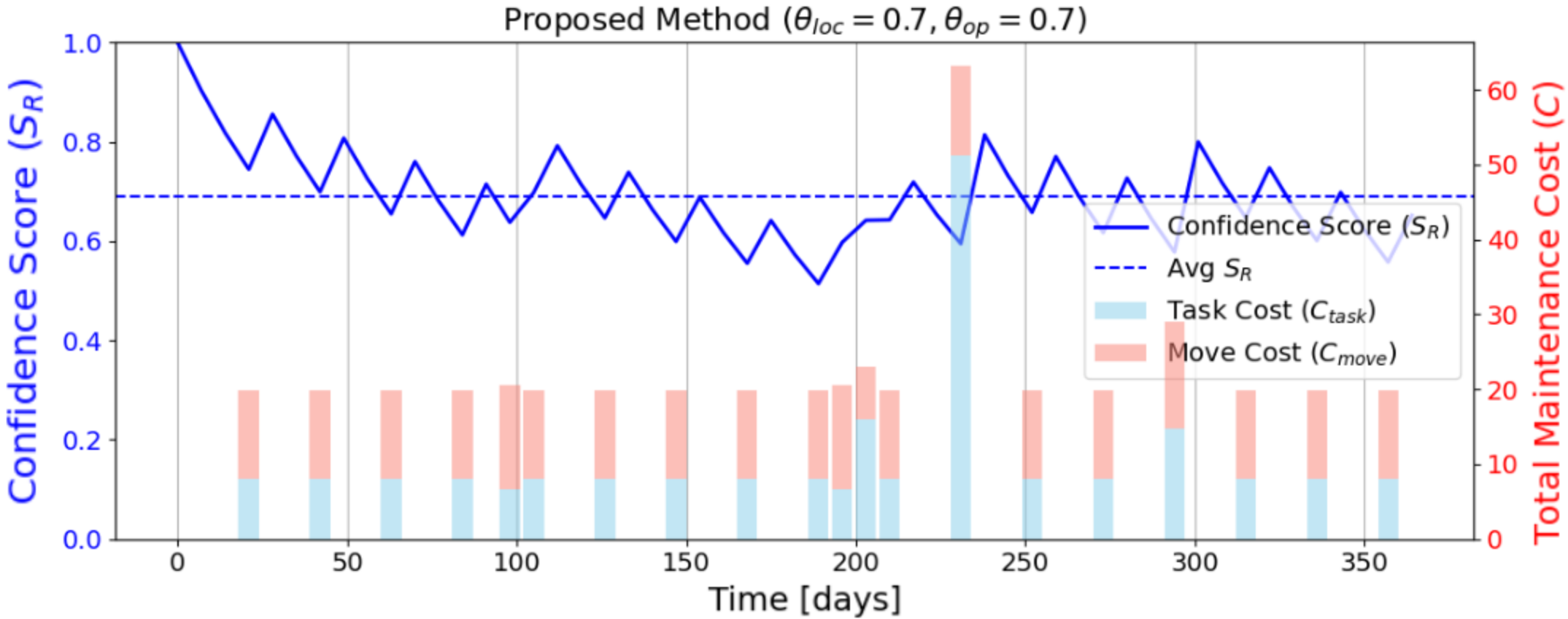
- Average Confidence (S_R)
- Total Maintenance Cost (USD)
  - Move Cost + Task Cost

Comparison Baselines (TBM)

- **Random Maintenance**: Inspects 25% or 50% of devices randomly.
- **Full Maintenance**: Inspects 100% of devices at fixed intervals.

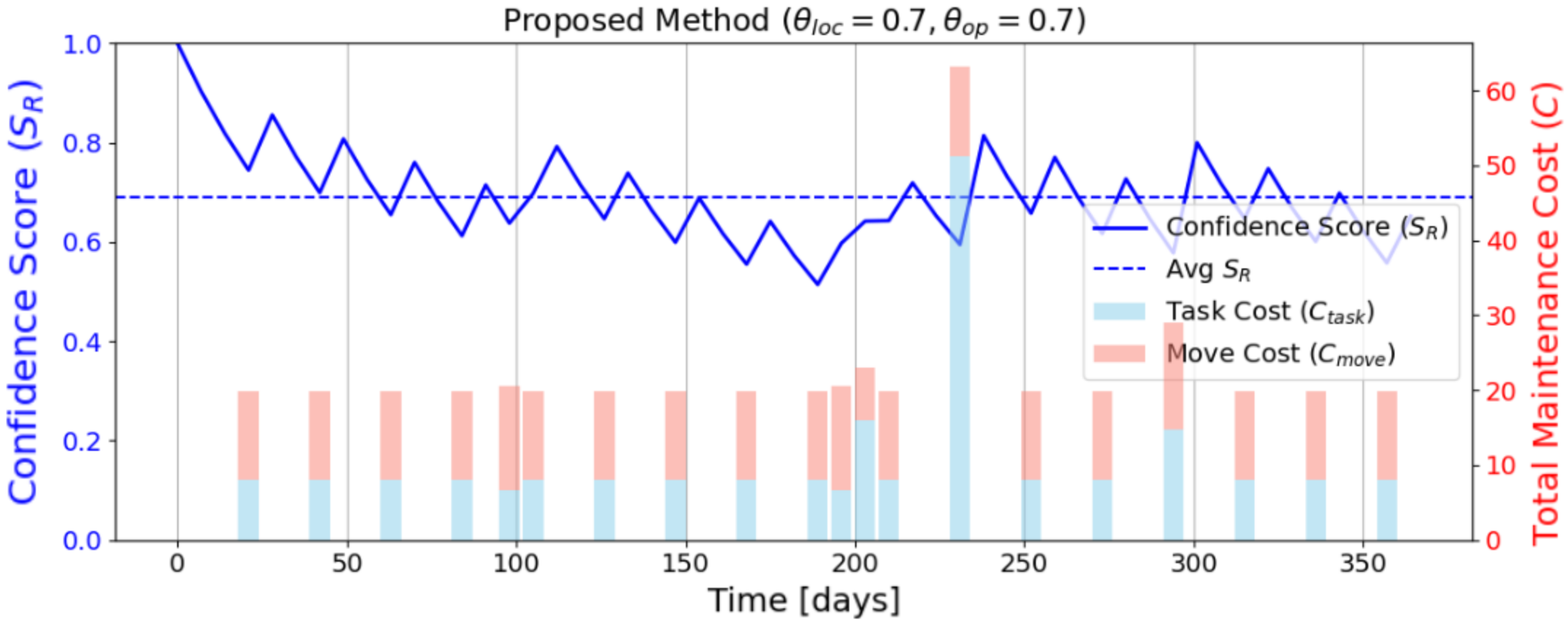
Simulation Results: Proposed Method over 1 Year

Consistent Confidence: Maintains high overall confidence (S_R) above the threshold throughout the year.



Simulation Results: Proposed Method over 1 Year

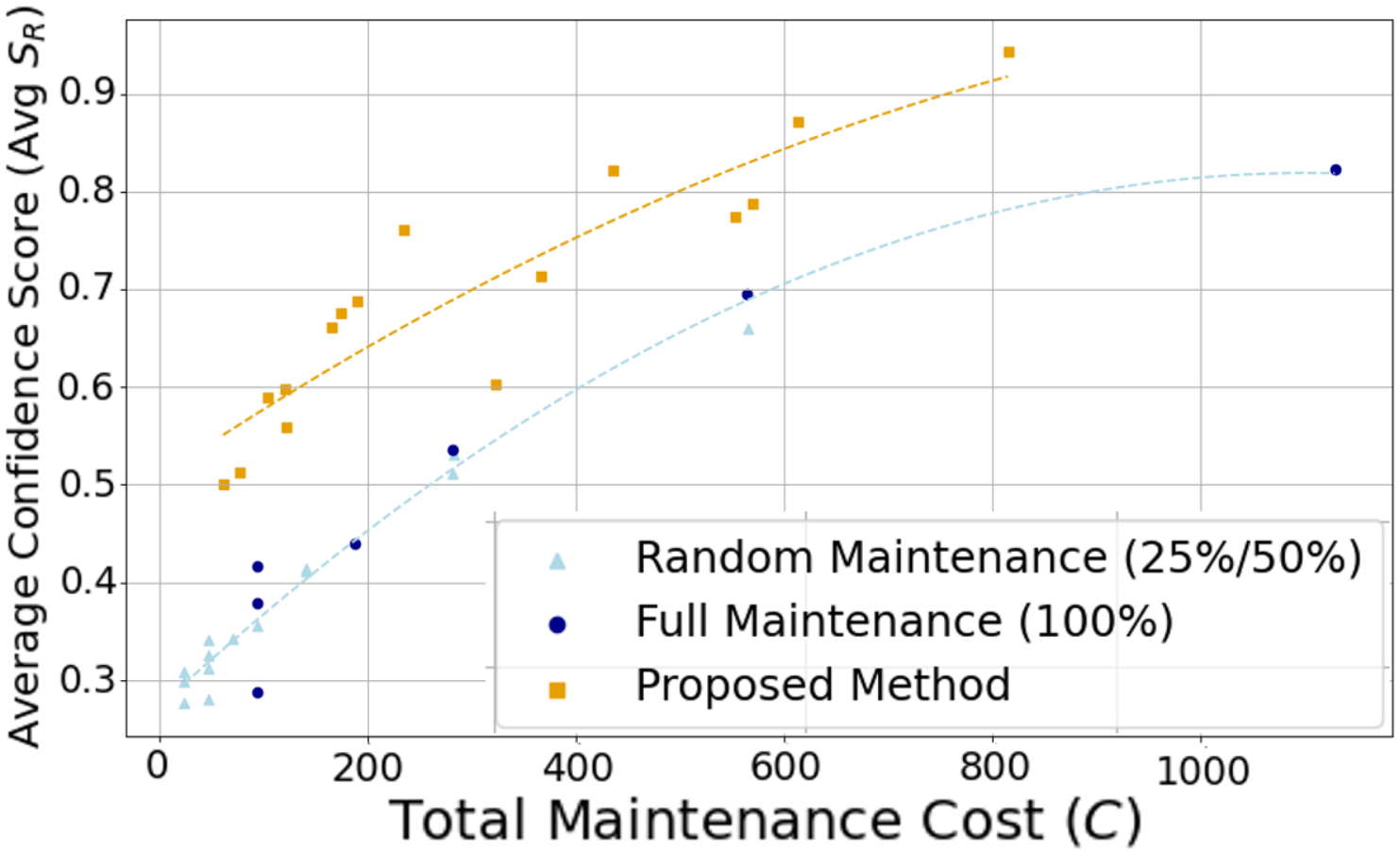
On-Demand Maintenance: Task and movement costs are incurred only when confidence drops, preventing unnecessary inspections.



Evaluation Results: Cost vs. Confidence Trade-off

Higher Efficiency

- Proposed method (orange squares) consistently lies above the baselines.
- Achieves higher average confidence (S_R) for similar or lower costs (C).



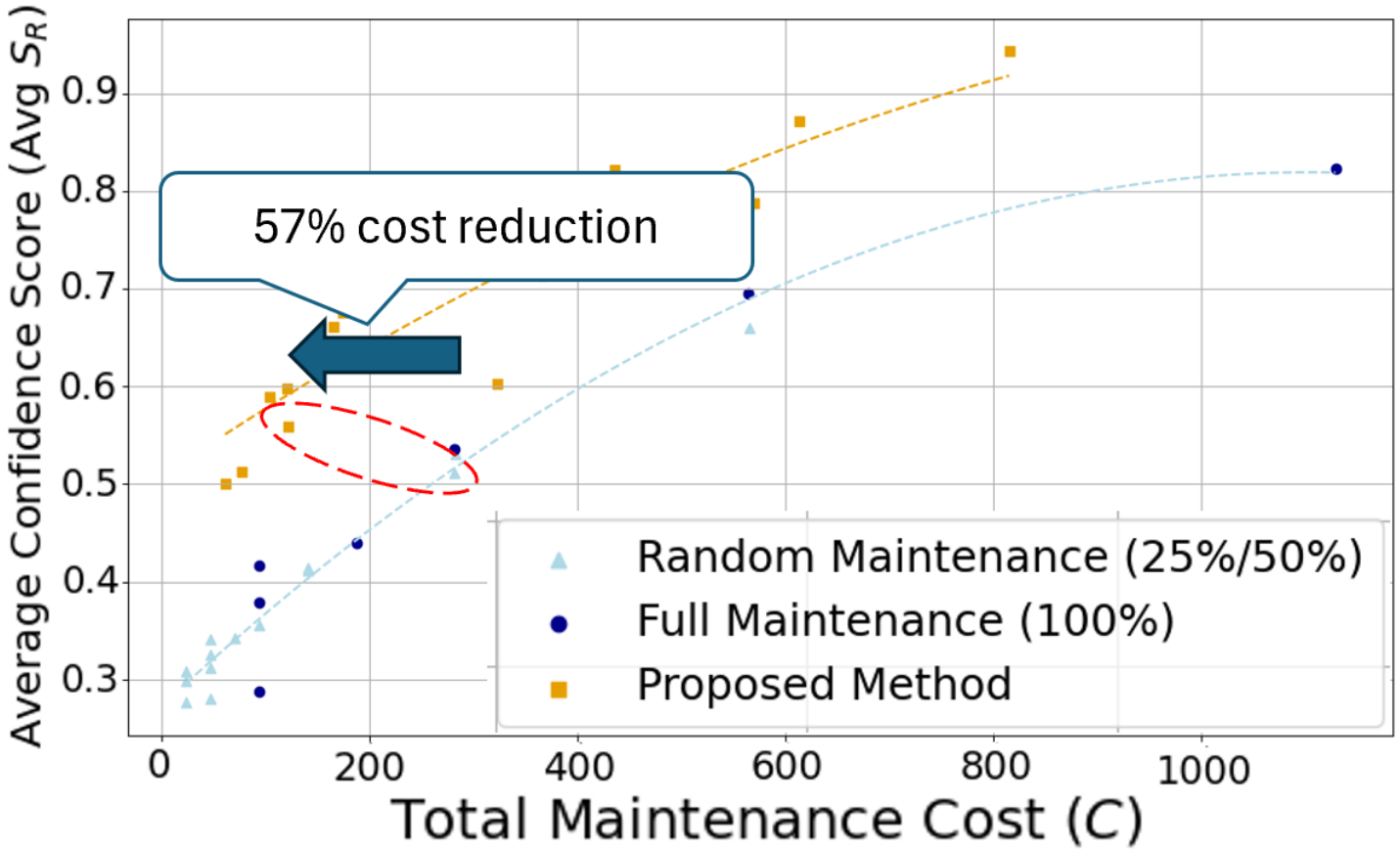
Evaluation Results: Cost vs. Confidence Trade-off

1. Significant Cost Reduction (vs. Random)

Proposed: Mean $S_R = 0.559$, Cost = 122 USD

Random (50% / 60 days): Mean $S_R = 0.531$, Cost = 283 USD

→ Achieved a **57% cost reduction** with a comparable confidence level.

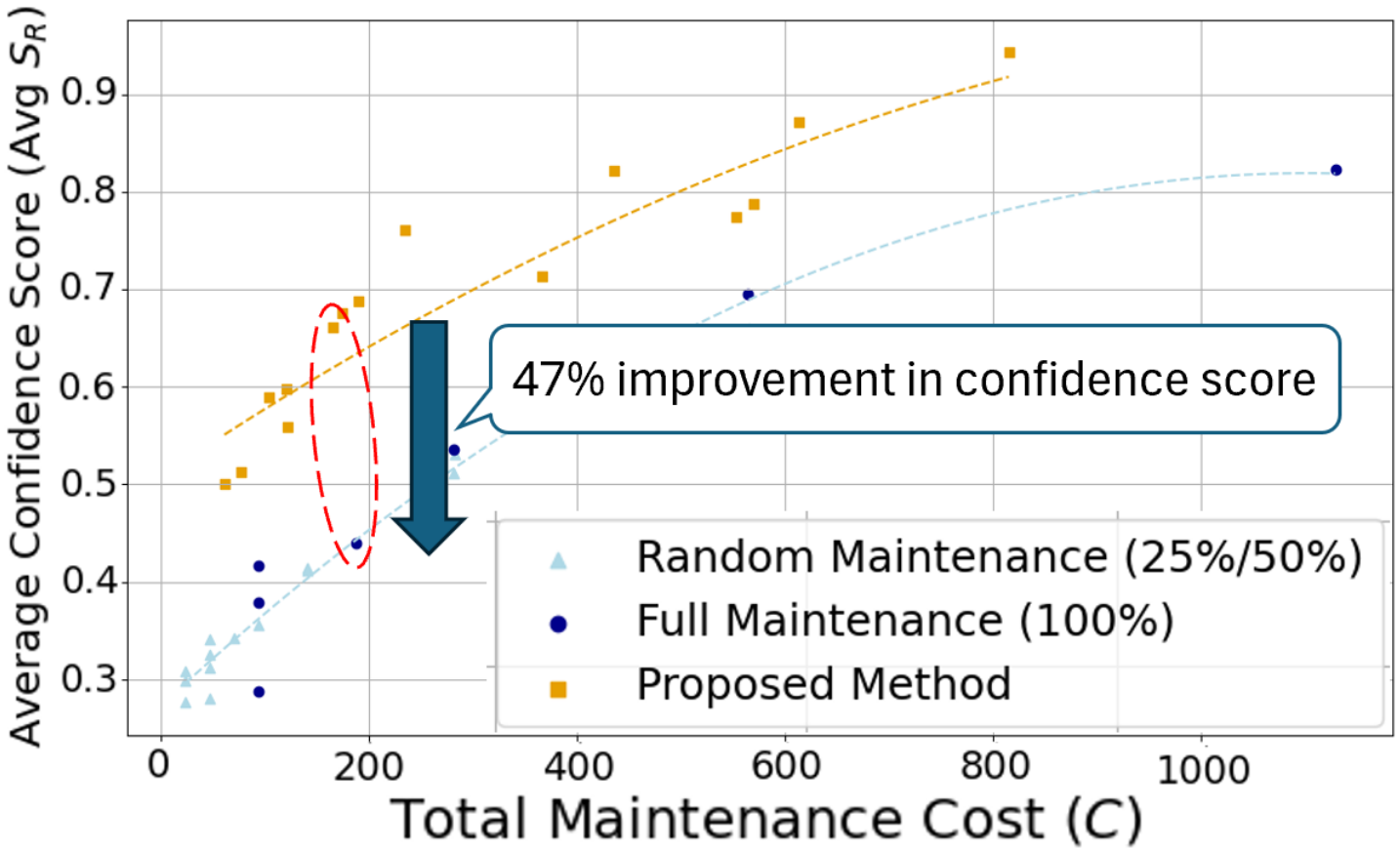


2. Significant Confidence Improvement (vs. Full)

Proposed: Mean $S_R = 0.661$, Cost = 165 USD

Full (100% / 180 days): Mean $S_R = 0.440$, Cost = 188 USD

→ Achieved a **47% confidence improvement** with a maintenance cost.



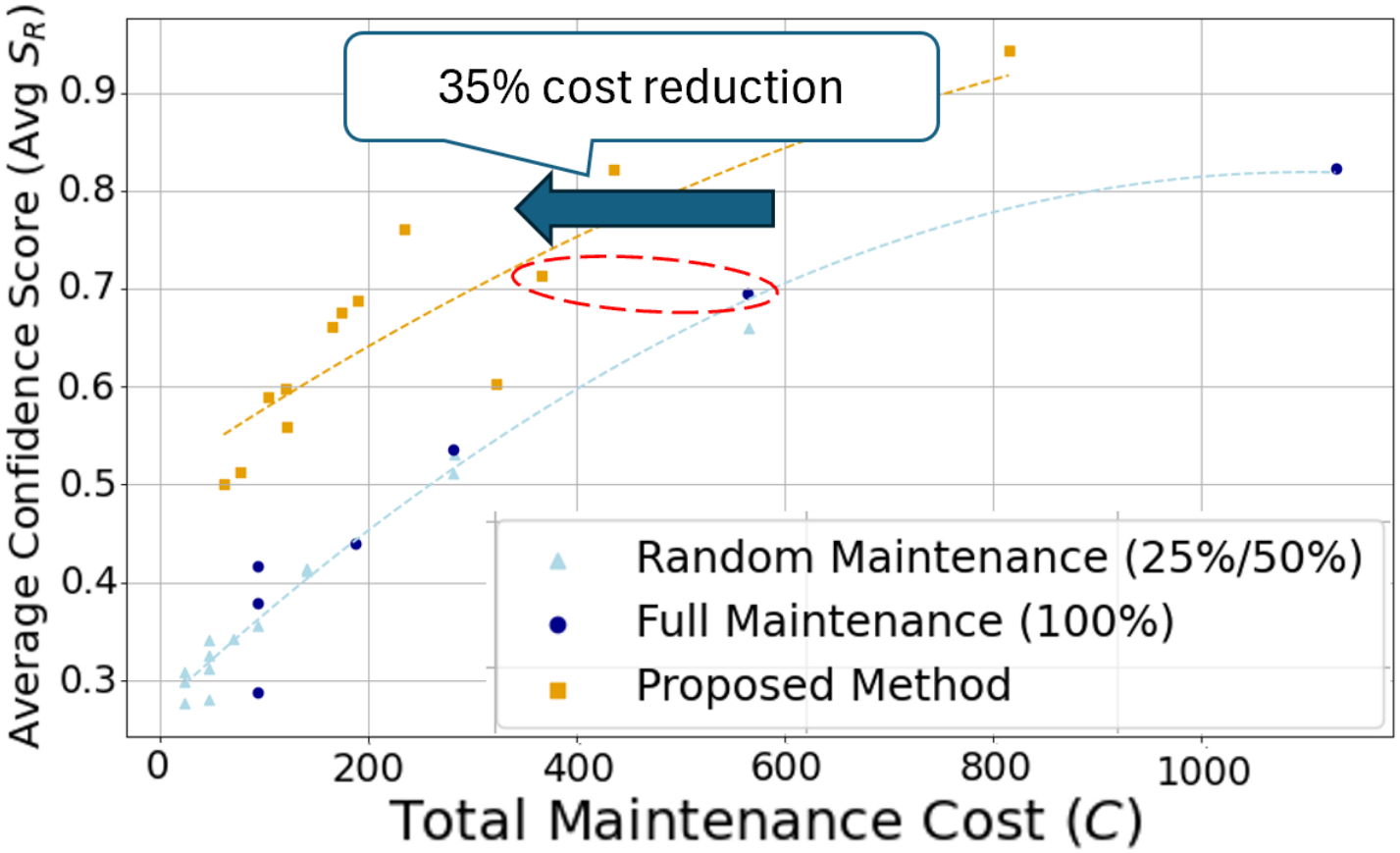
Evaluation Results: Cost vs. Confidence Trade-off

3. Significant Cost Reduction (vs. Full)

Proposed: Mean S_R = 0.714, Cost = 367 USD

Full (100% / 60 days): Mean S_R= 0.696, Cost = 565 USD

→ Achieved a **35% cost reduction** with a comparable confidence level.



Integration with Interactive DT Application

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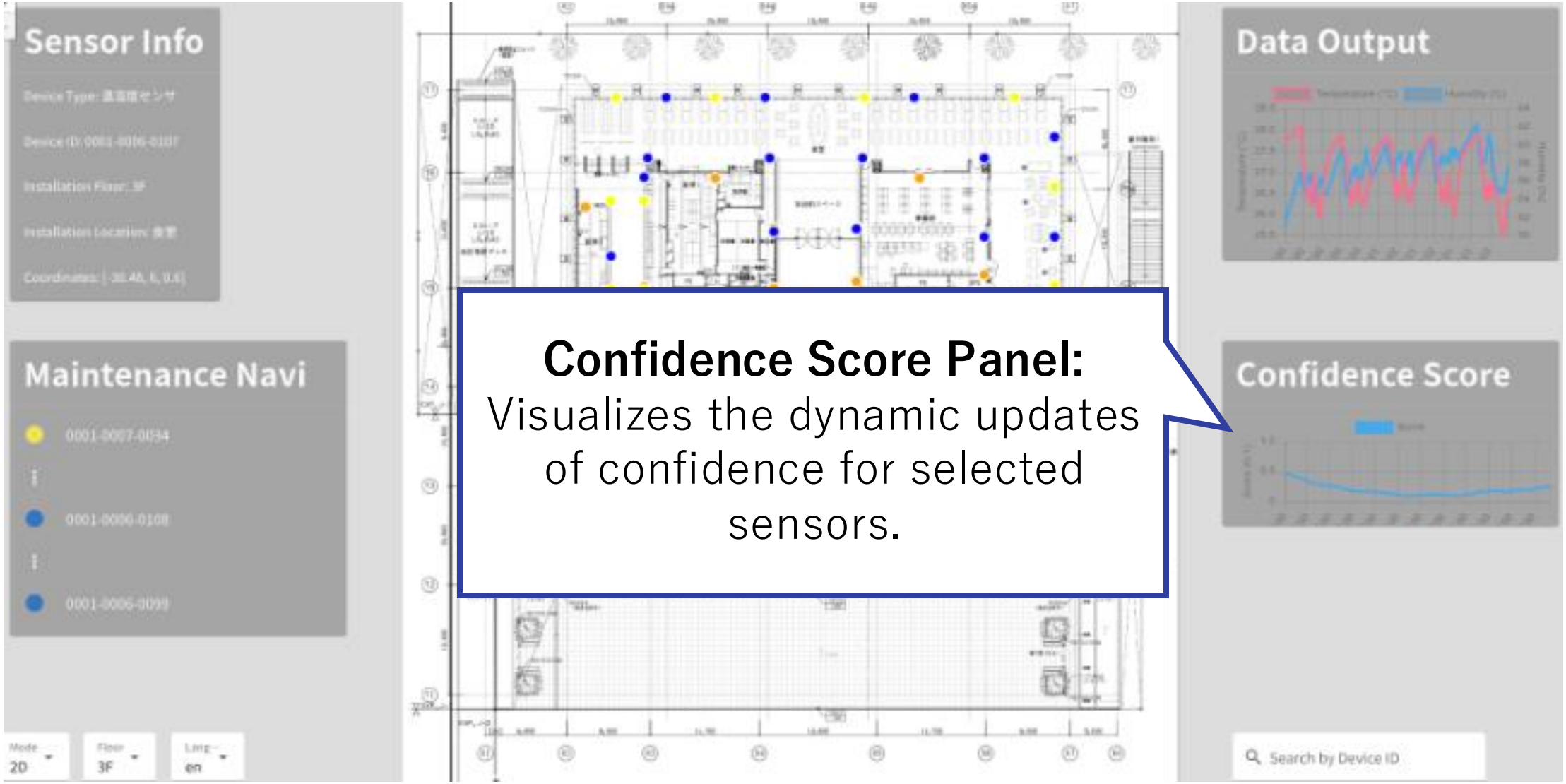
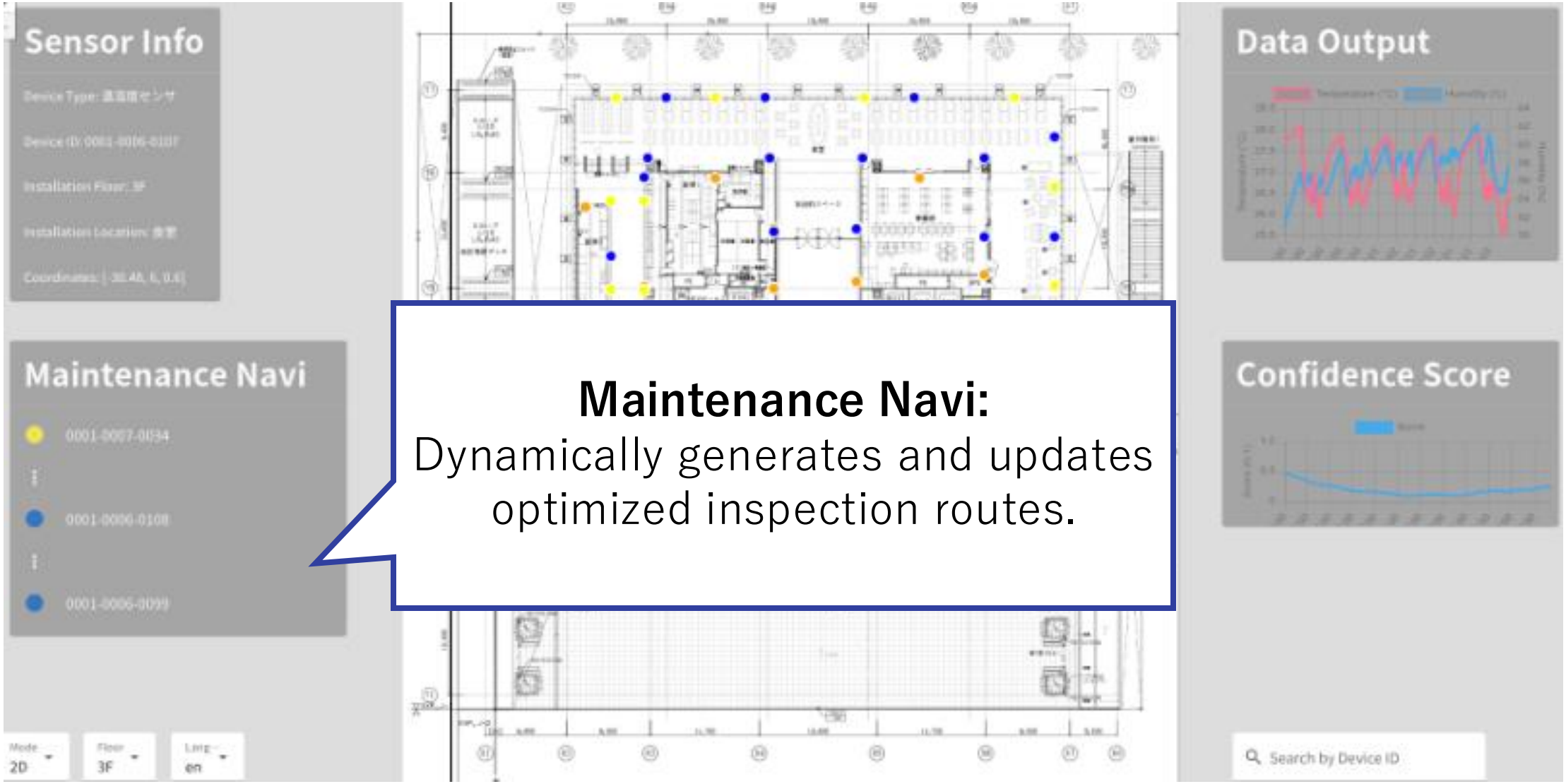


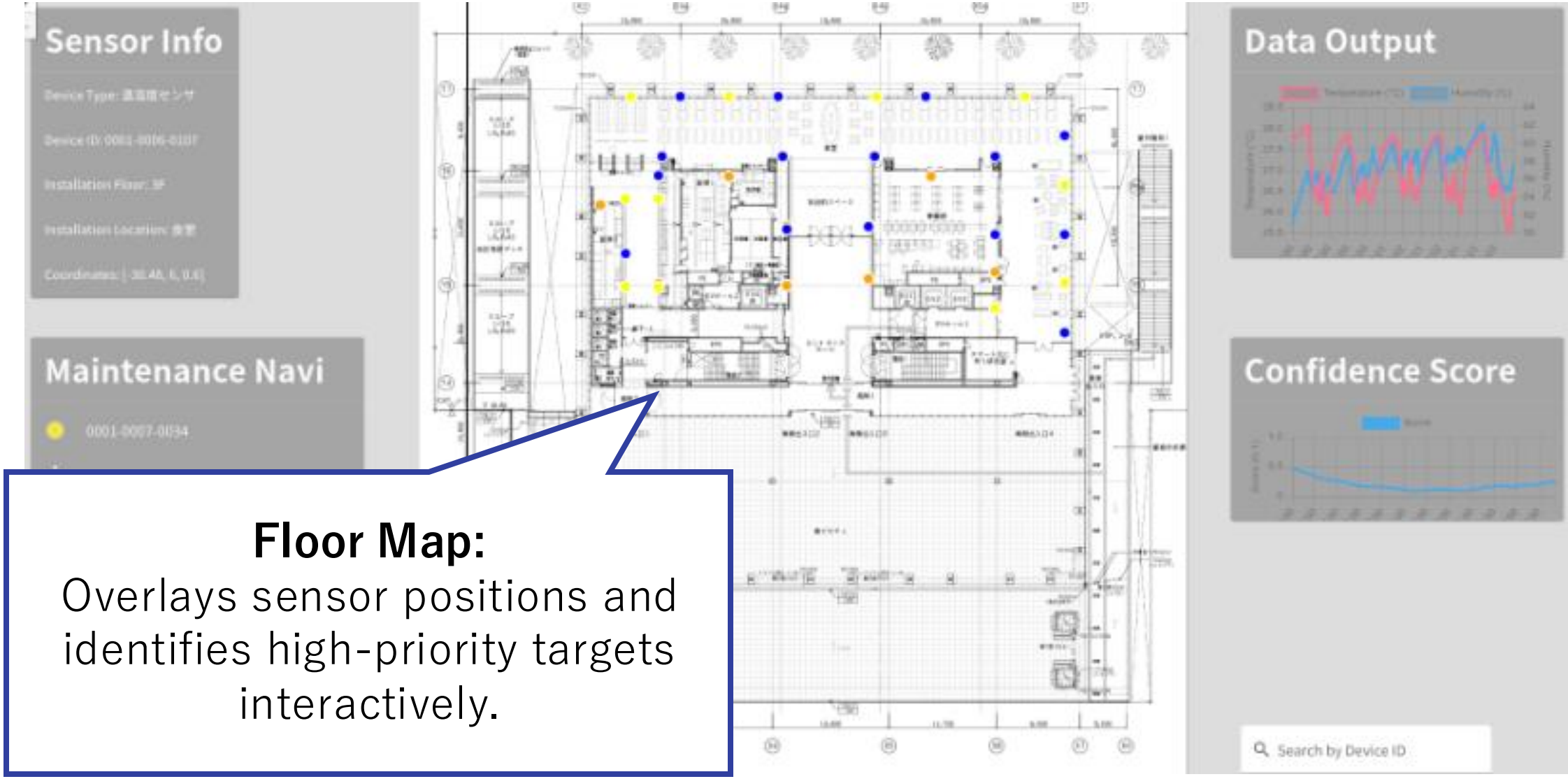
Confidence Score Panel:
Visualizes the dynamic updates of confidence for selected sensors.

Integration with Interactive DT Application



Maintenance Navi:
Dynamically generates and updates optimized inspection routes.

Integration with Interactive DT Application



Floor Map:
Overlays sensor positions and identifies high-priority targets interactively.

Conclusion

- Proposed a confidence-based maintenance framework for DTs.
- Integrated probabilistic modeling and route optimization.
- Achieved up to **57% cost reduction** maintaining high reliability.

Future Work

- **Extend properties:**
  Incorporate power supply and communication status into the score.
- **Information value:**
  Optimize routing based on uncertainty reduction (Information Gain).