Data-Driven Approach for Modelling the Deterioration and Planning Interventions on Infrastructure

Zachary Hamida, Ph.D.

Postdoctoral Researcher
Polytechnique Montréal, Canada
Department of Civil, Geological and Mining Engineering (CGM)

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Transportation Ministry of Quebec (MTQ)

Outline

Context

Deterioration Model based on Visual Inspections

Planning Maintenance

Reinforcement Learning Framework

Preliminary Results

Definitions

Visual Inspections (VI): Network-scale monitoring technique

Source: Google images

Definitions

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Network:

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Network: $\left\{ \underbrace{\quad}_{\text{Bridge \#001}}, \underbrace{\quad}_{\text{Bridge \#002}}, \ldots, \underbrace{\quad}_{\text{Bridge \#10}K} \right\}$

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Definitions

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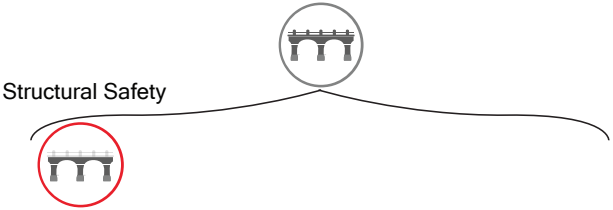
Network: $\left\{ \underbrace{\quad}_{\text{Bridge \#001}}, \underbrace{\quad}_{\text{Bridge \#002}}, \ldots, \underbrace{\quad}_{\text{Bridge \#10}K} \right\} \Longrightarrow$

Source: Google images

Data Hierarchy

Source: MTQ, Manual of Inspection

Data Hierarchy



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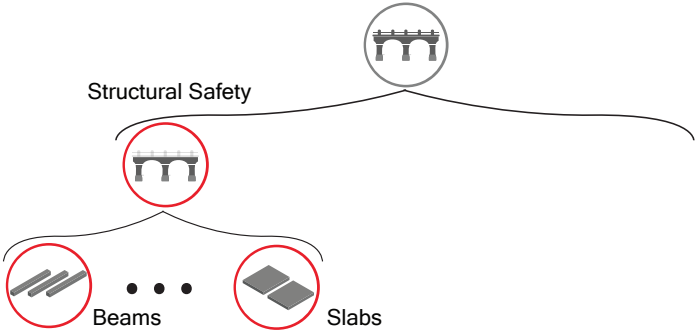

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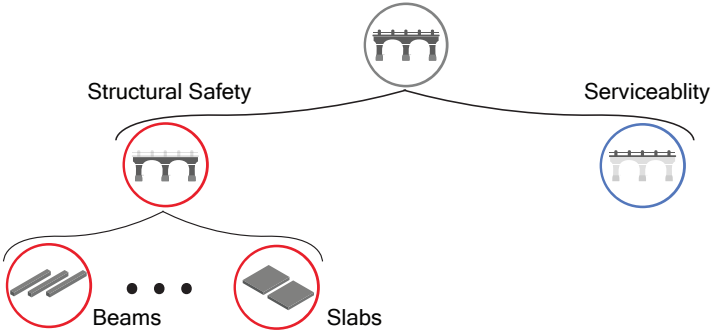

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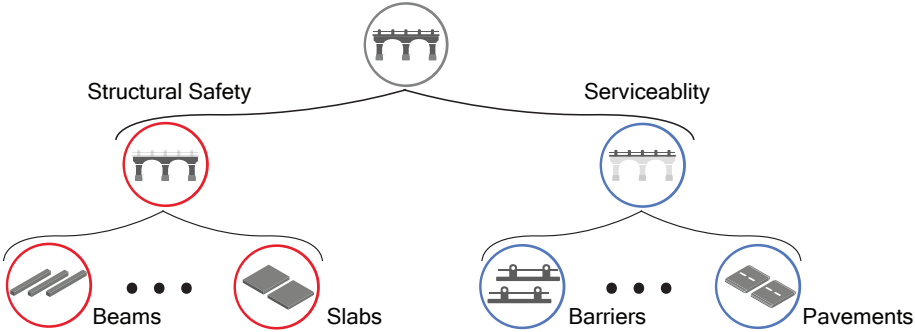

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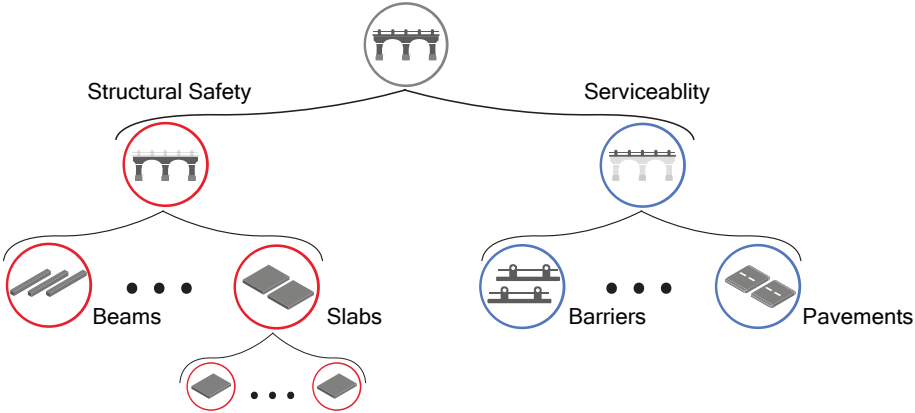

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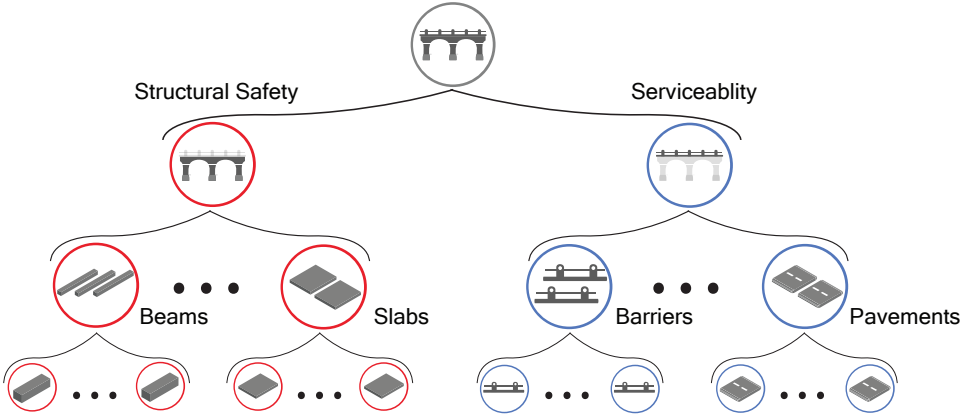

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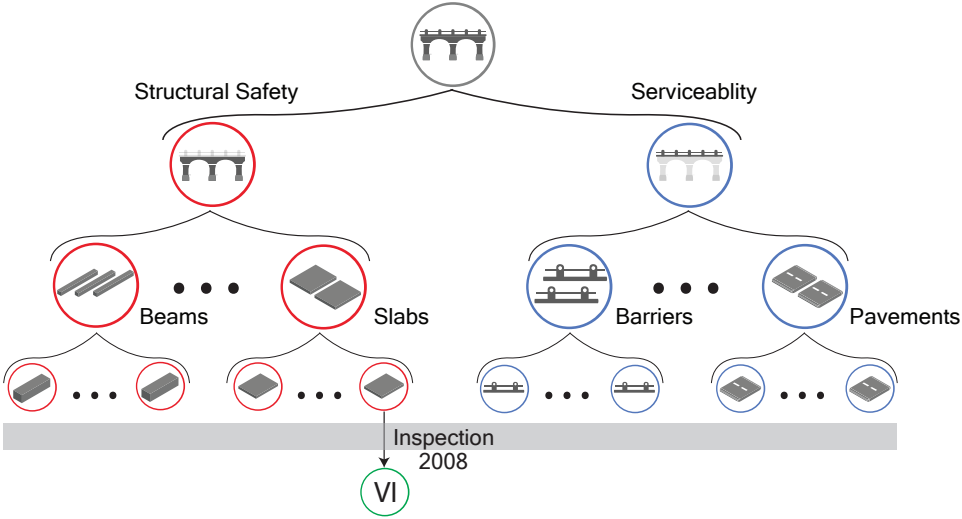

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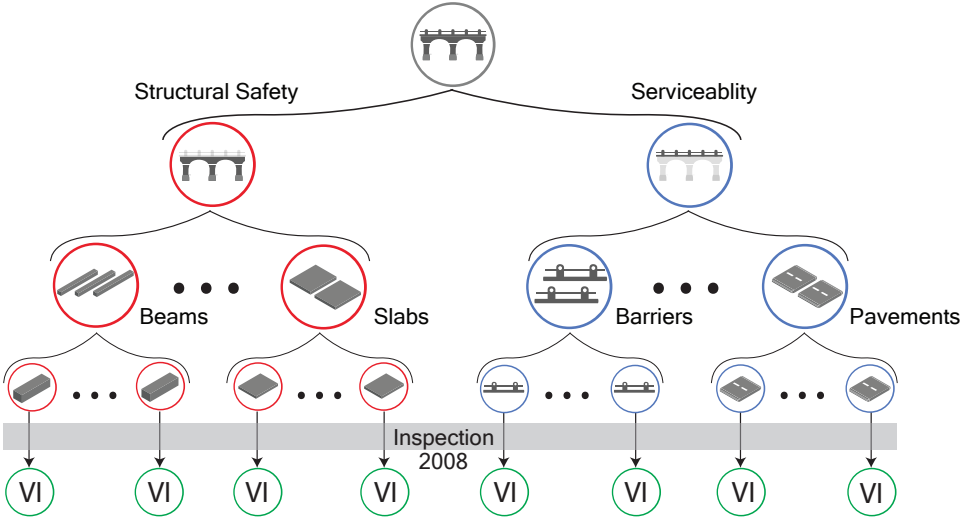

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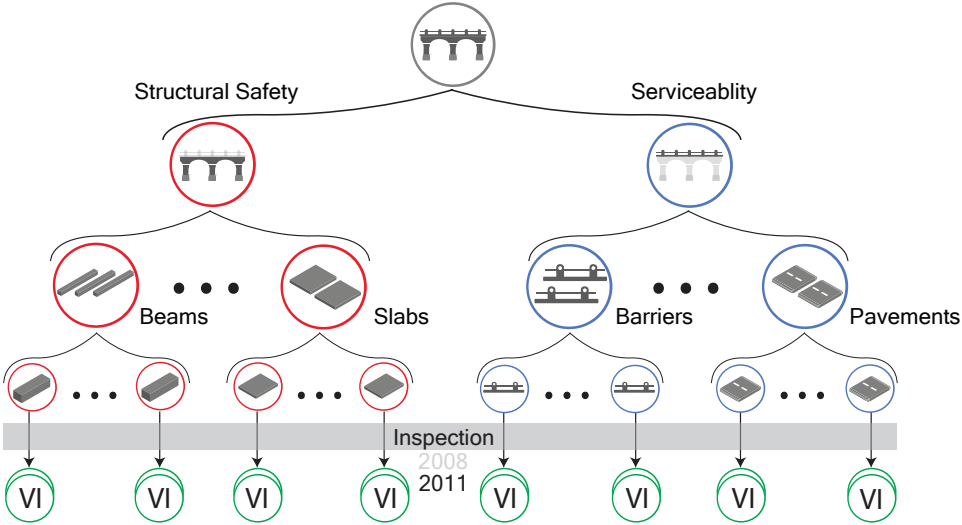

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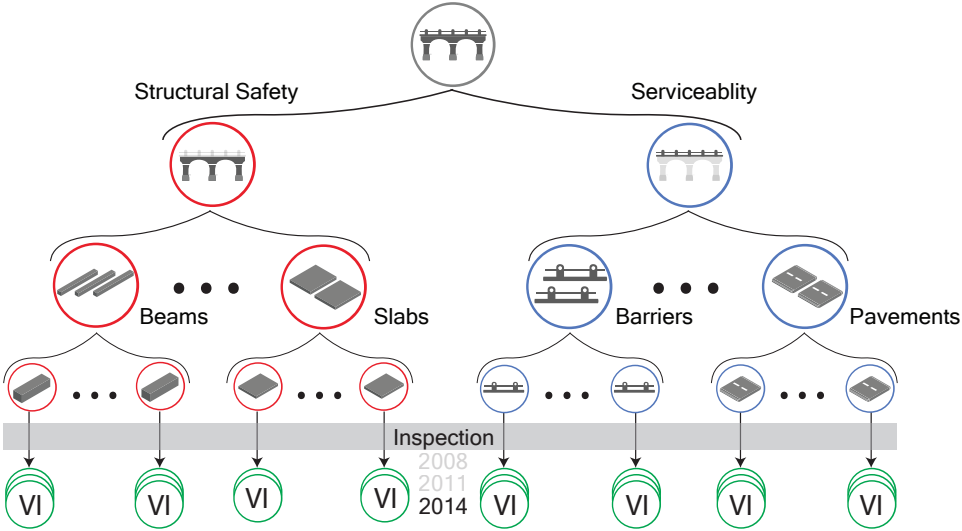

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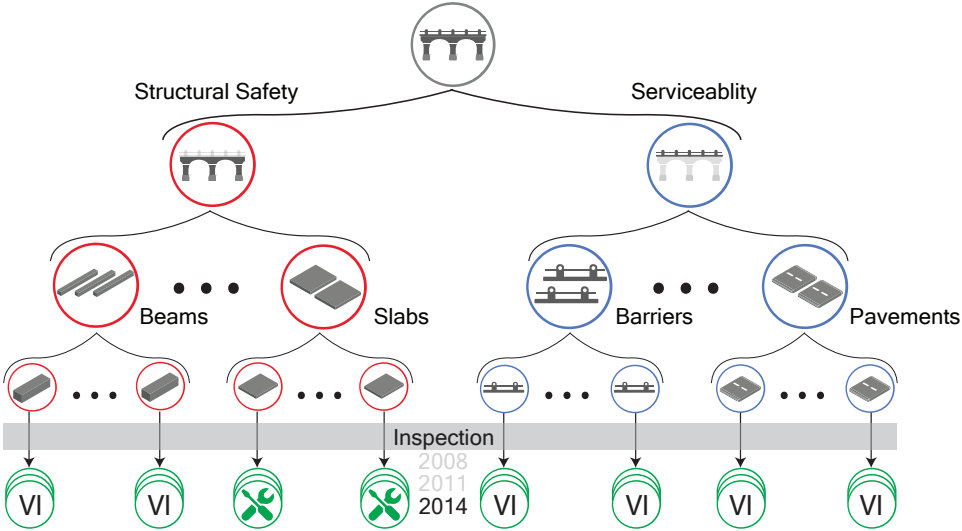

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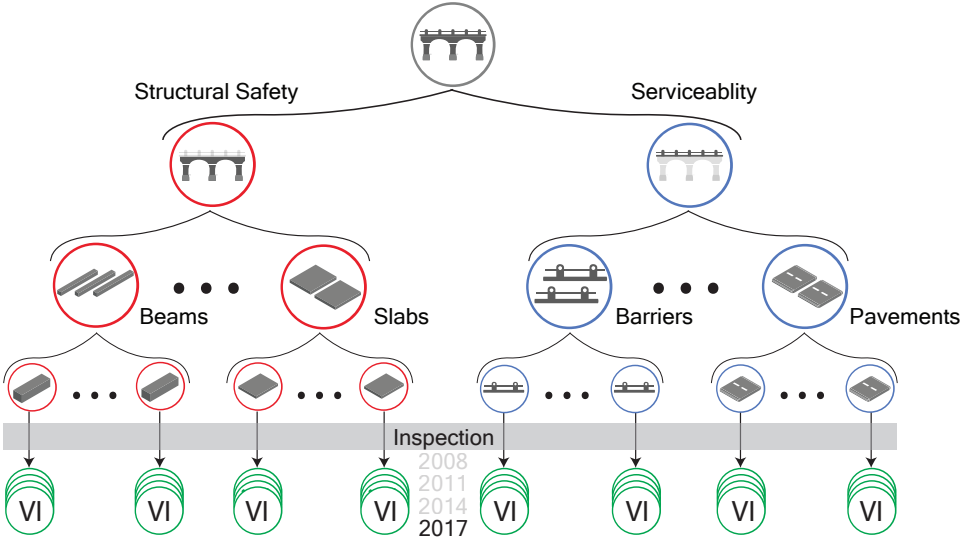

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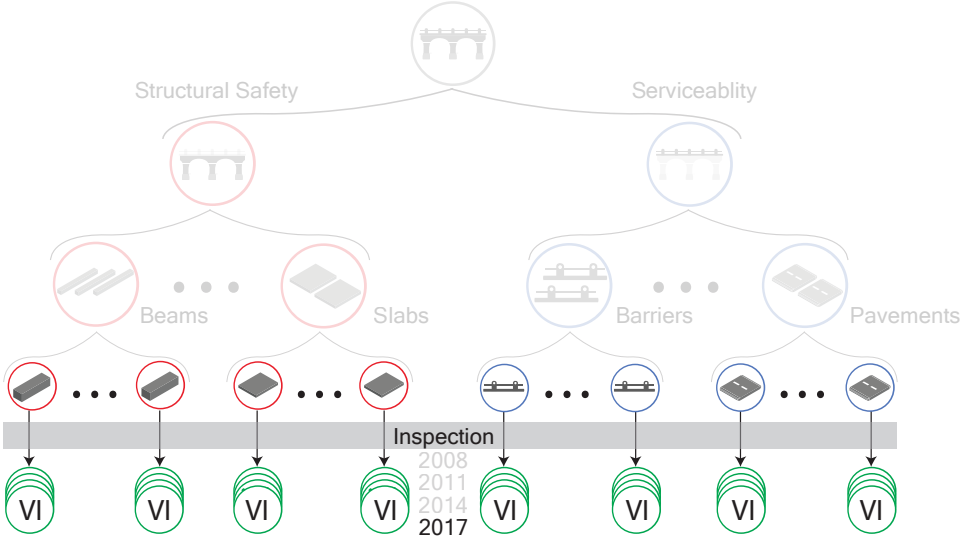

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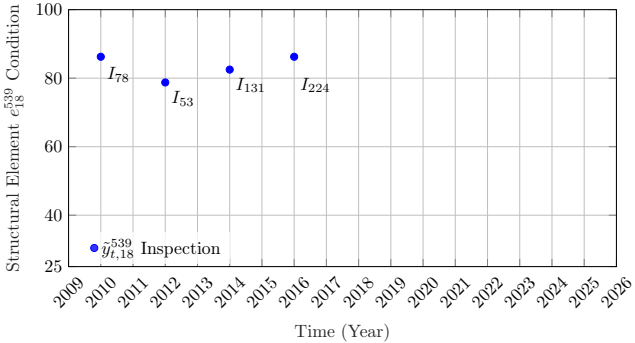
Example of Visual Inspections on a Structural Element



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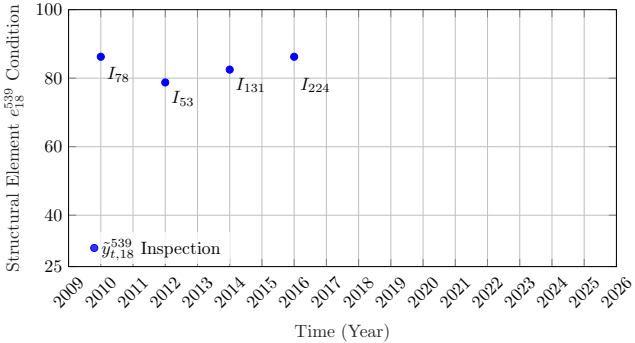

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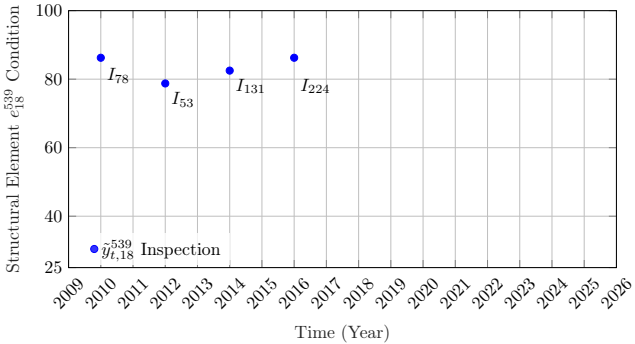
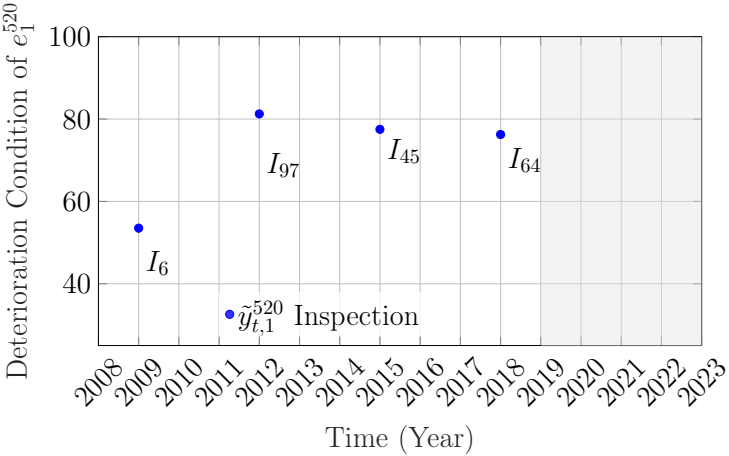


- ☑ Limited data.
- ☑ Subjective (high variability + different inspectors).

Example of Visual Inspections with an Intervention



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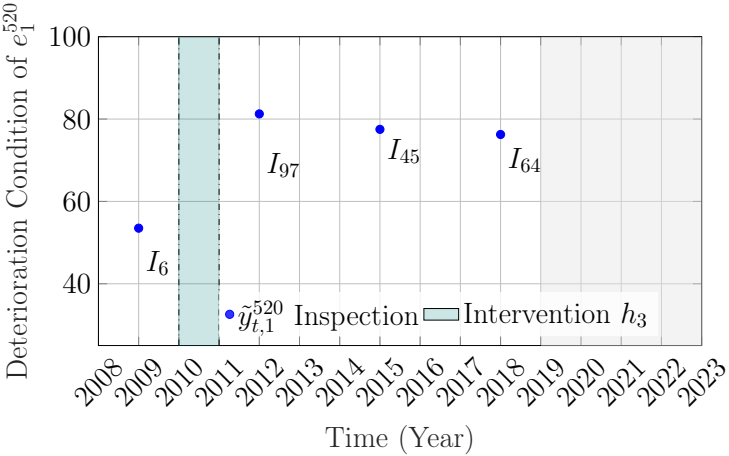

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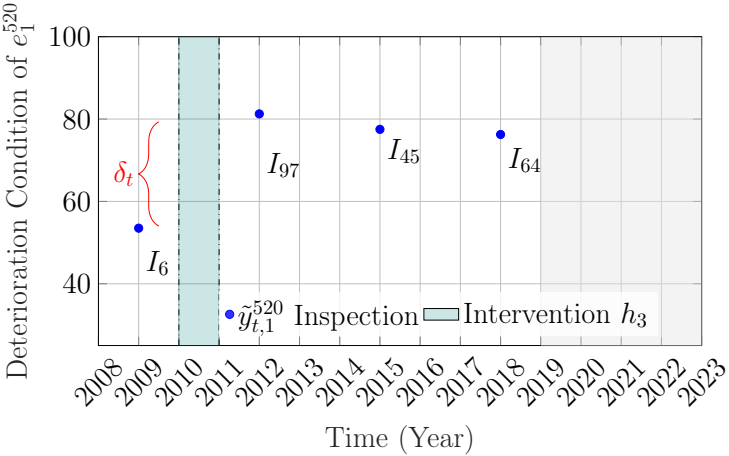

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- Quantify the **effect of interventions** on structural elements.
- Design a **decision-making** framework for network-scale maintenance.

Deterioration Behaviour Described by Kinematics

$$\overbrace{x_{t+1} = x_t + \dot{x}_t \Delta t + \frac{1}{2}\ddot{x}_t \Delta t^2 + w \quad \text{(Condition)}}^{\text{Kinematic Equations}}$$

Source: Hamida and Goulet, 2020

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$$\overbrace{\begin{aligned} x_{t+1} &= x_t + \dot{x}_t \Delta t + \tfrac{1}{2}\ddot{x}_t \Delta t^2 + w && \text{(Condition)} \\ \dot{x}_{t+1} &= \dot{x}_t + \ddot{x}_t \Delta t + \dot{w} && \text{(Speed)} \end{aligned}}^{\text{Kinematic Equations}}$$

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$$\underbrace{\begin{bmatrix} x_t \\ \dot{x}_t \\ \ddot{x}_t \end{bmatrix}}_{\boldsymbol{x}_t} = \underbrace{\begin{bmatrix} 1 & \Delta t & \frac{\Delta t^2}{2} \\ 0 & 1 & \Delta t \\ 0 & 0 & 1 \end{bmatrix}}_{\boldsymbol{A}} \cdot \underbrace{\begin{bmatrix} x_{t-1} \\ \dot{x}_{t-1} \\ \ddot{x}_{t-1} \end{bmatrix}}_{\boldsymbol{x}_{t-1}} + \underbrace{\begin{bmatrix} w_t \\ \dot{w}_t \\ \ddot{w}_t \end{bmatrix}}_{\boldsymbol{w}_t}$$

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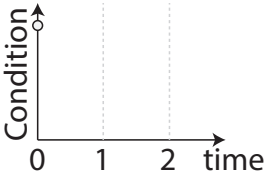

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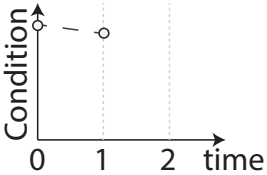

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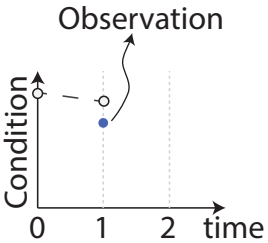

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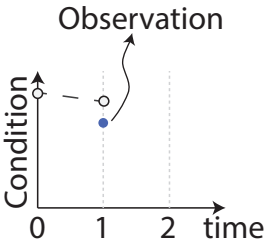

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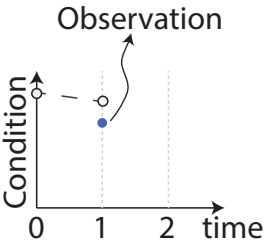

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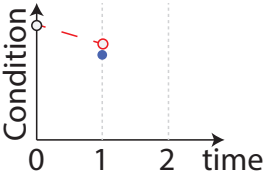

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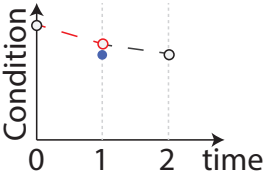

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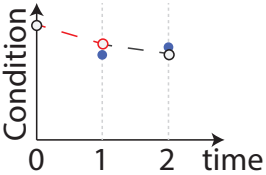
$$\overbrace{y_t = \boldsymbol{C}\boldsymbol{x}_t + v_t}^{\textbf{observation model}}, \quad \underbrace{v_t : V \sim \mathcal{N}(v; 0, \sigma_V^2)}_{\textbf{observation error}}$$



Source: Hamida and Goulet, 2020

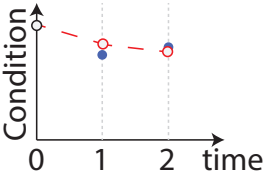
Deterioration Behaviour Described by Kinematics

$$\underbrace{\begin{bmatrix} x_t \\ \dot{x}_t \\ \ddot{x}_t \end{bmatrix}}_{\boldsymbol{x}_t} = \underbrace{\begin{bmatrix} 1 & \Delta t & \frac{\Delta t^2}{2} \\ 0 & 1 & \Delta t \\ 0 & 0 & 1 \end{bmatrix}}_{\boldsymbol{A}} \cdot \underbrace{\begin{bmatrix} x_{t-1} \\ \dot{x}_{t-1} \\ \ddot{x}_{t-1} \end{bmatrix}}_{\boldsymbol{x}_{t-1}} + \underbrace{\begin{bmatrix} w_t \\ \dot{w}_t \\ \ddot{w}_t \end{bmatrix}}_{\boldsymbol{w}_t}$$

Method: State-Space Models

$$\overbrace{\boldsymbol{x}_t = \boldsymbol{A}\boldsymbol{x}_{t-1} + \boldsymbol{w}_t}^{\textbf{transition model}}, \quad \underbrace{\boldsymbol{w}_t : \boldsymbol{W} \sim \mathcal{N}(\boldsymbol{w}; \boldsymbol{0}, \boldsymbol{Q}_t)}_{\textbf{process error}}$$

$$\overbrace{y_t = \boldsymbol{C}\boldsymbol{x}_t + v_t}^{\textbf{observation model}}, \quad \underbrace{v_t : V \sim \mathcal{N}(v; 0, \sigma_V^2)}_{\textbf{observation error}}$$



Source: Hamida and Goulet, 2020

Uncertainty of Observations (Inspectors)

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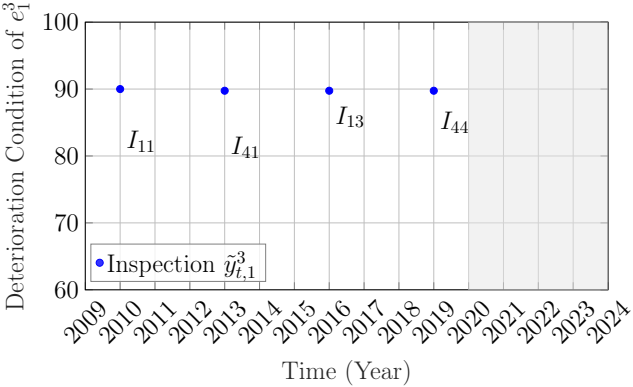
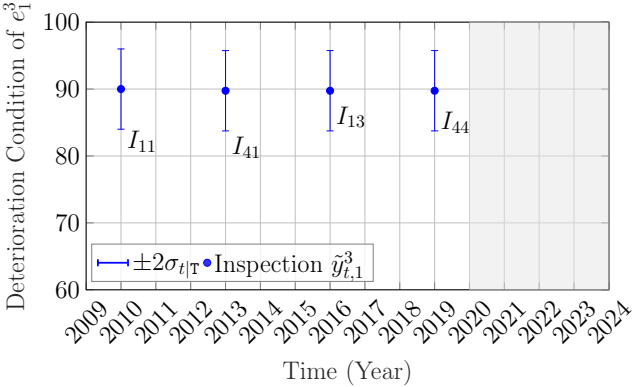


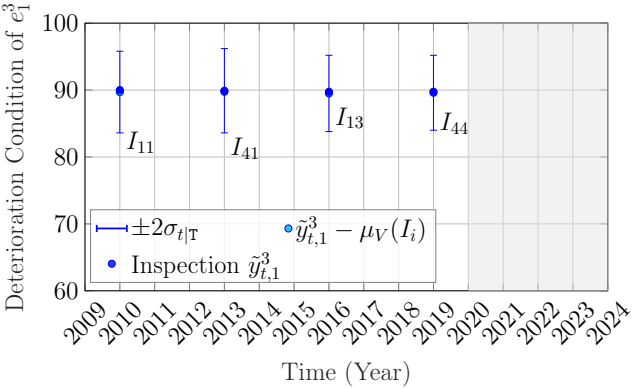
$$\overbrace{y_t = \boldsymbol{C}\boldsymbol{x}_t + v_t}^{\text{observation model}}, \quad \underbrace{v_t : V \sim \mathcal{N}(v; 0, \sigma_V^2)}_{\text{observation error}}$$

Uncertainty of Observations (Inspectors)



$$\overbrace{y_t = \boldsymbol{C}\boldsymbol{x}_t + v_t}^{\text{observation model}}, \quad \underbrace{v_t : V \sim \mathcal{N}(v; 0, \sigma_V^2)}_{\text{observation error}}$$

Uncertainty of Observations (Inspectors)



$$\overbrace{y_t = \boldsymbol{C}\boldsymbol{x}_t + v_t}^{\text{observation model}}, \quad \underbrace{v_t : V(I_i) \sim \mathcal{N}(v; \mu_V(I_i), \sigma_V^2(I_i))}_{\text{observation error}}$$

Synthetic Inspection Data

Synthetic Inspections

$\approx$

Real Inspections

Synthetic Inspection Data

Synthetic Inspections

$\approx$

Real Inspections

- ☑ Same number of elements.

Synthetic Inspection Data

Synthetic Inspections

$\approx$

Real Inspections

- ☑ Same number of elements.
- ☑ Same number of inspectors.

Synthetic Inspection Data

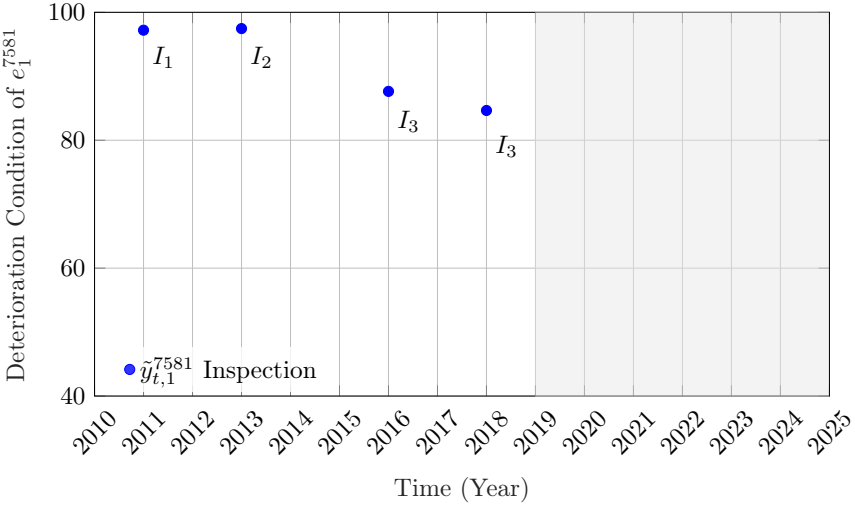
Synthetic Inspections

$\approx$

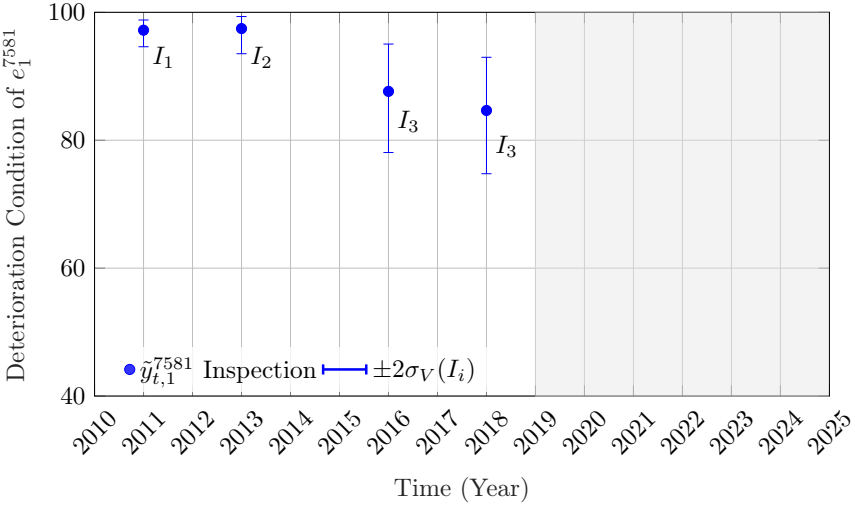
Real Inspections

- ☑ Same number of elements.
- ☑ Same number of inspectors.
- ☑ Same number of inspections per element.

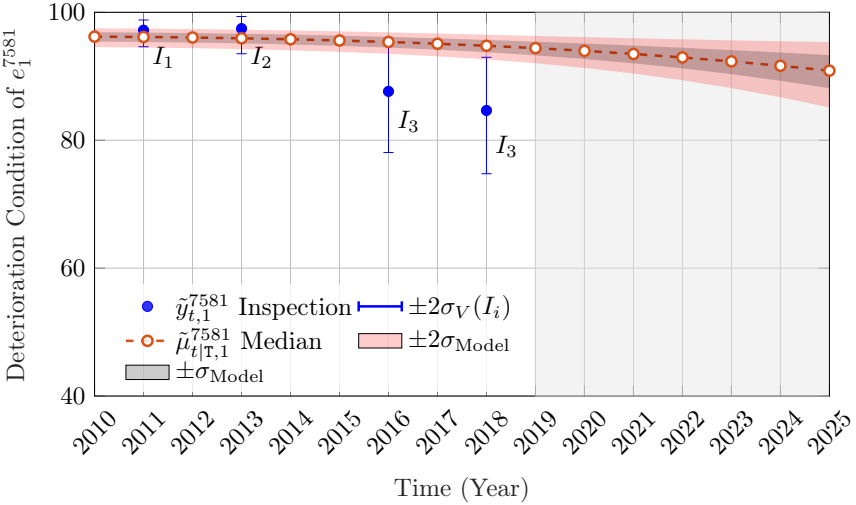
Structural Element - Synthetic Data



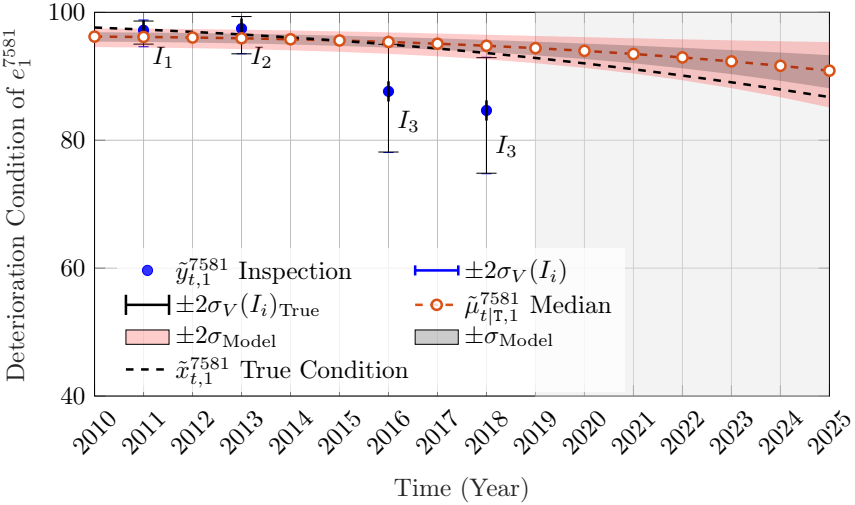
Structural Element - Synthetic Data



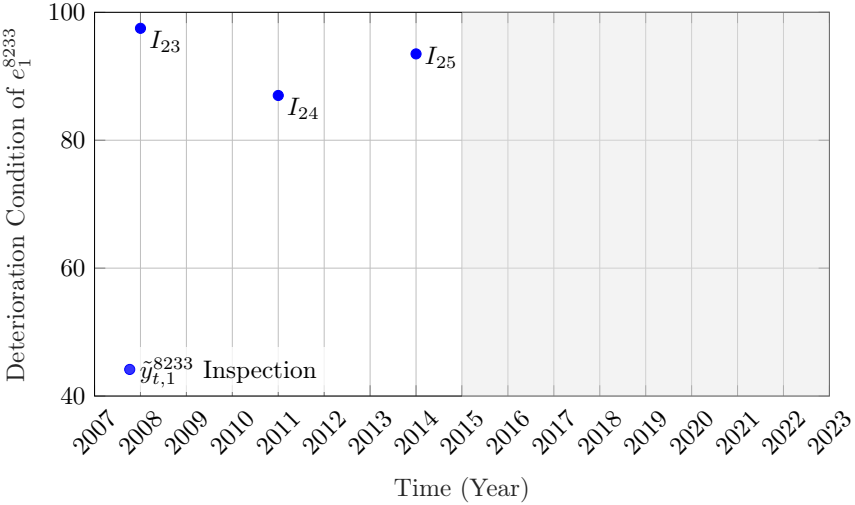
Structural Element - Synthetic Data



Structural Element - Synthetic Data

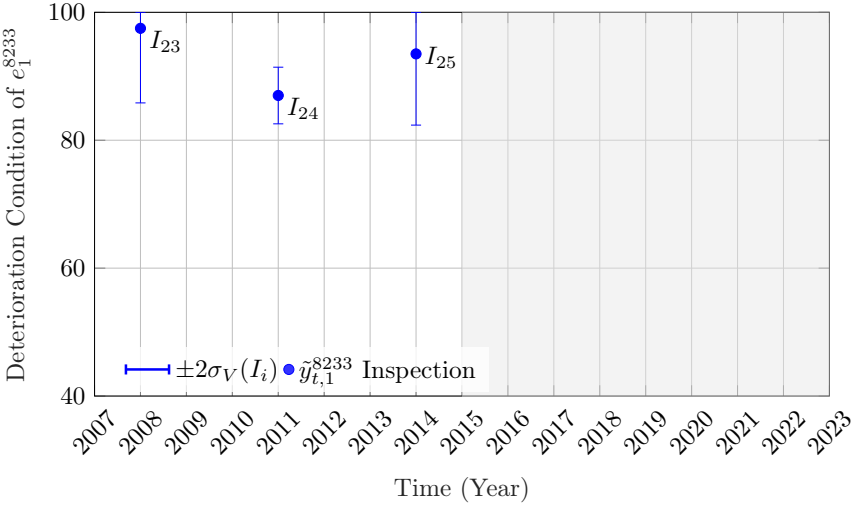


Beam Structural Element - Real Data



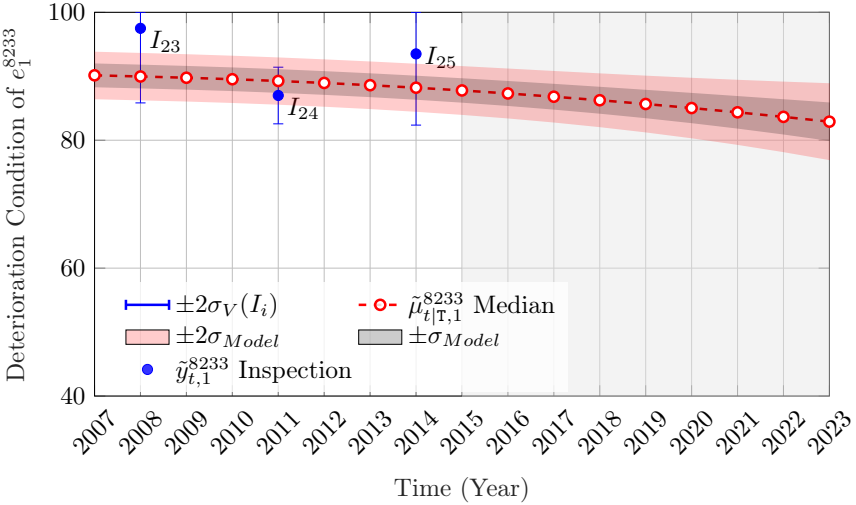
Source: Hamida and Goulet, 2020

Beam Structural Element - Real Data



Source: Hamida and Goulet, 2020

Beam Structural Element - Real Data



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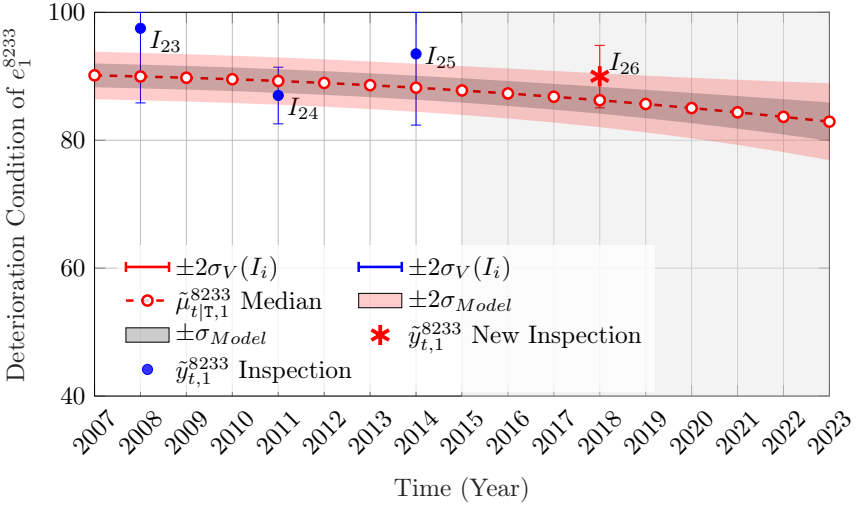
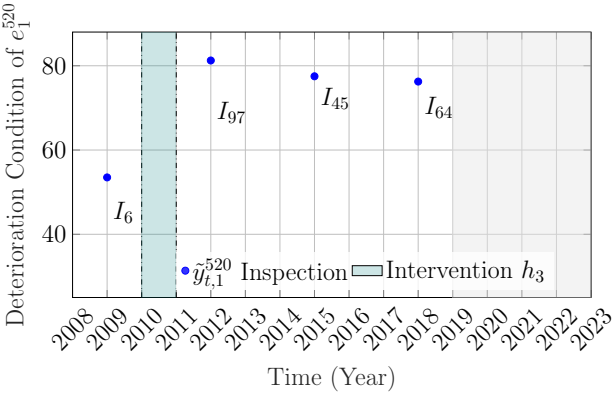
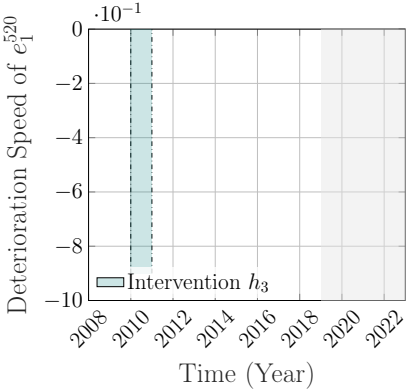
Beam Structural Element - Real Data



Source: Hamida and Goulet, 2020

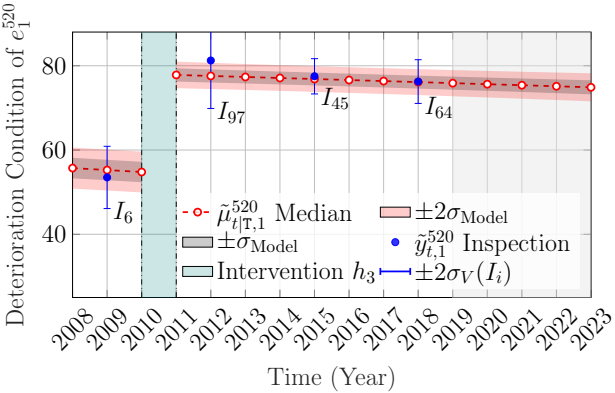
Structural Element Underwent Reparation

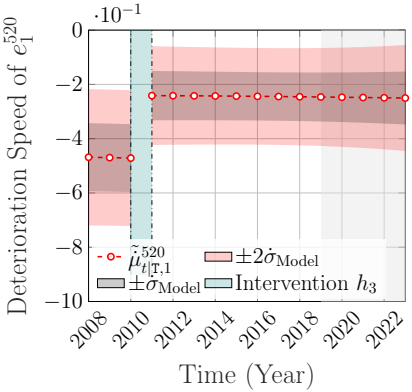




Source: Hamida and Goulet, 2021

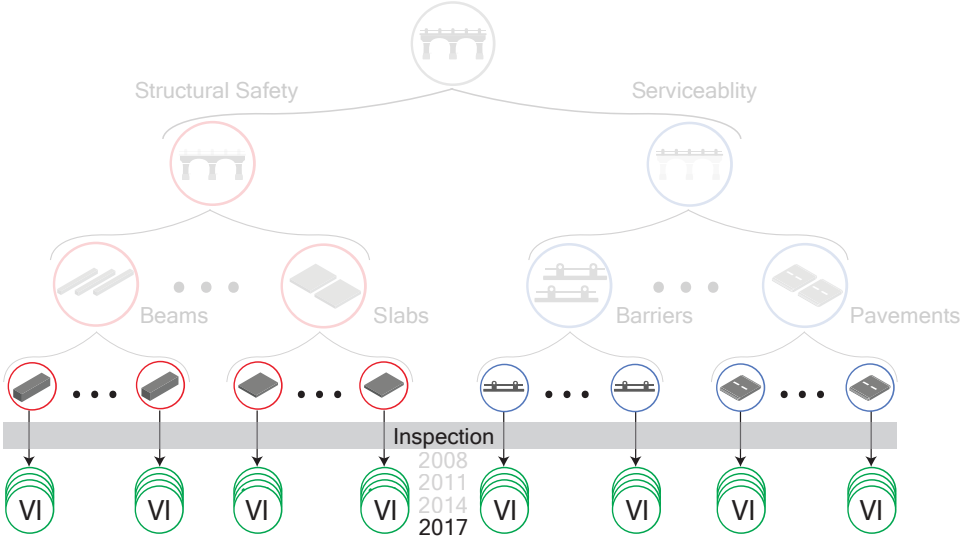
Structural Element Underwent Reparation





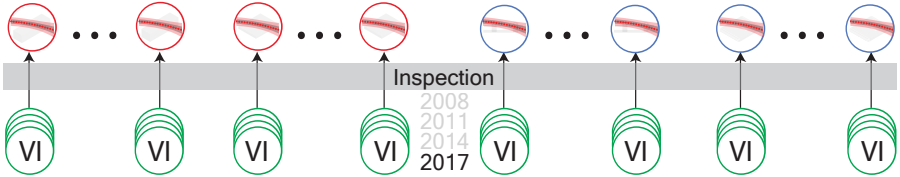
Source: Hamida and Goulet, 2021

Bridge Components



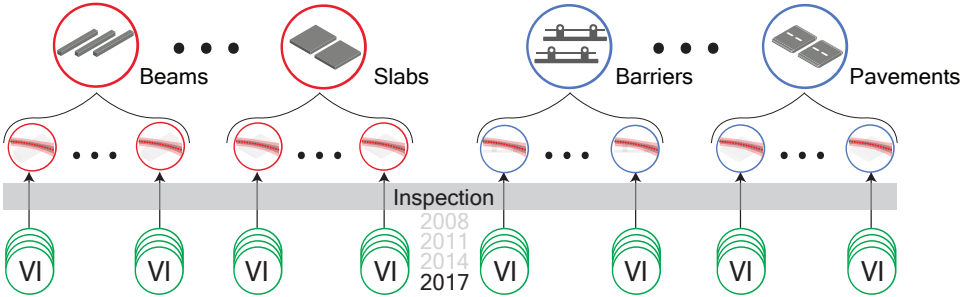
Source: Hamida and Goulet, 2022

Bridge Components



Source: Hamida and Goulet, 2022

Bridge Components



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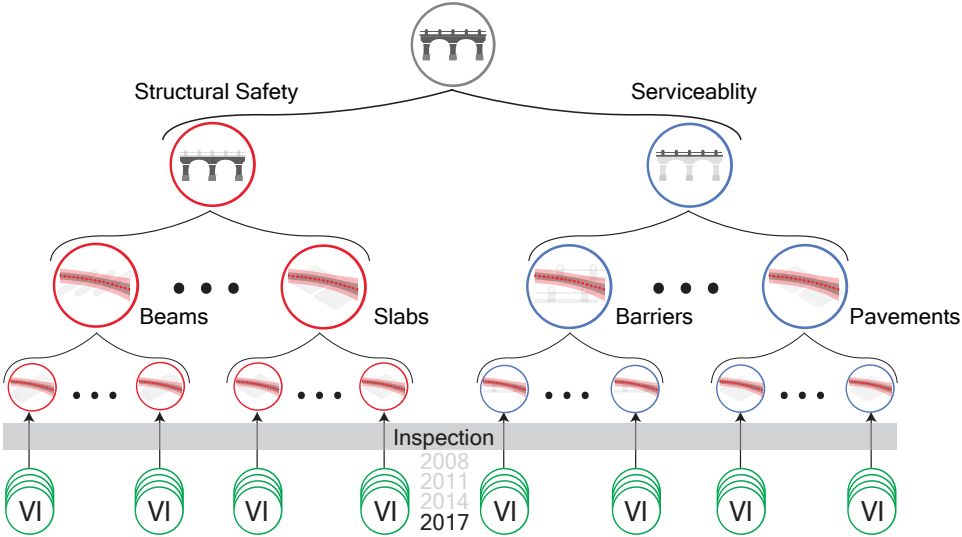
Bridge Components



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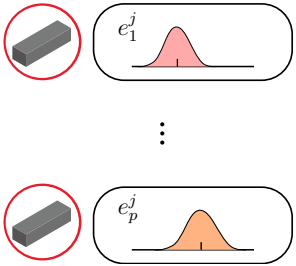
Gaussian Mixture Reduction

Gaussian Mixture Reduction

At any time t:



Gaussian Mixture Reduction

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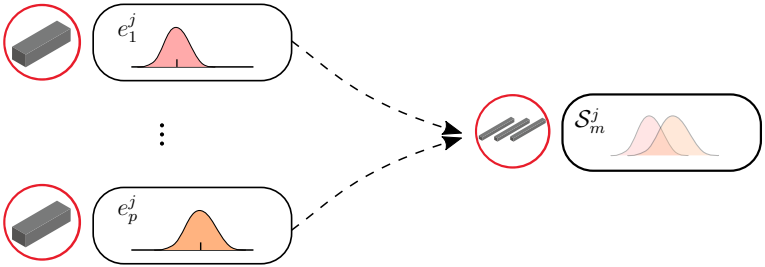

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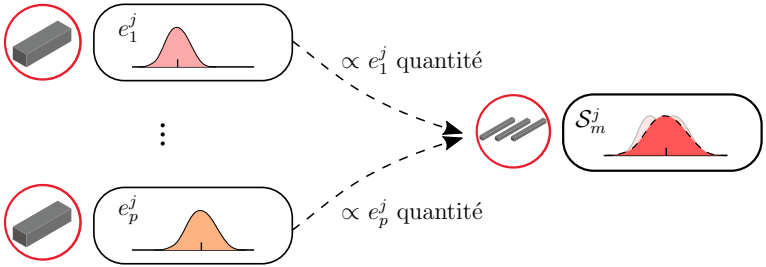
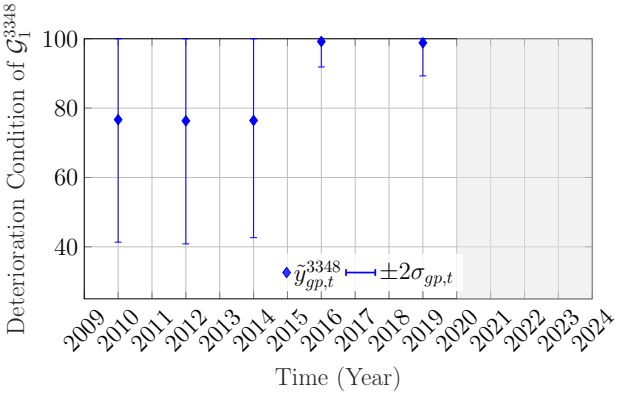
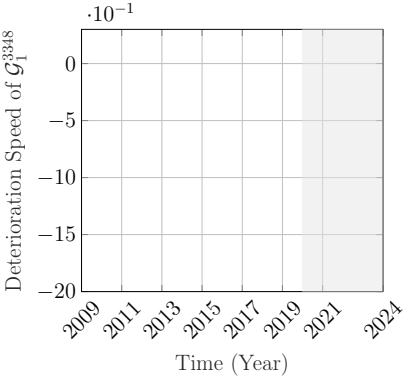
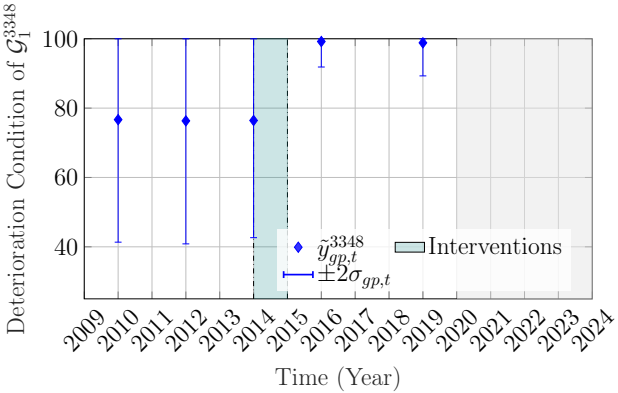


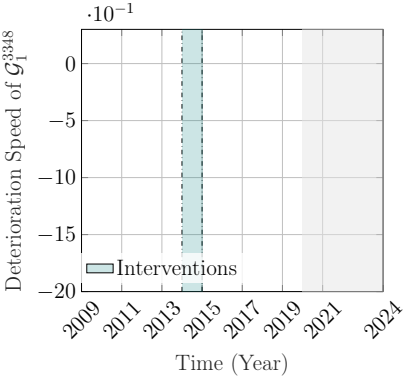
Primary Elements in Bridge b_{3348}



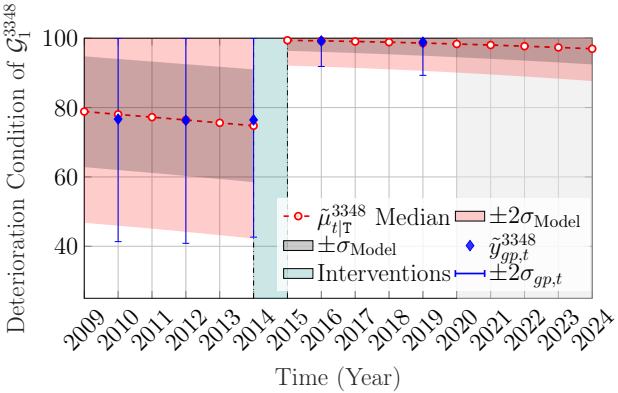


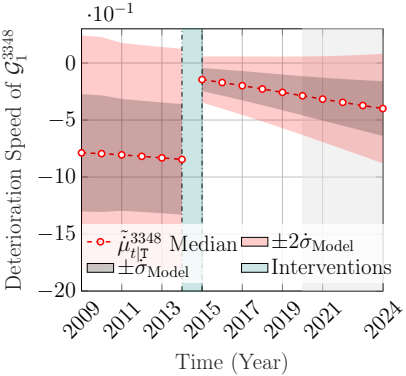
Primary Elements in Bridge b_{3348}



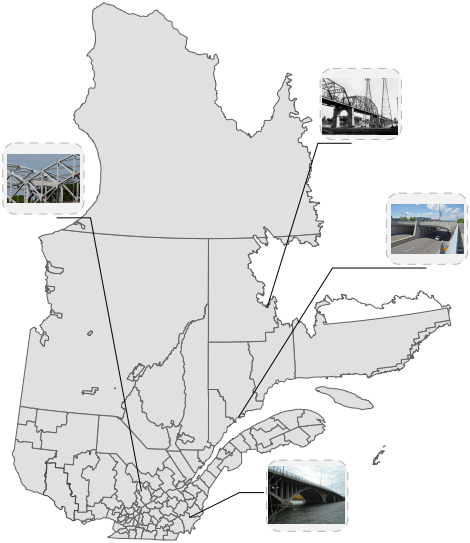


Primary Elements in Bridge b_{3348}



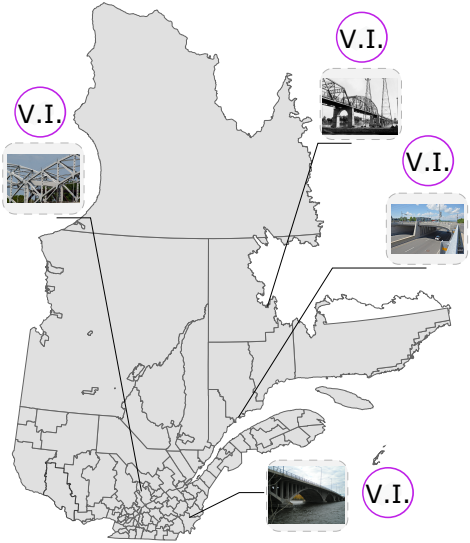


Network-Scale Planning



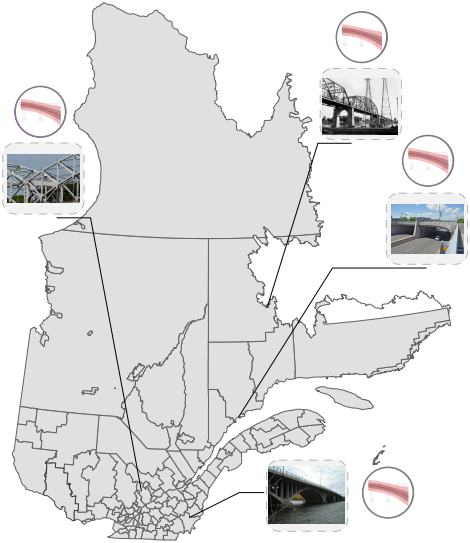
Network-Scale Planning

- Element-level monitoring



Network-Scale Planning

- ▷ Element-level monitoring
- ▷ Deterioration model

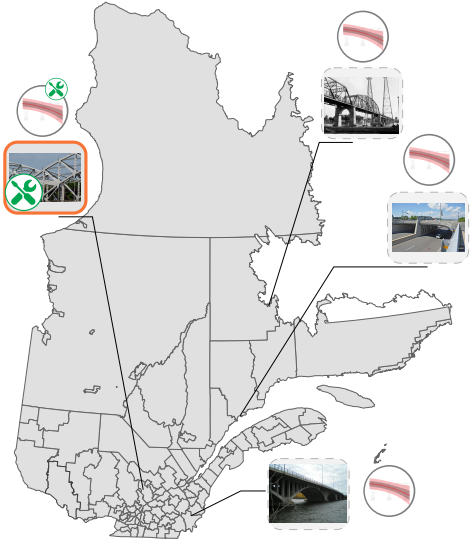


Network-Scale Planning

- ▷ Element-level monitoring
- ▷ Deterioration model

Network-Scale Planning

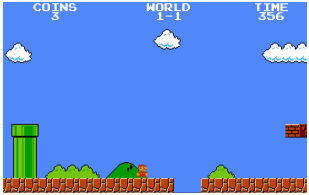
- ▷ Element-level monitoring
- ▷ Deterioration model
- ▷ **Decision-Making System**



Reinforcement Learning (RL)

Source: Google Images

Reinforcement Learning (RL)



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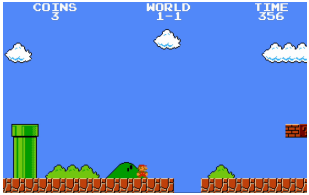

Bad decision (-1)

Source: Google Images

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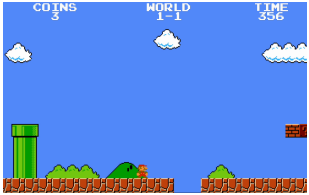

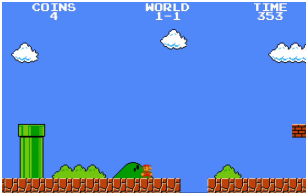

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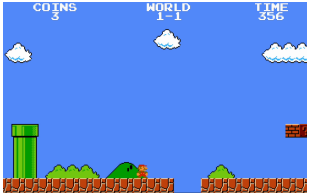

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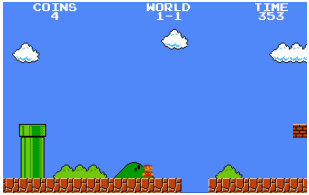

Good decision (+1)

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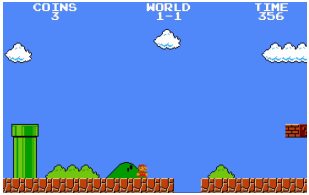
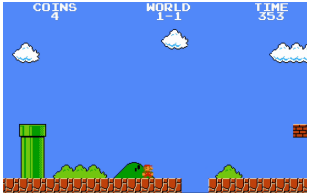
Reinforcement Learning (RL)



Bad decision (-1)

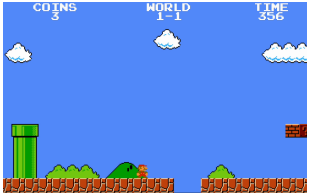


Good decision (+1)

▷ Agent: Mario.

Source: Google Images

Reinforcement Learning (RL)



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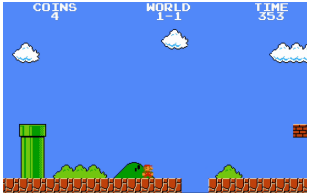
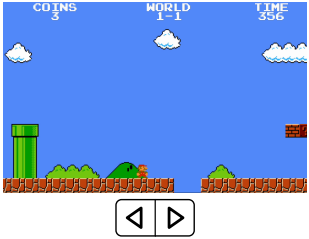


Good decision (+1)

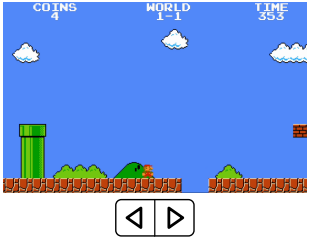
- ▷ Agent: Mario.
- ▷ Environnement: Mario World.

Source: Google Images

Reinforcement Learning (RL)



Bad decision (-1)

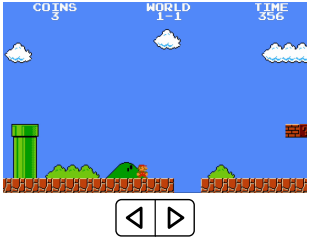


Good decision (+1)

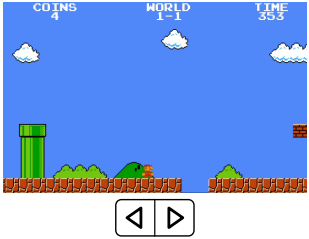
- ▷ Agent: Mario.
- ▷ Environnement: Mario World.
- ▷ Actions: Movement.

Source: Google Images

Reinforcement Learning (RL)



Bad decision (-1)



Good decision (+1)

- ▷ Agent: Mario.
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- ▷ Actions: Movement.
- ▷ Rewards: Win the game.

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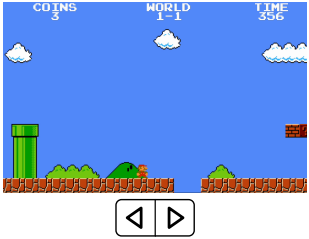

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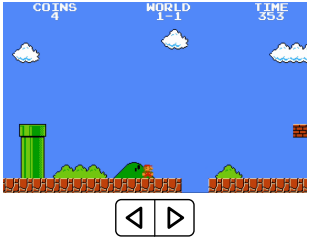

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RL Goal: learn a policy that maximizes the total expected discounted rewards.

Source: Google Images

Network-Scale Planning Challenges

Network-Scale Planning Challenges

Scale :

Network-Scale Planning Challenges

Scale :

$\underbrace{\qquad\qquad}_{\text{Elements}\times 10^5}$

Network-Scale Planning Challenges

Scale : $\underbrace{\text{Elements}}_{\times 10^5} \times \underbrace{\text{Actions}}$

Network-Scale Planning Challenges

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Uncertainty :

Network-Scale Planning Challenges

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Uncertainty : $\underbrace{\text{Deterioration Model}}$

Network-Scale Planning Challenges

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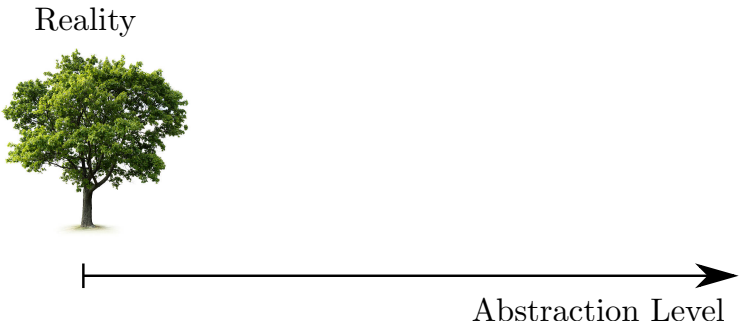
Uncertainty : $\underbrace{\text{Deterioration Model}} + \underbrace{\text{Effect of Interventions}}$

State Abstraction

State Abstraction

Reality

State Abstraction



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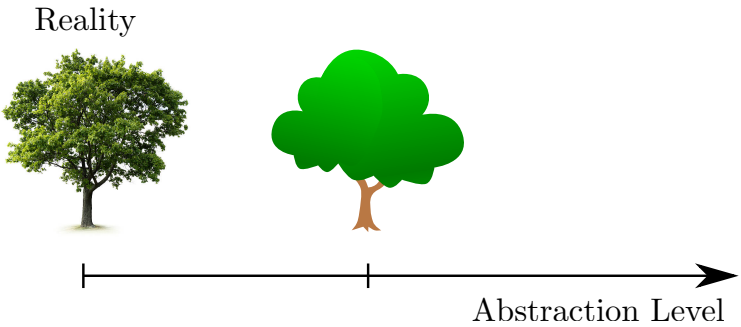

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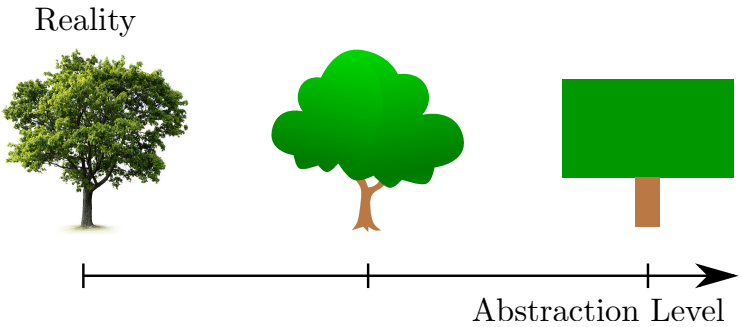

Temporal Abstraction

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$\mathcal{A}$: $\{a_0$: stay at home, a_1 : go to work $\}$

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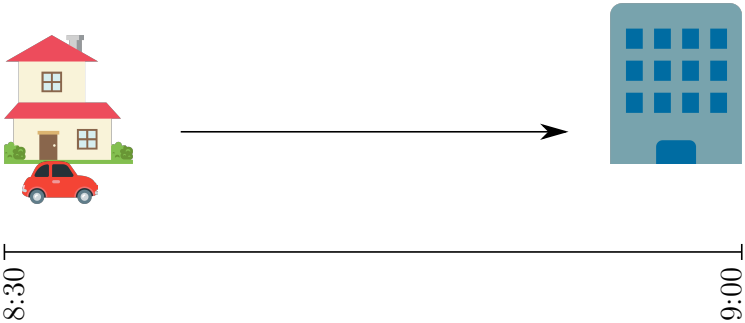

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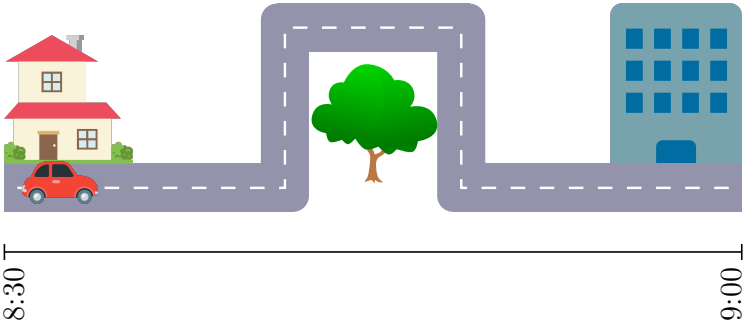

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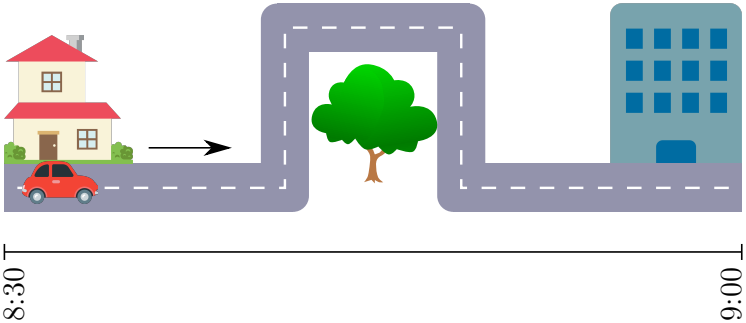

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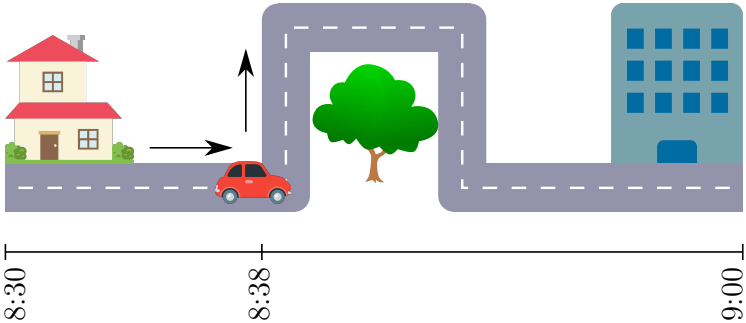

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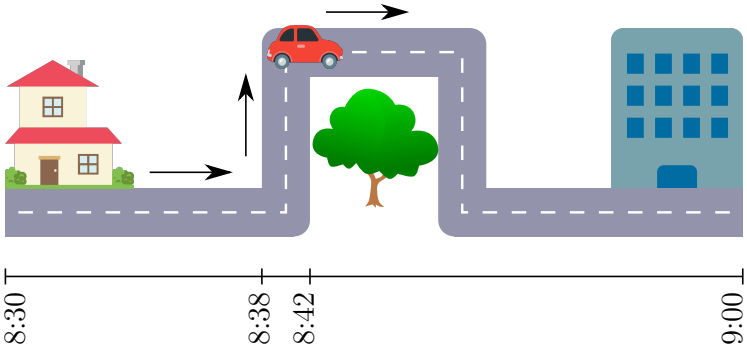

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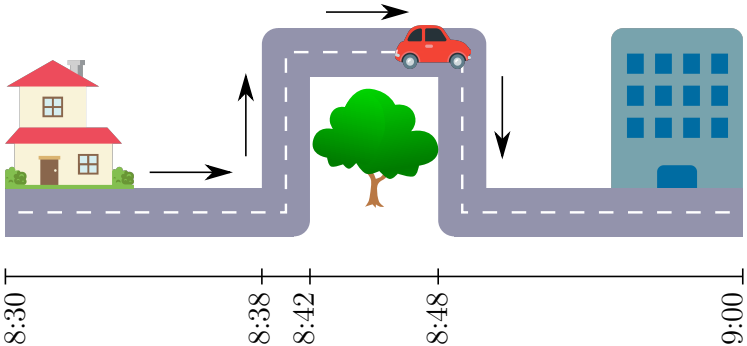

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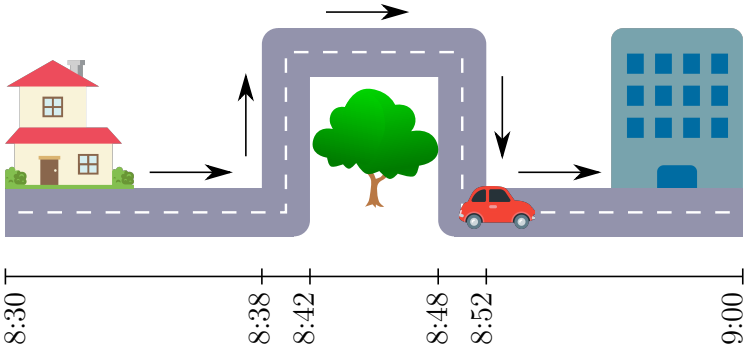

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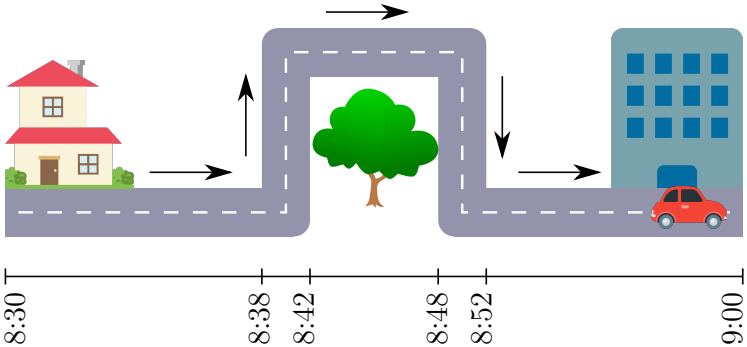

Network-Scale Maintenance Framework

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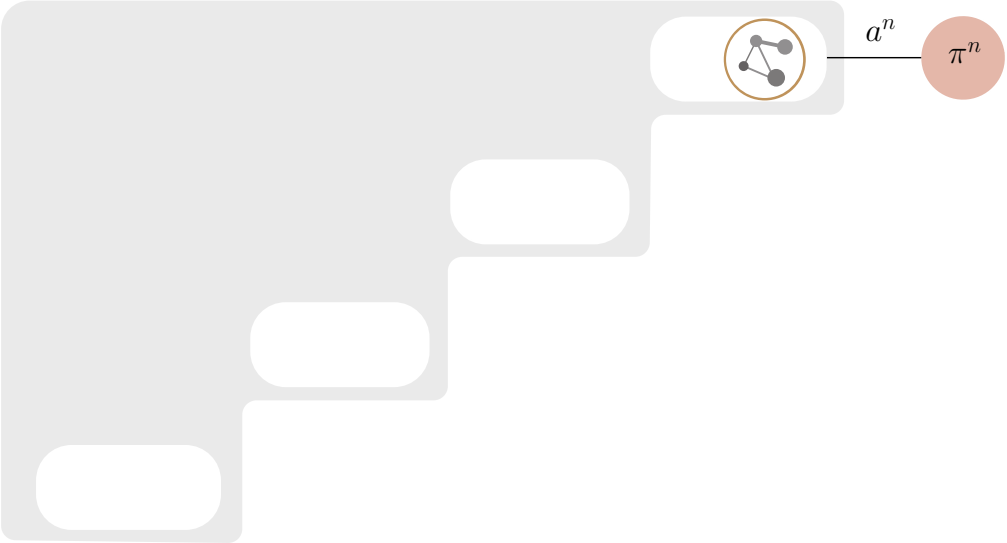

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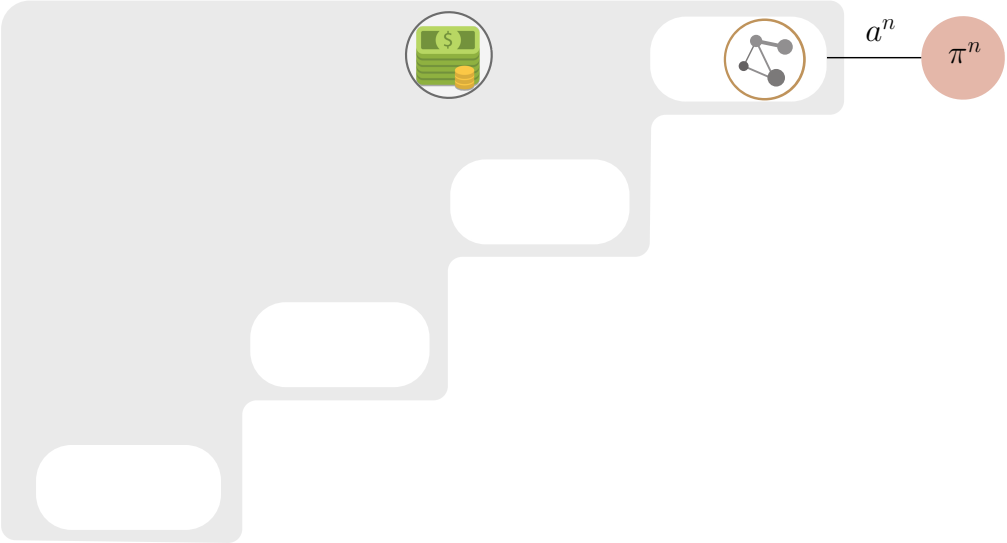

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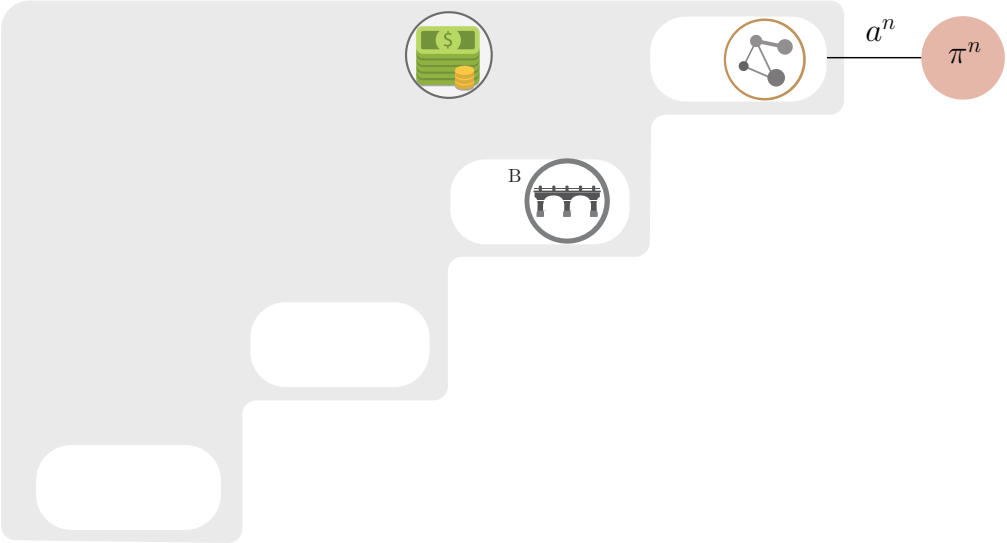

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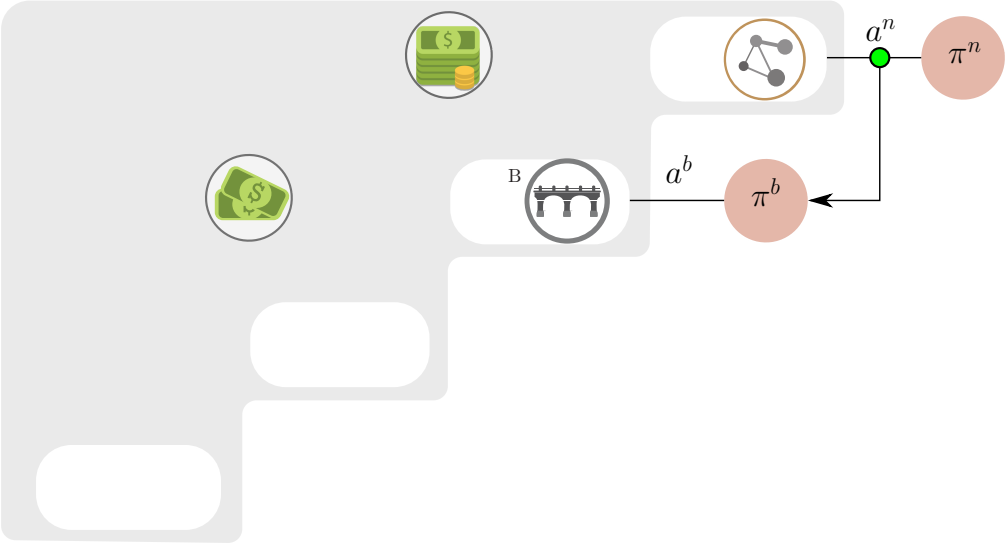

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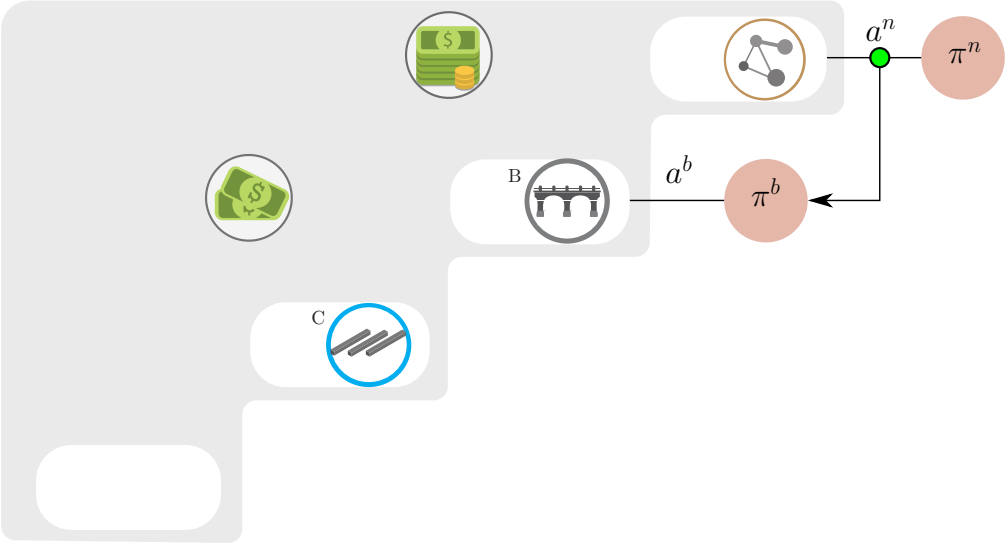

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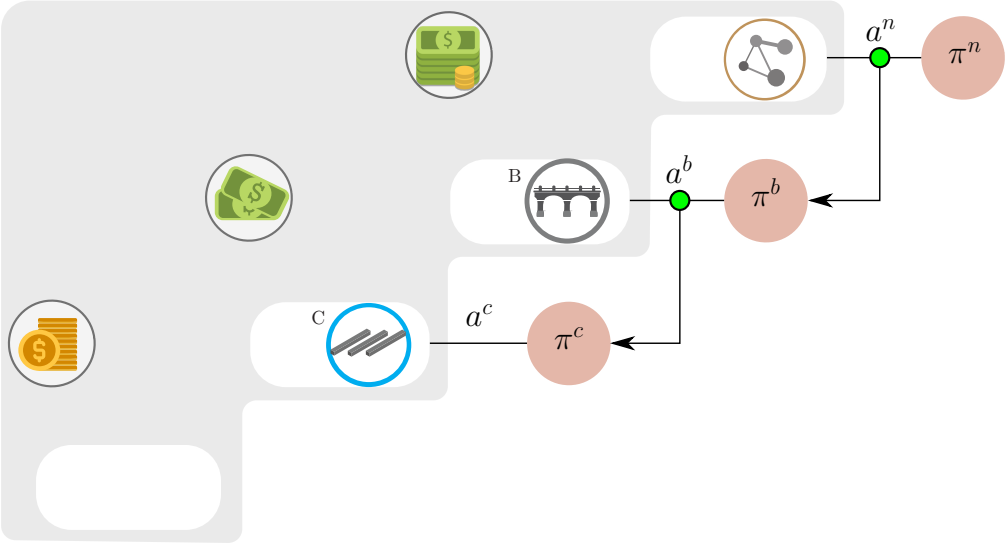

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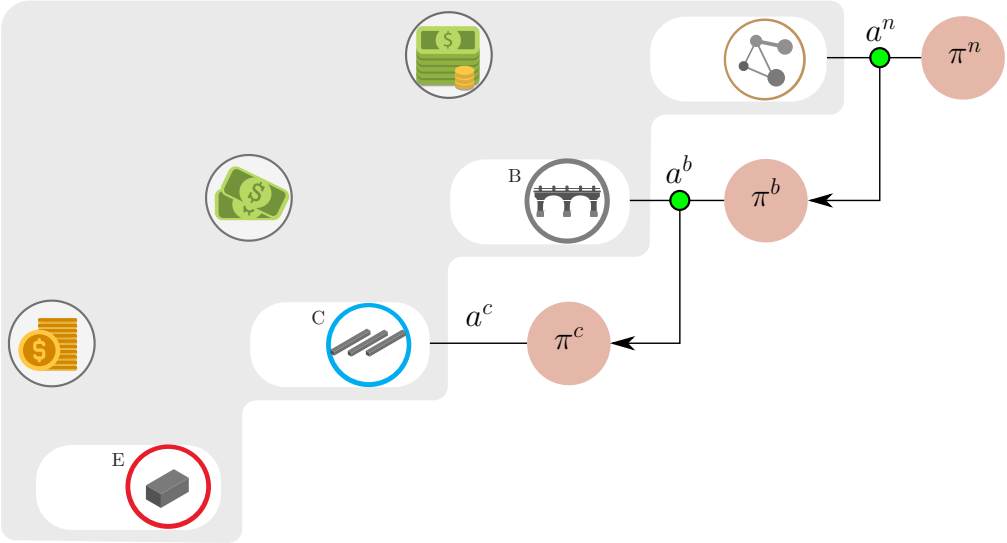

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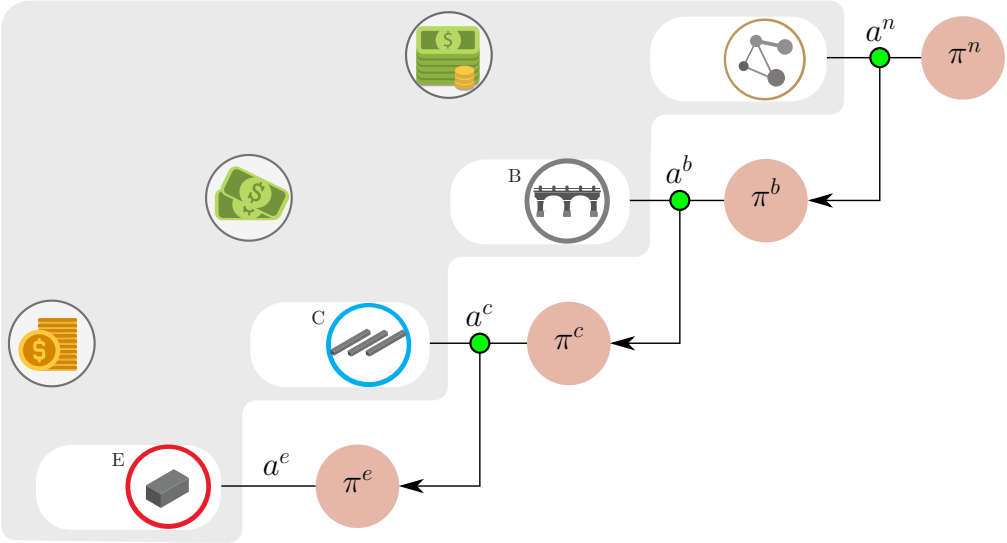

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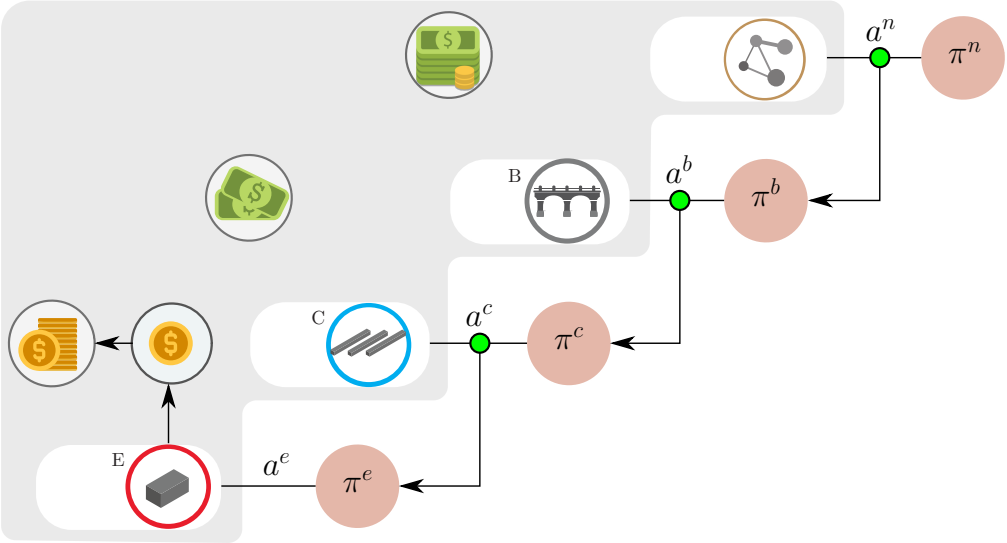

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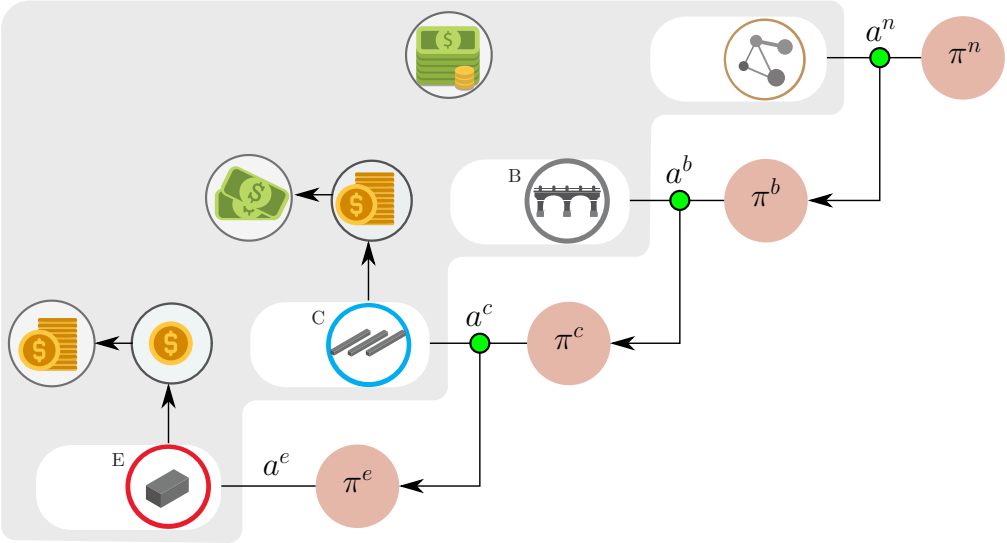

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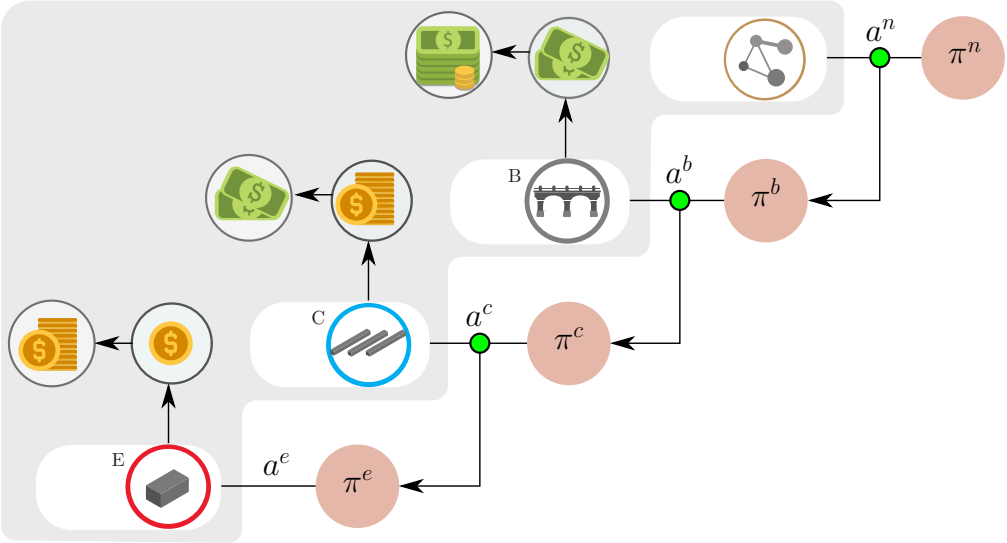

State Representation

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Network State :

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State Representation

$$\text{Network State}: \left\{ \underbrace{\quad}_{\text{Bridge \#001}} , \underbrace{\quad}_{\text{Bridge \#002}} , \ldots , \underbrace{\quad}_{\text{Bridge \#1}K} \right\}$$

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Bridge State :

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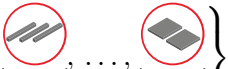

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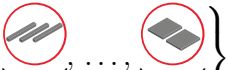

Category State :

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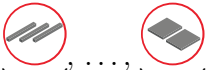
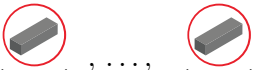


Category State : $\{ \underbrace{\quad}_{\text{Beam\#001}}, \ldots, \underbrace{\quad}_{\text{Beam \#100}} \}$



Toy-Problem: Element-Level

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- ▷ Episode length: $\mathtt{T} = 100$ years.

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Reinforcement Learning Setup:

- ▷ Episode length: $\mathtt{T} = 100$ years.
- ▷ Number of episodes: $\mathtt{E} = 5 \times 10^6$.

RL Results

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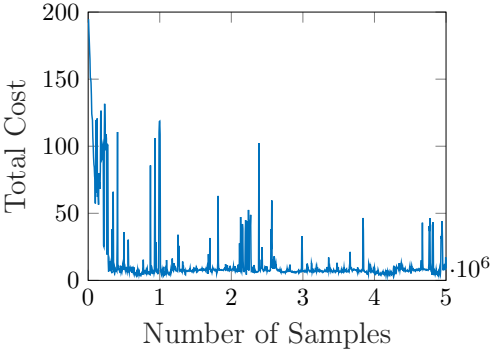

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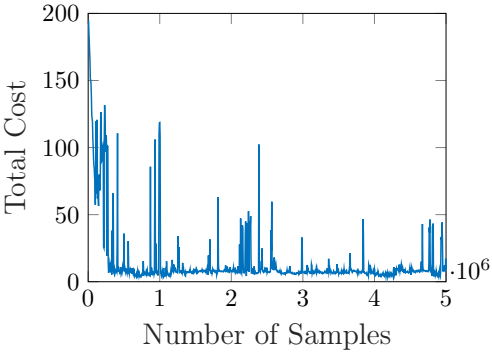
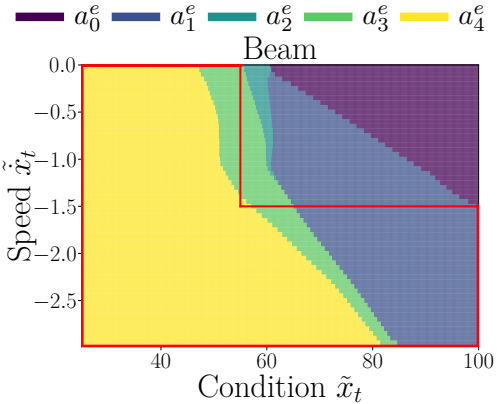

Total Cost
Number of Samples
$\cdot 10^6$


a_0^e a_1^e a_2^e a_3^e a_4^e
Beam
Speed $\tilde{\dot{x}}_t$
Condition $\tilde{x}_t$

Conclusions & Future Work

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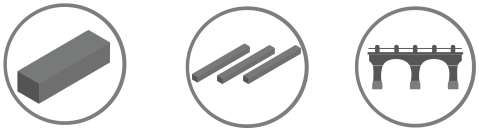
InfraPlanner

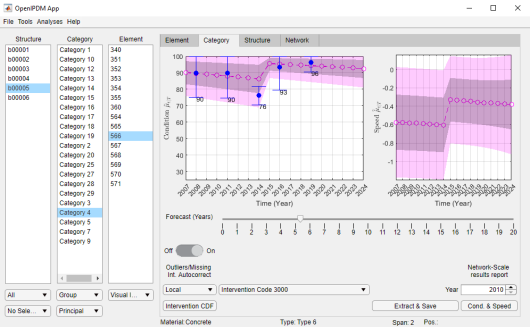


- Open-source RL environment developed in `Python`.
- Element-level, category-level and bridge-level.
- Probabilistic and deterministic states.

InfraPlanner is **available** on GitHub

https://github.com/CivML-PolyMtl/InfrastructuresPlanner

OpenIPDM



- Open-source software developed in MATLAB.
- Infrastructures Probabilistic Deterioration Modelling.
- User interface.

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