UNIANDES-UNIFI
Secondment kickoff:
Stochastic Optimization for CPSs

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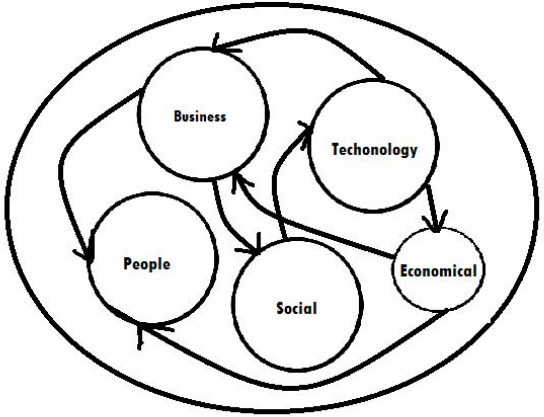
Decision Analytics Lab


QS
WORLD
UNIVERSITY
RANKINGS

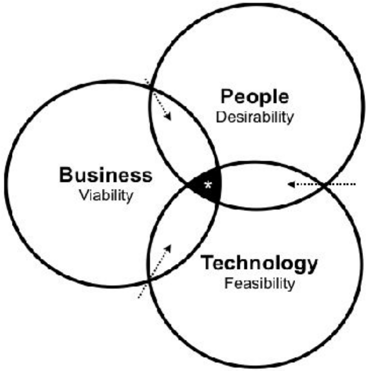
Industrial Engineering at Uniandes

Analytics-based systems design

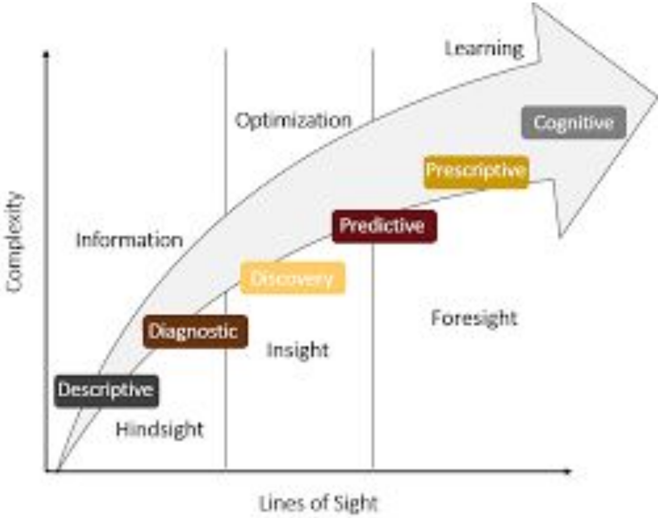
Systems Thinking



Design Thinking



Decision Analytics



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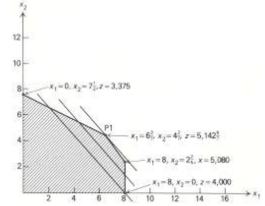
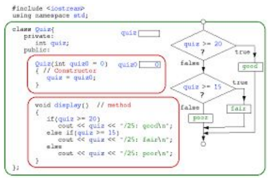
COPA Research Group @ Uniandes

Operations Research (OR)

- Mathematical modeling
  - Probabilistic
  - Statistical / ML
  - Simulation
  - Optimization



- Algorithmic design



- Decision Support Systems

- Production
- Logistical
- Infrastructure
- Energy
- Health
- Urban
- Financial

systems

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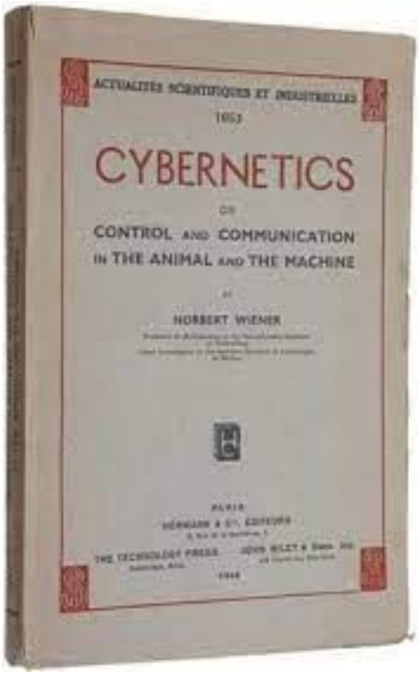
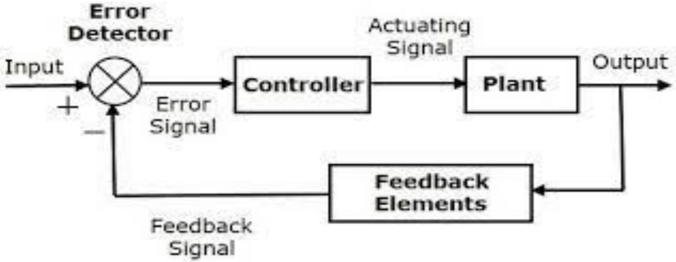
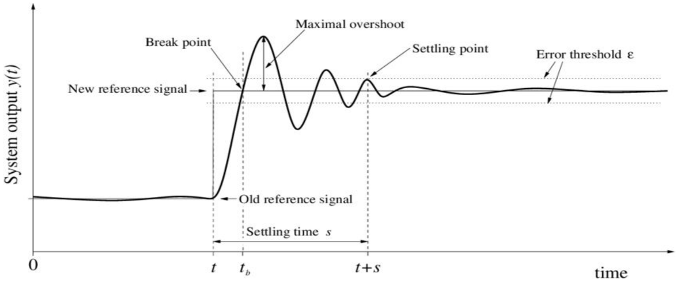
Cybernetics and complex systems background

Systems concepts behind analytical tools



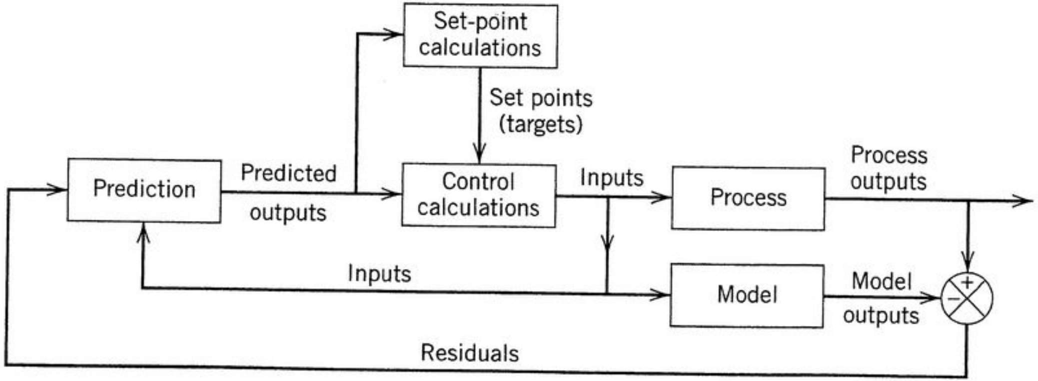




Optimization and control

A cybernetical ancestor of stochastic optimization

Anti-aircraft missile



Model Predictive Control

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Research communities in Stochastic Optimization

- Decision trees
- Stochastic search
- Optimal stopping
- Optimal control
- Markov decision processes
- Approximate/adaptive/neuro-dynamic programming
- Reinforcement learning
- Online algorithms
- Model predictive control
- Stochastic programming
- Robust optimization
- Ranking and selection
- Simulation optimization
- Multiarmed bandit problems
- Partially observable Markov decision processes.

How do I model and control
unknown external aspects
that can make my system go wrong?

Powell, W. B. (2019). **A unified framework for stochastic optimization**. European Journal of Operational Research, 275(3), 795-821.

Prof. Powell's proposed unifying framework

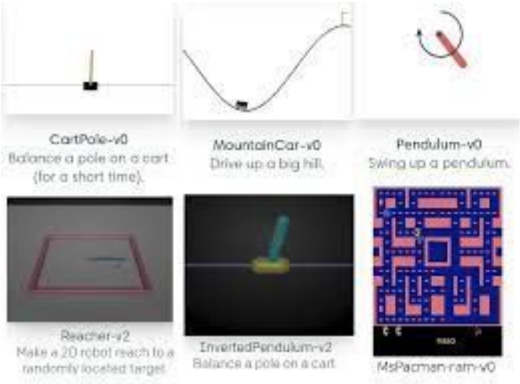
- State variables: S_t
- Decision variables: $x_t = X^{\pi}(S_t)$
- Exogenous info.: W_t
- Transition function: $S_{t+1} = S(S_t, x_t, W_{t+1})$
- Objective function: $C_t(S_t, X^{\pi}(S_t), W_{t+1})$

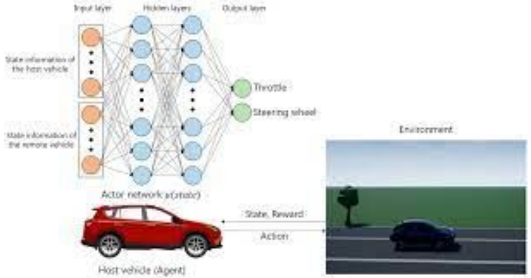
$$\min_{\pi} \mathbb{E}_{W_1,\ldots,W_T \mid S_0} \left\{ \sum_{t=0}^{T} C_t(S_t,\ X^{\pi}(S_t),\ W_{t+1}) \mid S_0 \right\}$$

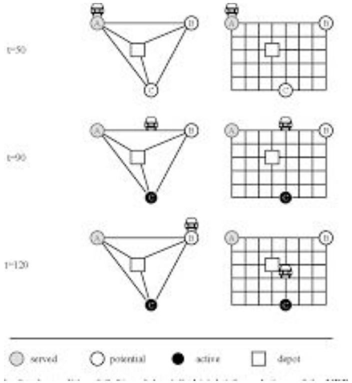
Challenges:

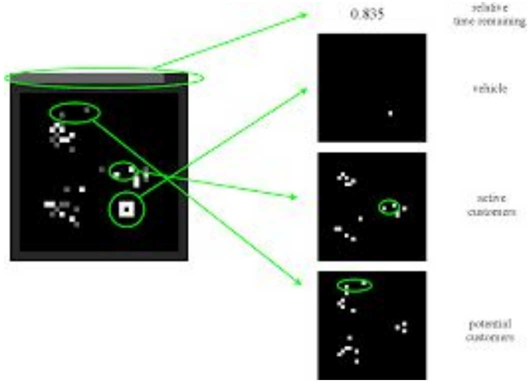
- Dynamics modeling
- Uncertainty modeling
- Policy Design

Research trends in *reinforcement learning* and ADP

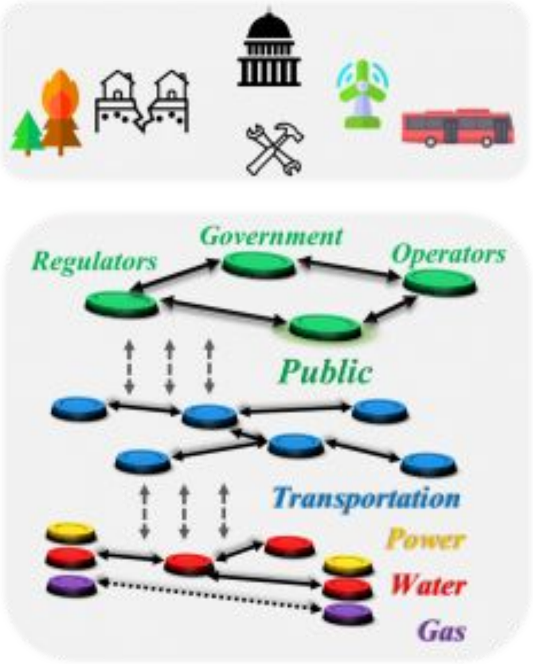


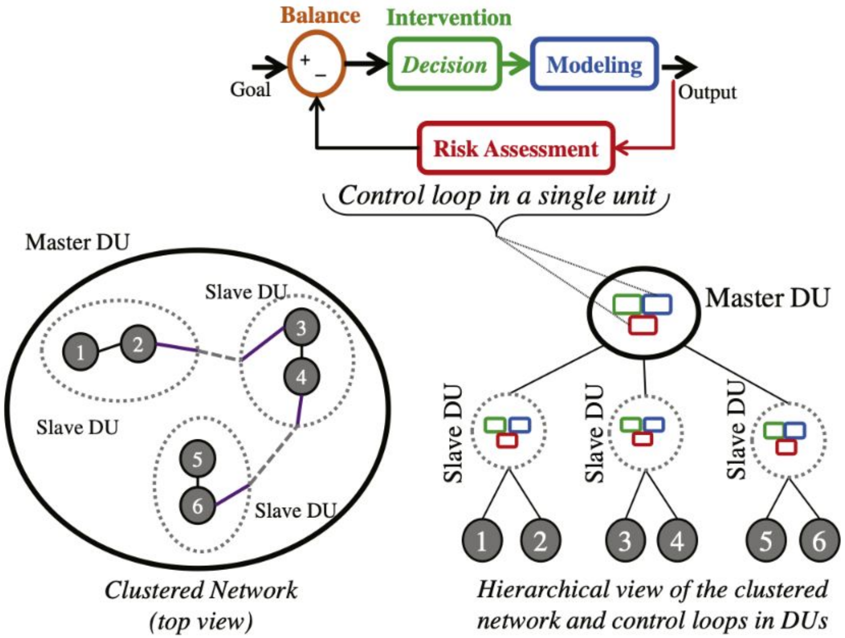






How to “control” complex Systems-of-Systems





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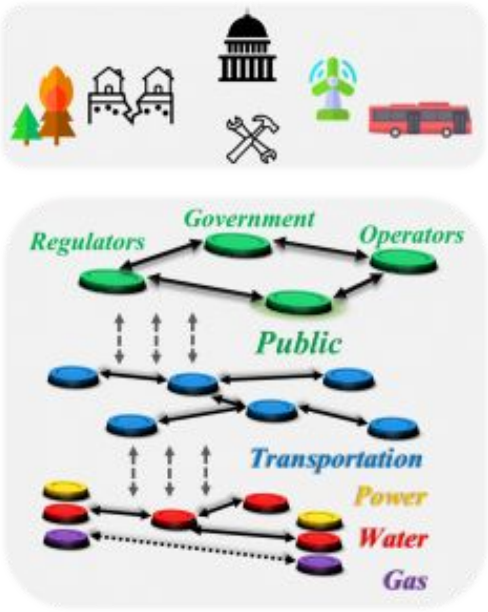
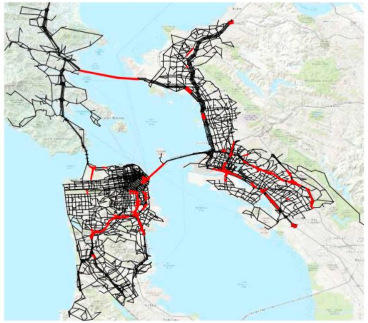
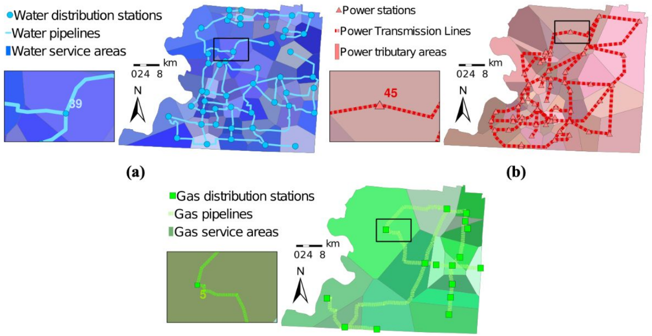
Resilience of interdependent infrastructure networks





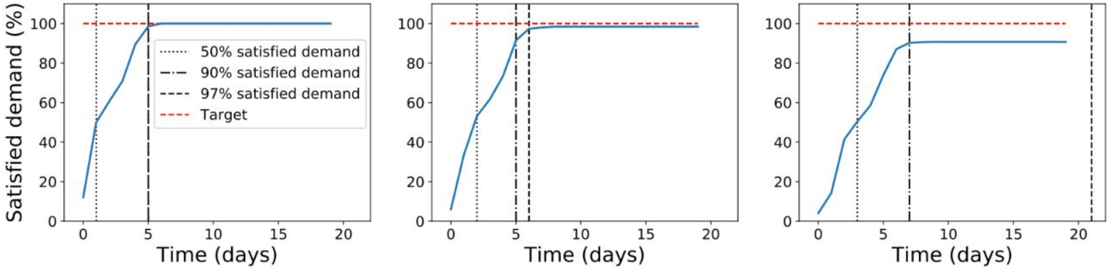


Service Recovery

Community-driven

Tradeoff

Operator-driven



Unrealistic central planner assumed!

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Current research lines

Decision Support Systems in the context of:

- **Supply Chain Analytics**

- Systems-of-Systems Analytics

- Open Data Analytics

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Intelligence for agri-food markets and supply chains

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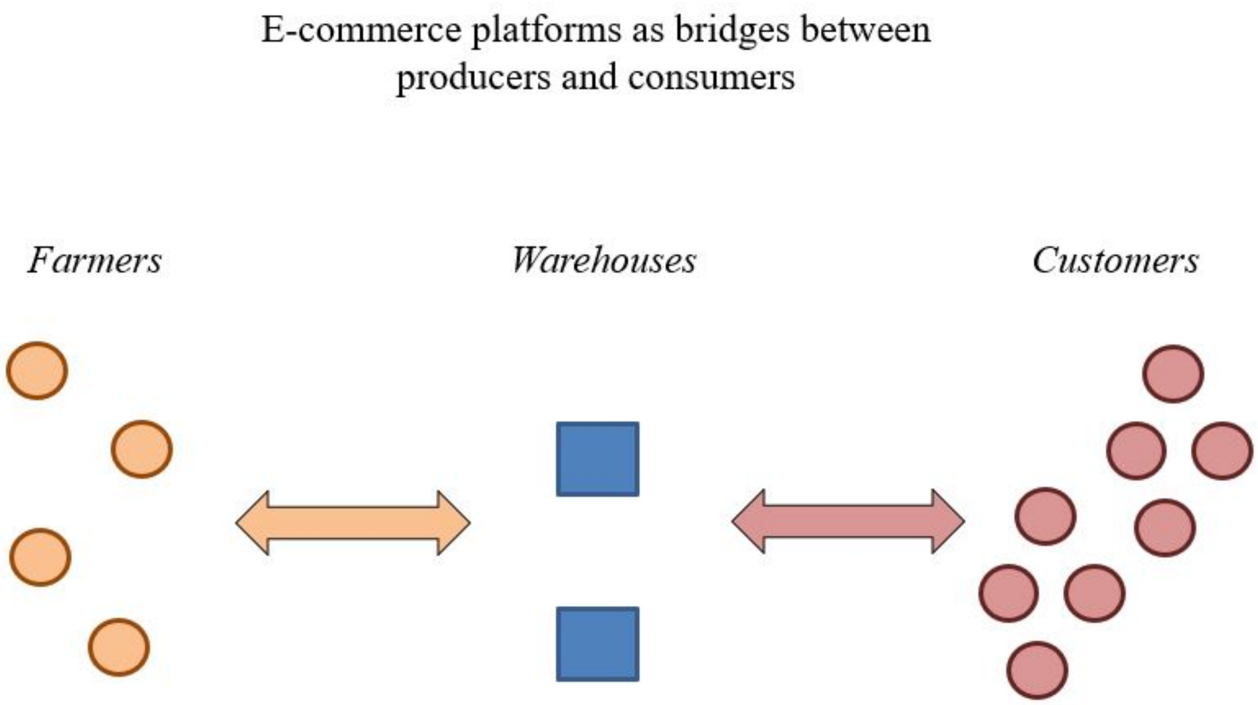
Intelligence for agri-food markets and supply chains



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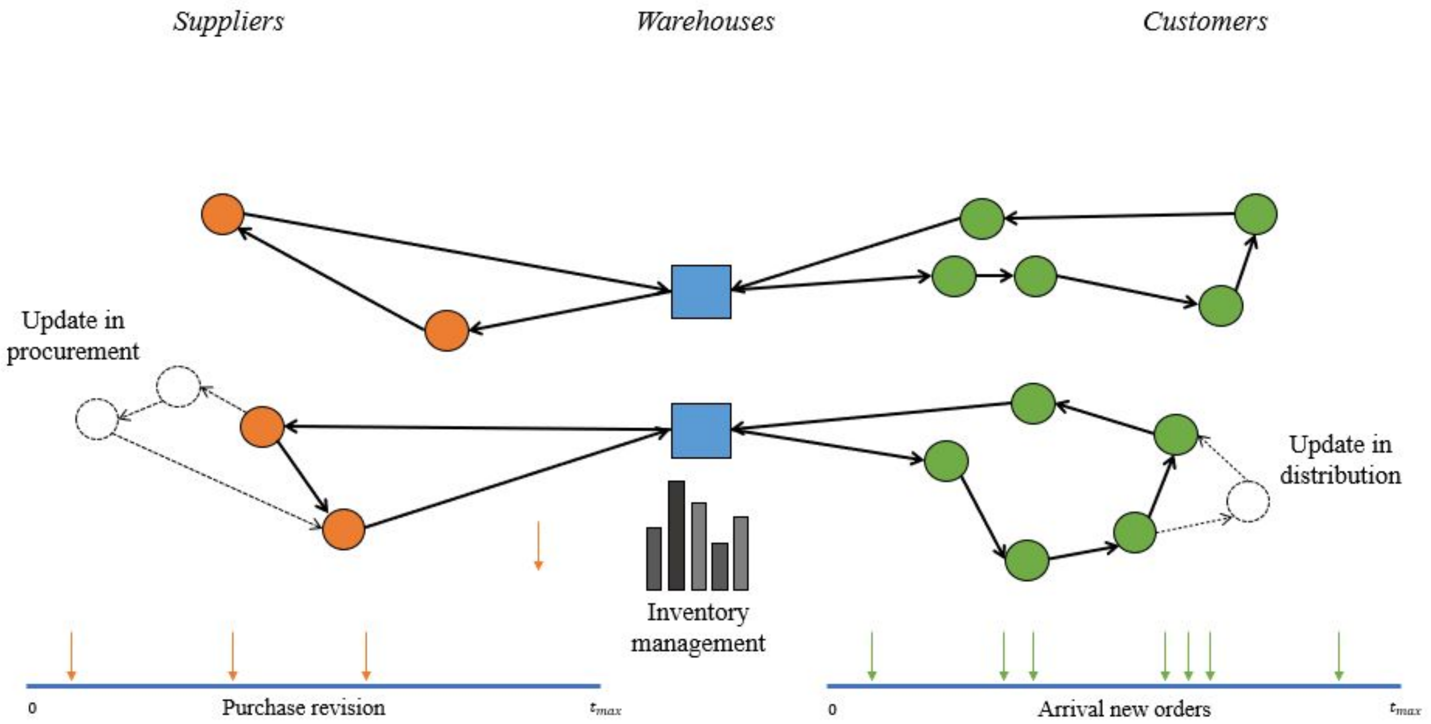
Intelligence for agri-food markets and supply chains



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Modeling under the stochastic optimization framework

Core elements

- **Metrics**: We want to minimize the total cost given by the purchasing, routing, inventory and backorders costs
- **State** ($\boldsymbol{S_t}$): inventory level for each product at the beginning at each period t. $\boldsymbol{S_t} = (\boldsymbol{I_{kt}})$
- **Decisions** ($\boldsymbol{x_t}$): We have to decide for each period
  - How much to replenish
  - How much to store
  - Select suppliers
  - How much to buy from each supplier
  - How to visit suppliers

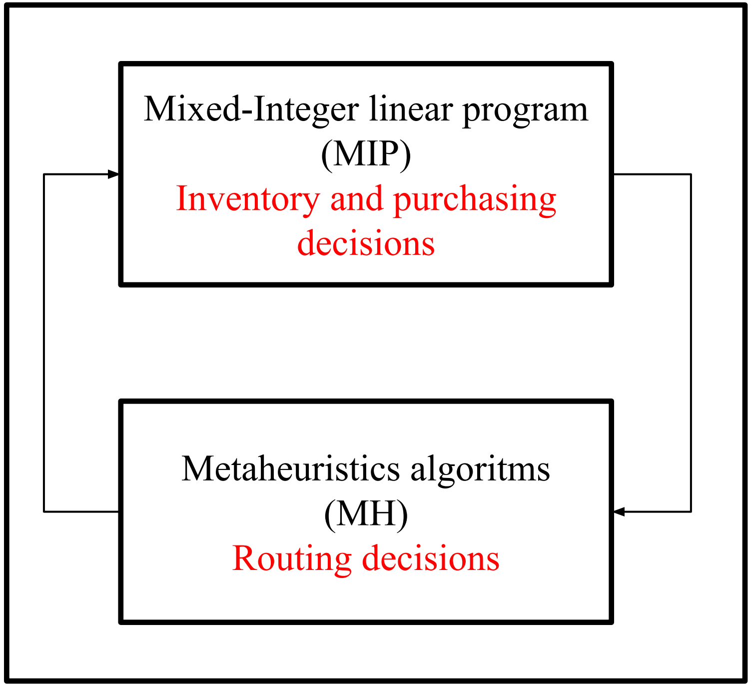
Decision variable $(\boldsymbol{x_t})$

- **Uncertainty sources** ($\boldsymbol{W_{t+1}}$): The demand for each product in the afternoon. $(\widehat{D}_{kt})$

Decision Analytics in *Inventory Routing Planning*

How can we find the value of these decision variables?

***Policy*: $x_t = \pi(s)$**



$$
\begin{aligned}
&\text{maximize} && \mathbf{c}^{\mathrm{T}}\mathbf{x} \\
&\text{subject to} && A\mathbf{x} + \mathbf{s} = \mathbf{b}, \\
& && \mathbf{s} \geq \mathbf{0}, \\
& && \mathbf{x} \geq \mathbf{0}, \\
&\text{and} && \mathbf{x} \in \mathbb{Z}^n,
\end{aligned}
$$

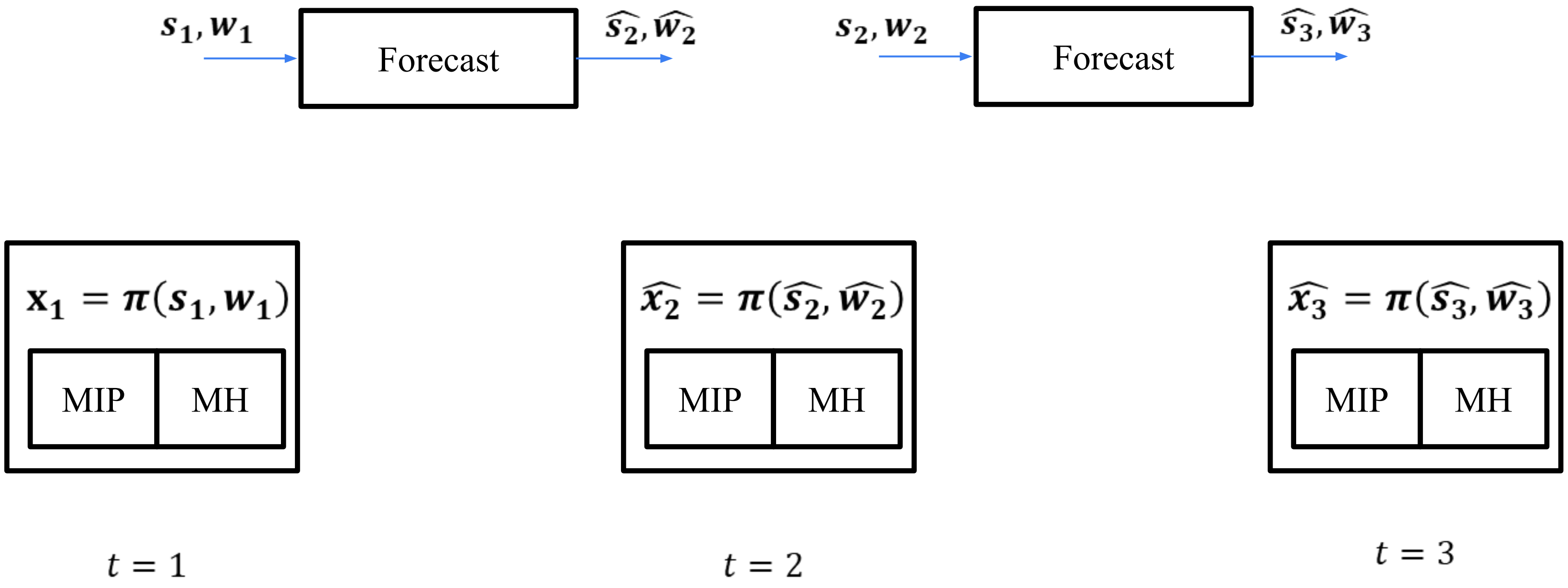
Algorithm 2 GenerateRoutes

Input: **List** T, M, **List** c_{ij} : transportation cost between nodes i and j, $z_{ikt}, w_{it}; Q$

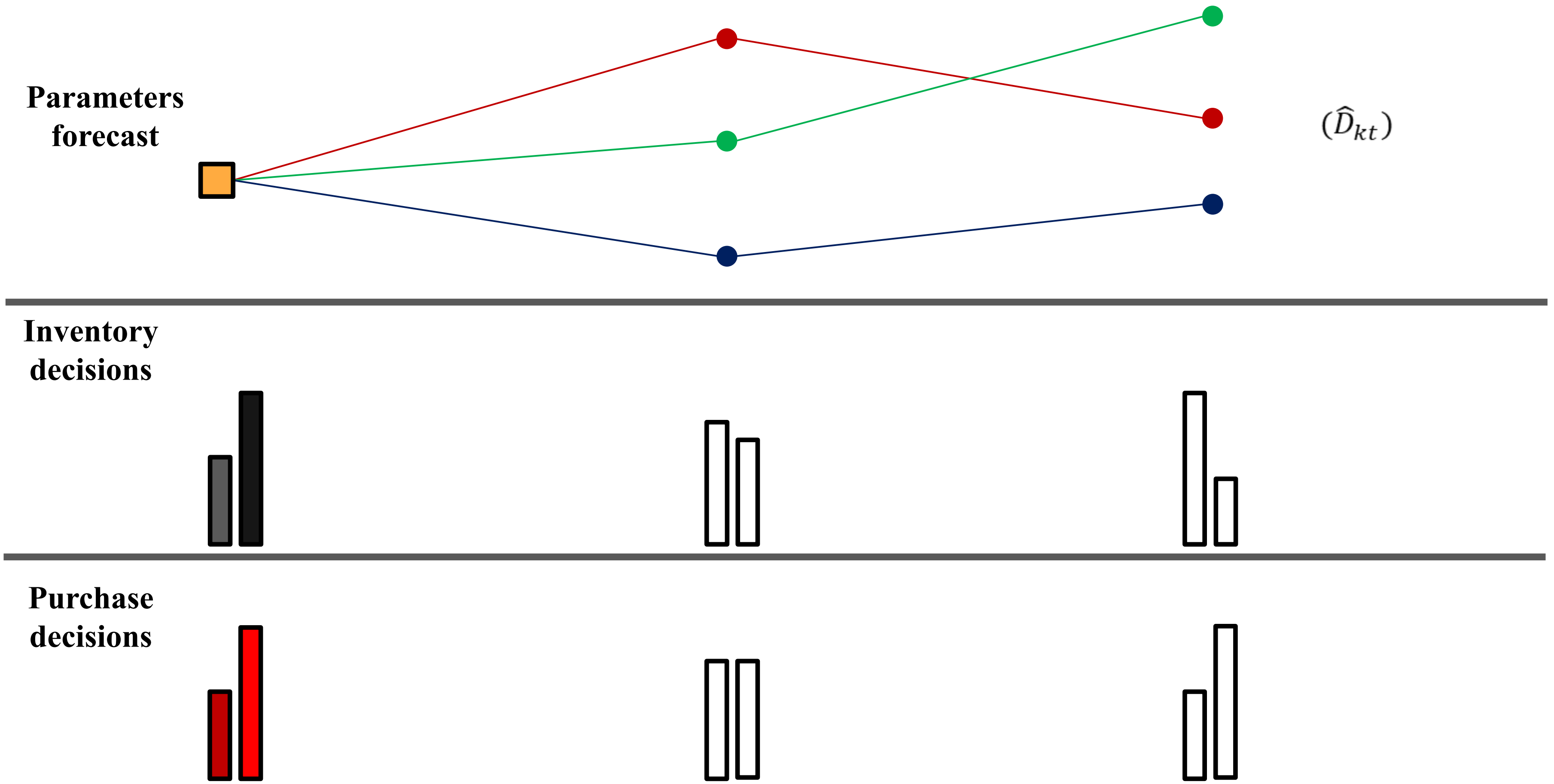
Output: **Routes** R : Routes of period t;

```
for t = 1 To |T| do
    Tour ← NearestNeighbourAlgorithm(M, w_it, c_ij)
    Graph ← GenerateAugmentedGraphCVRP(M, w_it, c_ij, Tour, Q)
    R_t ← BellmanFordShortestPathAlgorithm(Graph)
end for
return R
```

Decision Analytics in Inventory Routing Planning



Decision Analytics in *Inventory Routing Planning*



Current research lines

Decision Support Systems in the context of:

- Supply Chain Analytics
- **Systems-of-Systems Analytics**
- Open Data Analytics

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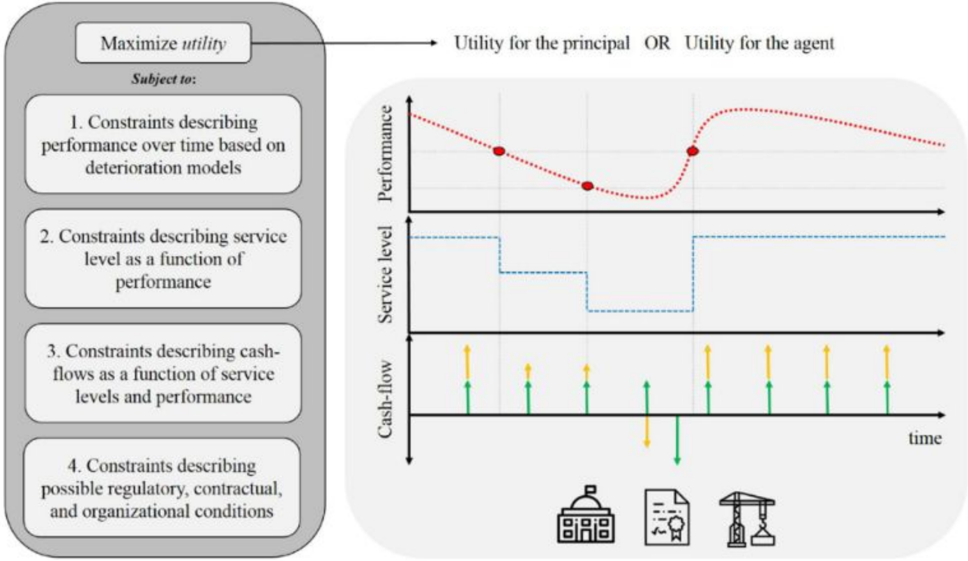
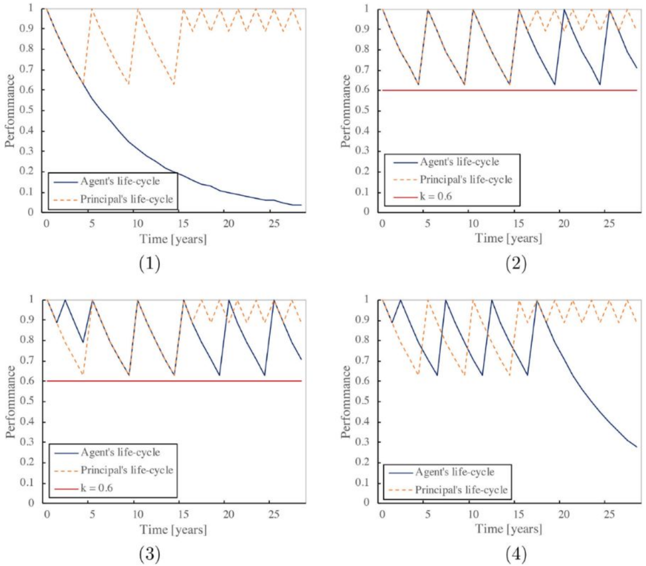
Conflicts of interest in Systems of Systems

Public-Private Partnerships





Regulations or incentives rely on oversight: sensing and monitoring

Illustration of a bi-level optimization problem

$$\min \mathrm{F} = 2x - 11y$$

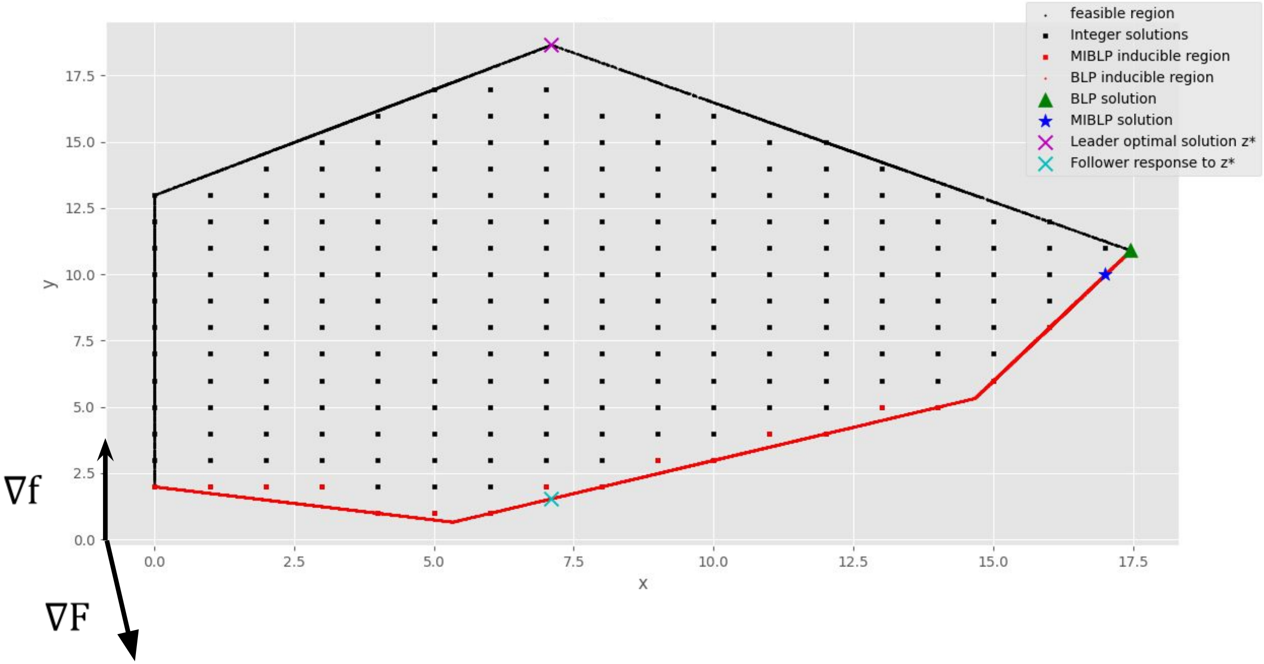
s.t.,

$$\min \mathrm{f} = 3y$$

s.t.,

$$\begin{aligned} x - 2y &\leq 4 \\ 2x - y &\leq 24 \\ 3x + 4y &\leq 96 \\ x + 7y &\leq 126 \\ -4x + 5y &\leq 65 \\ -x - 4y &\leq -8 \end{aligned}$$

$$x \in \mathbb{Z}^{\geq 0}$$
$$y \in \mathbb{Z}^{\geq 0}$$



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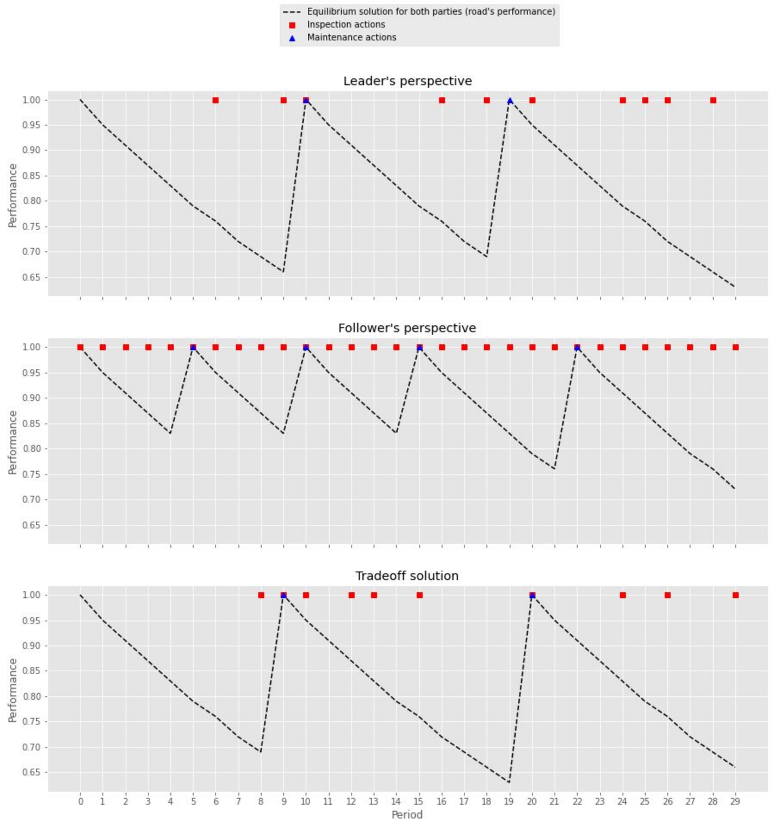
Agents' strategies under bi-level optimization



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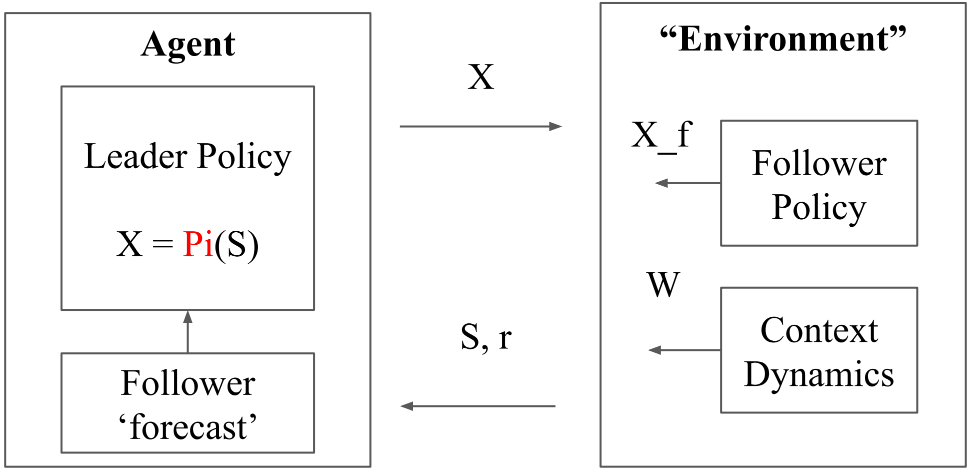
Bi-Level problem under Stochastic Optimization Framework

Wherever there is a group of interest (SoS), it's because there are things at stake;

we use Decision Analytics to get the best and fair of what's at stake



No deals?

We're out and thank you for your time!

- **Bi-level**: each party follows its own objective
  Optimization: get the most out of a zero-sum game;
  seek win-win solutions in non-zero sum games

- **Interdiction**: the counterpart seeks to cause the most damage
  Optimization: anticipate and protect from harmful actions
  (defender-attacker-defender)

In the CPS context:

Address tradeoffs between multiple stakeholders' interests (e.g., cost, safety)

Detect and prevent failure from stochastic failures or intentional attacks

Addressing V&V of CPSs under *Decision Analytics* lens

- **Modeling of CPSs under *SoS* and *Decision Analytics***
  - “Integrate decision making across soft and hard infrastructure in cyber-physical systems”
  - “Build consensus on common understanding, methodologies and practices for resilience assessment”

- **Test the *Sequential Decision Analytics* framework for CPSs**
  - “Model downstream effect of decisions <u>now</u> on (and from) from other components of the CP-SoS and the dynamic environment”

- **Exploit optimization to improve effectiveness and efficacy of V&V**
  - “Identify cyber-physical threats affecting systems for diagnostics, protection and resilience of railway infrastructure”
  - “Define new solutions of Model-Driven Engineering for the interdependency analysis and the prevention of cascading effects”

Conclusion

- The unified stochastic optimization framework appears as an amenable modeling approach for CPS, including the modeling of the dynamics and stochasticity of complex systems, and enabling the possibility to design and evaluate decision policies.

- As a result, we can borrow OR techniques, such as stochastic and bi-level optimization, to improve decisions about a system of interest in the face of:
  - Uncertain adversity
  - Interactions with other components in a CP-SoS
  - Disruptions ("natural" or targeted)

- The current trend of research on reinforcement learning and approximate dynamic programming can lead to fresh approaches to CPS problems, calling the attention of such communities to open challenges.

Thanks!

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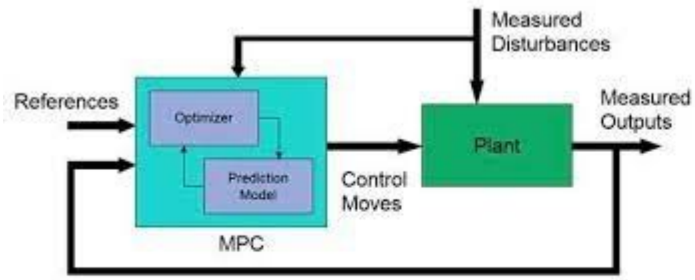
The popular image of a dam as a concrete wall might not be easily identified with a complex engineering system. However, the resulting engineering of the natural environment in which the dam sits becomes a complex engineering system and therefore must be treated as such. This changes completely the safety requirements of the system, from a purely structural angle to one of operation management.

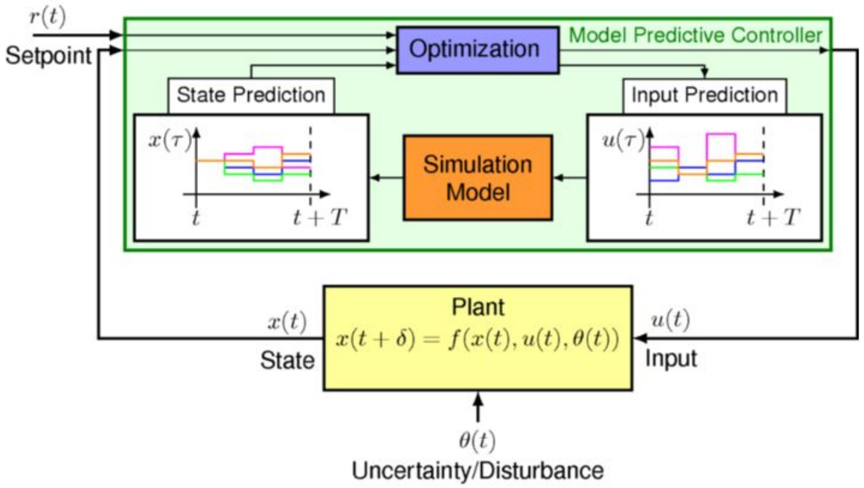
The idea of static operation procedures to regulate a system in an extremely dynamic environment is a liability to the safety of the system. For such long-living systems, design-time control's effectiveness fades in time as it is dwarfed by the lifespan of the designed object.

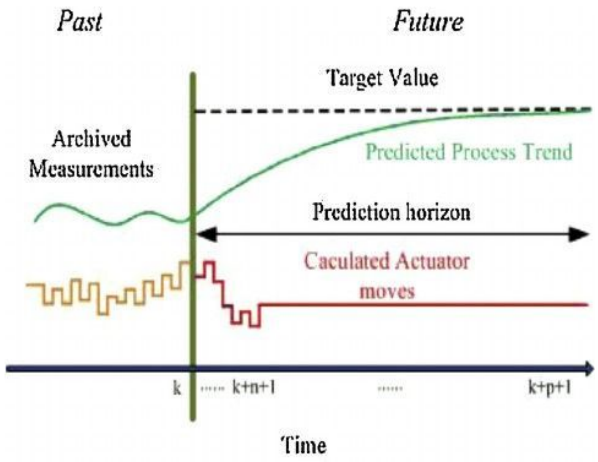
While engineering cannot solve this fundamentally social problem, the use of common infrastructure, it can indeed help by supporting existing assets with demand management strategies, which are at the heart of systems engineering.

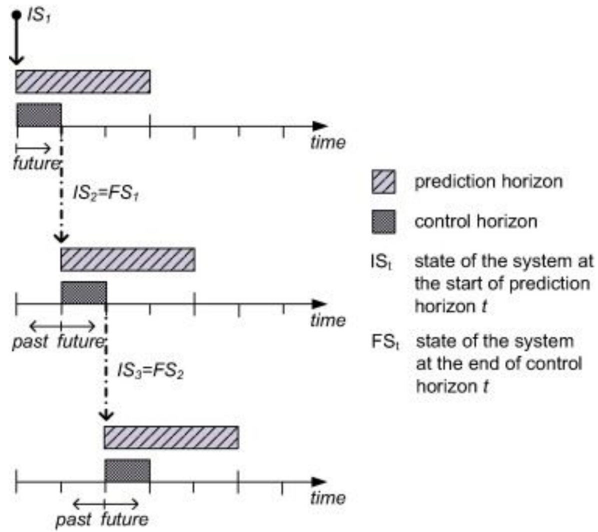
This could be achieved by implementing control and feedback strategies to include the users in the design and management process.

MODEL PREDICTIVE CONTROL







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