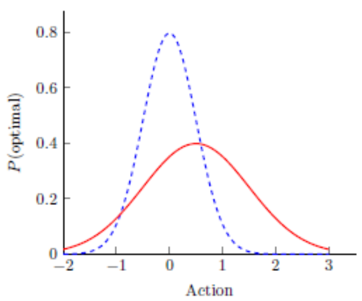
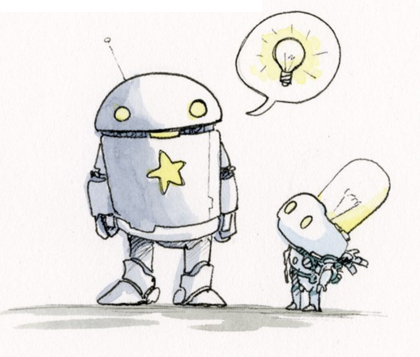




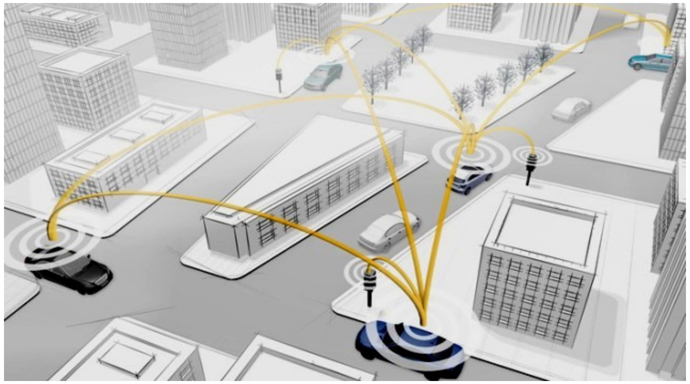
A SIMULATION-BASED ARCHITECTURE FOR SMART CYBER-PHYSICAL SYSTEMS

THOMAS GABOR, LENZ BELZNER, MARIE KIERMEIER, MICHAEL TILL BECK, ALEXANDER NEITZ

LMU MUNICH
INSTITUTE FOR INFORMATICS

SMART CYBER-PHYSICAL SYSTEMS

E.g. autonomous factories, smart cities, ...



Partially uncontrolled environment

Incomplete design-time knowledge

Complex decisions at runtime

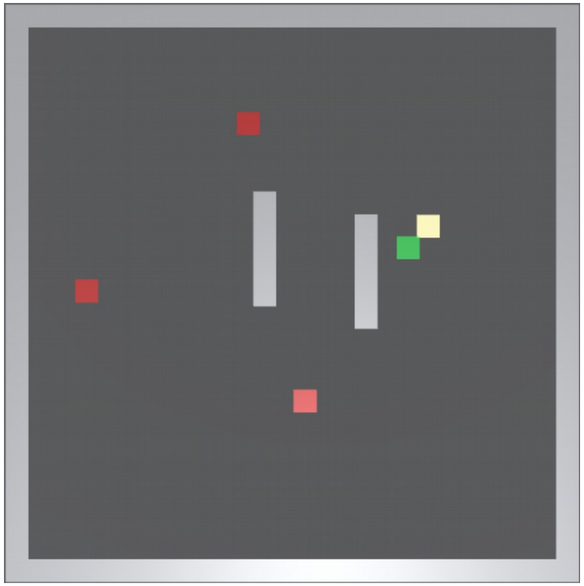
Space of behavioral solutions available

Task:

Choose adequate solution in time

CHALLENGES

- **Challenge 1:** Changing environment
  - Non-stationary optimal behavior
- **Challenge 2:** Aleatoric uncertainty
  - Optimal behavior is probabilistic
  - Irreducible
- **Challenge 3:** Epistemic uncertainty
  - “Small data”
  - Reducible
- **Challenge 4:** Behavioral uncertainty
  - Due to resource constraints



A SIMULATION-BASED ARCHITECTURE FOR SMART CYBER-PHYSICAL SYSTEMS

MOTIVATION

Planning

- Given an MDP
- State space S, action space A
- Model of domain dynamics P(S|S x A)
- Reward function R : S x A x S → $\mathbb{R}$ (encoding system goals)
- **Find strategy P(A|S) that maximizes expectation of gathered reward**

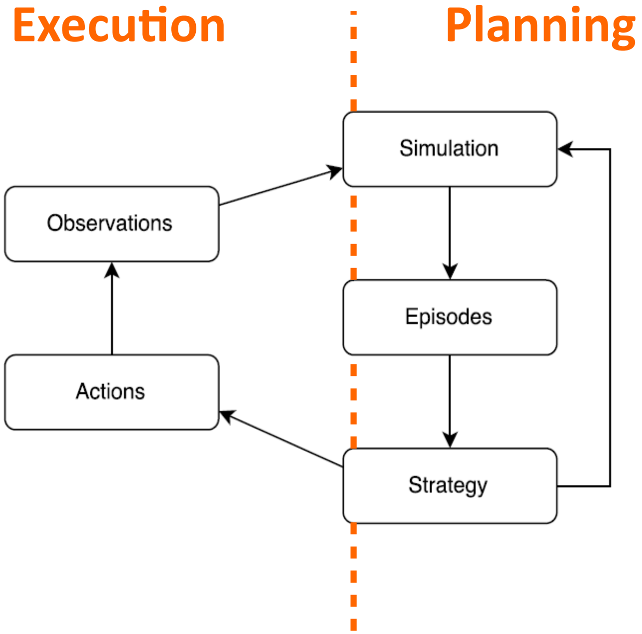
Challenge

- Partially uncontrolled domains
- Environment changes without system taking action
- Necessitates efficient decision making

ONLINE PLANNING

Simulation-Based Online Planning

- Interleaving of planning and execution
- Concentrates planning effort on current situation
- Fast planning by sampling the search space

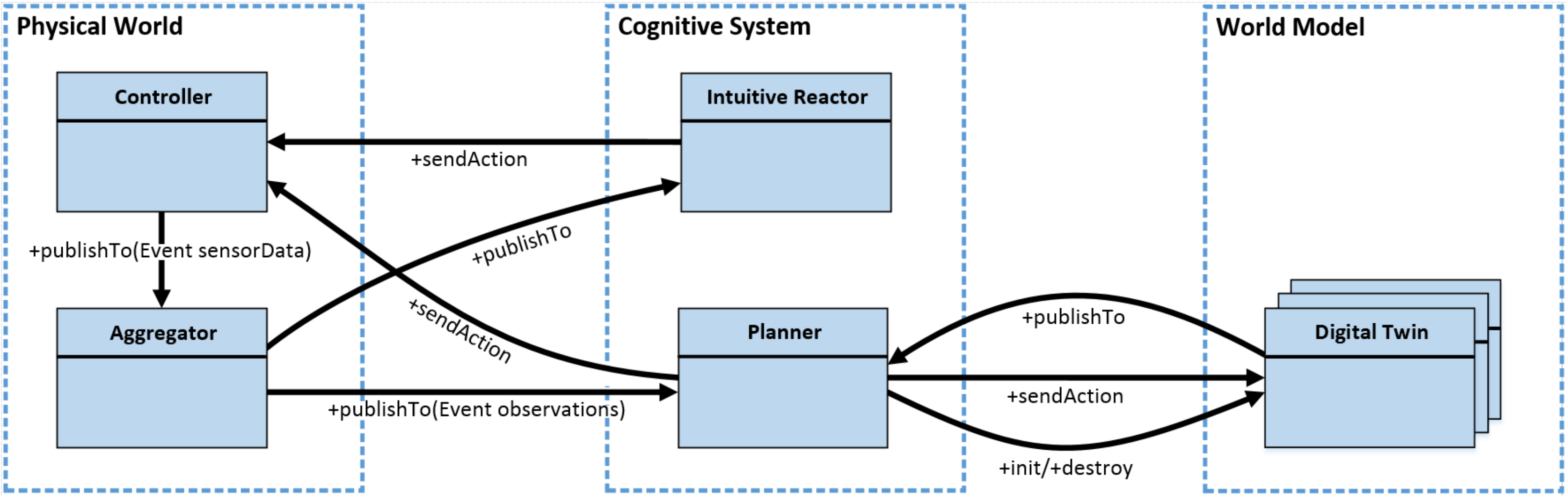


State of the Art (excerpt)

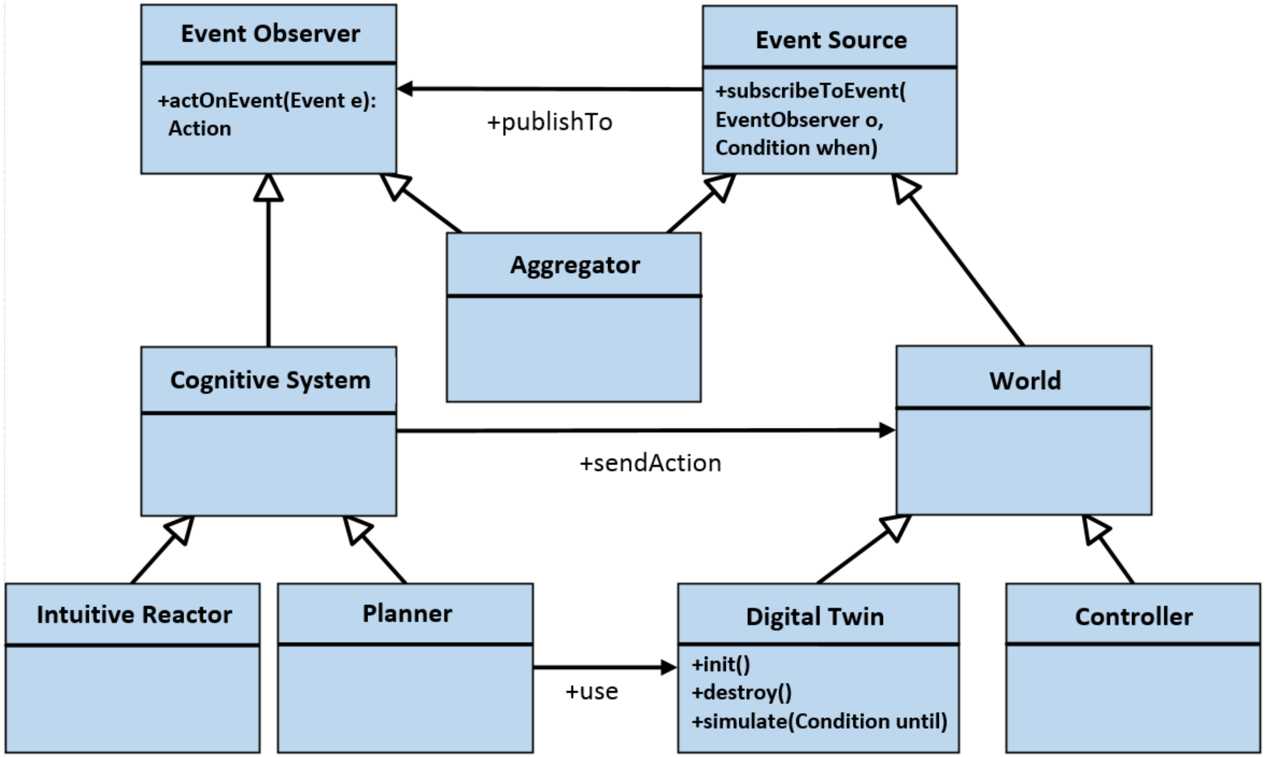
- Discrete Bandid-Based Planners: MCTS, UCT, SHOT
- Rolling Horizon Evolutionary Algorithms
- Continuous Bandid-Based Planners: HOOT, HOLOP
- Cross Entropy Open Loop Planning

Kocsis, Levente, and Csaba Szepesvári. "Bandit based monte-carlo planning." Machine Learning: ECML 2006.
Chaslot, Guillaume. "Monte-carlo tree search." Diss. Universiteit Maastricht. 2010.
Cazenave, Tristan. "Sequential halving applied to trees." Computational Intelligence and AI in Games. 2015.
Perez Liebana, Diego, et al. "Open Loop Search for General Video Game Playing." ACM GECCO. 2015.
Mansley, Christopher R., Ari Weinstein, and Michael L. Littman. "Sample-Based Planning for Continuous Action Markov Decision Processes." ICAPS. 2011.
Weinstein, Ari, and Michael L. Littman. "Bandit-Based Planning and Learning in Continuous-Action Markov Decision Processes." ICAPS. 2012.
Weinstein, Ari, and Michael L. Littman. "Open-loop planning in large-scale stochastic domains." AAAI. 2013.

THE DIGITAL TWIN ARCHITECTURE



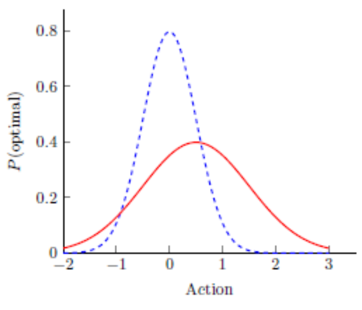
THE DIGITAL TWIN ARCHITECTURE

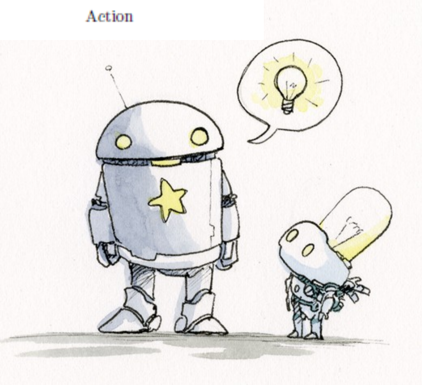


CONTROL TIERS

- Four tiers of control

- **Physical necessity**
  - Laws of nature, domain inherent
  - In particular important for high-fidelity simulations
- **Machine-environment interface**
  - Circuit control, sensors, actuators, computational hardware
  - Is a system design variable (in contrast to physical necessity)
  - Fixed in hardware, not easily changed at runtime
- **Immediate reaction**
  - Watchdogs, fixed behavioral rulesets, expert systems
  - Software, changeable at runtime
- **Planned reaction**
  - Utility functions, online planning, use of the digital twin
  - Software, changeable at runtime





CHALLENGES, APPROACHES & CASE STUDIES

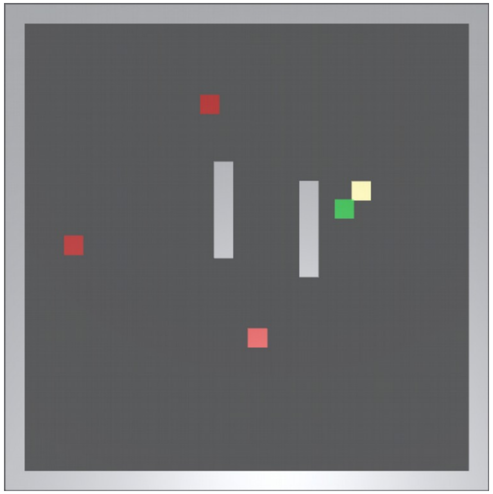
CHALLENGES & CASE STUDIES

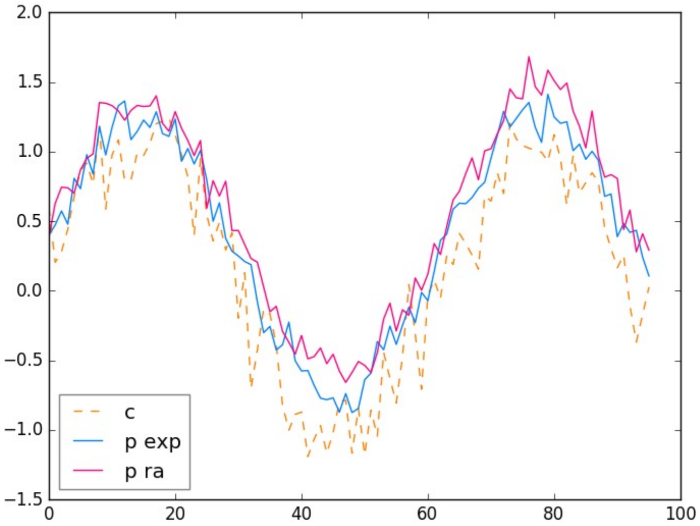
Challenges for digital twin control

- Scalability to complex models → adaptive abstraction
- Safe operation → risk awareness

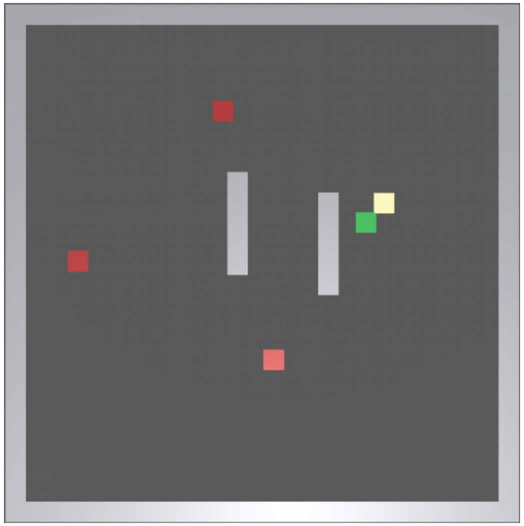
Case Studies

- Smart factory agent control
- Smart grid energy commitment





TIME ADAPTIVE MOTION PLANNING



- Consider a smart factory
- Materials and machines move probabilistically
- Model based motion planning

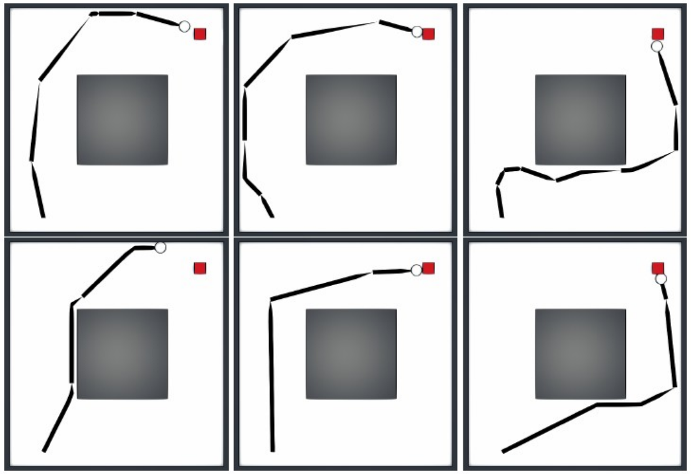
- **Problem:**
  - Environment changes continuously
  - Optimality of behavior changes continuously
  - Simulation is expensive
- **Goal:** Collect targets
- **Constraint:** Avoid static and dynamic obstacles
- **How to actuate in order to collect targets and avoid obstacles?**

- **We answer this question using a simulation @ runtime**
  - Evaluate potential actuations with the digital twin
  - Use of **time adaptation** for situative abstraction

TIME ADAPTIVE MOTION PLANNING

- Fixed temporal resolution is not always optimal
  - Typical hyperparameter problem: Where to fix?

- Assumption: A simulation is available as a function of time P(S|S x A x T)
- Idea: Incrementally identify 'important' moments
  - Optimize action duration
  - Yields adaptation of simulation effort to current situation
- A similar argument can be made for simulation depth

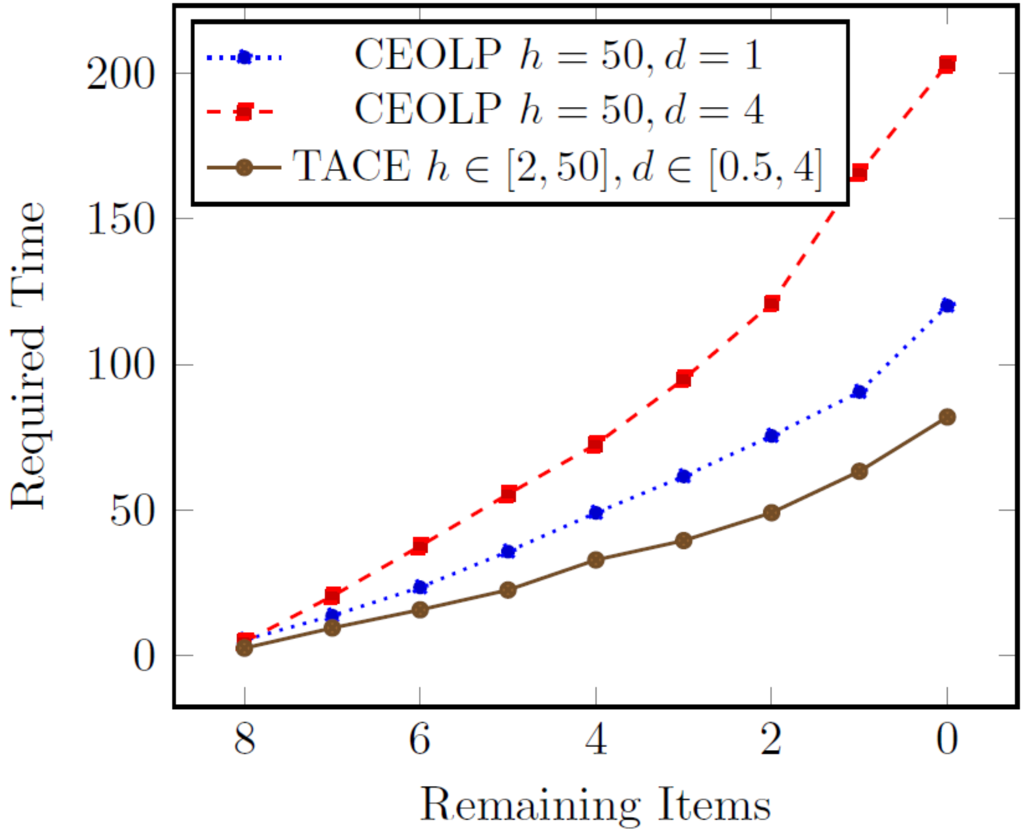


Belzner, Lenz. "Time-Adaptive Cross Entropy Planning." ACM SAC 2016.

RESULTS

With/without temporal abstraction for empirical worst/best case parameters

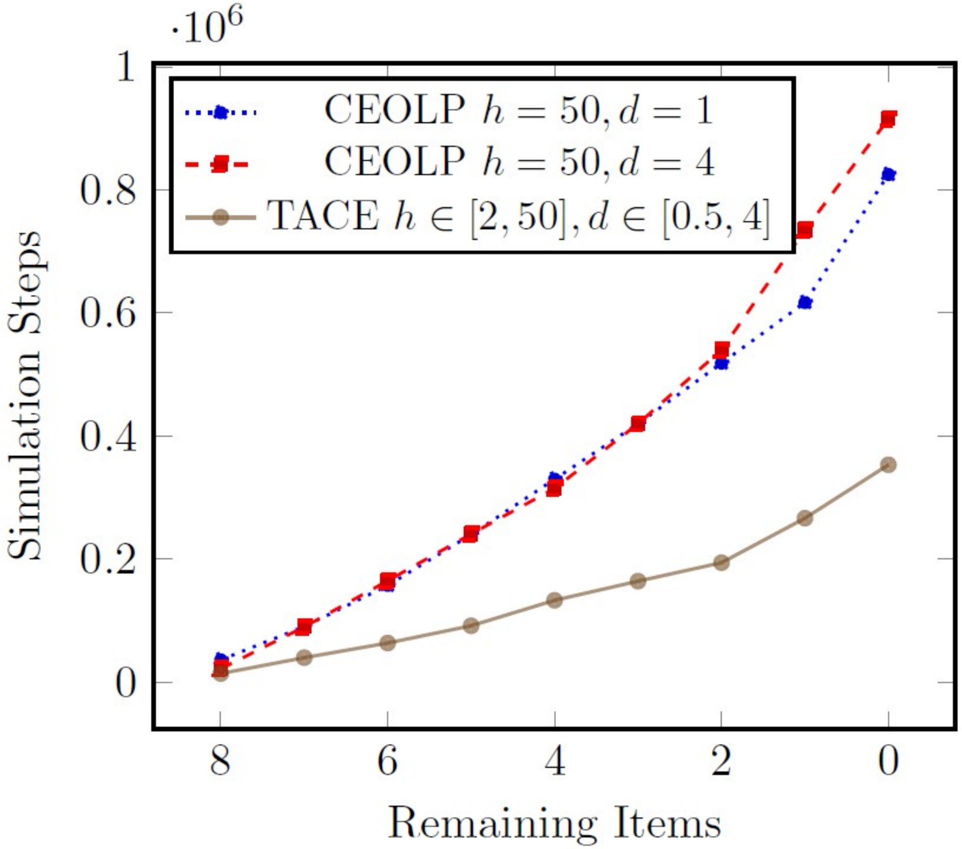
→ Temporal abstraction reduces time needed to collect the items



RESULTS

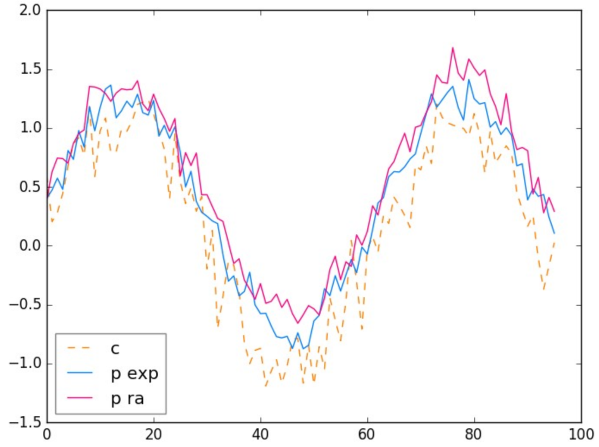
Temporal abstraction reduces simulation effort

→ Enables effective use of simulation



RISK-AWARE COMMITMENT IN THE GRID

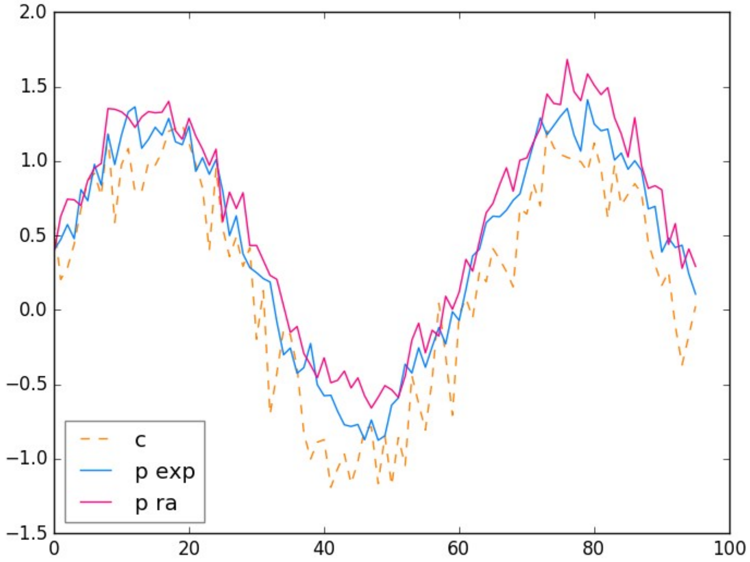
- Consider a smart grid
- Highly volatile/variable energy consumption
- Continuous reconfiguration of energy production

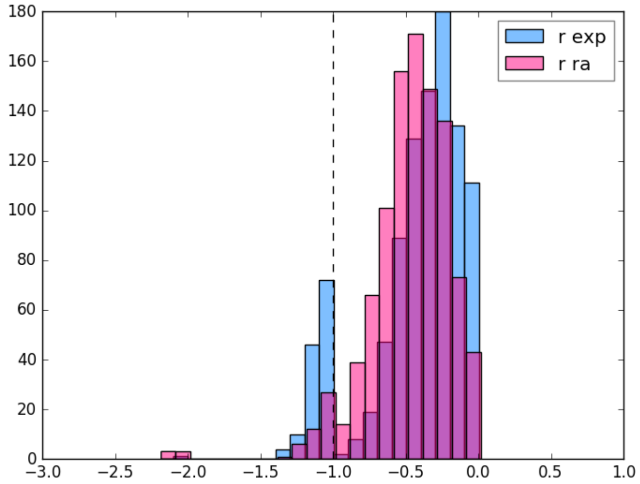


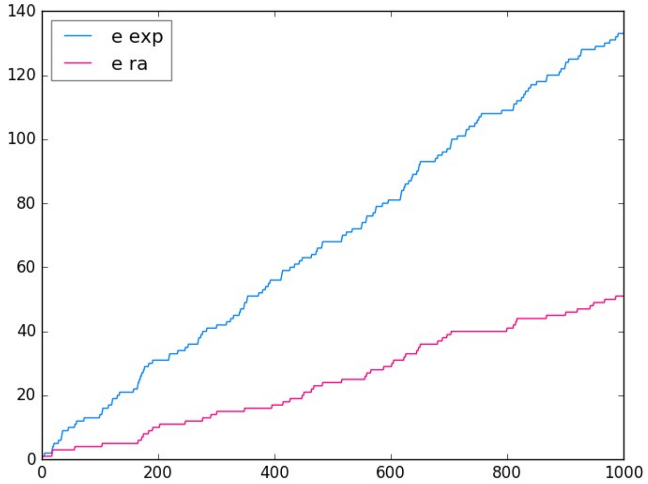
- **Problem:**
  - Overproduction induces cost
  - Power supply has to be guaranteed
  - Only a limited quantity can be sold to other markets
- **Goal:** Minimize production – consumption
- **Constraint:** 0 < production – consumption < maximum oversupply
- **How much power to produce on next commitment?**

- **We answer this question using a simulation @ runtime**
  - Evaluate potential production allotments with the digital twin
  - We compared risk-neutral and **risk-aware** strategies
  - Both use simulations, but differ in their evaluation

RISK-AWARE COMMITMENT IN THE GRID







ABSTRACTION, SAFETY & UNCERTAINTY ?

Safe adaptive abstraction

- Adaptive abstraction may provide scalability
- Potentially “abstracting away” risks?
- How to provide (statistical) guarantees?

Learning/adapting models @runtime

- Machine learning enables model adaptation @runtime
- However, this introduces model uncertainty
- How to treat safety issues under model uncertainty?
- E.g. behavior optimization vs. model confidence
- Possible approach → QoS-awareness
  - Optimize “up to” QoS requirement
  - Maximize confidence
- Consequences of adaptive abstraction and model uncertainty?

SUMMARY & NEXT

Summary

- Smart simulation-based CPS
- Digital twin architecture
- Control tiers
- Application examples
- Challenges for simulation-based control

Up next

- QoS-awareness, V&V @runtime
- Learning models @runtime
- Combining abstraction & safety
- Distributed simulation-based CPS