CENTER FOR DATA-INTENSIVE CYBER-PHYSICAL SYSTEMS

ENERGY AWARE BUILDINGS

Modelling, Analysis & Optimization using Model Checking & Machine Learning

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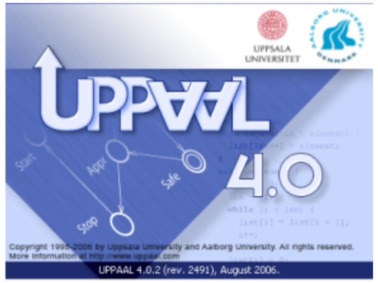
Aalborg Universitet



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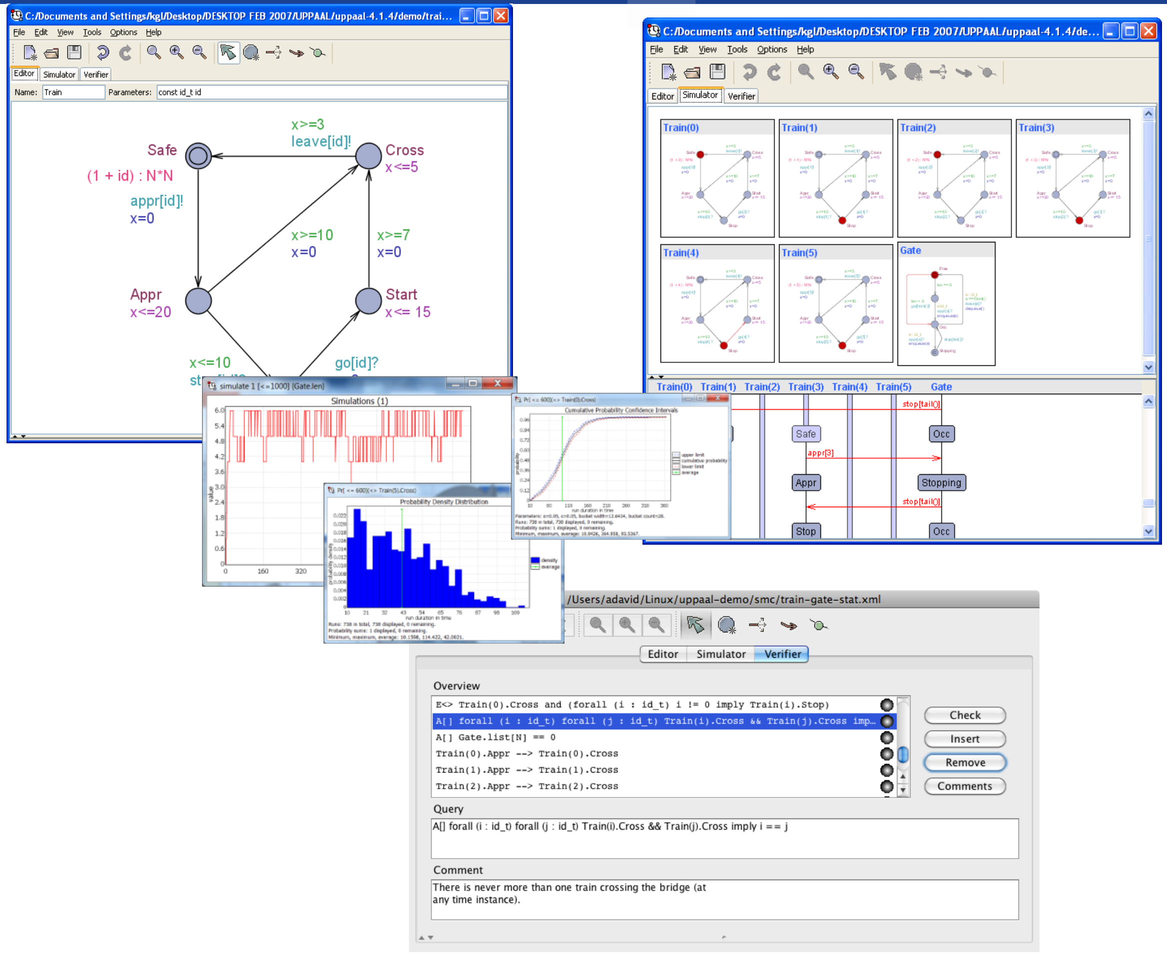
UPPAAL Tool Suite



1995

Verification — CLASSIC

Optimization — CORA — 2001

Testing — TRON — 2004

Synthesis — TIGA — 2005

Component — ECDAR — 2010

Performance Analysis — SMC — 2011

Machine Learning — STRATEGO — 2014

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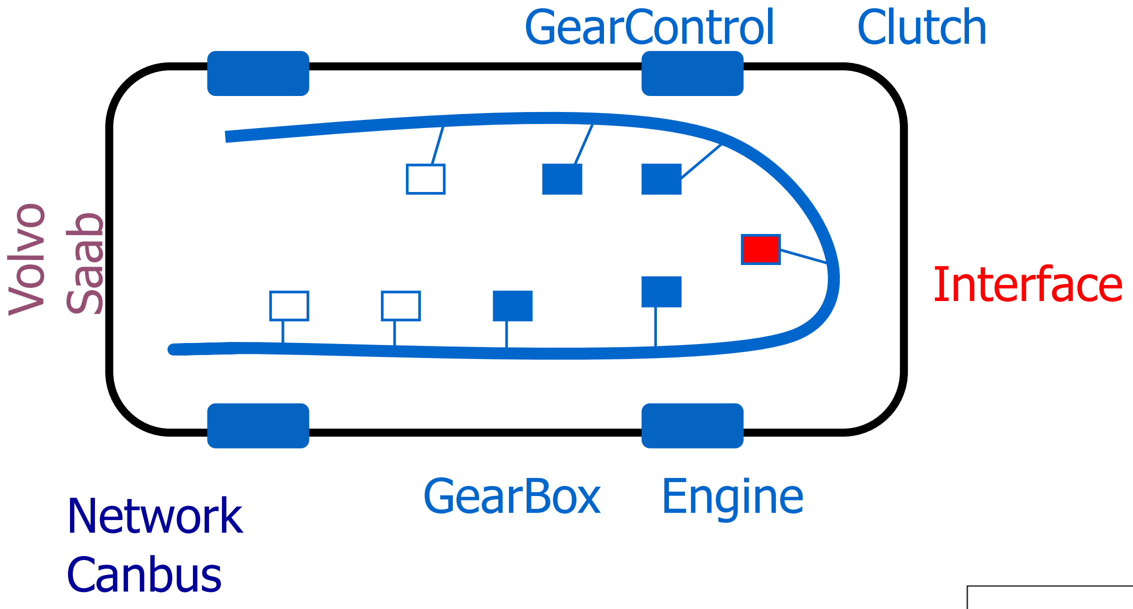
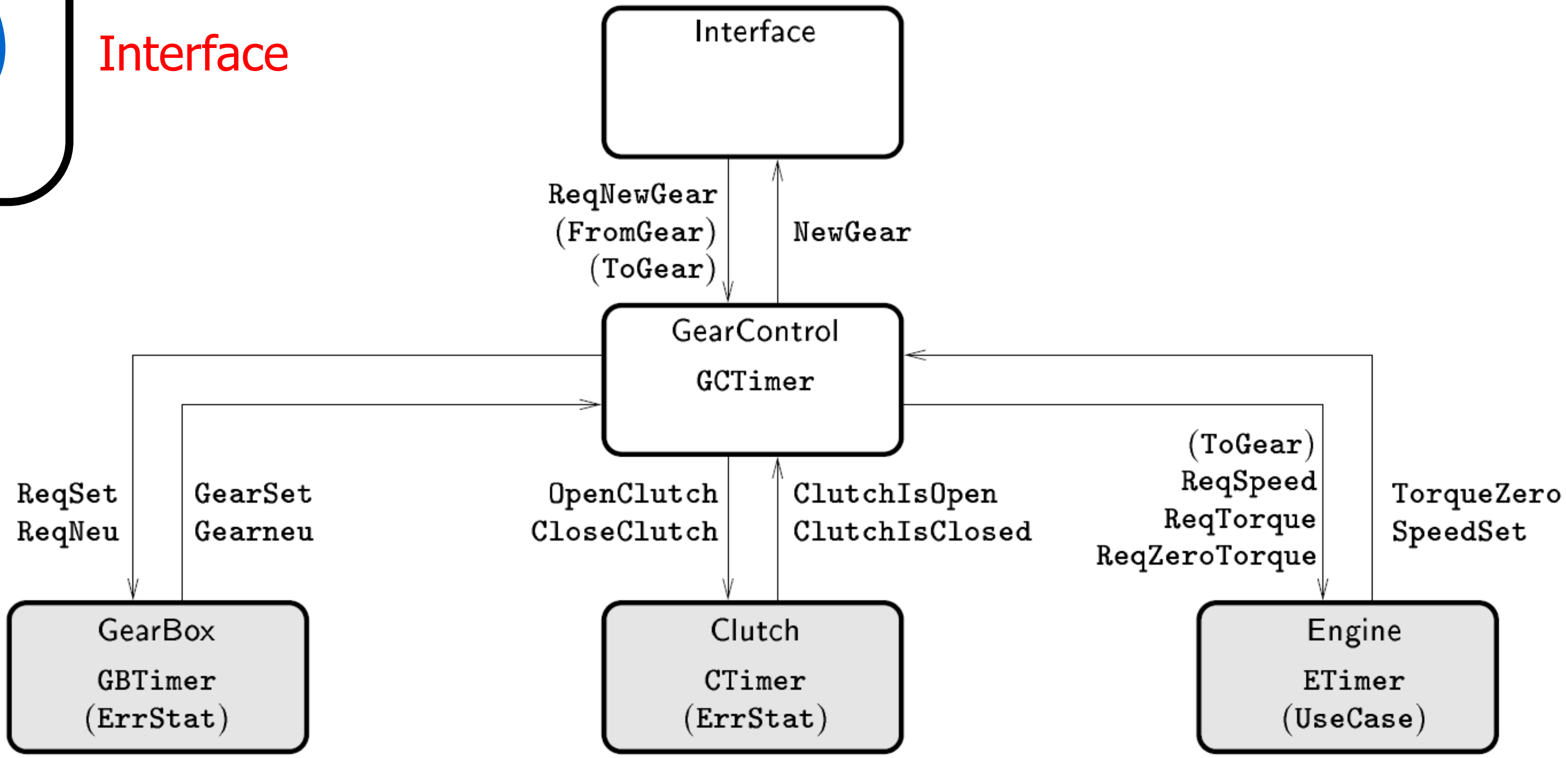
Gear Controller
with MECEL AB



Flowgraph

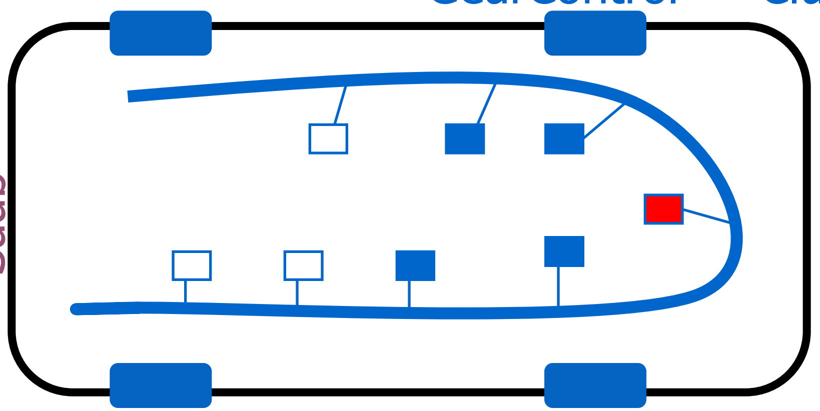


Magnus Lindahl
Paul Pettersson
Wang Yi
2001

Gear Controller

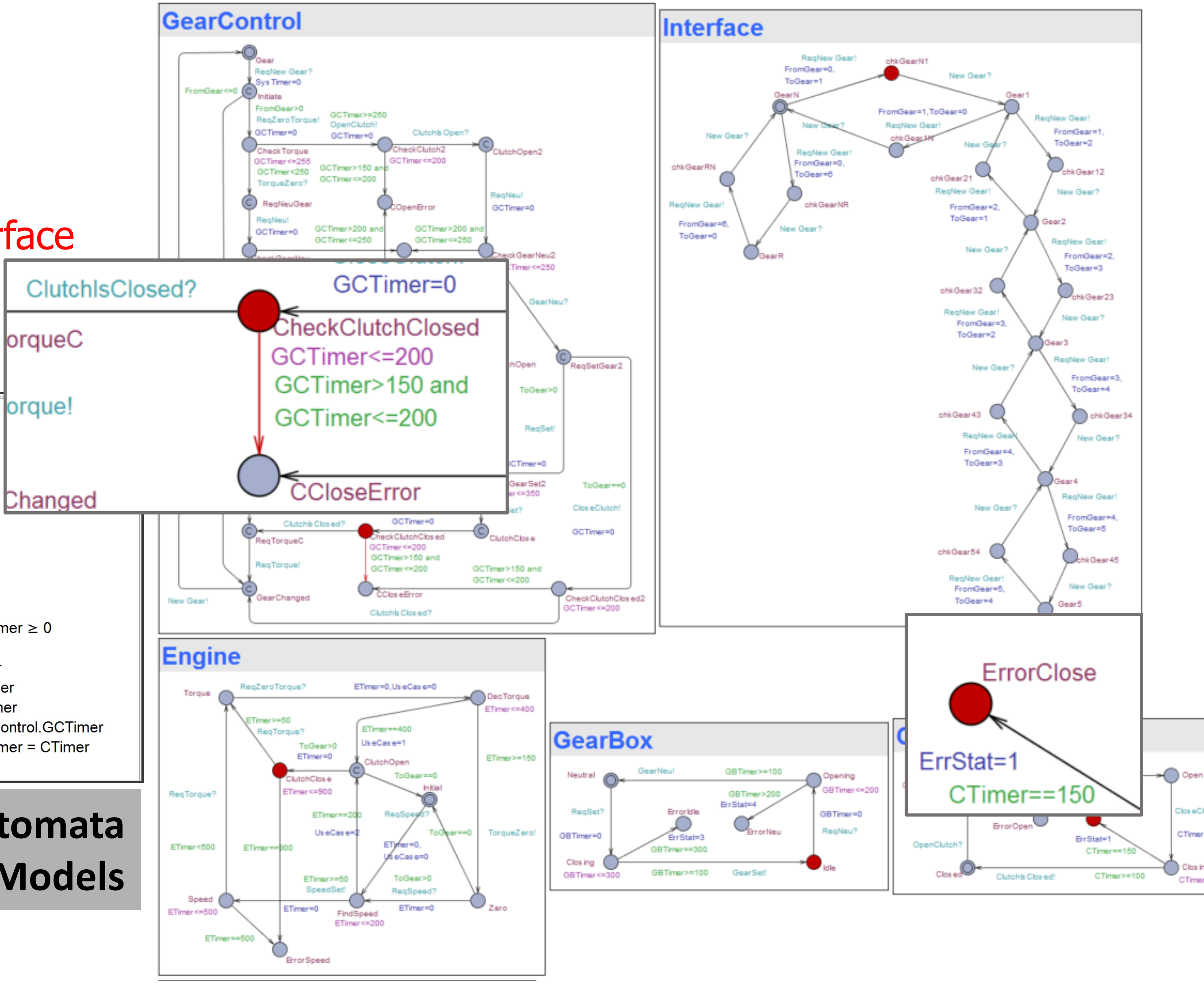
with MECEL AB

AALBORG UNIVERSITY
DENMARK



<Global variables>
- UseCase = 0
- FromGear = 0
- ToGear = 0
- ErrStat = 0

<Constraints>
- CTimer ≥ 0
- ETimer ≥ 0
- GBTimer ≥ 0
- GCTimer ≥ 0
- SysTimer ≥ 0
- GearControl.GCTimer ≥ 0
- CTimer = ETimer
- ETimer = GBTimer
- GBTimer = GCTimer
- GCTimer = SysTimer
- SysTimer = GearControl.GCTimer
- GearControl.GCTimer = CTimer



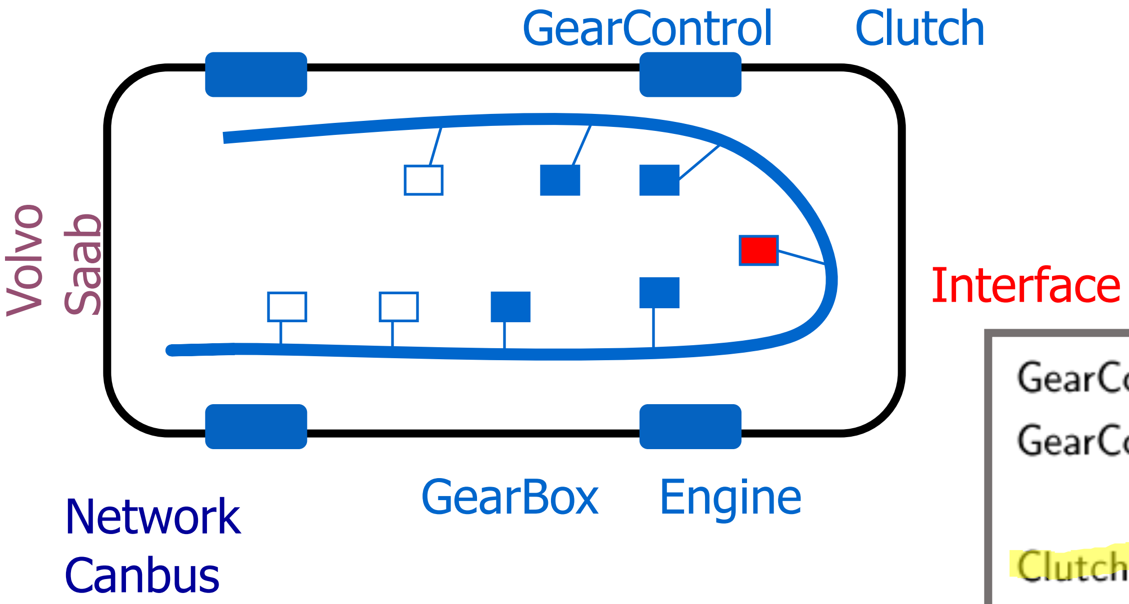
Magnus Lindahl
Paul Pettersson
Wang Yi

2001

Timed Automata Models

Gear Controller

with MECEL AB



Requirements

$\mathsf{GearControl@Initiate} \leadsto_{\leq 1500} ((\mathtt{ErrStat} = 0) \Rightarrow \mathsf{GearControl@GearChanged})$

$\mathsf{GearControl@Initiate} \leadsto_{\leq 1000} ((\mathtt{ErrStat} = 0 \land \mathtt{UseCase} = 0) \Rightarrow \mathsf{GearControl@GearChanged})$

$\mathsf{Clutch@ErrorClose} \leadsto_{\leq 200} \mathsf{GearControl@CCloseError}$

$\mathsf{Clutch@ErrorOpen} \leadsto_{\leq 200} \mathsf{GearControl@COpenError}$

$\mathsf{GearBox@ErrorIdle} \leadsto_{\leq 350} \mathsf{GearControl@GSetError}$

$\mathsf{GearBox@ErrorNeu} \leadsto_{\leq 200} \mathsf{GearControl@GNeuError}$

$Inv\ (\mathsf{GearControl@CCloseError} \Rightarrow \mathsf{Clutch@ErrorClose})$

$Inv\ (\mathsf{GearControl@COpenError} \Rightarrow \mathsf{Clutch@ErrorOpen})$

$Inv\ (\mathsf{GearControl@GSetError} \Rightarrow \mathsf{GearBox@ErrorIdle})$

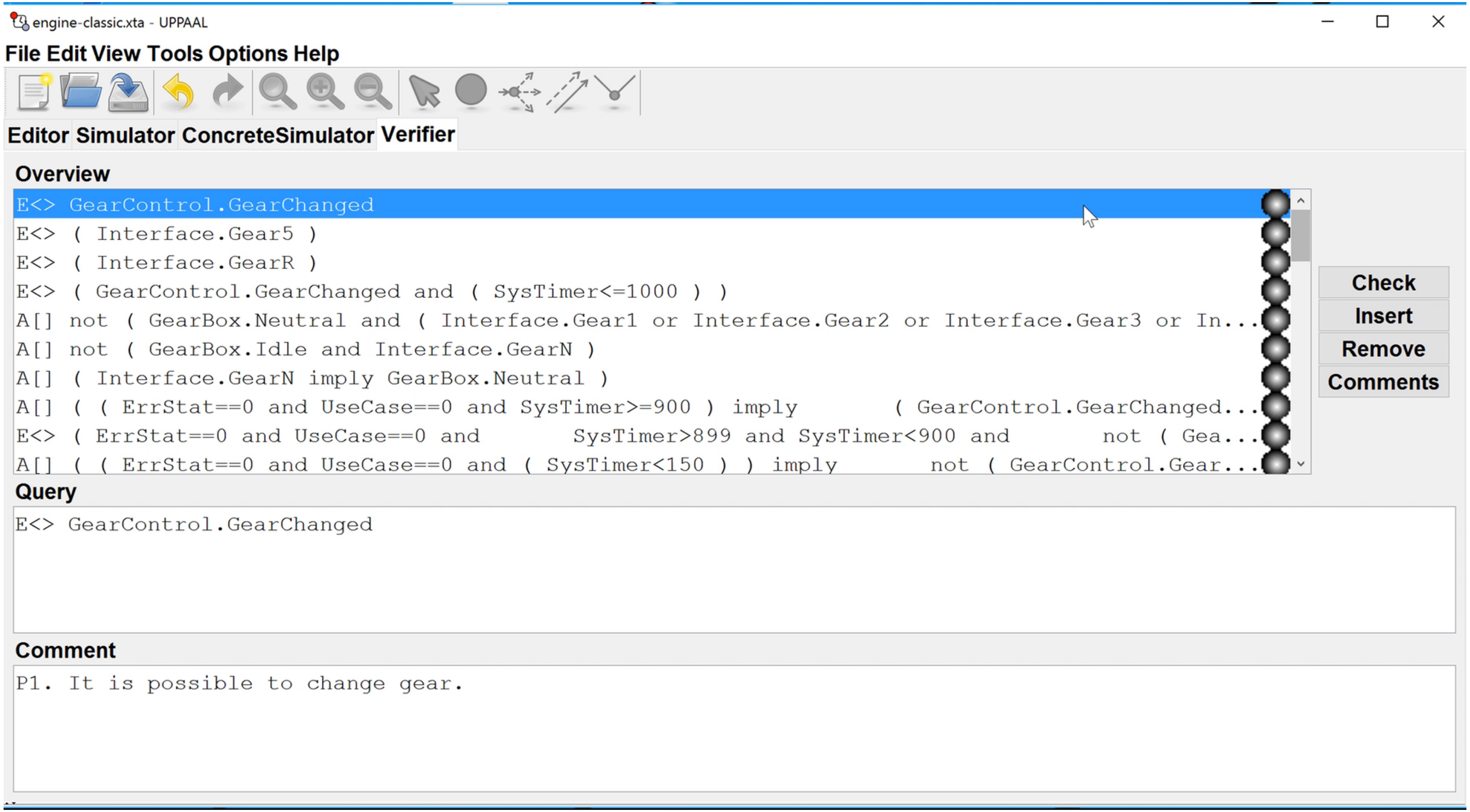
$Inv\ (\mathsf{GearControl@GNeuError} \Rightarrow \mathsf{GearBox@ErrorNeu})$

$Inv\ (\mathsf{Engine@ErrorSpeed} \Rightarrow \mathtt{ErrStat} \neq 0)$

$Inv\ (\mathsf{Engine@Torque} \Rightarrow \mathsf{Clutch@Closed})$

Magnus Lindahl
Paul Pettersson
Wang Yi
2001

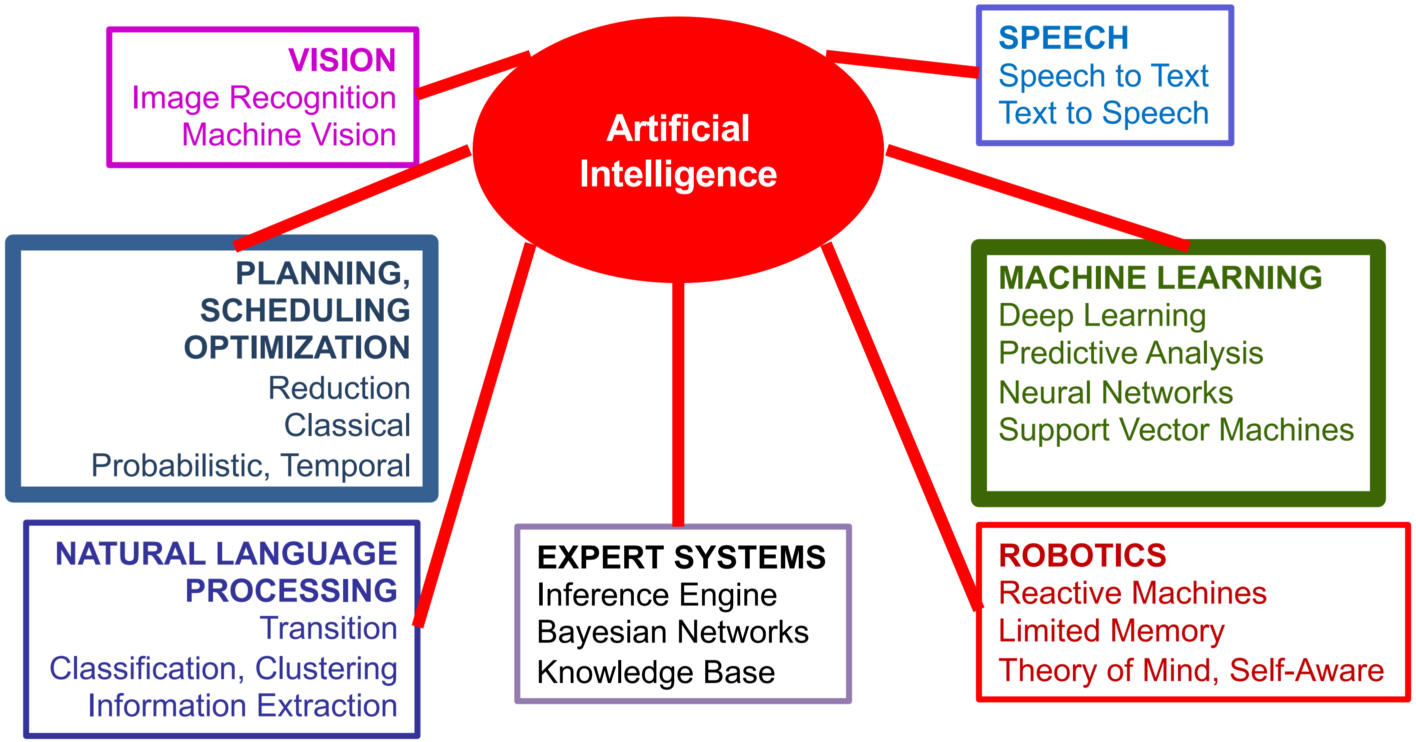
UPPAAL Model Checking – Demo



SMART HOUSES

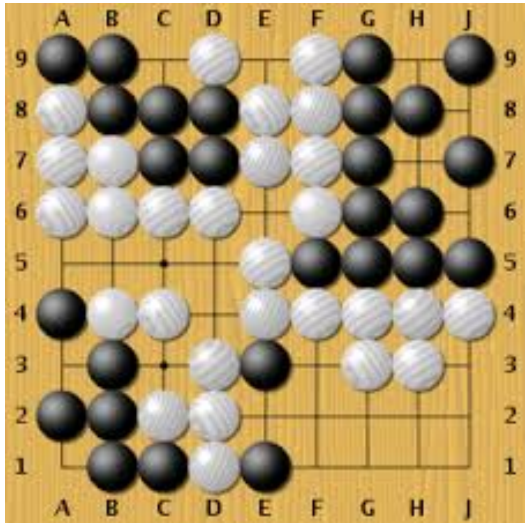
- Automatic control of a number of functions in a house.
- Formulated as a **game** between **environment** and the **controller**.
- Automatic synthesis of improved, optimal and personalized control strategy.
- From **abstract game strategies** to **concrete code** running on **real hard-ware**.

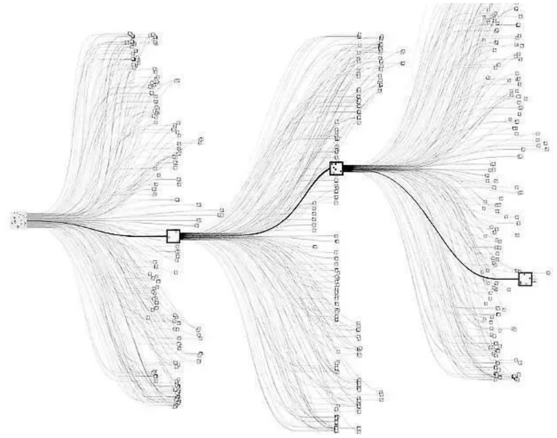
AI and Machine Learning

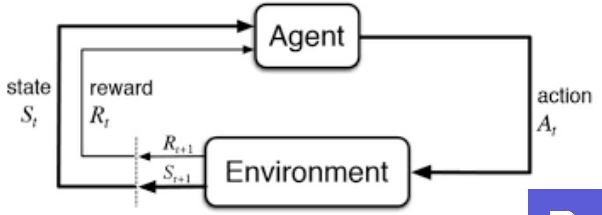


AI and Machine Learning

Monte Carlo Tree Search







Reinforcement Learning

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OPTIMAL FLOOR HEATING

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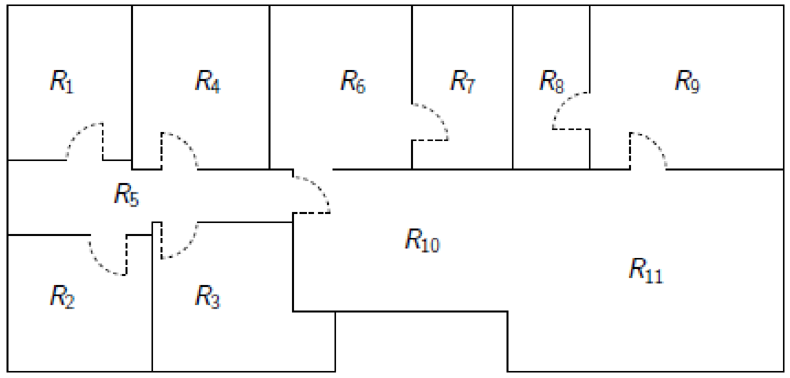
Floor Heating Scenario

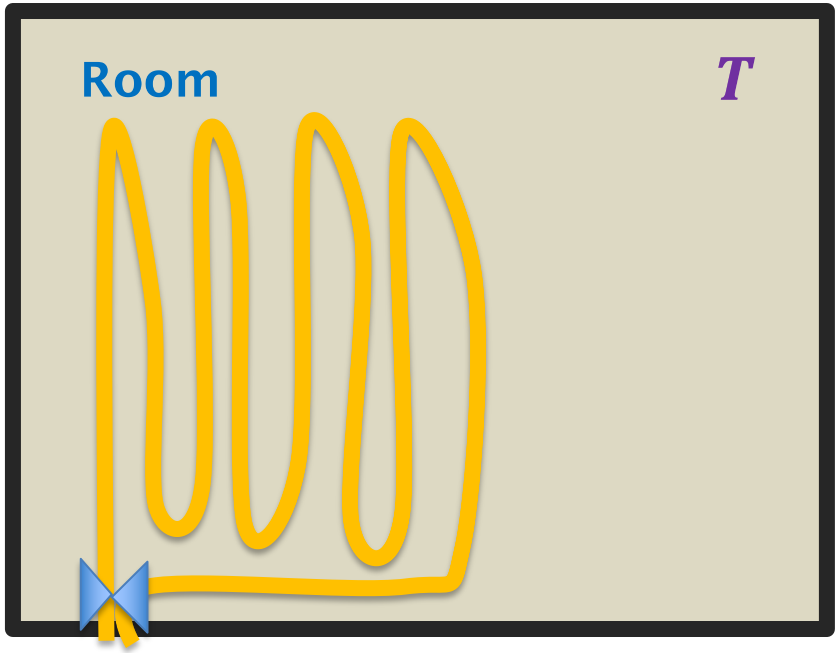
- Each room has a hot water loop that can be opened/closed
- Loops are controlled via activating / deactivating valves.
- Rooms equipped with wireless temperature sensors (report every 15 minutes).
- Each room has its user-defined target temperature.



Control Task:

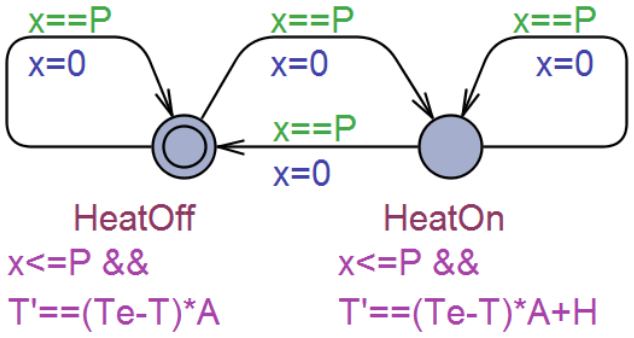
maintain room temperatures
as close as possible to
target temperatures

1-Room / 1-Window Game



T_e

Room




```
const double Tg = 21.0; // room temp. goal
const double Te = 15.0; // environment temp.
const double H = 0.04;   // power of heater
const double Aclosed = 0.002; // heat loss when window closed
const double Aopen = 0.004;    // heat loss when window open
const int P = 15; // heater switching period
const int h = 60; // 1 hour = 60 time units
```

DiCyPS
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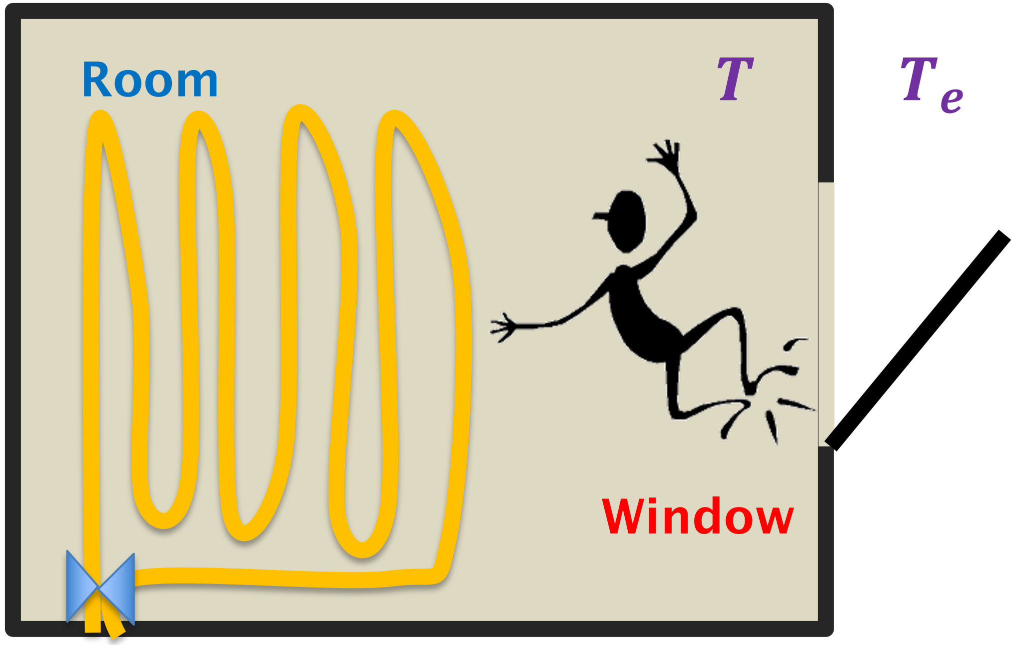
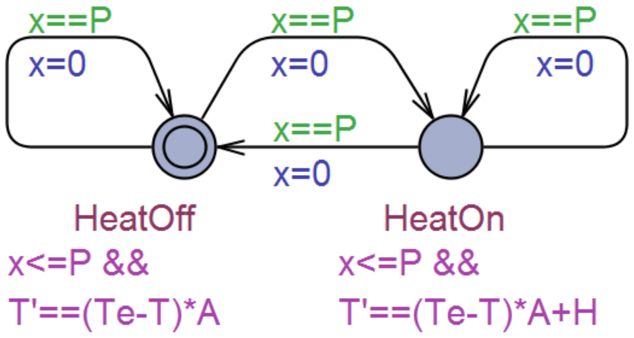
1-Room / 1-Window Game

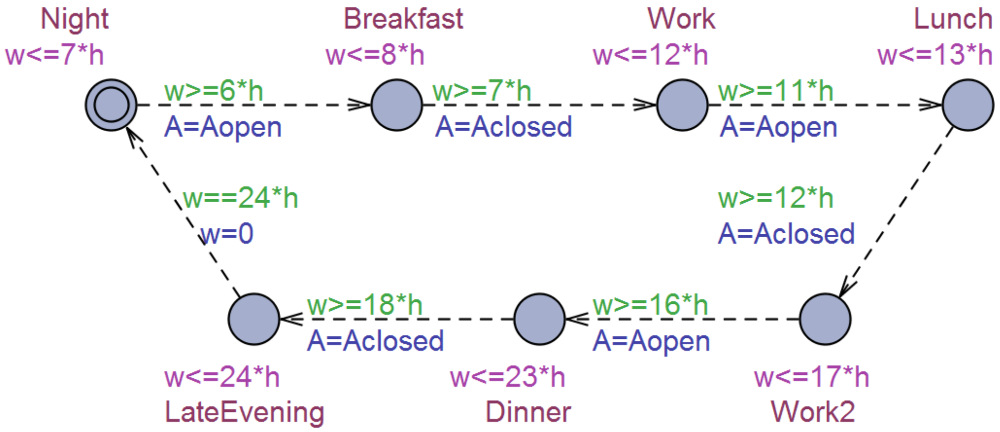


Find **strategy** that minimizes expected **discomfort**:

$$D(H) = \int_{t=0}^{t=H} \left(T(t) - T_g(t)\right)^2 dt$$

Room





Window

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heatedroom.xml - UPPAAL

File Edit View Tools Options Help

Editor Simulator ConcreteSimulator Verifier

Overview

```
// Optimal Control Strategy for 15 Periods
strategy opt = minE (D) [<=15*P]: <> t==15*P
simulate 10 [<=15*P] { T, Window.Open+15, Room.HeatOn+17 } under opt
simulate 10 [<=15*P] { D } under opt
E[<=15*P; 10](max:D) under opt
```

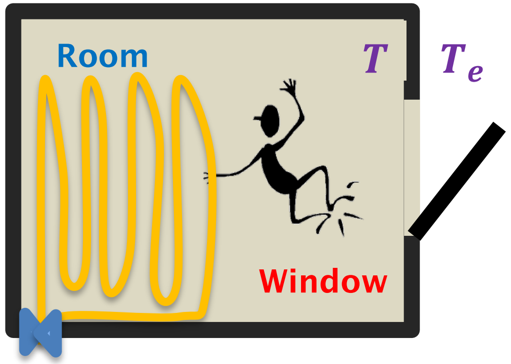
Check
Insert
Remove
Comments

Query

```
simulate 10 [<=30*P] { D }
```

Comment

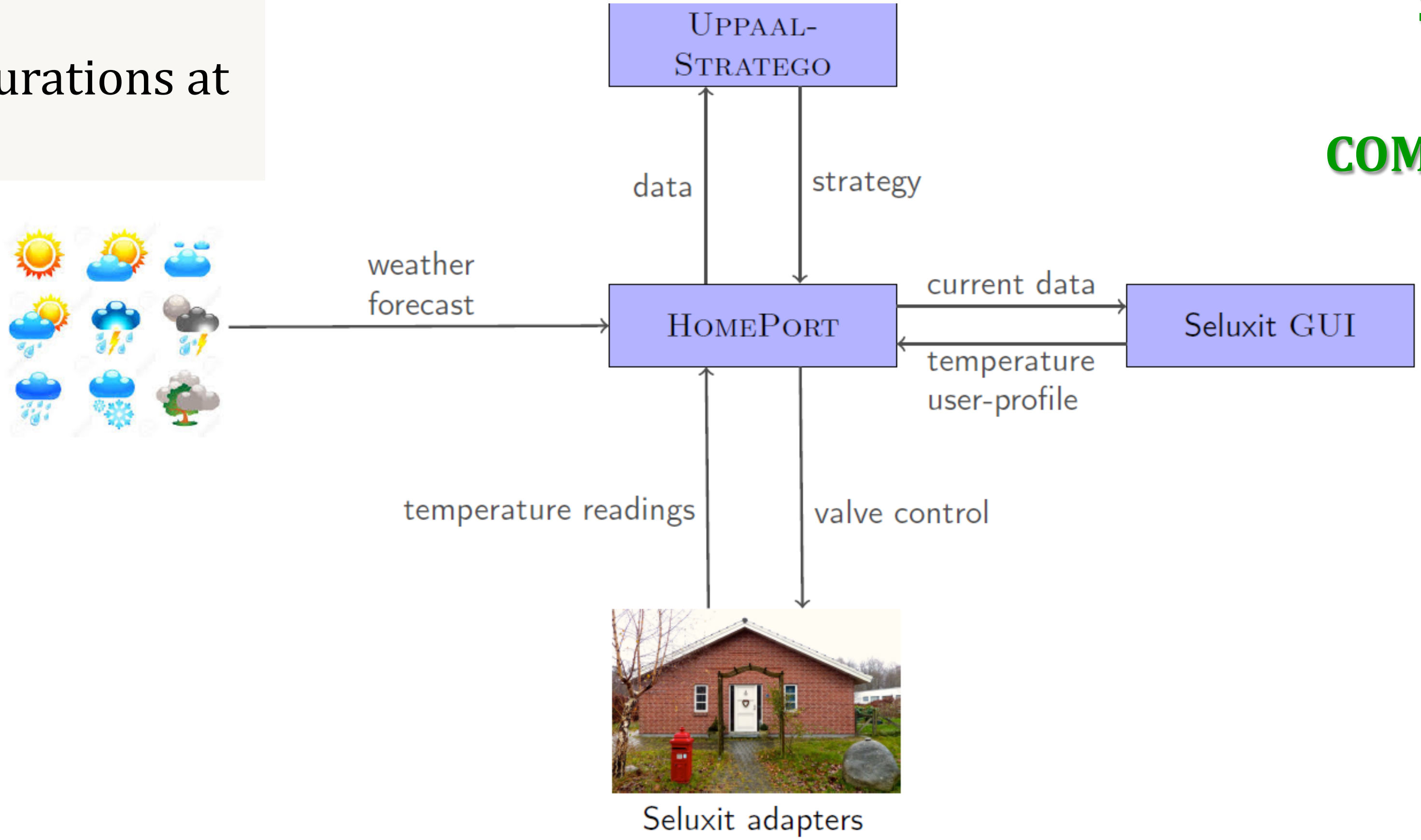
demonstration how the distance function behaves with random controller



Full Floor Heating Case

CHALLENGE
2^{11} valve configurations at each 15 minutes

SYNTHESIS BY LEARNING
ON-LINE SYNTHESIS
COMPOSITIONAL SYNTHESIS



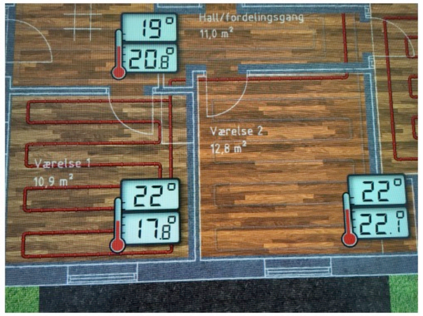
seluxit

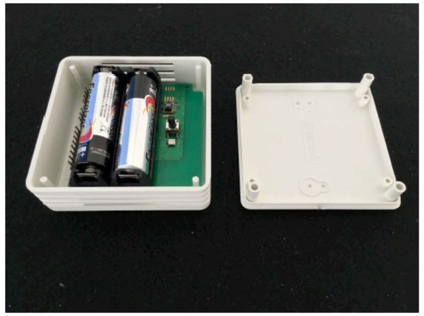
3 day scenario

Full Floor Heating Case

Weather	Distance			Energy		
	Bang-Bang	Stratego	imp.	Bang-Bang	Stratego	imp.
Aalborg	14583	8342	**43**%	14180	12626	**10**%
Anadyr	2385515	1483272	**37**%	23040	22475	**2**%
Ankara	17985	10464	**41**%	17468	15684	**10**%
Minneapolis	22052	12175	**44**%	18165	15882	**12**%
Murmansk	399421	187941	**52**%	22355	21011	**6**%

Weather	Distance			Energy		
	Bang-Bang	Stratego	imp.	Bang-Bang	Stratego	imp.
Aalborg	14583	8552	**41**%	14180	12590	**11**%
Anadyr	2385515	1503448	**36**%	23040	22371	**2**%
Ankara	17985	10511	**41**%	17468	15697	**10**%
Minneapolis	22052	12725	**42**%	18165	15837	**12**%
Murmansk	399421	191441	**52**%	22355	20923	**6**%





Evaluation of under modified parameters (0-20%)

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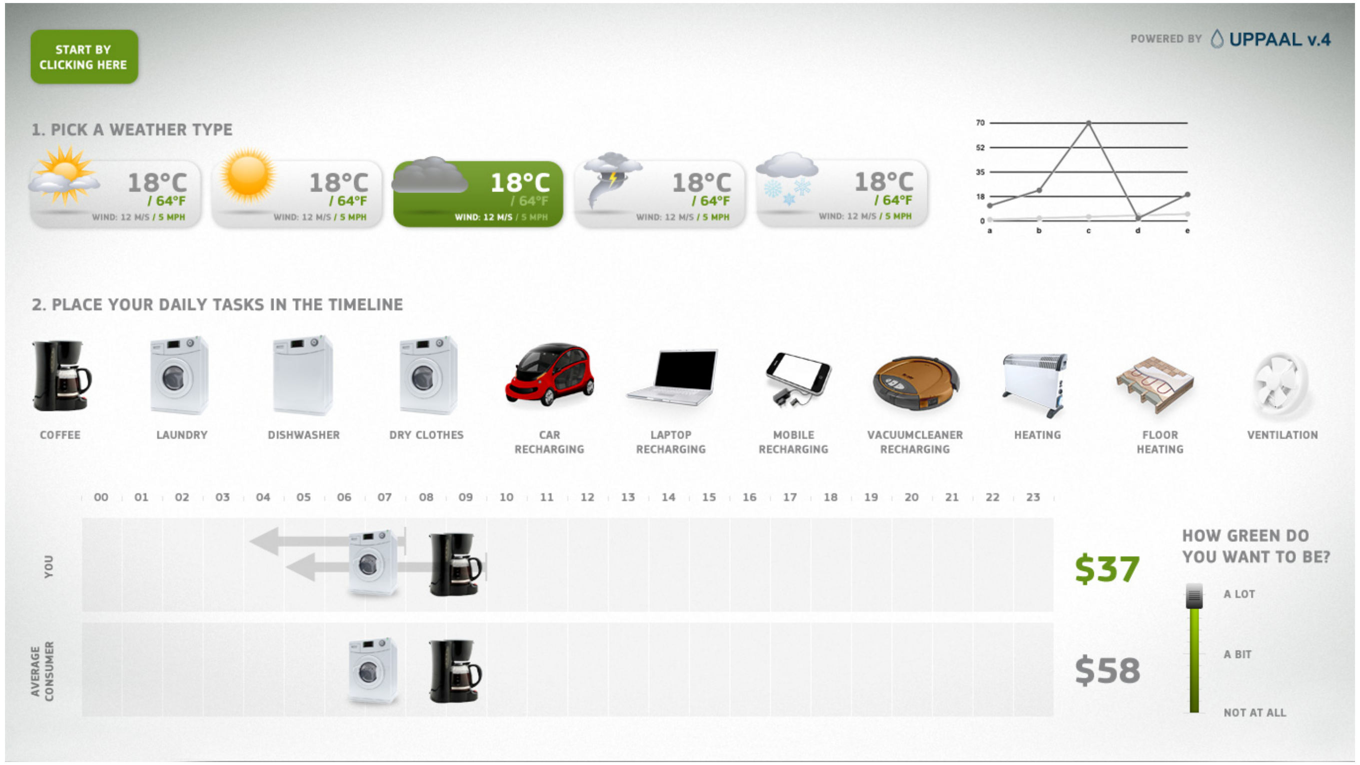
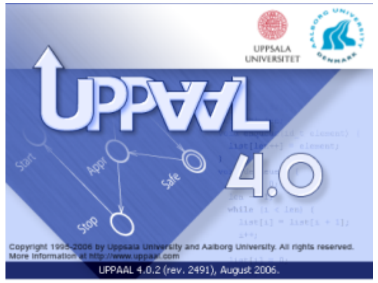
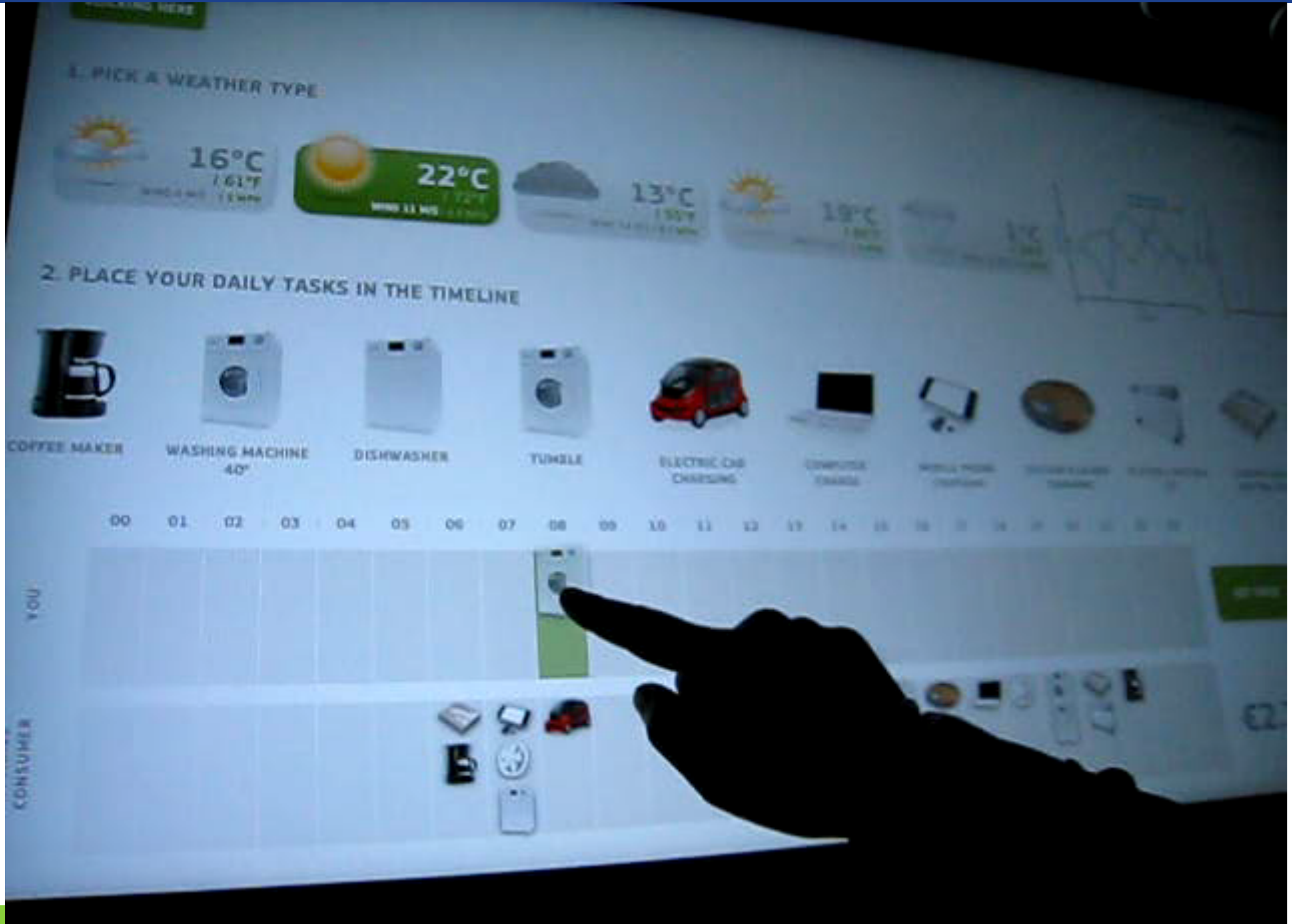
FLEXIBILITY & FLEX OFFERS

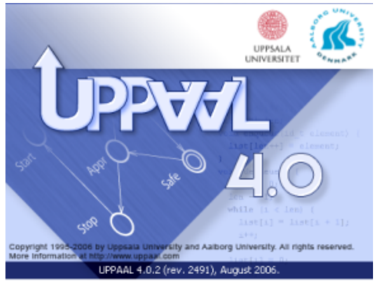
FLEXIBILITY



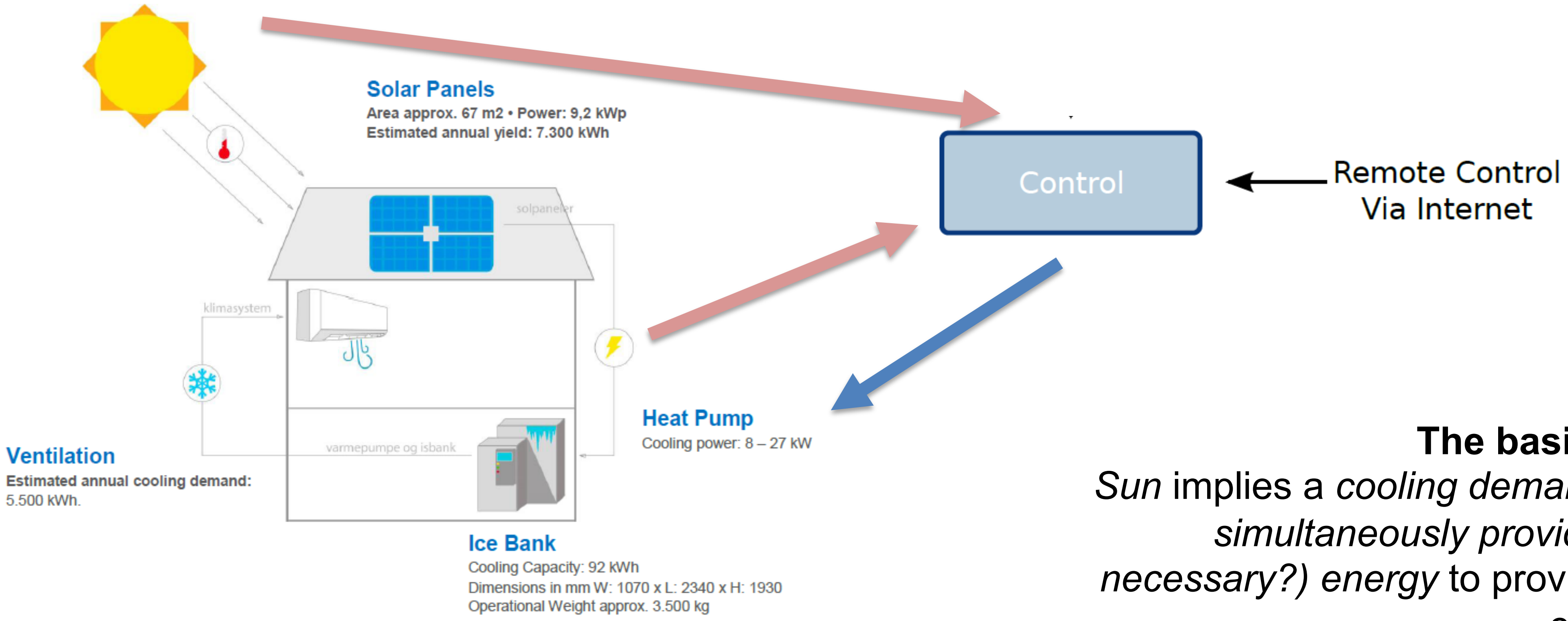


FLEXIBILITY





FLEX OFFERS and Reinforcement Learning

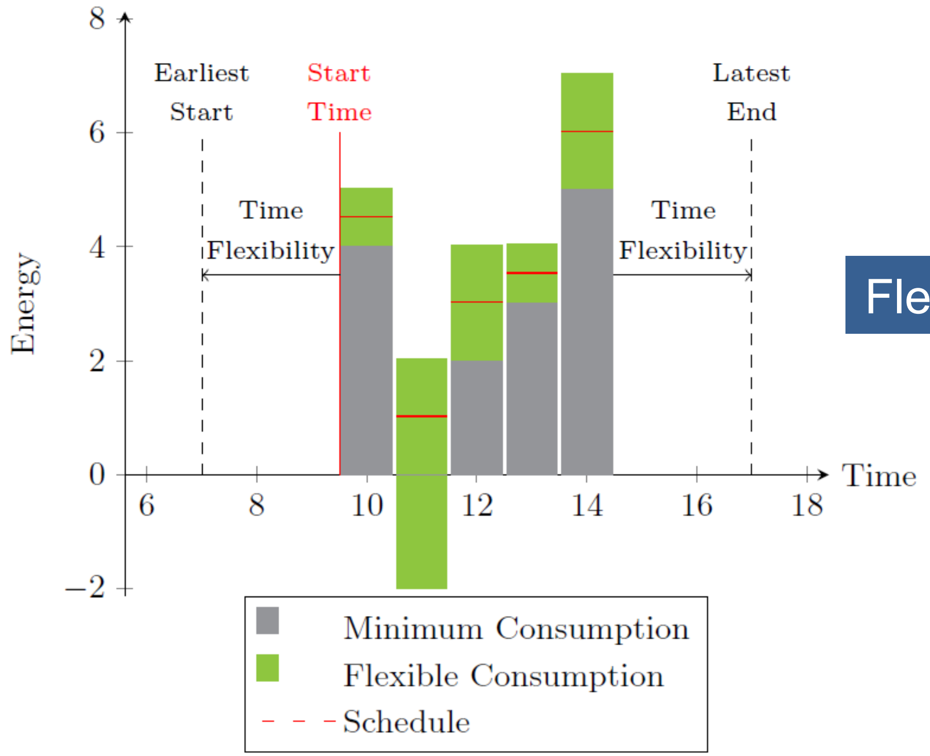


The basic idea

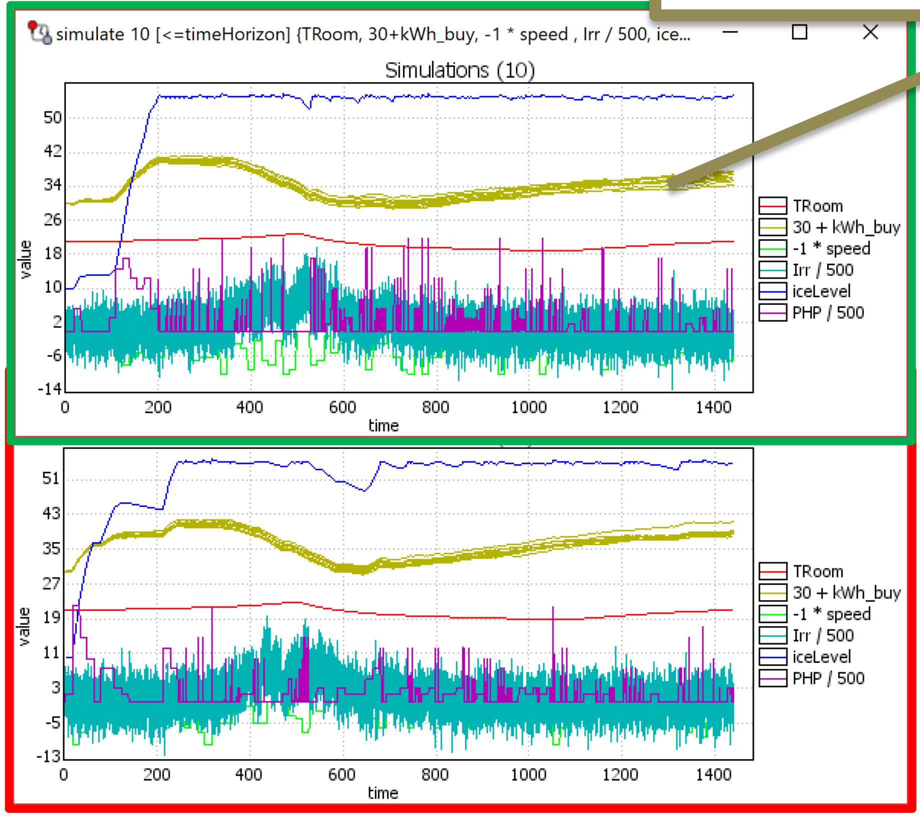
Sun implies a *cooling demand* and *simultaneously provide (the necessary?) energy* to provide the cooling.

FLEX OFFERS

Probabilistic flex-offers found from strategies for minimizing (maximizing) **kWh_buy**



Flexoffer




```
strategy min(max)kWh =
     min(max)E (kWh_buy) [<=H]: <> (i - offset) == H
```

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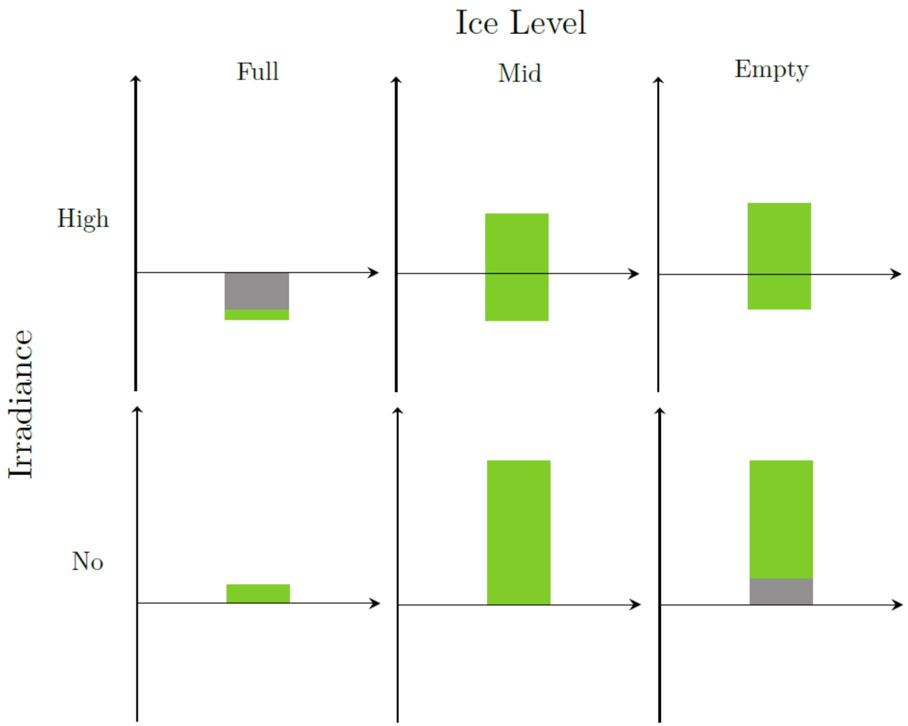
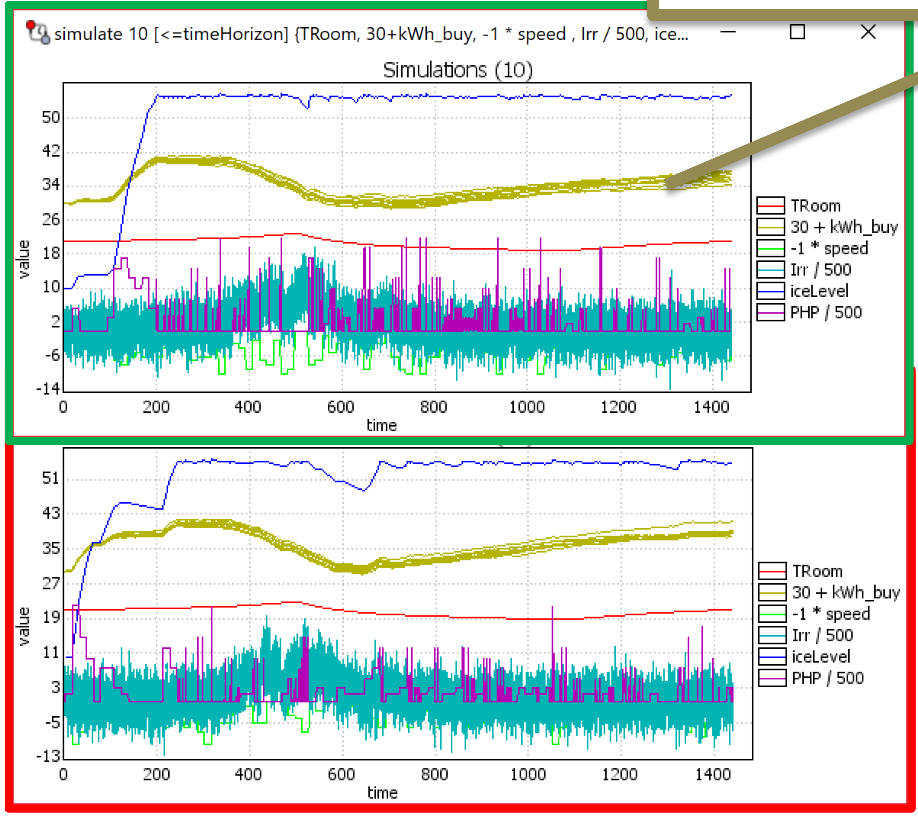
FLEX OFFERS

Probabilistic flex-offers found from strategies for minimizing (maximizing) **kWh_buy**






```
strategy min(max)kWh =
     min(max)E (kWh_buy) [<=H]: <> (i - offset) == H
```

MORE GAMES USING UPPAAL

- **Traffic Control**
- Zone-based climate control **pig-stables**
- Profit-optimal, energy-aware schedules for **satelittes**
- Optimal control of **heat-pumps**
- Personalized **light control** in home automation
- Safe and energy optimal control of **hydralic pumps**
- **COVID19**

www.uppaal.org