Constraint Programming for Decision Making in Self-Organizing, Adaptive Systems

Alexander Schiendorfer

Motivation

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Constraint programming

- Declarative paradigm to problem solving
- Specifying problems as *variables*, *domains*, and *constraints*
- A *versatile* tool for combinatorial and optimisation problems (resource allocation, job-shop scheduling etc)

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Self-organizing, adaptive Systems:

- Claim to achieve higher robustness by local rules that lead to re-structuring
- *Fault-tolerance* by added redundancies
- Typically require a feedback loop along with reconfigurations (e.g., MAPE cycle, Observer-Controller, . . .) Ramirez and Cheng (2010)
- Intended system behaviour can be described in terms of first-order predicates over a system's variables
- $\rightarrow$ Use constraints from *specification* for the implementation of *reconfiguration*)

Two worlds

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Constraints for Specification and Analysis

- Derived from Requirements Engineering processes
- Formal description in, e.g., OCL
- Models available for formal analysis

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Constraints for Engineering and Optimization

- Decision making for reconfigurations
- Self-optimization using constraint models of agents that are combined automatically

A first example

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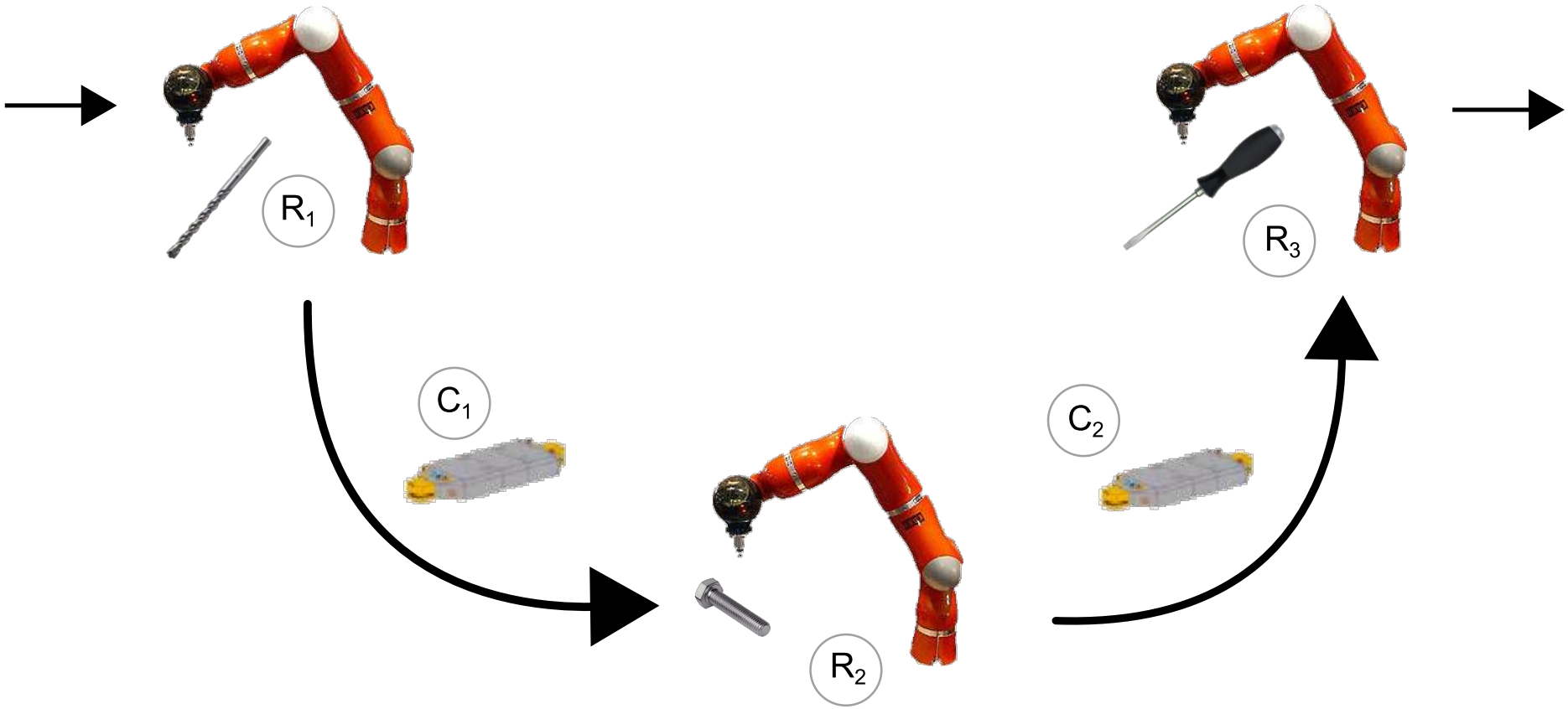

A bit more formally

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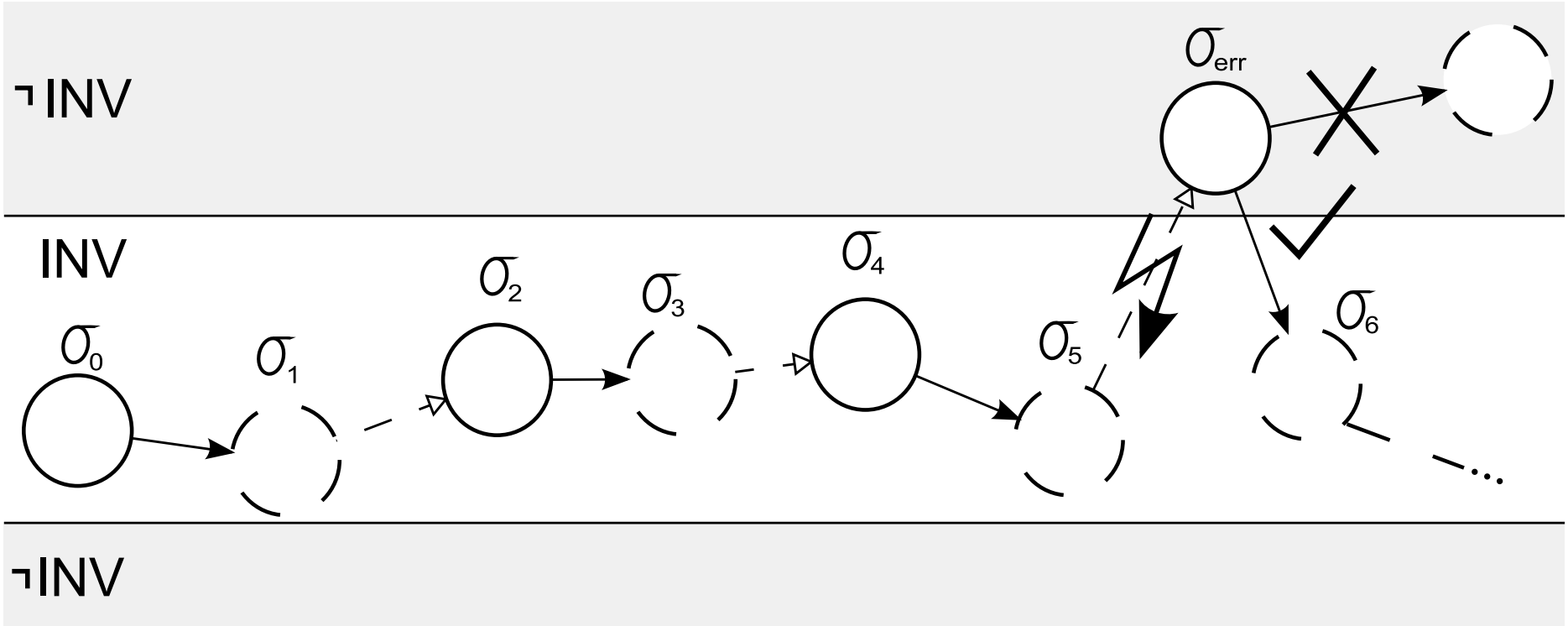
The **R**estore-**I**nvariant-**A**pproach



Nafz et al. (2013)

General Idea

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1. Notice change in the system that violates the invariant
   1. Assume, a driller breaks $\rightarrow$ drill $\notin$ *availableRoles*
   2. Assume further, this robot is assigned to drill *assignedRole* $=$ drill
   3. e.g., *assignedRole* $\notin$ *availableRoles*
2. Search for new assignment using constraint programming
3. *Restore the invariant*
4. Provable correctness as long as the system is within the corridor (using, e.g., theorem provers such as KIV or model checking tools, hybrid automata, . . .)

A second example . . .

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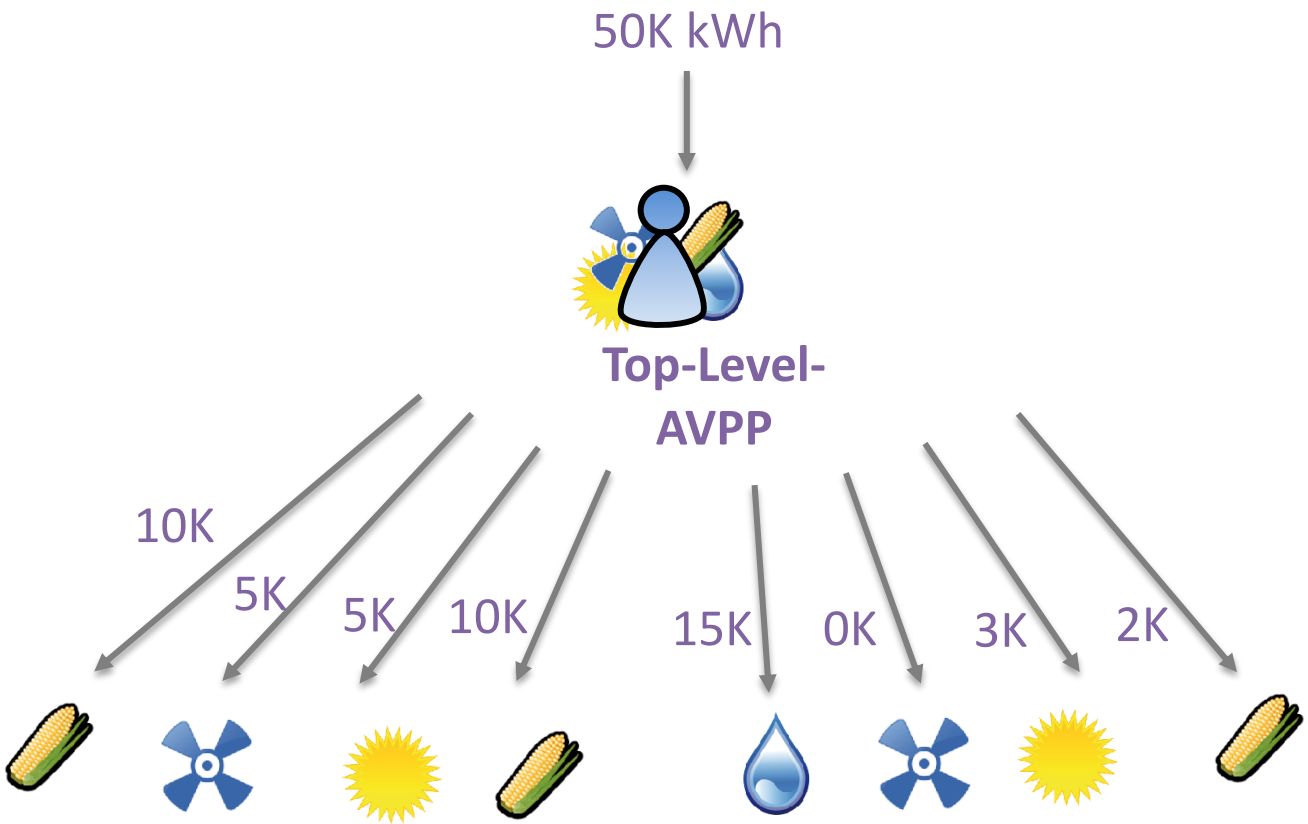
Unit Commitment in Power Management



Time-dependent resource allocation

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Variation of general resource allocation

- Demand is given for a time frame $\mathcal{T}$
- Agents are subject to constraints such as minimal or maximal rates and *inertia*
- Therefore, *proactive* allocation necessary!
- Limited rates of change between consecutive time steps

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$$\begin{aligned}
\underset{\mathcal{P}}{\text{minimise}} \quad & \sum_{t \in \mathcal{T}} |\mathcal{D}_t - \sum_{a \in \mathcal{A}} \mathcal{P}_t^a| \\
\text{subject to} \quad & \exists [x, y] \in L^a : x \leq \mathcal{P}_t^a \leq y, \, \forall a \in \mathcal{A}, \, t \in \mathcal{T} \\
& \mathcal{P}_{t+1}^a \geq c_{\min}^a(\Sigma_t^a), \, \forall a \in \mathcal{A}, \, t \in \mathcal{T} \\
& \mathcal{P}_{t+1}^a \leq c_{\max}^a(\Sigma_t^a), \forall a \in \mathcal{A}, \, t \in \mathcal{T}
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For instance, if $\mathcal{P}_{t+1}^a \leq \mathcal{P}_t^a + 30$, then $\langle 50, 80, 110 \rangle$✓ but $\langle 50, 90, 125 \rangle$×

Roadmap

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Within this realm

- A formalism to deal with over-constrained problems and specify *preferences*
- A framework to *synthesize* a set of constraint models into one optimization problem
- Algorithms to *abstract* a constraint model from a set of constraint models
- Learning-based to techniques to *build* models
- Tools to support the *elicitation* of preferences

Constraint Relationships – An example

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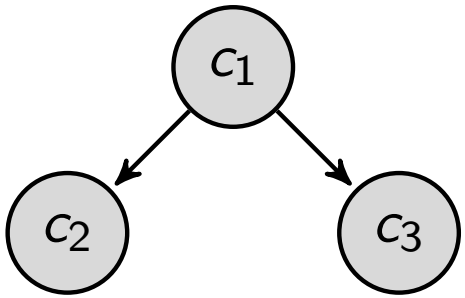
Schiendorfer et al. (2013); Knapp and Schiendorfer (2014)

- Variables: X, Y, Z
- Domains: $\{0, 1, 2\}$
- Constraints:
  - $c_1 : x + 1 = y$
  - $c_2 : z = y + 2$
  - $c_3 : x + y \leq 3$



- Not all three constraints can be satisfied simultaneously
- E.g. c_2 forces z to be 2 and y to be 0, conflicting with c_1
- We can choose between solutions satisfying $\{c_1, c_3\}$ or $\{c_2, c_3\}$
- How to settle this conflict?

Dealing with Heterogeneity

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Table : Different cold and hot start-up times in h for power plant types Jarass and Obermair (2012); Mayer et al. (2013)

Plant type	Cold start-up (down $>$ 48h)	Hot start-up (down $<$ 8h)
Black coal	4 – 5	2
Brown coal	6 – 8	2 – 4
Gas turbine	0.5	0.25
Photothermal	4 – 5	2

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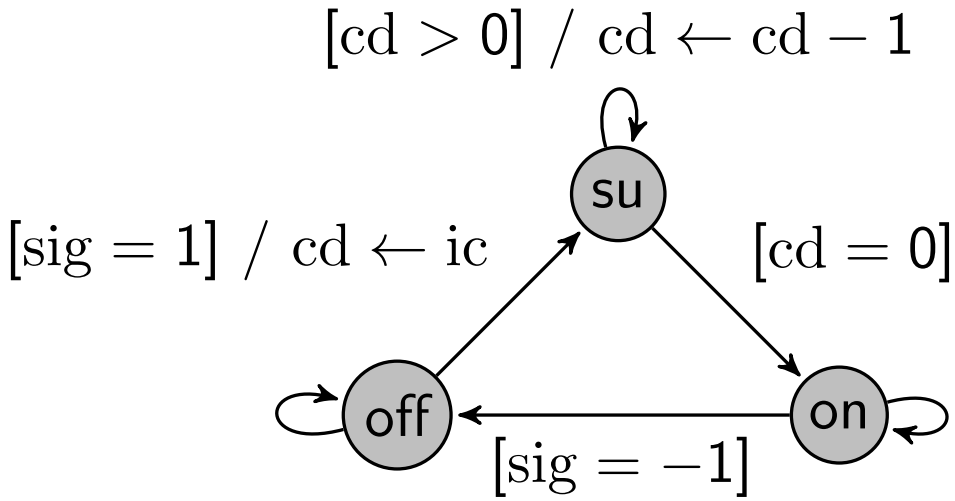
Modelling variable start-up times



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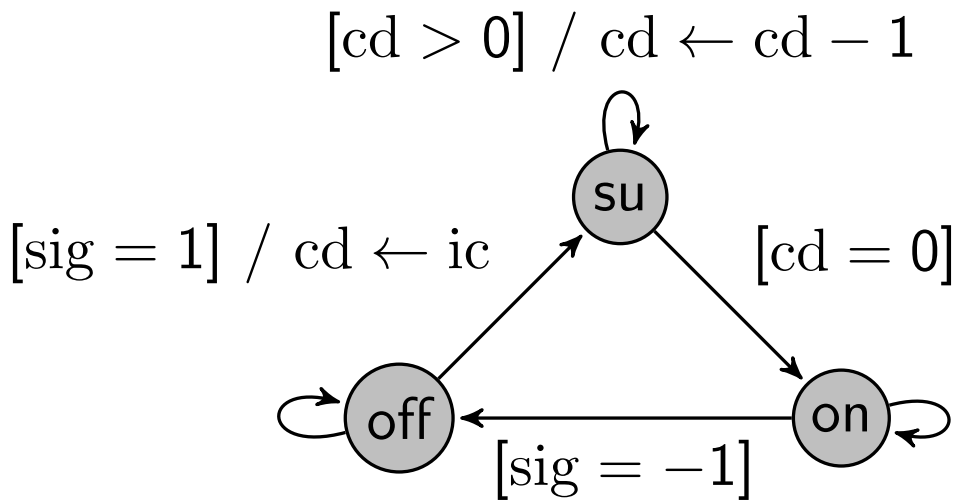
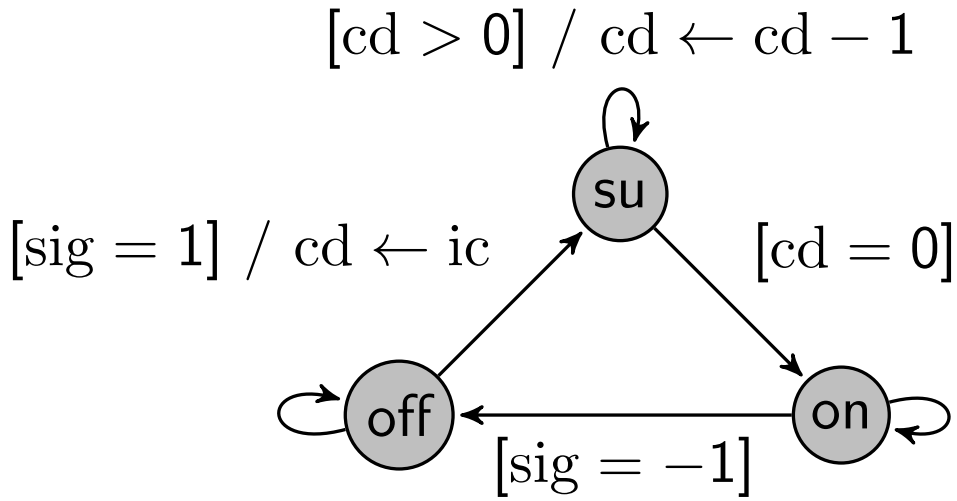


How to manage both kinds of plants (and others)?

Modelling variable start-up times



How to manage both kinds of plants (and others)?
→ Separation of shared or *public* interface variables (production) and *private* variables modelling internal aspects (e.g., for the current down-time, start-up duration at this particular down-time, etc.)
Schiendorfer et al. (2014)

Learning Models from Data

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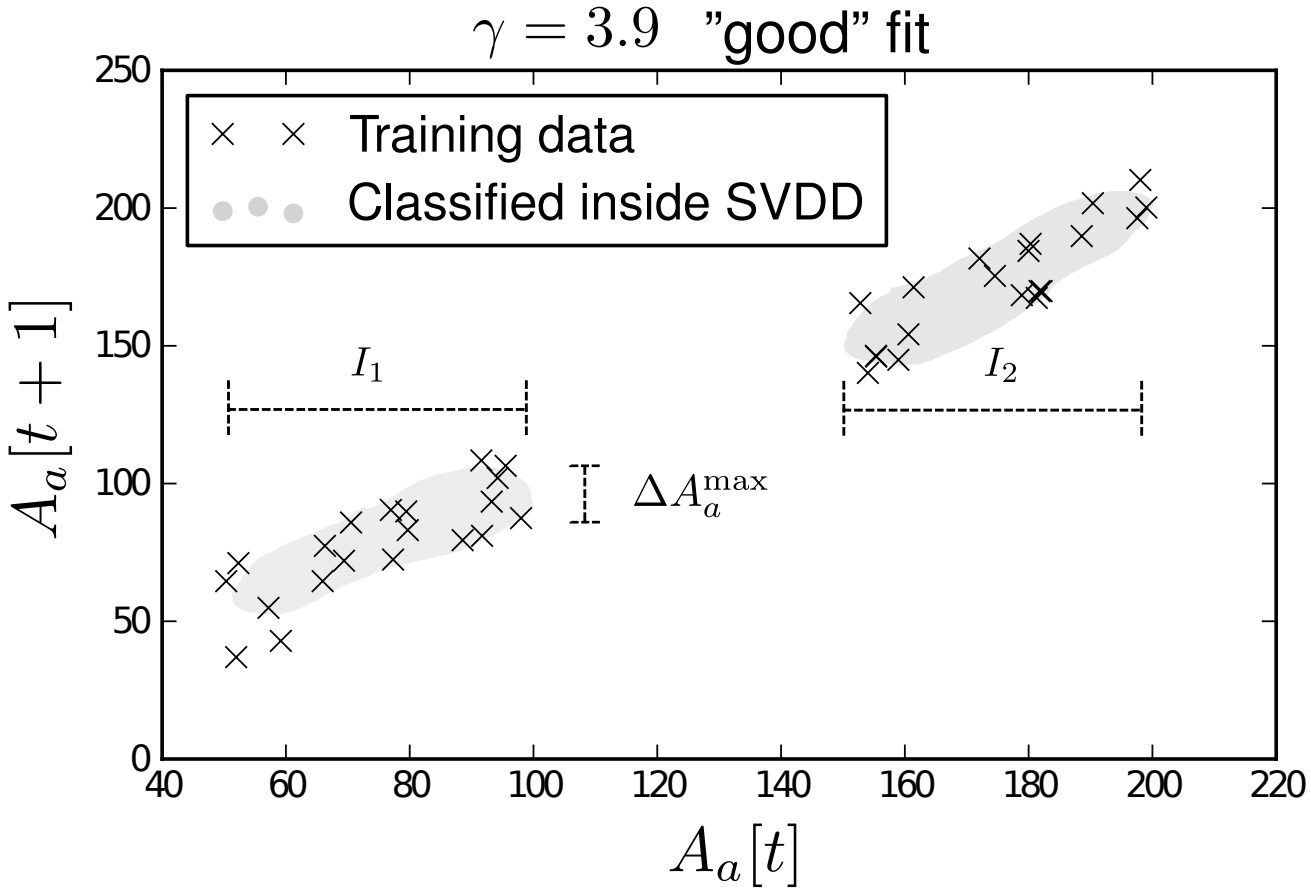
First Approach with Support Vector Data Description



Preference Elicitation

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- Claim: Use simplicity of constraint relationships to offer a more intuitive way of expressing preferences to users
- Show users *solutions* (in terms of violated constraints) and let them state "I like solution A more than B".
- Find a constraint relationship that is consistent with a user's preference decisions
- $\rightarrow$ Tool: Abductive Logical Programming using CHR

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?- worsens([a,b], [b,c]), worsens([b], [a]).
crbetter(c,b)
crbetter(a,b)
crbetter(c,a)
```

Future work

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Theoretical

- Theoretical relationships of constraint relationships (and partial valuation structures) to other frameworks
- Abstraction algorithms for other application domains (e.g., energy consumers)
- Statistical model checking to obtain design-time guarantees

Practical

- Use automata-based models for simulation and engineering of constraint models
- Implementation of a reachability checker for hybrid automata
- Learning/abductive reasoning for preference elicitation
- Investigate alternative machine learning algorithms for model building
- Combine multiple paradigms: constraint-based models, automatas, machine learning models and optimization problem

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