Benchmarks for cyber-physical systems:

A modular model library for building automation systems

ADHS 2018

University of Oxford

Introduction

- growing interest in cyber-physical systems (CPS)
- smart buildings are exemplars of CPS

Introduction

- growing interest in cyber-physical systems (CPS)
- smart buildings are exemplars of CPS
- research aims of interest:
  - ensure comfort
  - minimise consumption
  - ascertain reliability

Introduction

- growing interest in cyber-physical systems (CPS)
- smart buildings are exemplars of CPS
- research aims of interest:
  - ensure comfort
  - minimise consumption
  - ascertain reliability
- need for framework to verify correctness

Introduction

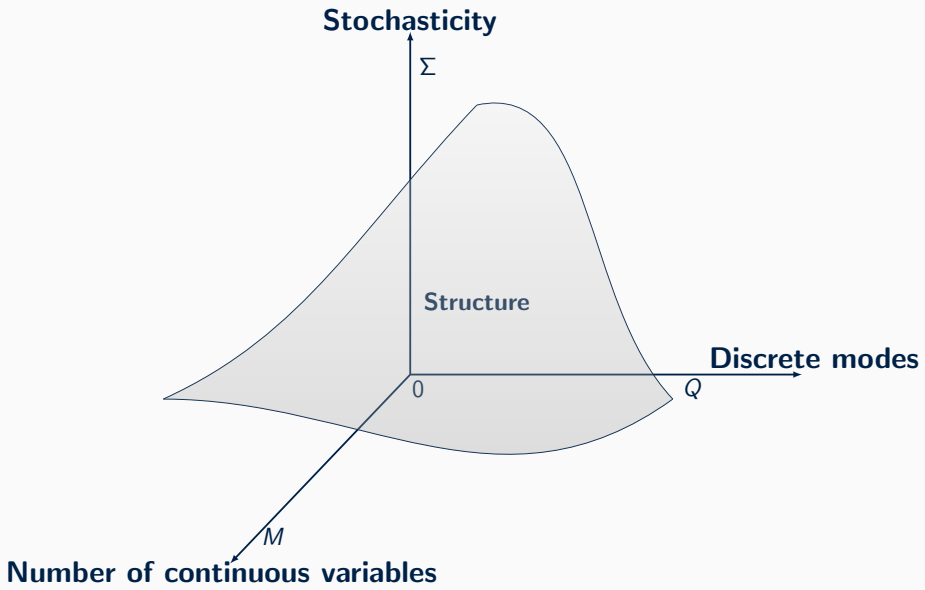
- we focus on building automation systems (BAS)

Introduction

- we focus on building automation systems (BAS)
- mixed digital controls & continuous processes
- choice of model is an art
- different trade-offs of complexities

Introduction

- we focus on building automation systems (BAS)
- mixed digital controls & continuous processes
- choice of model is an art
- different trade-offs of complexities

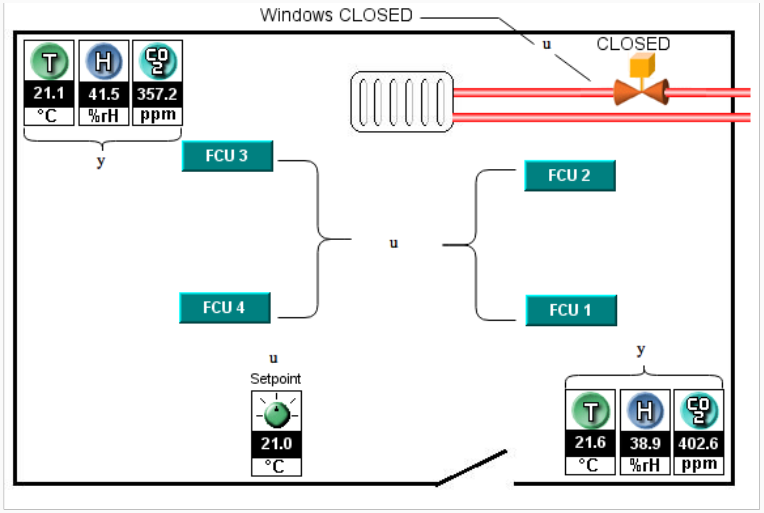


Building Automation Systems (BAS) setup

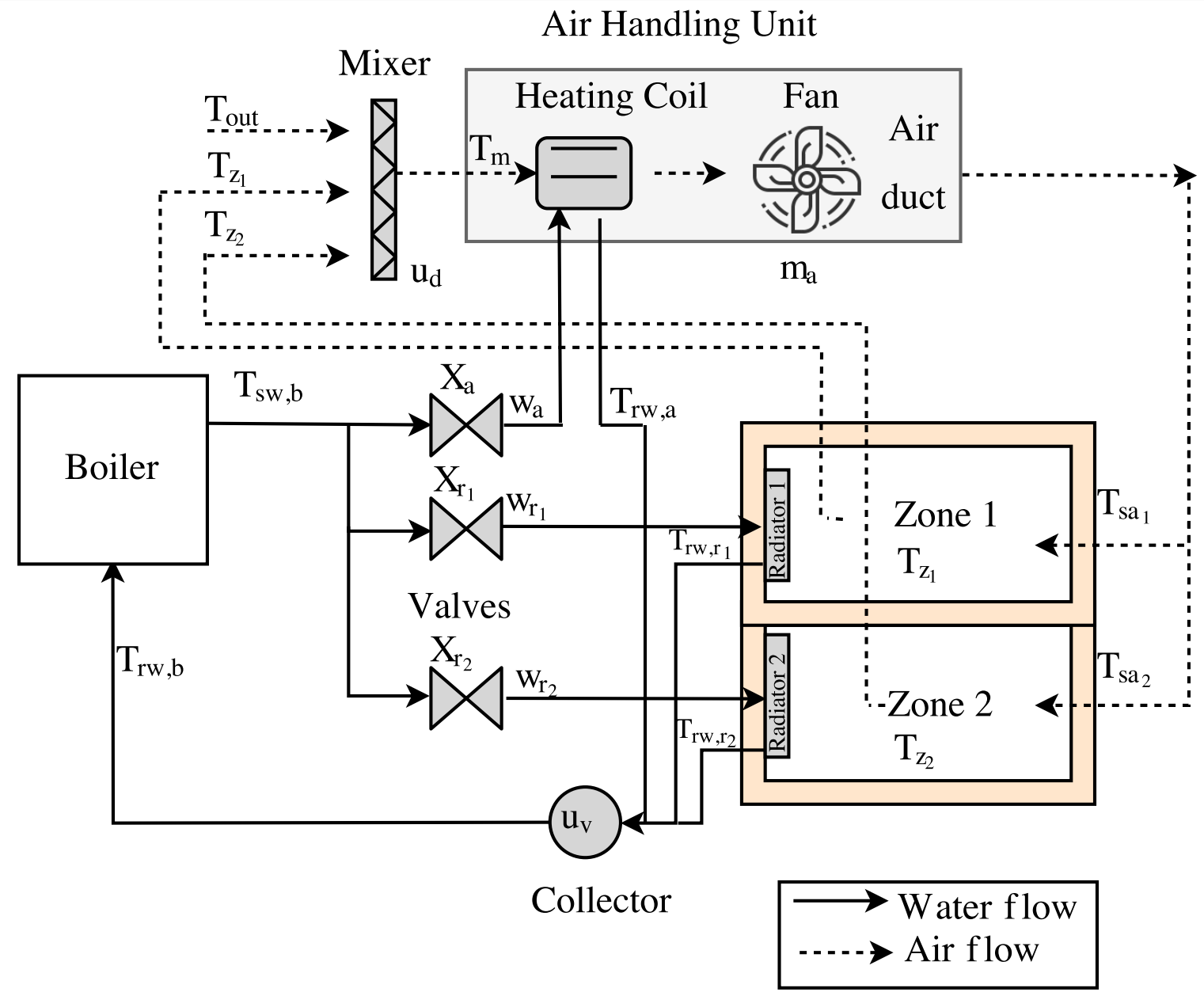
- vary in size and topology of building,
- smart buildings laboratory within the University of Oxford
- highly sensorised setup
- focus on modelling temperature

Building Automation Systems (BAS) setup

- vary in size and topology of building,
- smart buildings laboratory within the University of Oxford
- highly sensorised setup
- focus on modelling temperature



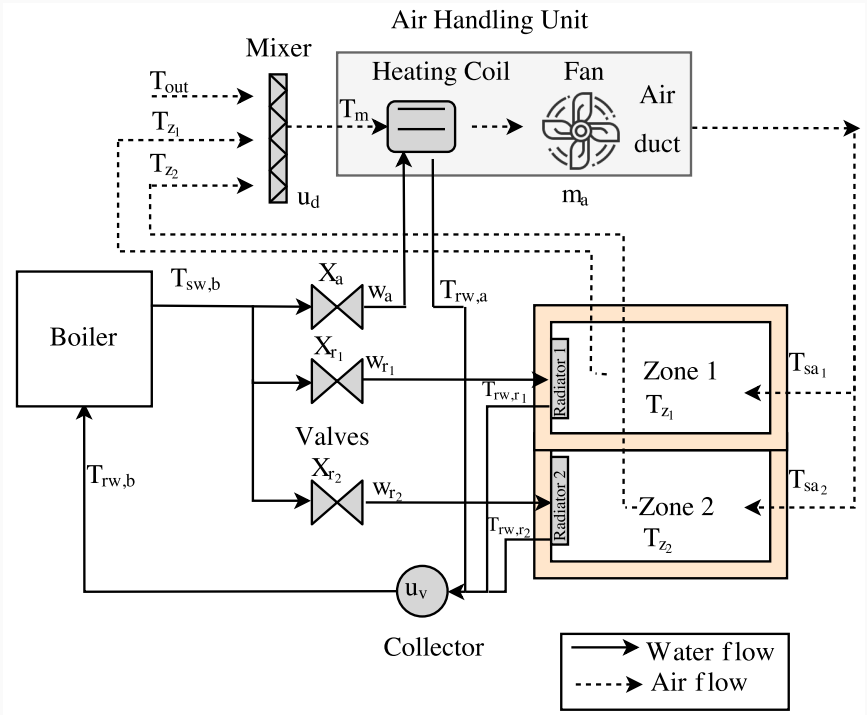
Building Automation Systems (BAS) setup



Library of models

Components

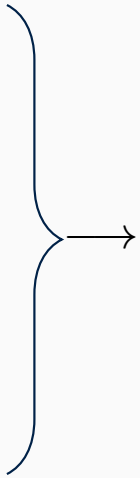
- boiler
- valve
- heating coil
- mixer
- ...
- ...
- zone



Library of models

Components

- **boiler**
- valve
- heating coil
- mixer
- ...
- ...
- zone



Model description

- 1 discrete variable : B_{en}
- 1 continuous variable : $T_{sw,b}$
- 1 output : $T_{sw,b}$
- process noise: σ_{sw}
- constants; τ_{sw}, k_b

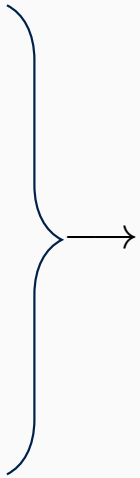
Model dynamics

$$dT_{sw,b}(t) = \begin{cases} 0 & B_{en}(t) = 0 \\ (\tau_{sw})^{-1} \left[(-T_{sw,b}(t) + k_b)dt\right] + \sigma_{sw} dW & B_{en}(t) = 1 \end{cases}$$

Library of models

Components

- boiler
- valve
- heating coil
- mixer
- ...
- ...
- zone



Types

- algebraic / differential
- non / linear
- continuous variables
- discrete modes
- noise

Coupling

- input-output
- control laws

Library of models

Characteristics:

- modular structure
- flexible as it allows for generation of different benchmarks

Format:

- Matlab files

`github.com/natchi92/BASBenchmarks`

Case studies

How do we construct benchmarks using library?

Case studies

How do we construct benchmarks using library?

- select individual components modules
- couple using input-output relationships

Case studies

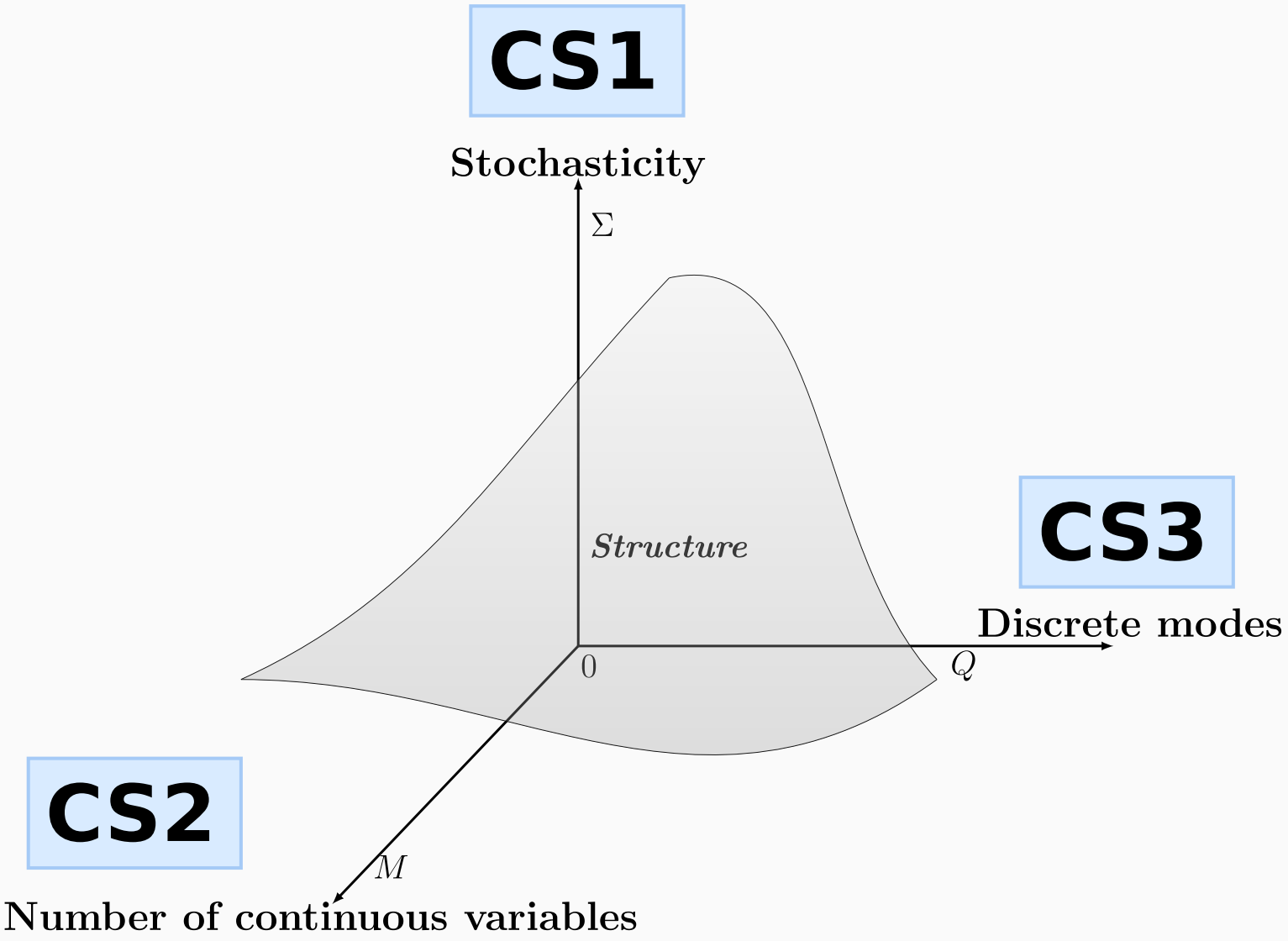
How do we construct benchmarks using library?

- select individual components modules
- couple using input-output relationships

Case studies:

- set-up three case studies
- each trading off a particular characteristic

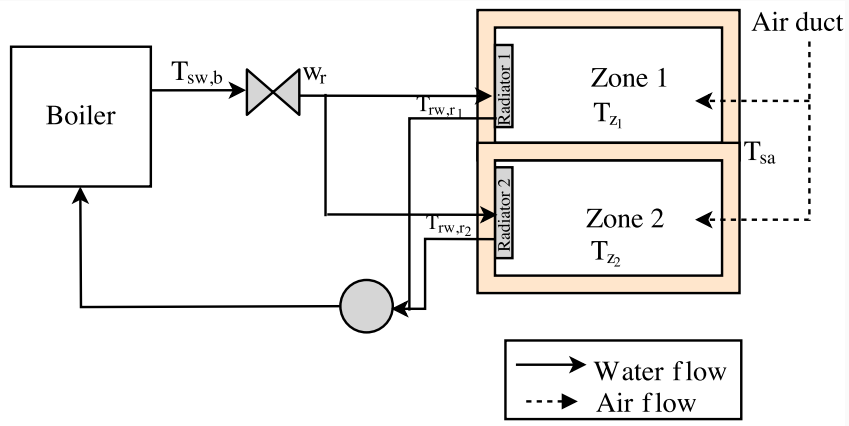
Case studies



CS1: deterministic or stochastic dynamics

- two zones, one radiator and a common supply air:

- we consider two different dynamics:
  - purely deterministic ones;
  - a stochastic model
- we discretise time



CS1: deterministic or stochastic dynamics

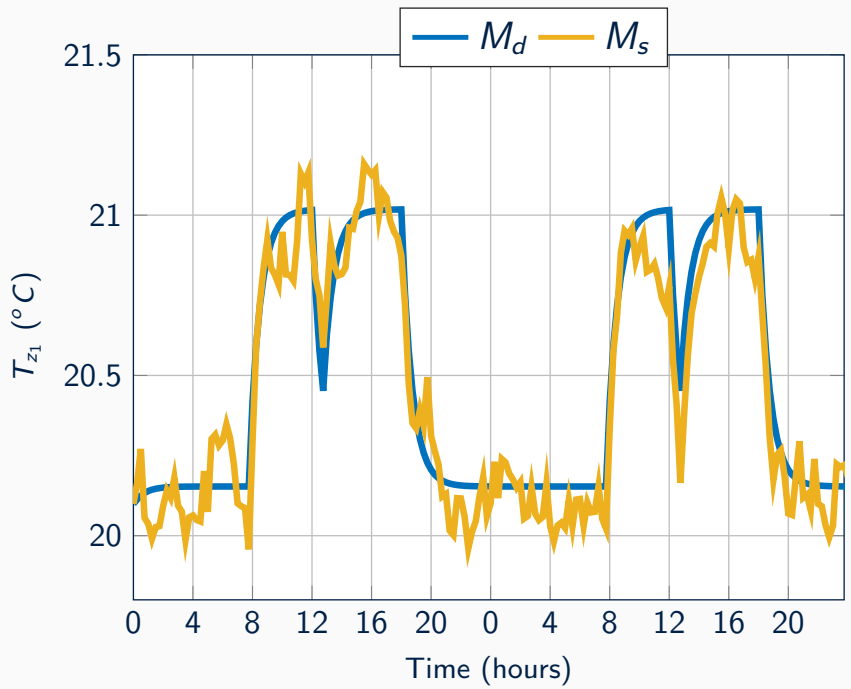
- $x \in \mathbb{R}^4, u \in \mathbb{R}, y \in \mathbb{R}^2, \Sigma \in \mathbb{R}^4$
- constant gain vector Q_d
- task: decide if traces remain within safe set for given time period

M_d: deterministic

$$x[k+1] = Ax[k] + Bu[k] + Q_d$$

M_s: stochastic

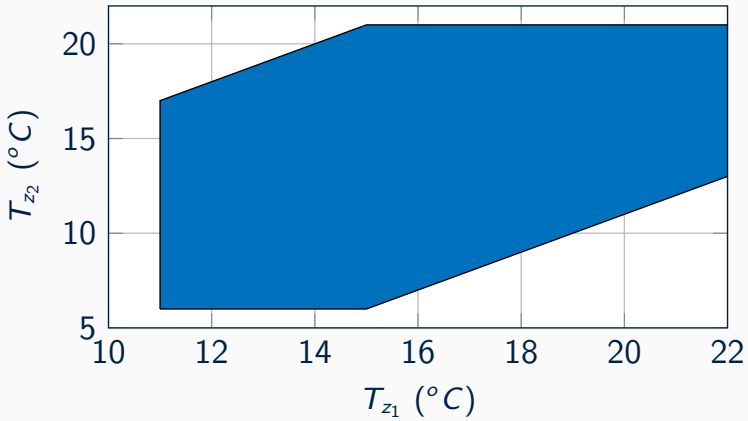
$$x[k+1] = Ax[k] + Bu[k] + Q_d + \Sigma W[k]$$



CS1: deterministic or stochastic dynamics

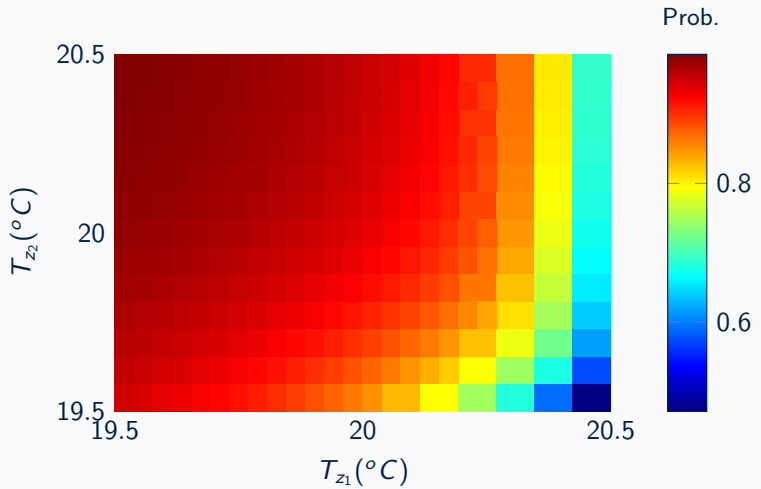
deterministic model

- reachability analysis (ra)
- tool: Axelerator

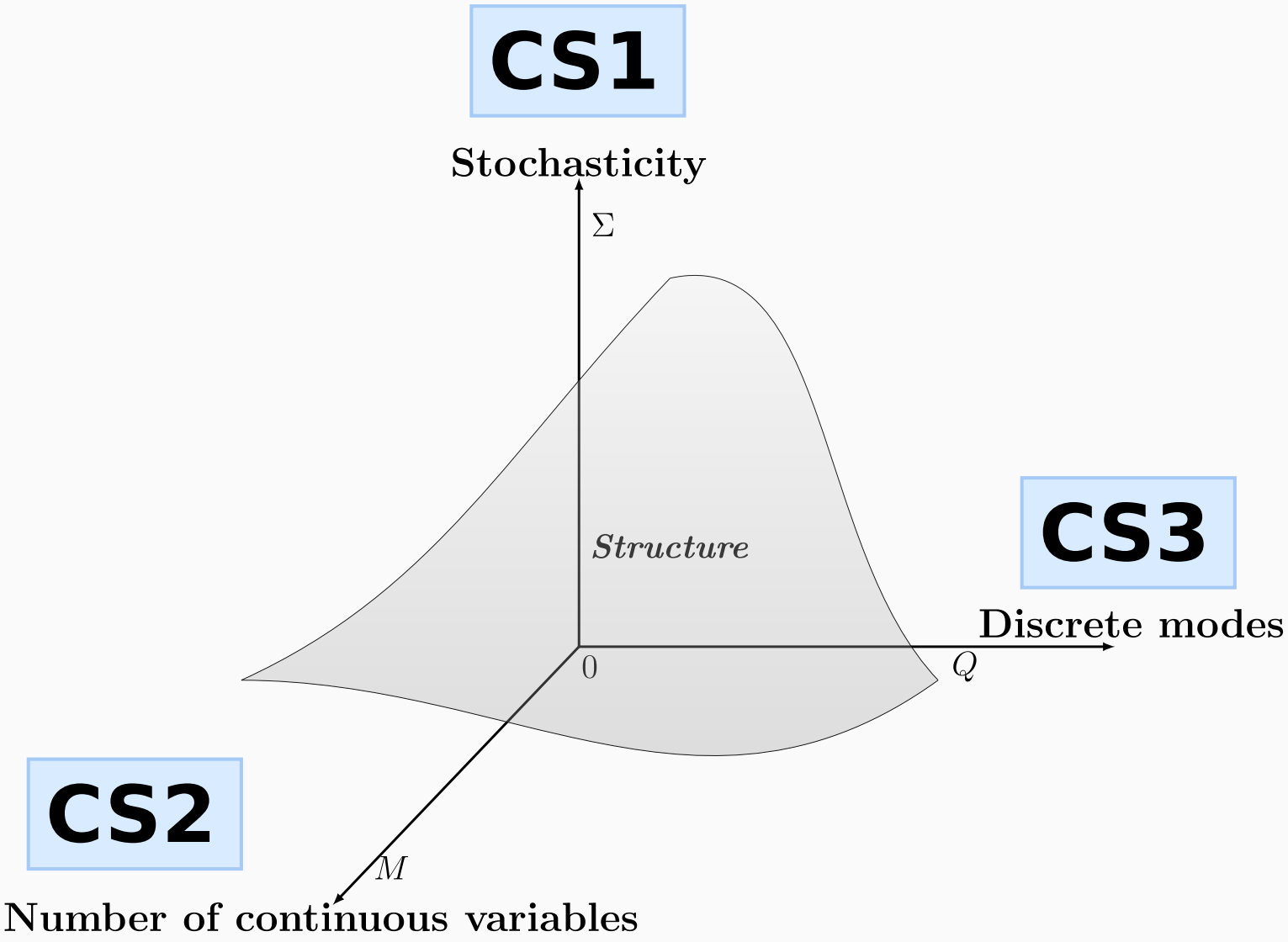


stochastic model

- probabilistic ra
- tool: FAUST^2

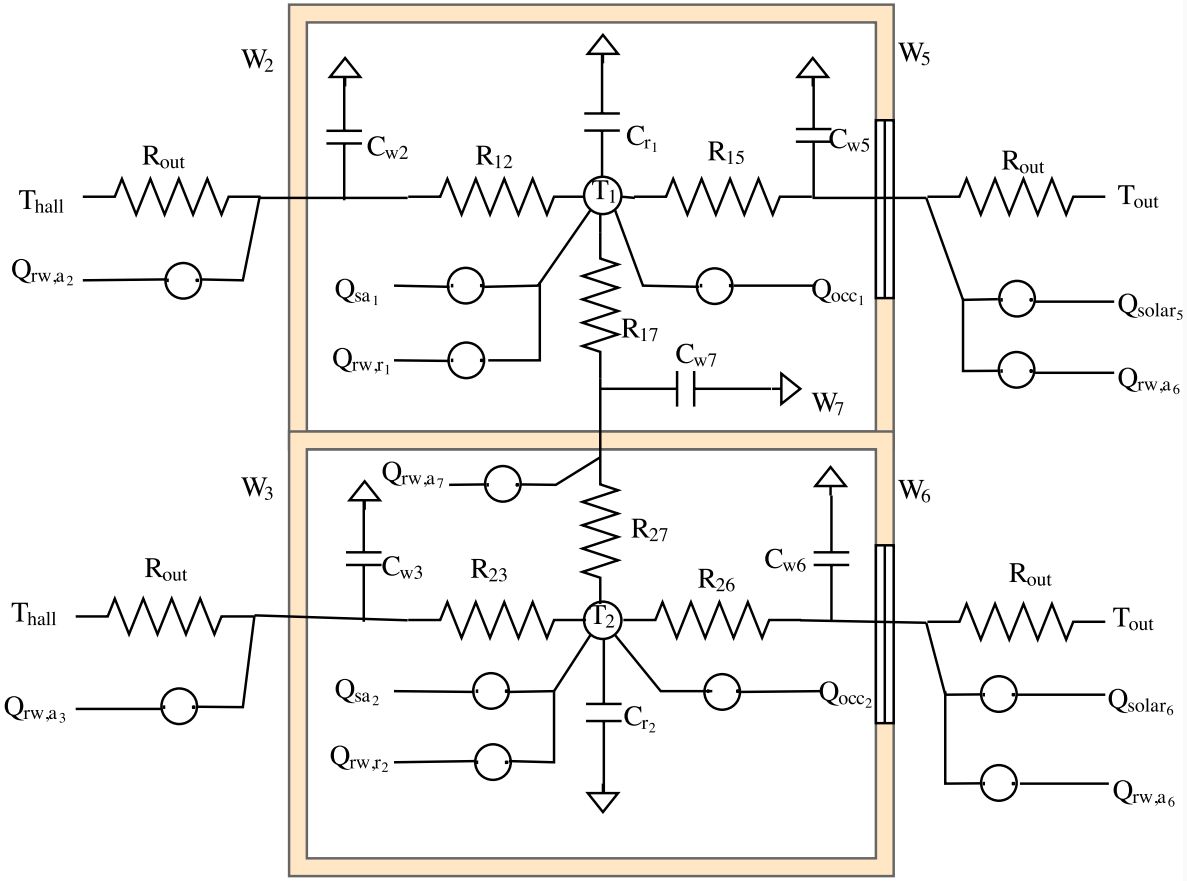


Case studies



CS2: large number of continuous variables

- focus on internal dynamics of two zones



CS2: large number of continuous variables

- discretise model
- neglect process noise
- $x_c \in \mathbb{R}^7, u_c \in \mathbb{R}, y_c \in \mathbb{R}^2, d_c \in \mathbb{R}^5$
- constant gain vector Q_c

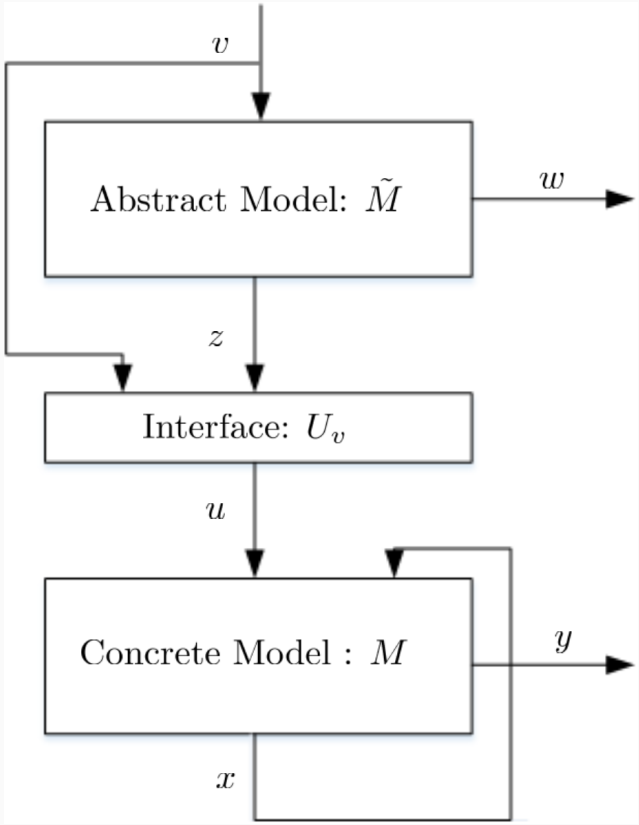
$$\mathbf{M}_c : \begin{cases} x_c[k+1] & = A_c x_c[k] + B_c u_c[k] + F_c d_c[k] + Q_c \\ y_c[k] & = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} x_c[k]. \end{cases}$$

CS2: large number of continuous variables

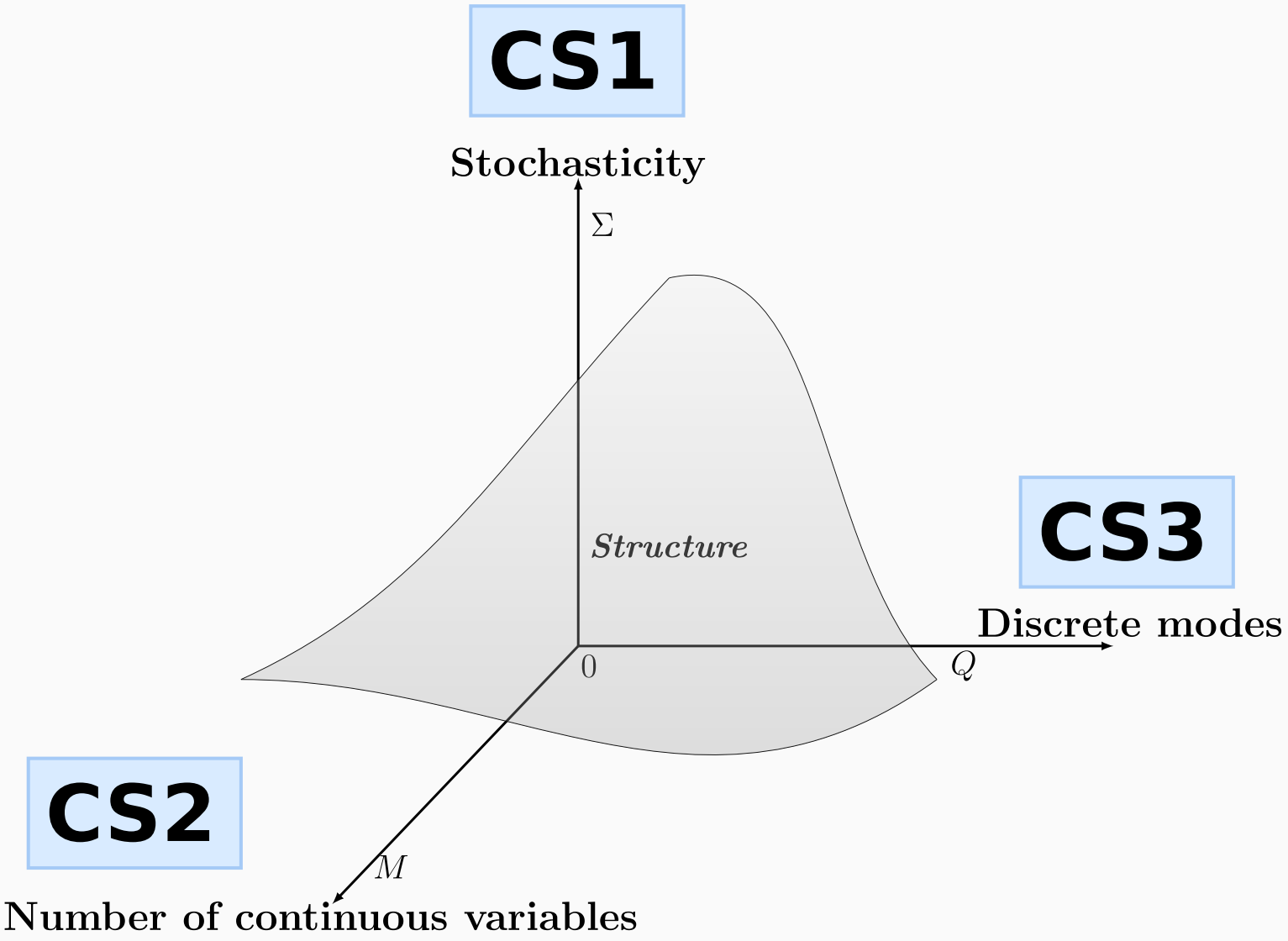
- task: synthesis policy that minimises deviation from mean

policy synthesis

- set of abstract models
- relate via (ε, δ) simulation relations
- synthesise policy on abstract
- refine policy for original model
- resulting policy: safety probability of $p = 0.7657$



Case studies



CS3: multiple switching controls

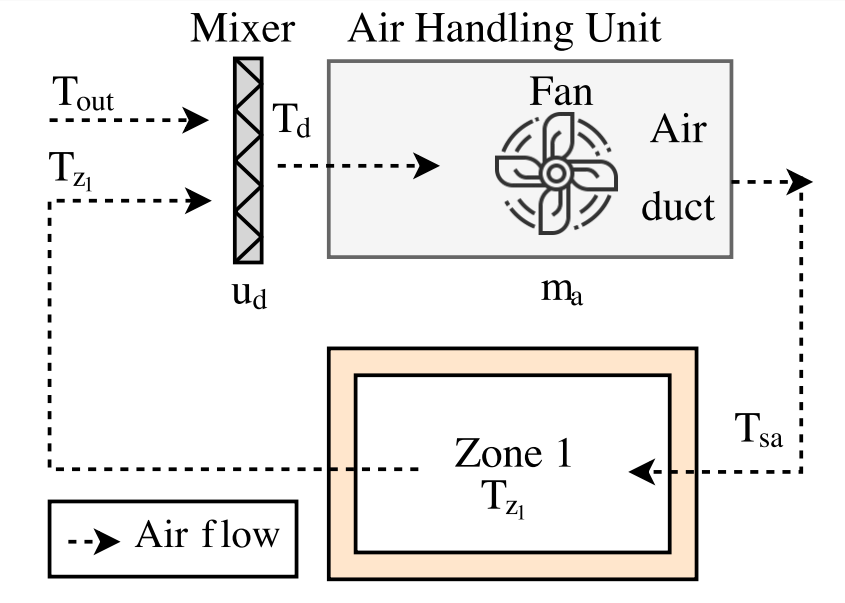
- focus on mixer, AHU air duct, and 1 zone components
- mixer position and fan settings used to maintain a comfortable temperature within the zone

CS3: multiple switching controls

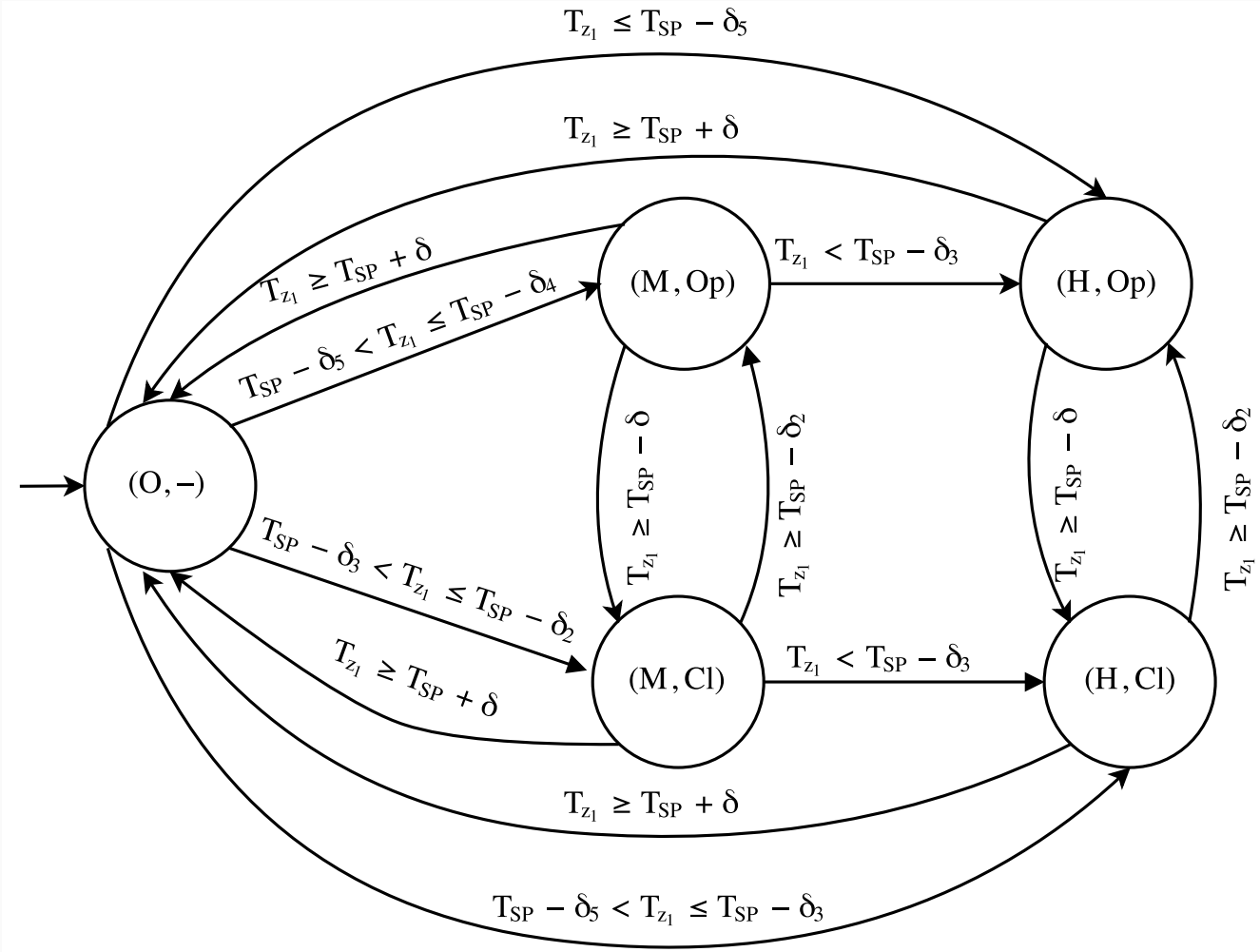
- focus on mixer, AHU air duct, and 1 zone components
- mixer position and fan settings used to maintain a comfortable temperature within the zone

switching controls

- mixer: open (Op) or closed (Cl).
- fan: (off O, medium M, and high H)



CS3: multiple switching controls



CS3: multiple switching controls

- discrete modes q are in the set:

$$\{(O,-),(M,Op),(M,Cl),\ (H,Op),(H,Cl)\},$$

CS3: multiple switching controls

- discrete modes q are in the set:

$$\{(O,-),(M,Op),(M,Cl),\ (H,Op),(H,Cl)\},$$

- continuous dynamics:
  - zone temperature (T_{z_1}) and supply air temperature (T_{sa})
  - continuous-time ordinary differential equations
  - neglect process noise

CS3: multiple switching controls

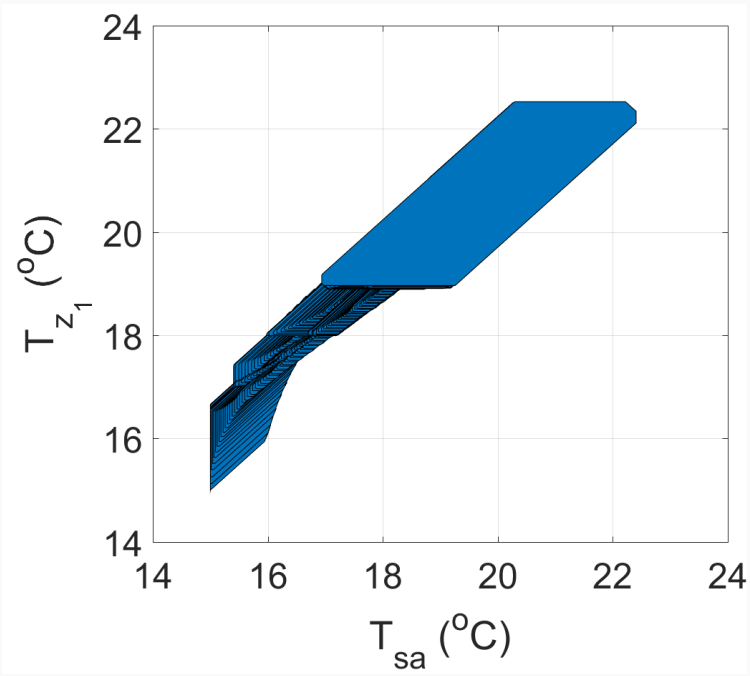
- discrete modes q are in the set:

$$\{(O, -), (M, Op), (M, Cl), (H, Op), (H, Cl)\},$$

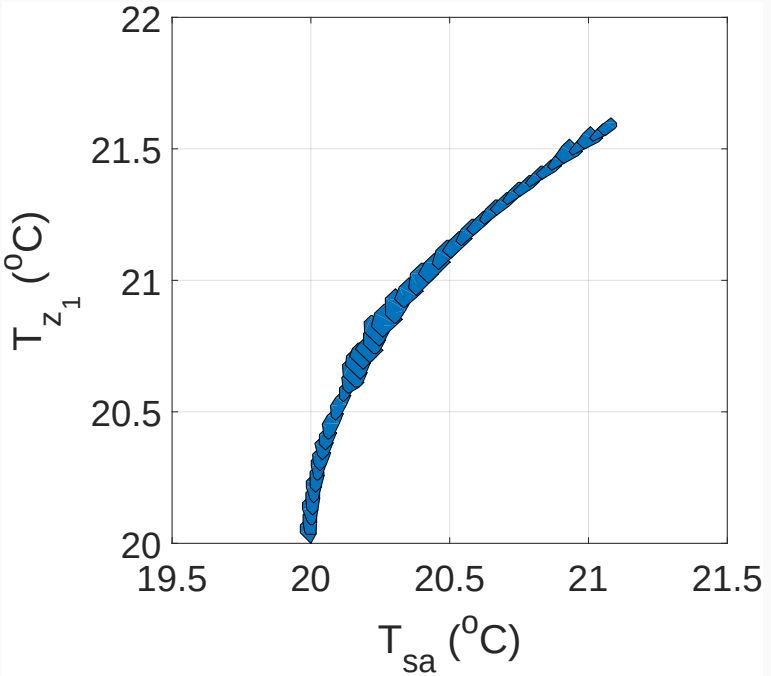
- continuous dynamics:
  - zone temperature (T_{z_1}) and supply air temperature (T_{sa})
  - continuous-time ordinary differential equations
  - neglect process noise
- transitions occur when crossing spatial guards:
  - denote deviations from temperature set-point

CS3: multiple switching controls

- task: reachability analysis of the hybrid model
- tool: SpaceEx



(a) Initial condition: $T_{z_1} = 15^o C$, $T_{sa} = 15^o C$



(b) Initial condition: $T_{z_1} = 20^o C$, $T_{sa} = 20^o C$

Summary

- presented a modular & compositional library of models

Summary

- presented a modular & compositional library of models
- identified three sources of complexity:
  - presence of stochasticity
  - number of continuous variables
  - number of discrete modes

Summary

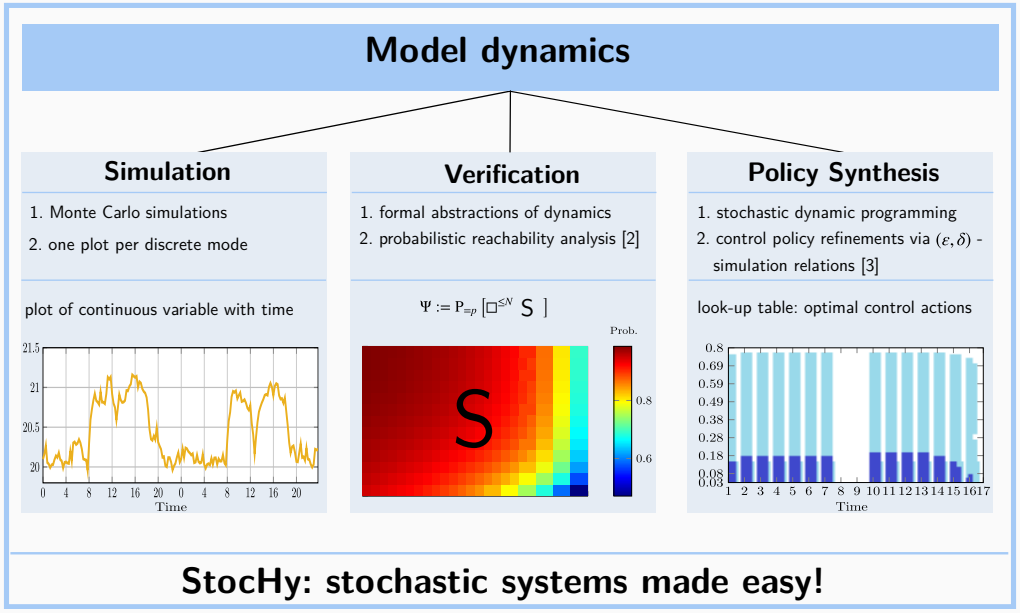
- presented a modular & compositional library of models
- identified three sources of complexity:
  - presence of stochasticity
  - number of continuous variables
  - number of discrete modes
- three different case studies
- need for a unified framework to address these complexities

Future work

- extension of library components
- formal description language

Future work

- extension of library components
- formal description language
- StocHy: Stochastic hybrid systems made easy!



Come find us at poster session!

Thank you!

nathalie.cauchi@cs.ox.ac.uk

github.com/natchi92/BASBenchmarks

Questions?