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Comparing state estimation techniques for model predictive control

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PERFORMANCE PLUS

Goal

State estimation of states of simple (non-linear) Modelica model

Quantitative and qualitative comparison of different algorithms

This project has received funding from the European Union’s Seventh Programme for research, technological development and demonstration under grant agreement No 308991.

Why

Model predictive control on real buildings

- Optimizing future control starts from current state
- Current state not fully measured

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How

Compare three state estimation algorithms:

1. Deterministic state estimation
2. Moving horizon estimation
3. Unscented Kalman Filter

in three different cases:

- Ideal (simple model – simple model)
- Non-ideal (simple model – complex model)
- Real (simple model – real building)

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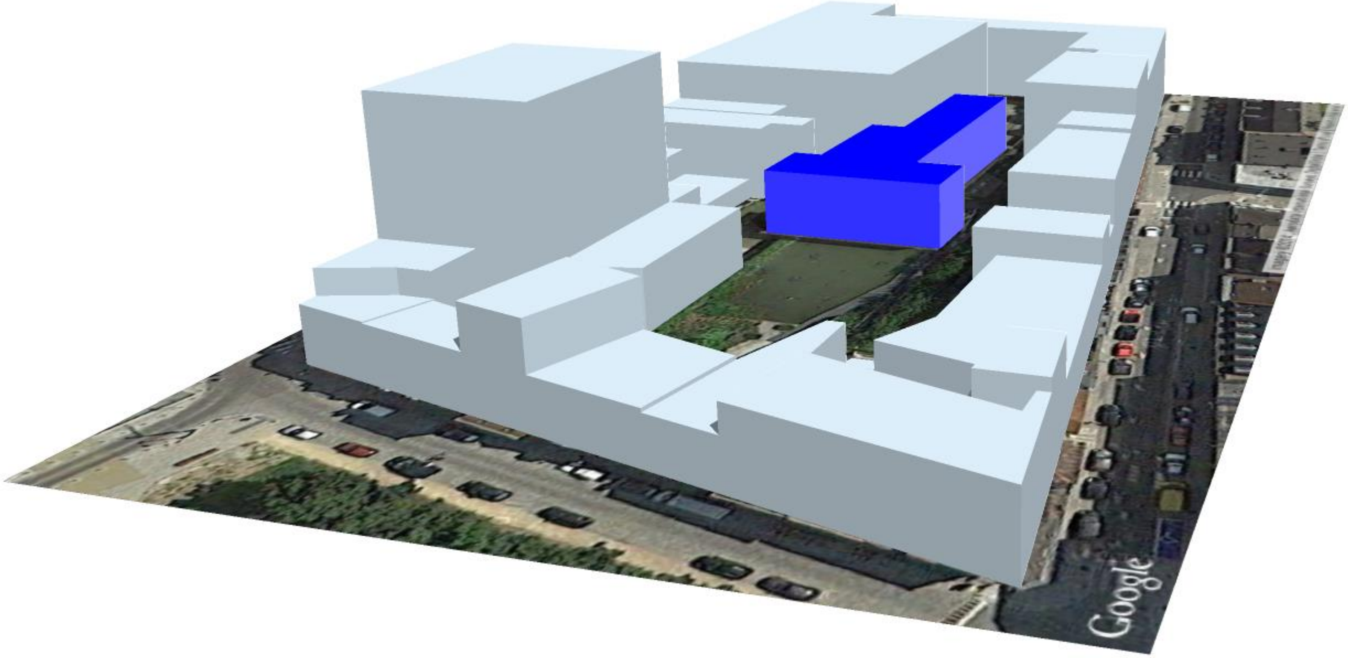
System

3E headquarters in Brussels

Two floors, 40 – 80 people

Renewed heating system



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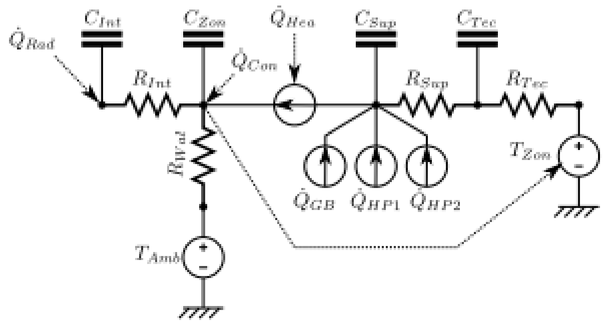
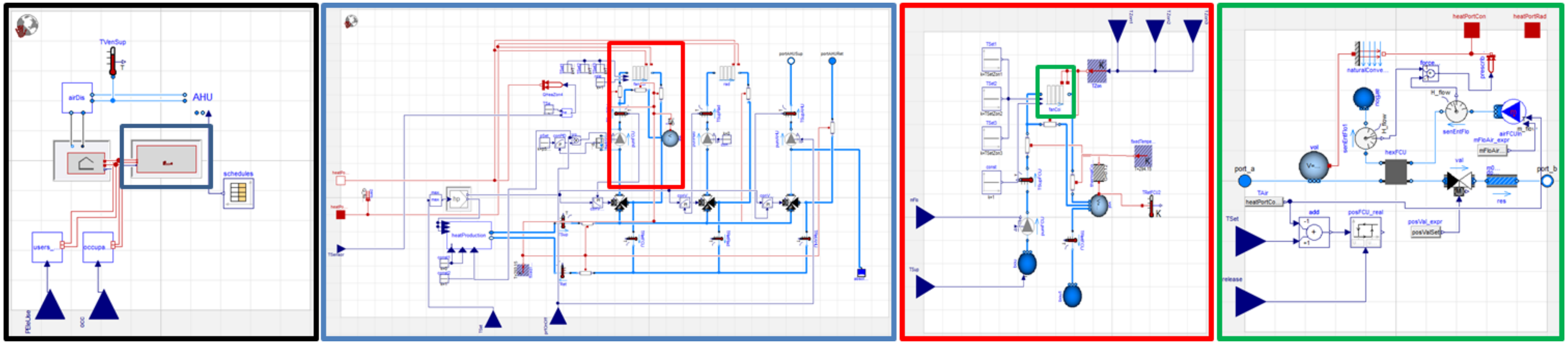
Models

1 

1. Simple building model
2. Complex building model
3. Real building

2 

3 

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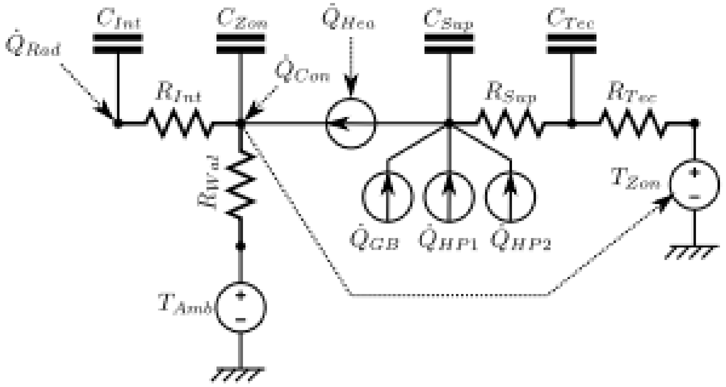
3 different cases, same inputs dataset

Ideal (simple-simple):

- All states known
- Noise properties added/known (Gaussian? Uniform?)
- Use only 'output' states for estimation
- Compare states directly with counterpart (open loop simulation, 1 day?)



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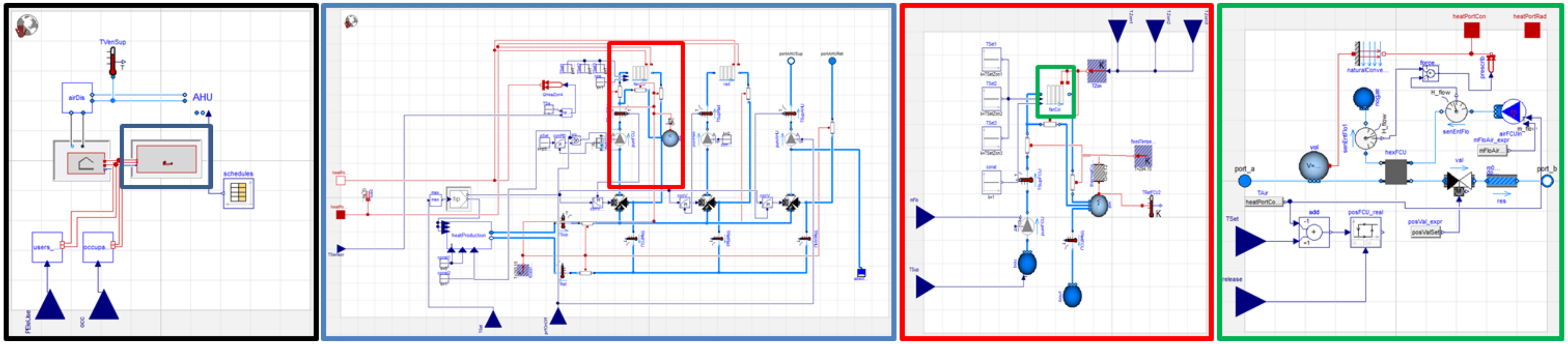
3 different cases, same inputs dataset

Ideal (simple-simple)

Non-ideal (simple-complex):

- All variables available
- Noise properties to ‘measurements’ are known
- Check output state with measured counterpart
- Investigate all states



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3 different cases, same inputs dataset

Ideal (simple-simple)

Non-ideal (simple-complex)

Real case (simple-real):

- Measurements have intrinsic error
- Investigate all states and compare to other cases

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State estimation (example)

Model for state estimation (paper, Rao et al. 2003)

d2c (Ts=1s, matlab)

discrete model → continuous model

$$\dot{x} = \begin{bmatrix} .99 & .2 \\ -.1 & .03 \end{bmatrix} x + \begin{bmatrix} 0 \\ 1 \end{bmatrix} w \qquad \dot{x} = \begin{bmatrix} .01 & .34 \\ -.17 & -1.16 \end{bmatrix} x + \begin{bmatrix} .2 \\ 1.68 \end{bmatrix} w$$

$$y = \begin{bmatrix} 1 \\ -3 \end{bmatrix} x + v_k \qquad y = \begin{bmatrix} 1 \\ -3 \end{bmatrix} x + v_k$$

y = output to fit

w = disturbance which is unknown (to the model)

N(μ=0,σ=1), only positive values

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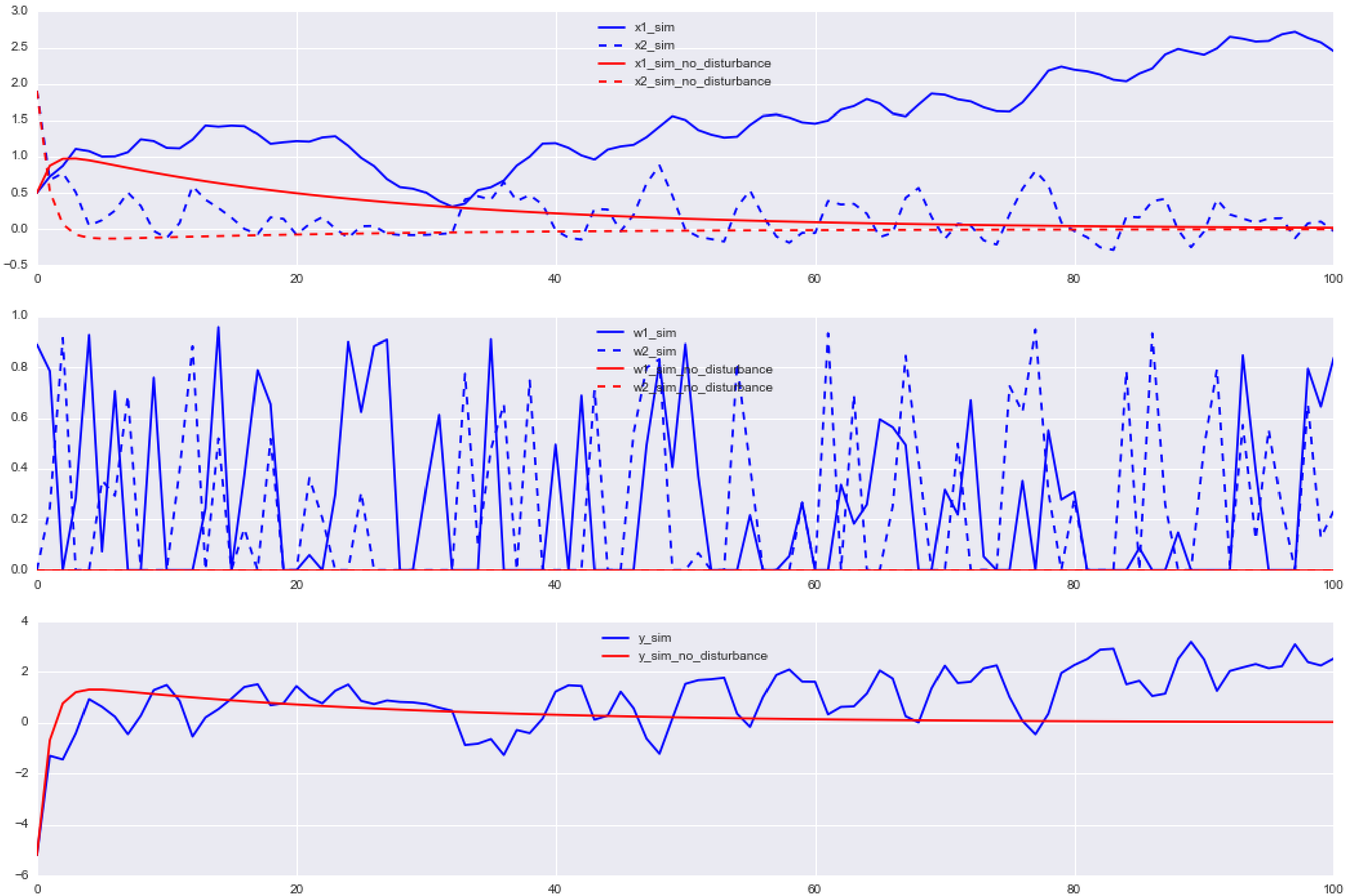
No state estimation (no disturbance)



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State estimation

Mitigate effect of unknown disturbance

- Kalman filter approaches (→3)
  - Prediction (guess)
  - Correction (statistical knowledge of the unknown disturbance)
  - *(Calculation)*

- Moving horizon approach (→1,2)
  - Find optimal values for variables and/or parameters which fit model output to measurements over past horizon
  - Allows constraint formulation
  - *(Optimization)*

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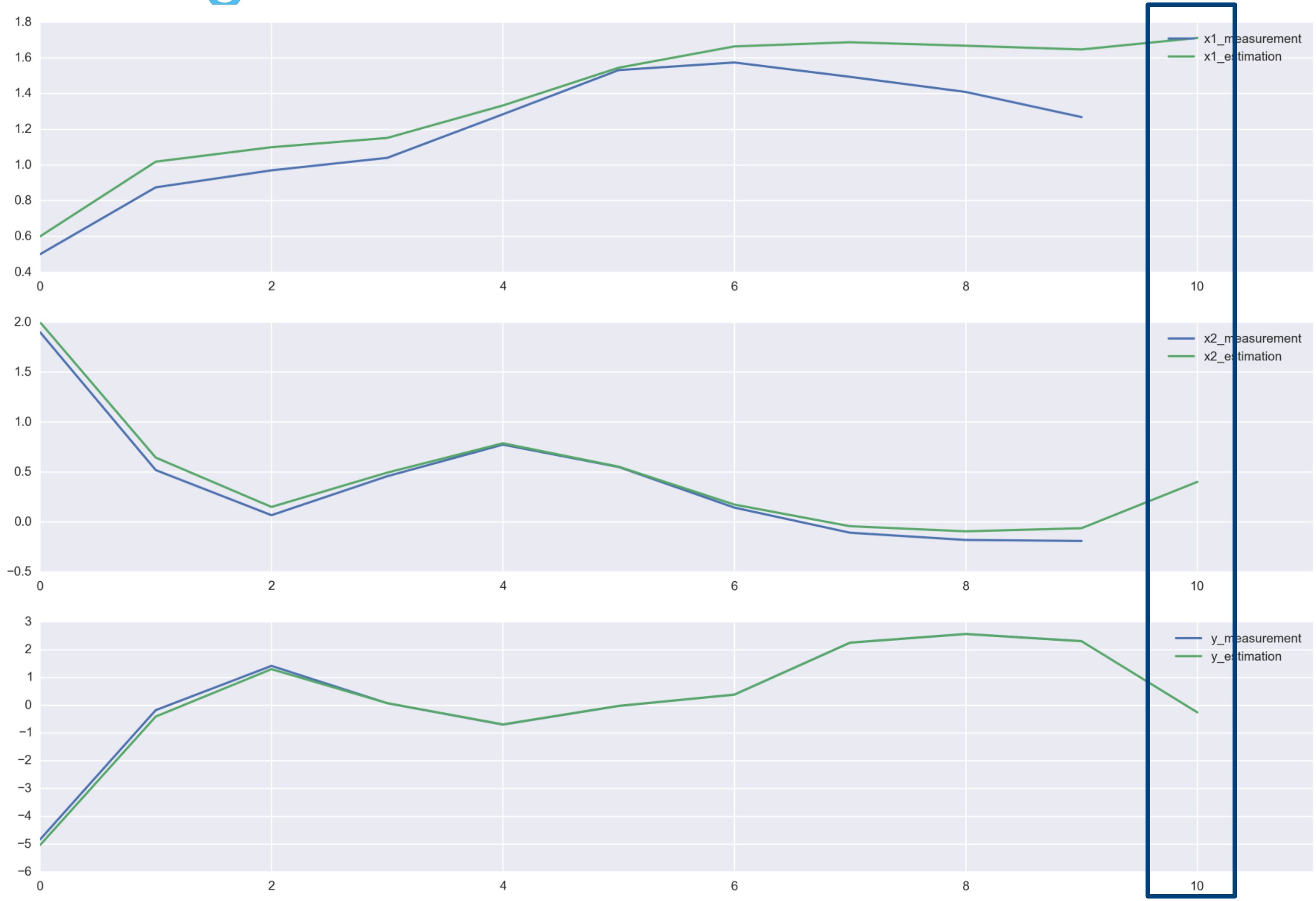
Moving horizon estimation



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Moving horizon estimation

Deterministic

$$\min_{x_0} \sum (y - y_{meas})^T \boldsymbol{R}^{-1} (y - y_{meas})$$

- Initial values of the states to get best output over the past horizon
- Ok if disturbances have low influence
- Easiest implementation

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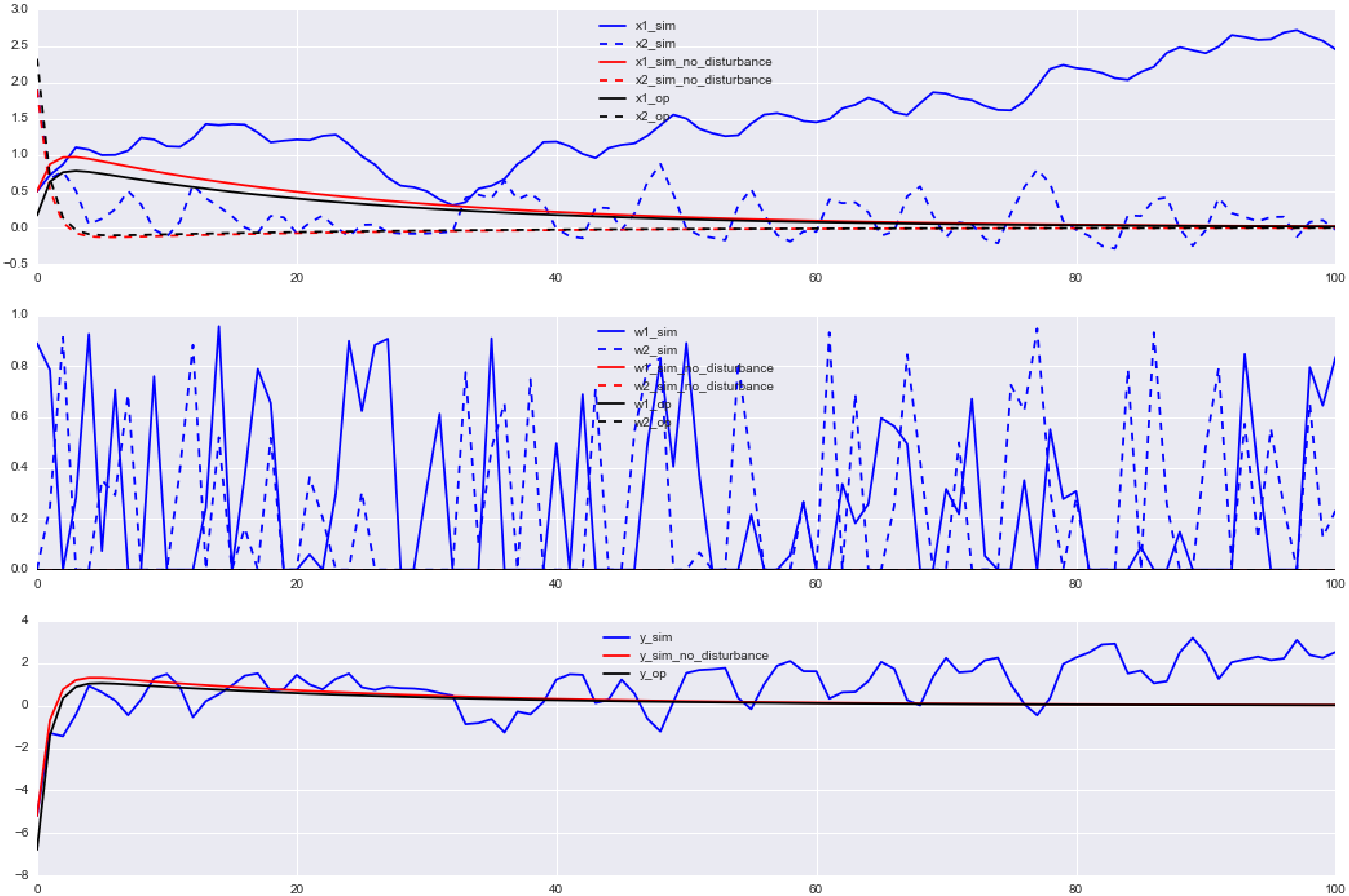
Moving horizon estimation (determistic)



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Moving horizon estimation

Statistical $\min_{\{x_0\}\{w_k\}} \sum (y - y_{meas})^T \boldsymbol{R}^{-1}(y - y_{meas}) + (w_k)^T \boldsymbol{Q}^{-1}(w_k)$

- Fit the output ‘y’
- Try to estimate minimal disturbances ‘w’

→ Add unknown state disturbance to the Modelica model

$$\dot{x} = \begin{bmatrix} .01 & .34 \\ -.17 & -1.16 \end{bmatrix} x + \begin{bmatrix} .2 \\ 1.68 \end{bmatrix} w$$

$$y = \begin{bmatrix} 1 \\ -3 \end{bmatrix} x + v_k$$

```
model sim
    extends partial_sim();
    Modelica.Blocks.Interfaces.RealInput w1;
    Modelica.Blocks.Interfaces.RealInput w2;
equation
    der(x1) = a11*x1 + a12*x2 + b1*w1;
    der(x2) = a21*x1 + a22*x2 + b2*w2;
end sim;
```

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Moving horizon estimation (solutions)

$$\min_{\{x_0\}\{w_k\}} \sum (y - y_{meas})^T \boldsymbol{R}^{-1} (y - y_{meas}) + (w_k)^T \boldsymbol{Q}^{-1} (w_k)$$

Use of ExternalData class in JModelica.org

Different solutions for different weights.

- Large ratio R^{-1} over Q^{-1} : disturbances have smaller covariance
- Look at
  - Q^{-1} =1, R^{-1} =1e2 (best guess, paper)
  - Q^{-1} =1, R^{-1} =1e4 (high)
  - Q^{-1} =1, R^{-1} =1e-2 (low)

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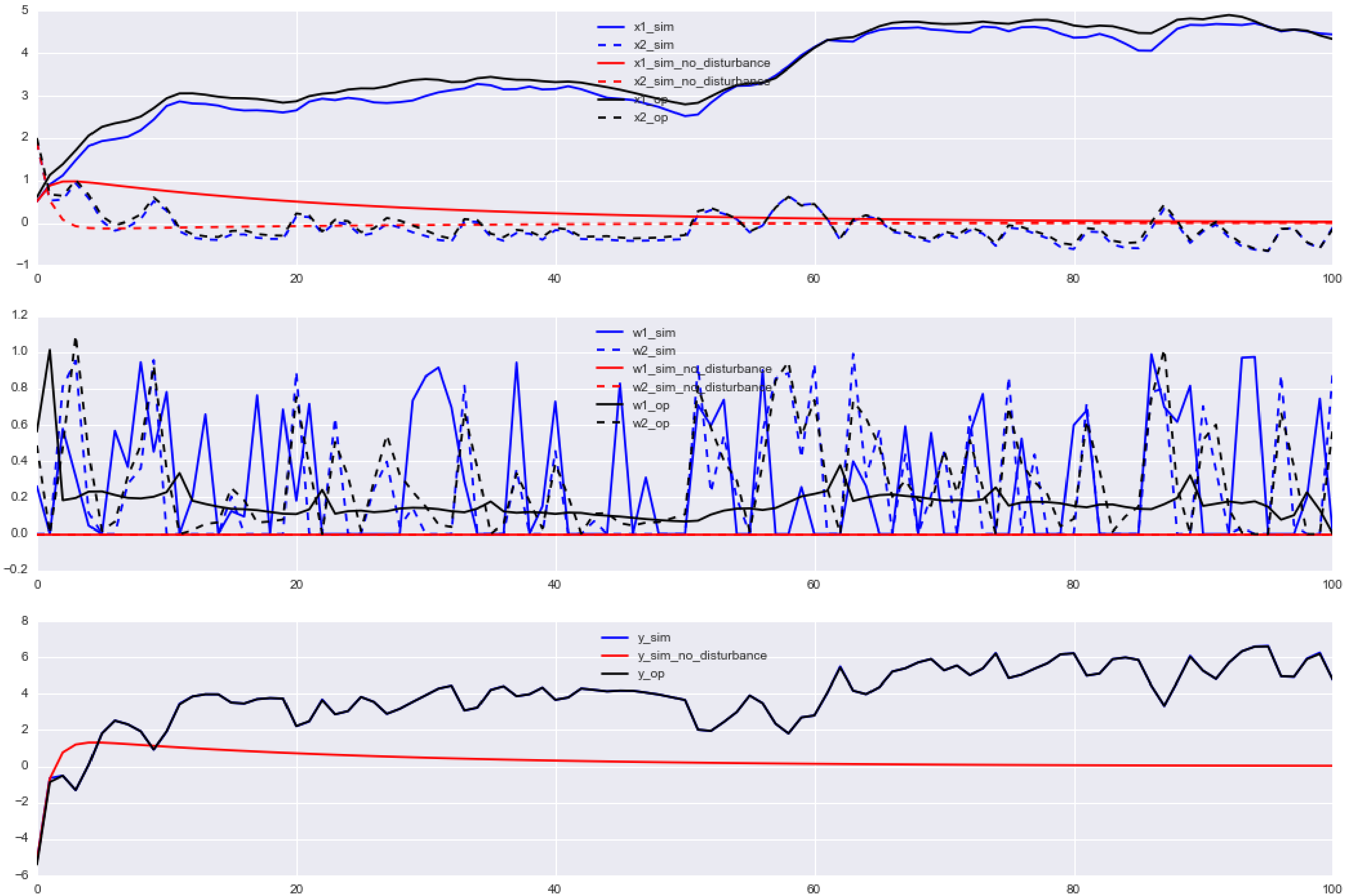
Q^{-1} =1, R^{-1} =1e2 (best guess)



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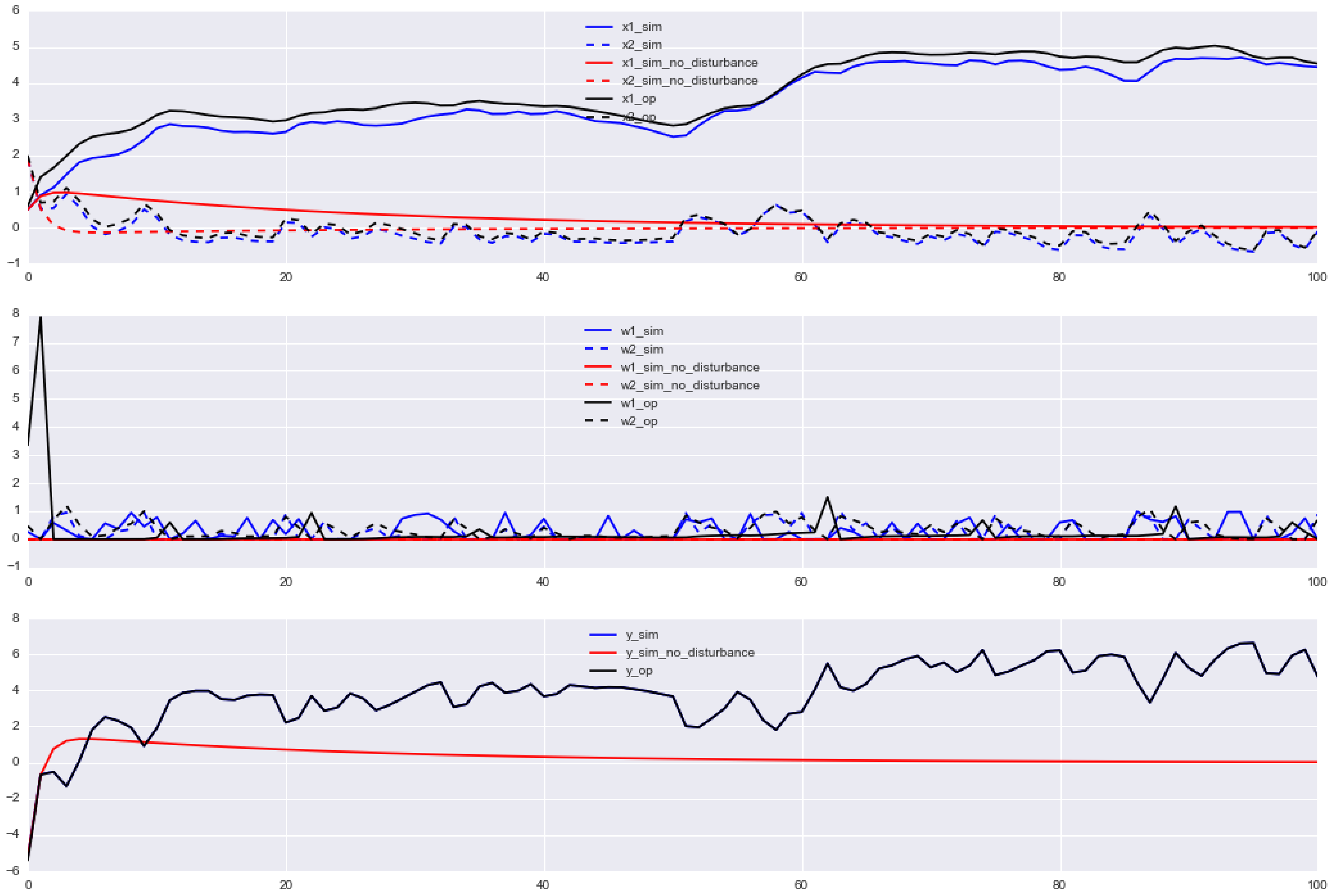
Q^{-1} =1, R^{-1} =1e4 (high)



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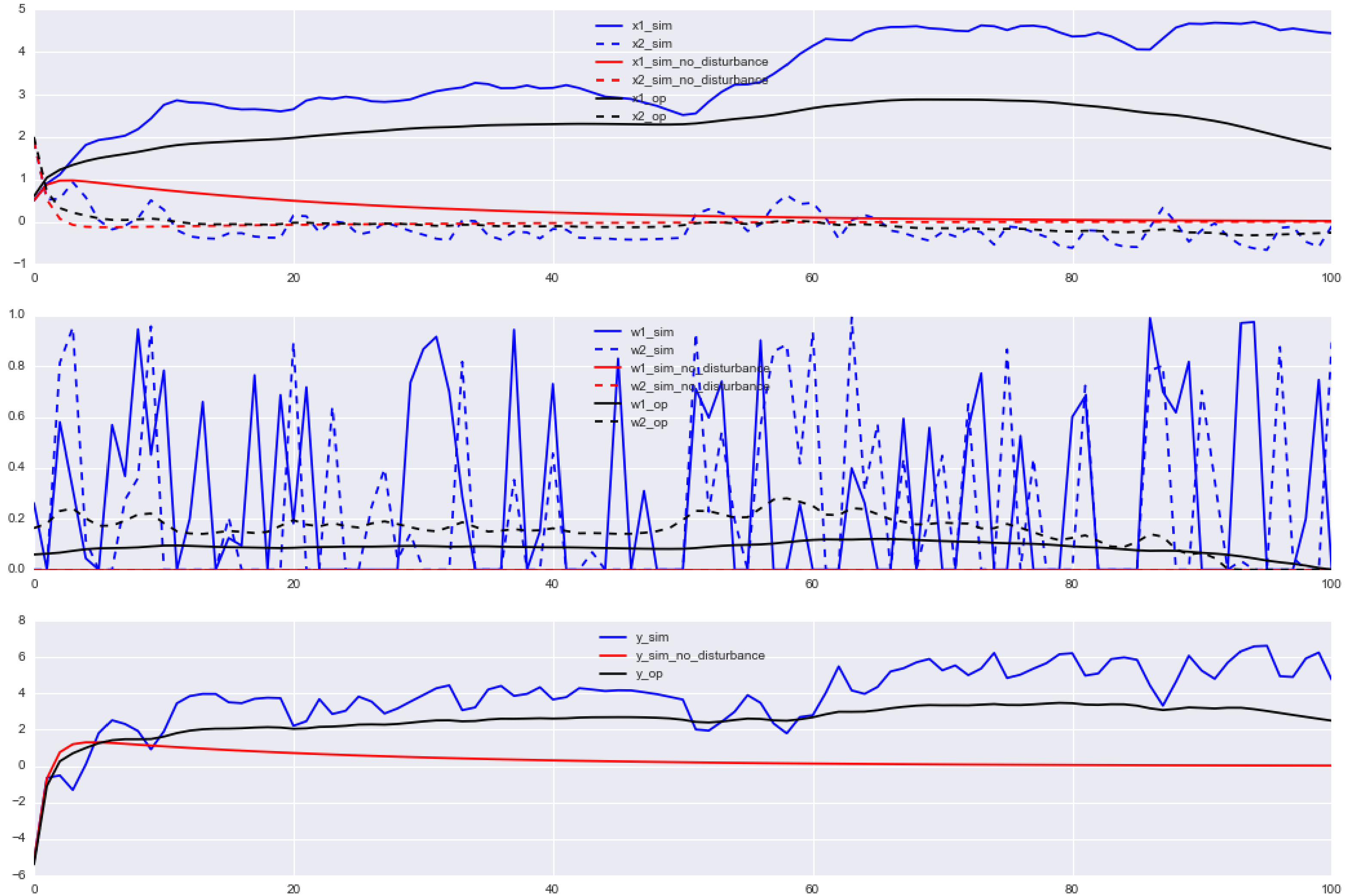
Q^{-1} =1. R^{-1} =1e-2 (low)



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Evaluate

Open loop simulation on next period

Calculate rmse

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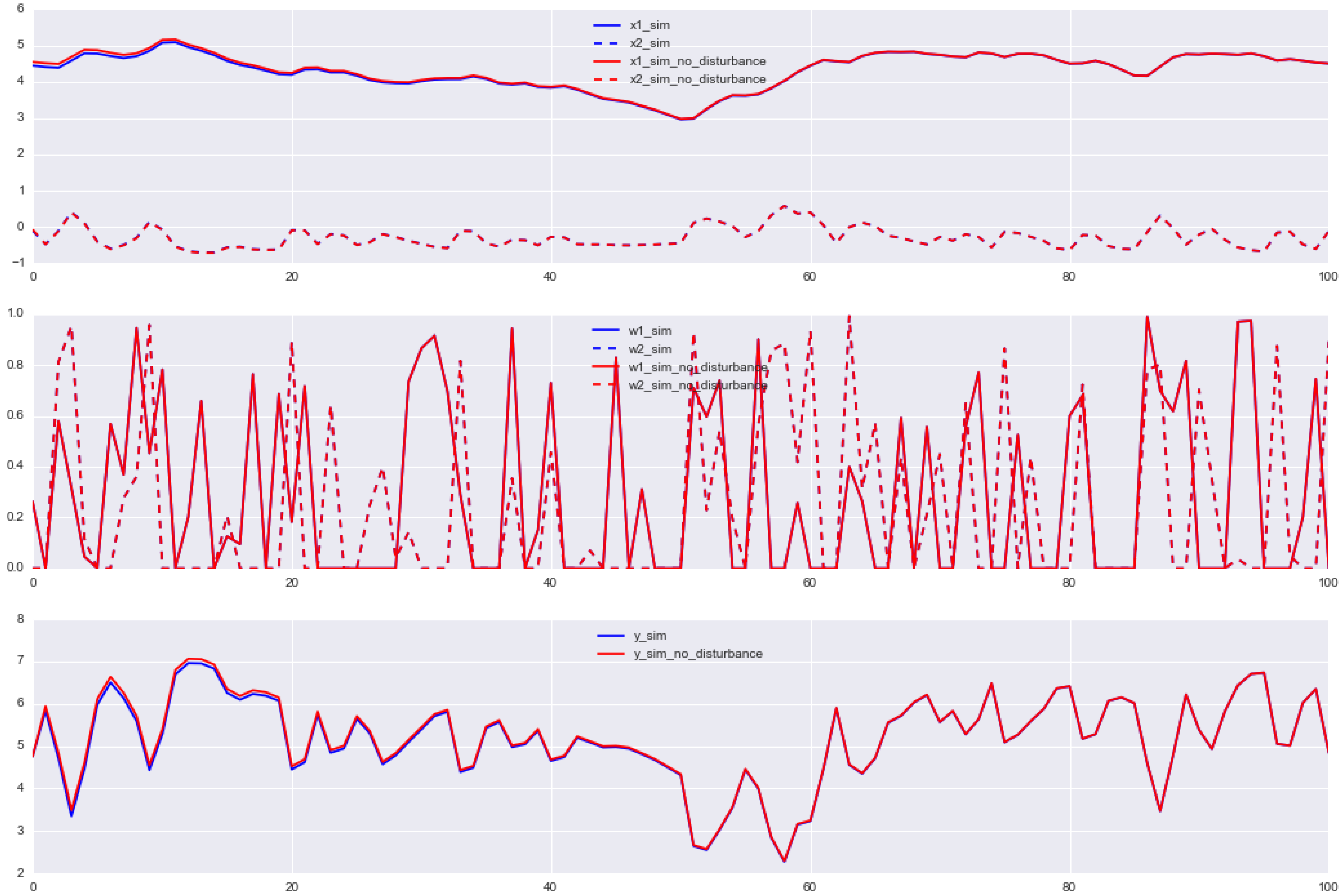
Evaluate



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Evaluate

Q^{-1} =1, R^{-1} =1e2 (normal, paper)

- rmse x1 : 0.044
- rmse x2 : 0.007
- rmse y : 0.060

Q^{-1} =1, R^{-1} =1e4 (high)

- rmse x1 : 0.040
- rmse x2 : 0.007
- rmse y : 0.056

Q^{-1} =1, R^{-1} =1e-2 (low)

- rmse x1 : 1.019
- rmse x2 : 0.143
- rmse y : 1.425

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Challenges

- Best way to implement?
  - Weights?
  - Variable w discrete or continuous?

- What about end effect?
  - Only output state mathers!
  - Similar to mpc

- States in buildings are not equal

$$\dot{x} = \begin{bmatrix} .01 & .34 \\ -.17 & -1.16 \end{bmatrix} x + \begin{bmatrix} .2 \\ 1.68 \end{bmatrix} w$$

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