Sustainable HVAC: Research Opportunities for Modelicans

Scott A. Bortoff

Chief Scientist

26 October 2022

MITSUBISHI ELECTRIC RESEARCH LABORATORIES (MERL)
Cambridge, Massachusetts, USA
http://www.merl.com

Sometimes I'm optimistic…

…but there is work to do.

Outline

- A peak inside MERL.
  - What do we do?
  - What are our challenges?
- Research and Development Opportunities
  - HVAC equipment level.
    - Why's this so hard?
    - MPC?
    - Model Reduction / Analysis
    - Hybrid multi-mode modeling, simulation
    - Carbon capture?
  - HVAC System / Building Level. MPC ?
  - Service / "Solutions" Level
    - Digital Twin ?
    - Estimation, calibration, feedback.

Objectives:

1. Alignment of incentives.
2. Get out of your silo.

Counter Example:

Mitsubishi Electric

Air Conditioning Systems

Automotive Equipment

Building Systems

Energy Systems

Factory Automation Systems

Home Products

Information & Comm. Systems

Public Systems

Semiconductors & Devices

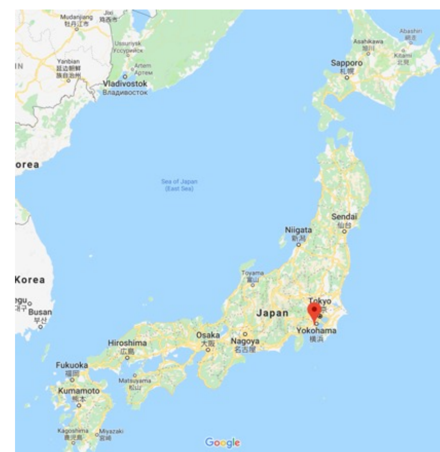
Space Systems

Transportation Systems

Visual Information Systems

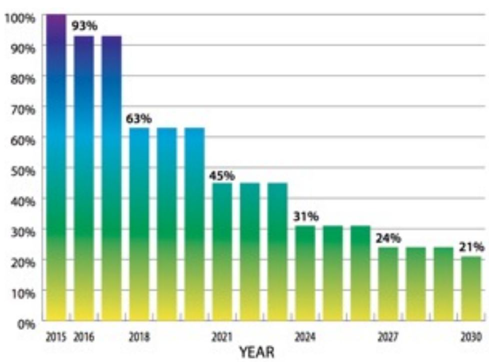
Mitsubishi Electric Sustie Building

- Certified ZEB* while under construction
- Medium-sized office building: 5,000 m^3, 4 floors
- PV, Radiant + Convective Cooling, VRF equipment
- Some DC Power, Natural Lighting, System Control
- **First year of operation – better than Net Zero**

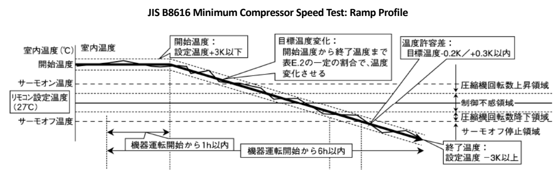


Trends – Making Model-Based Design More Important

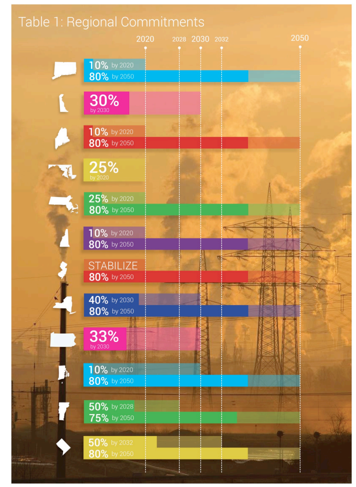
F-Gas Phase-Out



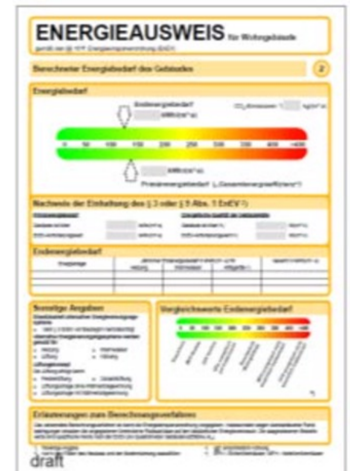
New Testing Standards



Electrification



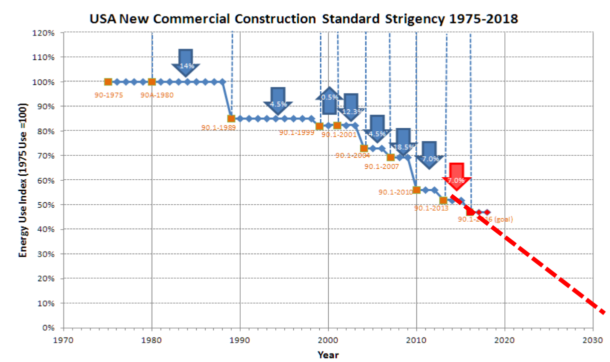
Building Performance



ZEB

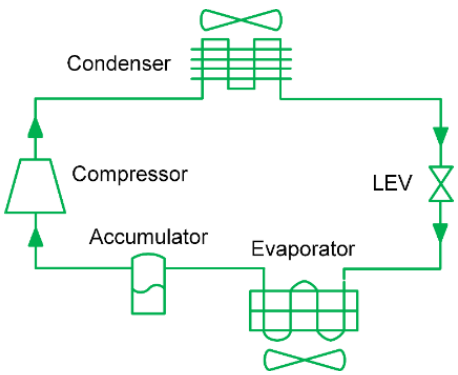
HVAC as Service

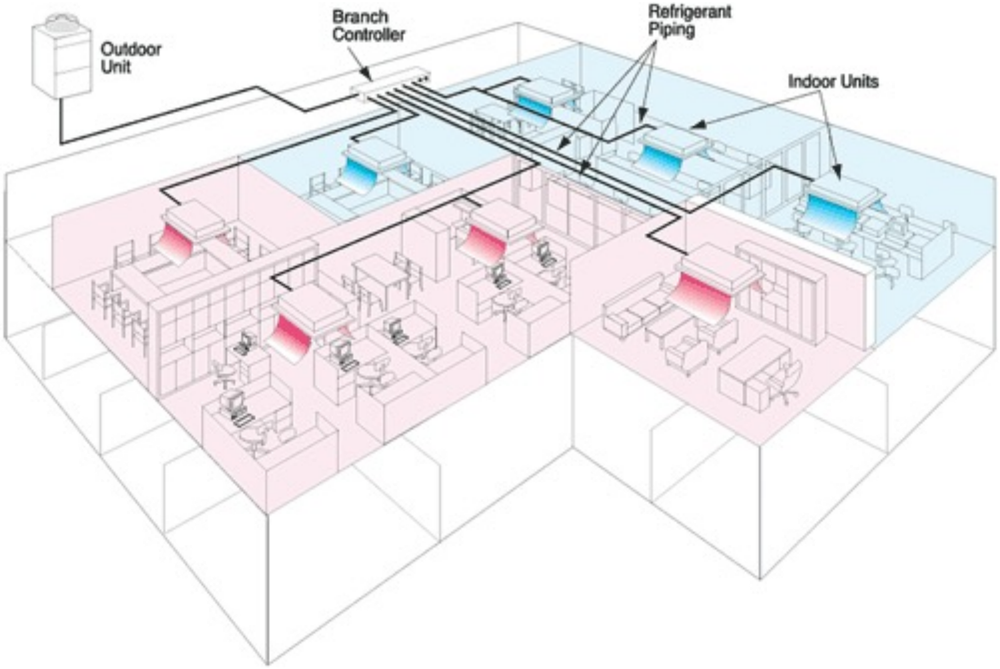
Building Standards

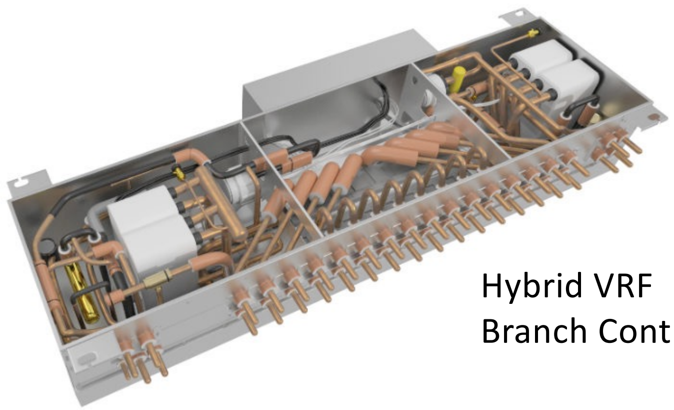


Implications on Products

- More variable actuation. Compressor speeds, valves, fans etc.
- Wider operating envelopes and conditions.
- More integration horizontally and vertically.
- Limited measurements.
- Dynamic system is increasingly…
  - Multivariable, interacting, coupled.
  - Nonlinear. Loop gain changes.
  - Many constraints. Operating limits.







Hybrid VRF
Branch Controller

MERL Strategy - Mathematical Model – Based Design (M-MBD)

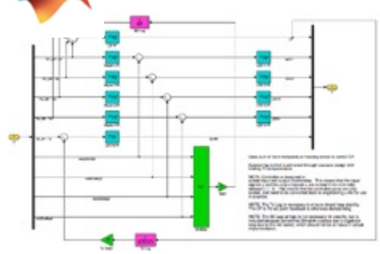
Definition: A <u>mathematical</u> method for designing complex architectures, <u>control,</u> signal processing and communication systems*

Models

Models + tools that <u>enable</u> mathematical methods ...

Libraries

Matlab & Simulink



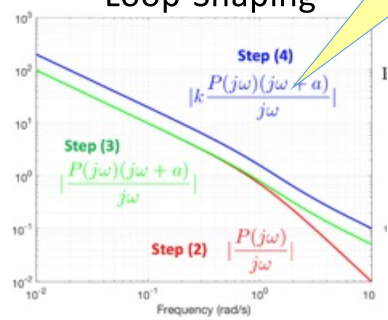
Not too many tools! KISS

Know-How (Methods)

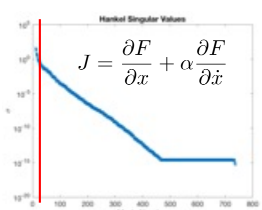
<u>Mathematical</u> methods of design and analysis

Not just trial-and-error simulation

Loop-Shaping



Model Reduction



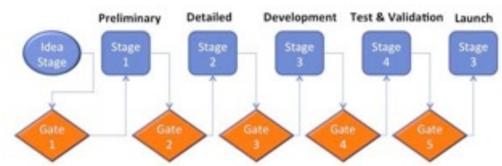
$$J = \frac{\partial F}{\partial x} + \alpha \frac{\partial F}{\partial \dot{x}}$$

$$\dot{x} = Ax + Bu$$
$$y = Cx + Du$$

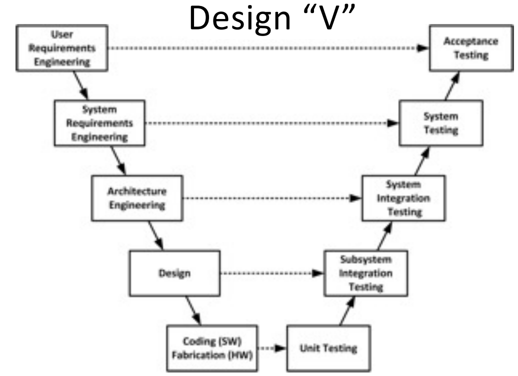
$$Y = H(j\omega)U$$

Process

Stage Gate Reviews



Design “V”

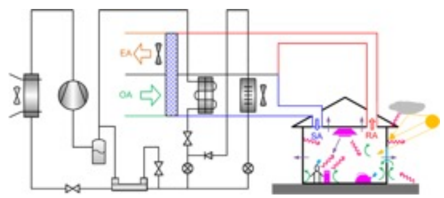


* https://en.wikipedia.org/wiki/Model-based_design

MERL HVAC Strategy: Mathematical Model-Based Design

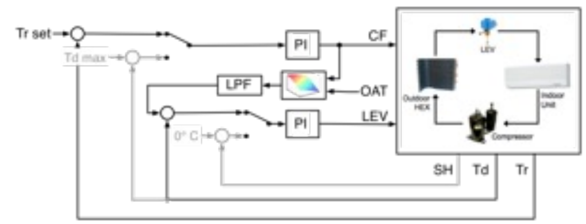
Build Models

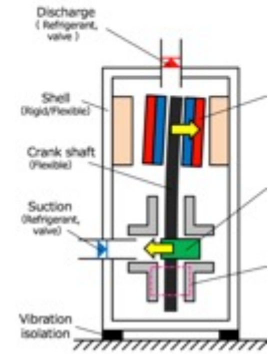
$$\frac{\partial(m_{flows}[i]l)}{\partial t} + \frac{\partial(\rho v^2 A)}{\partial x} = -A\frac{\partial p}{\partial x} - Fs_{fg}[i]$$



- System-level dynamic models
- Accrue reusable libraries
- Use: More than simulation

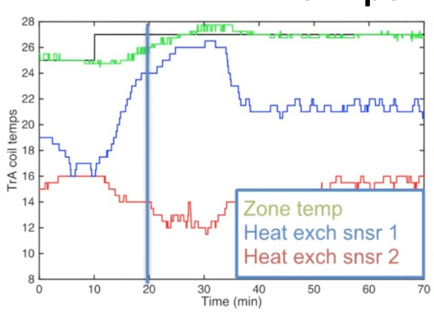
Solve Robust Design Problems

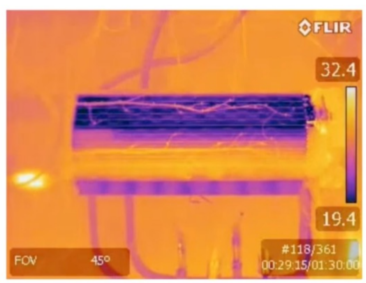




- Control: RAC, HAC, HVRF, Hyper Dry...
- Estimation: Digital Twin, Load Estimation...
- Dynamic Analysis: Pressure Oscillation, Vibration...

Do Experiments

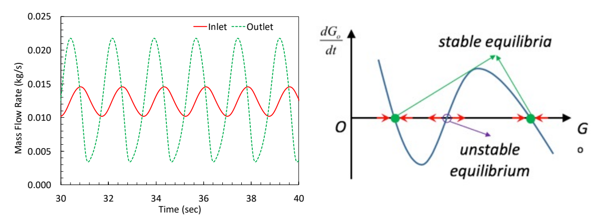




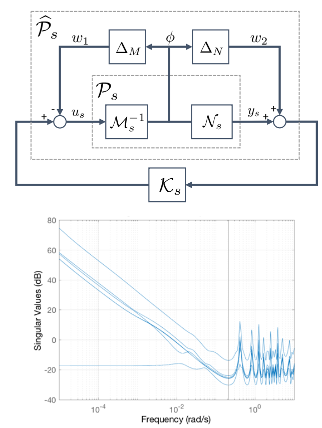
- Equipment: 1-Zone RAC, 4-Zone HAC
- Purpose: Measure dynamic response
- Use: Model and control algorithm validation

Use Math

Dynamical Systems Theory

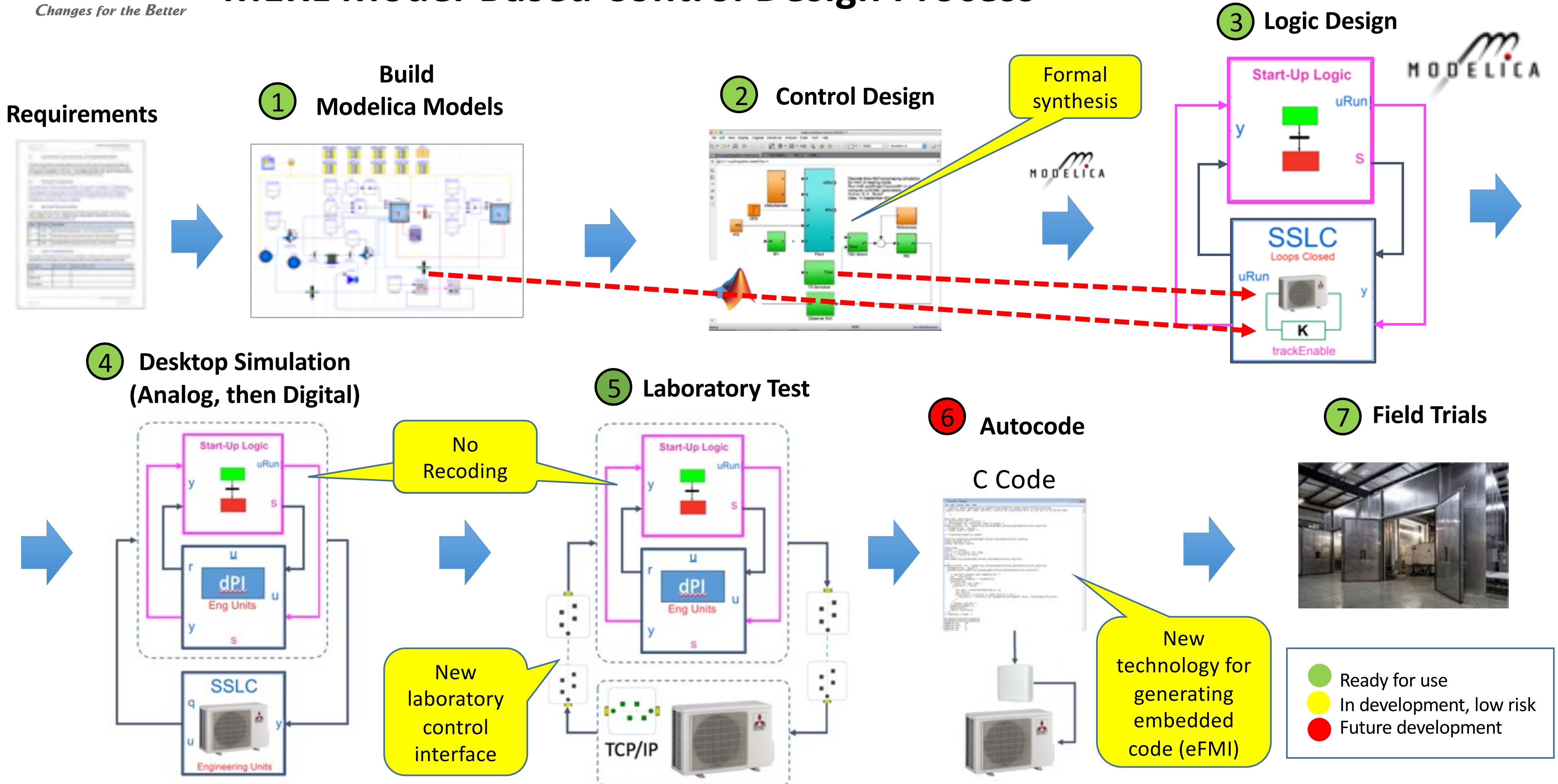


Control Theory



- Solve fundamental problems
- The “M-” in “M-MBD” = Math
- Rigorous solutions

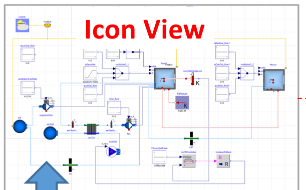
MERL Model-Based Control Design Process

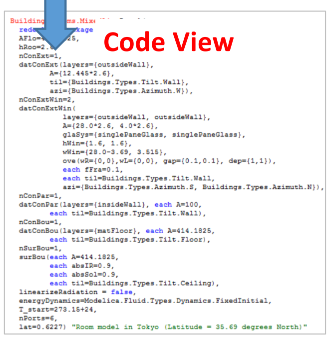


Modelica Enables M-MBD

Formal methods – not "guess and check"

① Modelica





Math View

$$0 = F(x, \dot{x}, u)$$

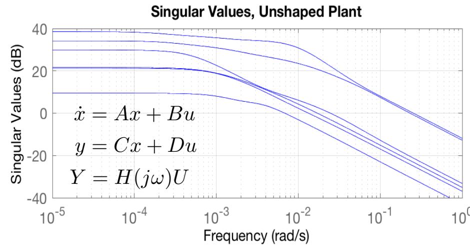
$$J = \frac{\partial F}{\partial x} + \alpha \frac{\partial F}{\partial \dot{x}}$$

Key Step

Modelica: Automatic

They only simulate

Frequency Response

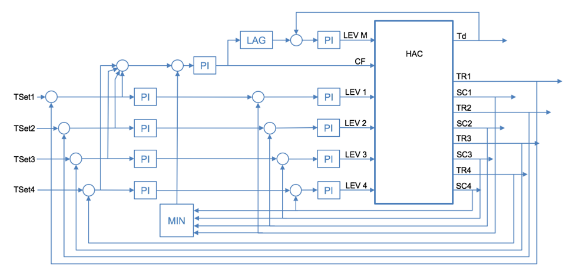


Other tools do not support this!

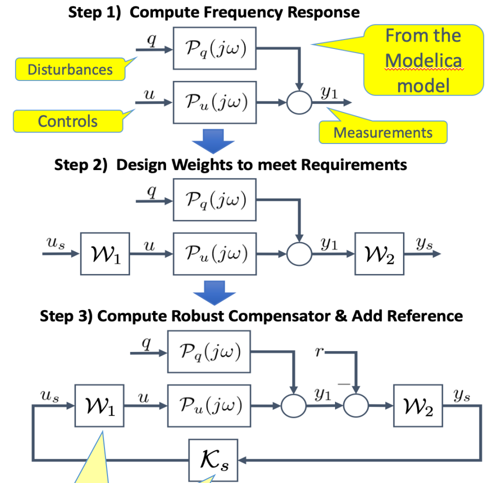
TRNSYS 17

EnergyPlus

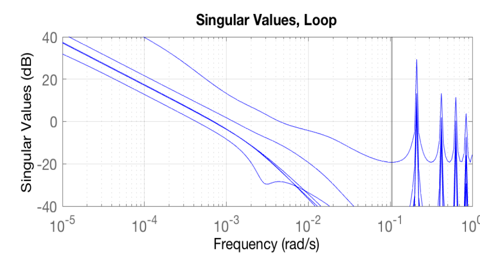
Feedback Control Configuration

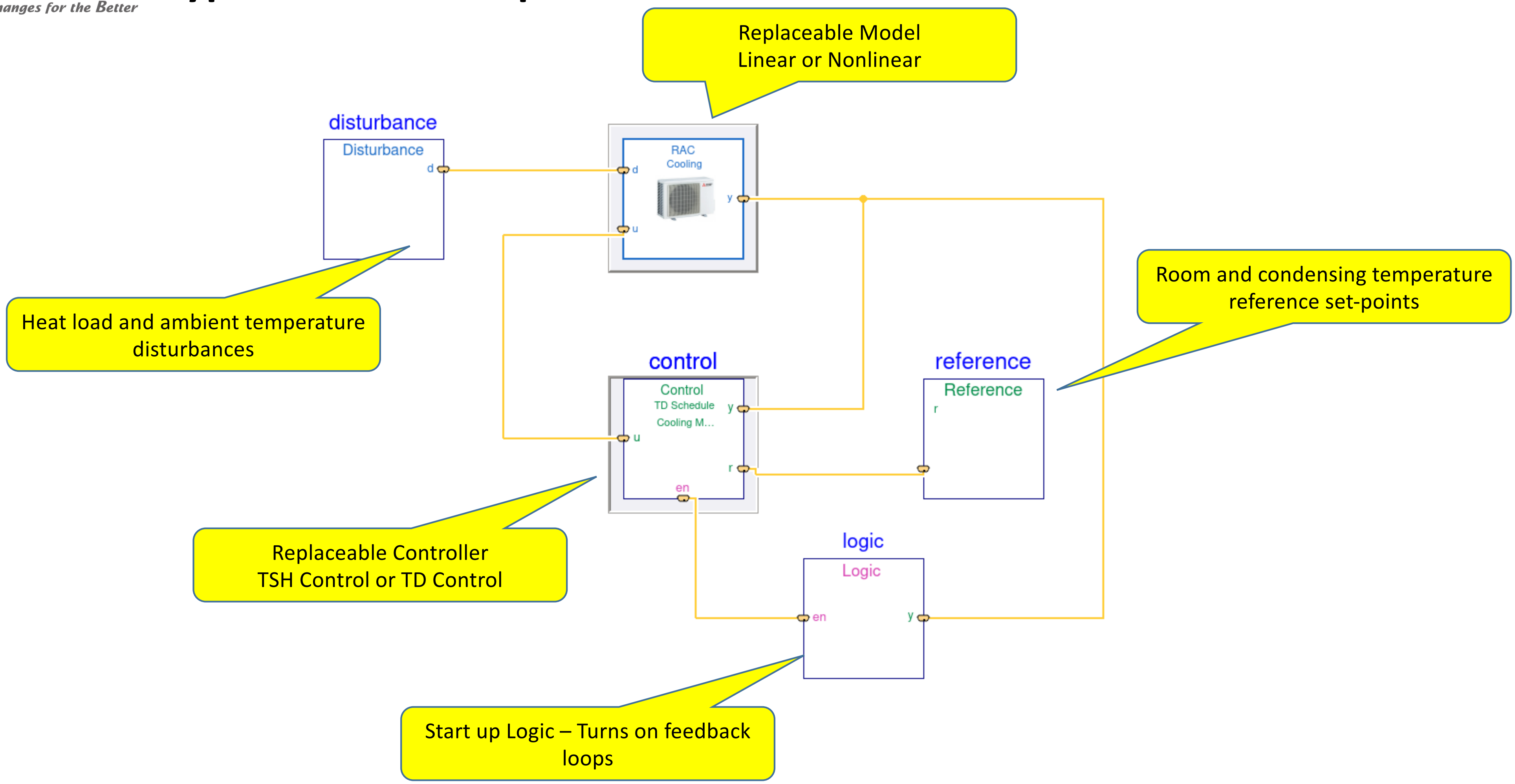


② Feedback Control Design



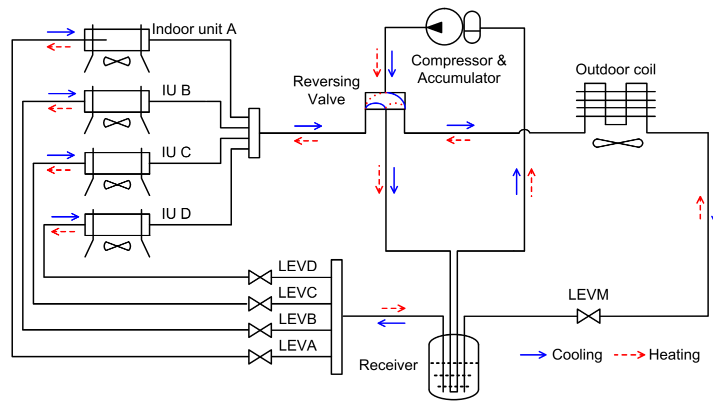
Mathematical methods (M-MBD)




Replaceable Model
Linear or Nonlinear
disturbance
Disturbance
d
RAC
Cooling
d
u
y
Heat load and ambient temperature disturbances
control
Control
TD Schedule
Cooling M...
y
u
r
en
reference
Reference
r
Room and condensing temperature reference set-points
Replaceable Controller
TSH Control or TD Control
logic
Logic
en
y
Start up Logic – Turns on feedback loops

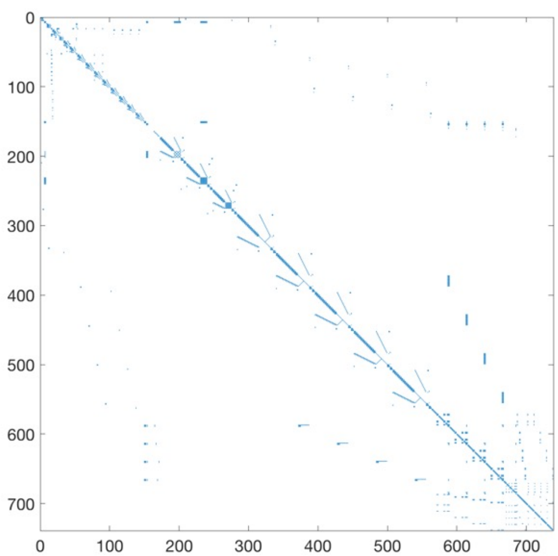
Stiff, Sparse, Ill-Conditioned

- Sparse: Jacobian is <1% non-zero. Symbolic construction is vital.
- Stiff: Time Constants from 1ms – 1Ms → Implicit Solvers
- But…Linearizations are reducable if you are careful.

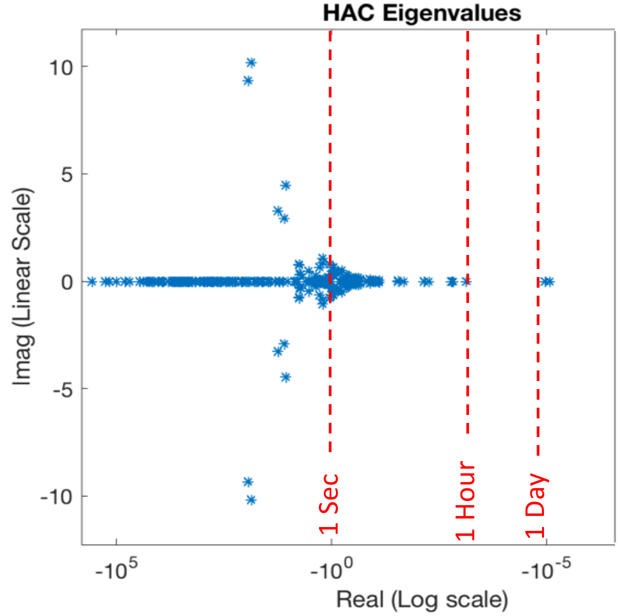


Non-zero elements of $J = \frac{\partial F}{\partial x} + \alpha \frac{\partial F}{\partial \dot{x}}$

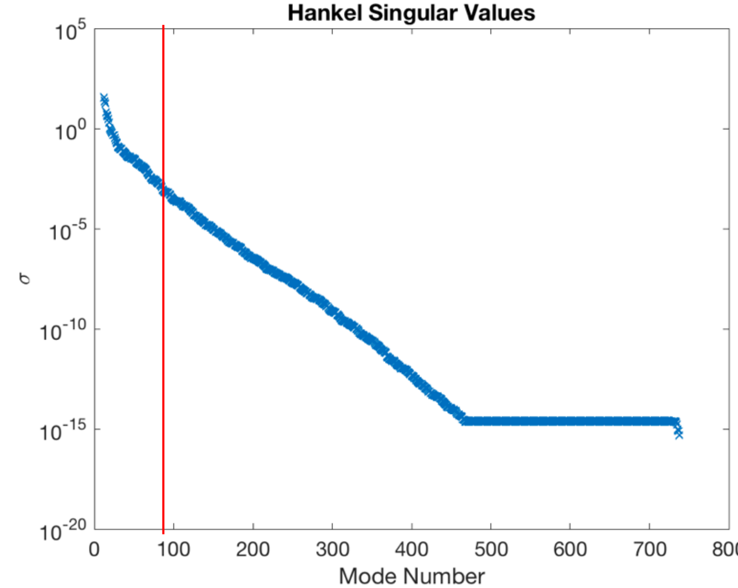
Sparse



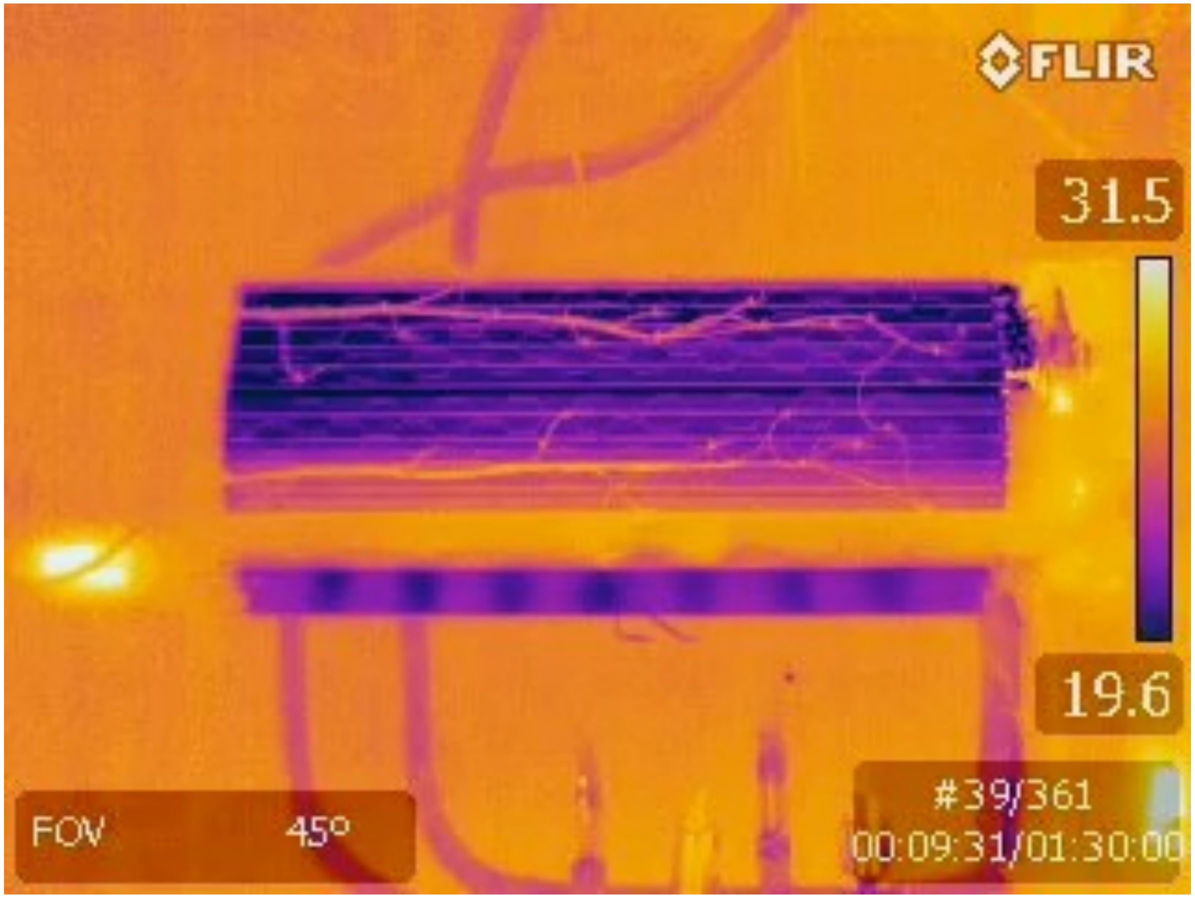
Stiff



Reduceable



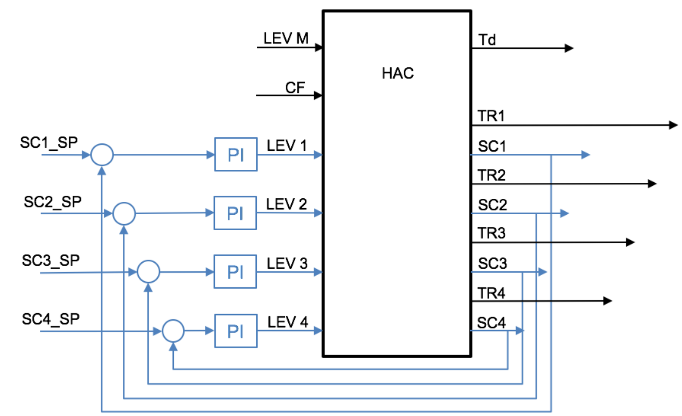
Indoor Unit in Cooling Mode (Evaporator)

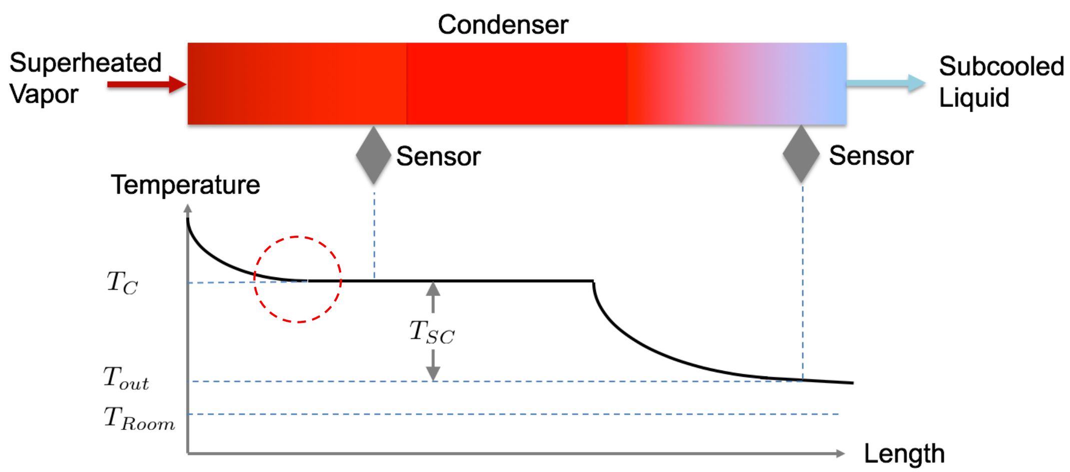


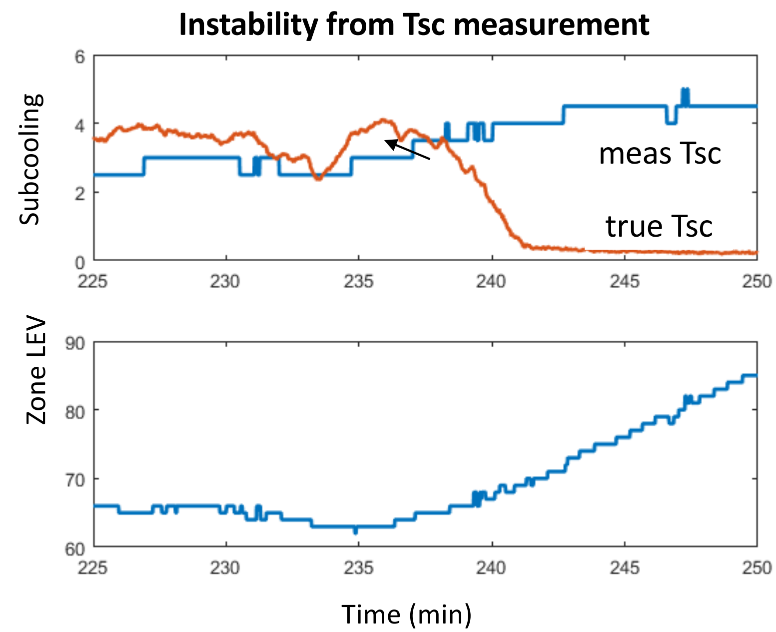
Refrigerant Subcooling Loop Gain Change

Sometimes superheated vapor passes beyond sensor 1:

- Subcooling calculation is incorrect
- Transfer function from LEV to Tsc changes sign
- Inner Loop becomes unstable



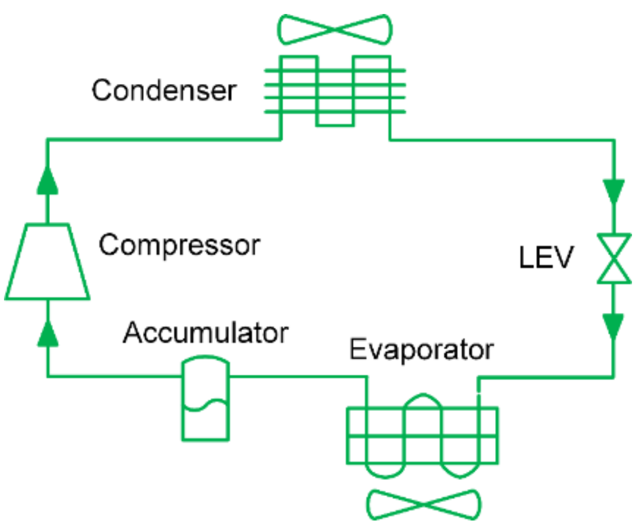




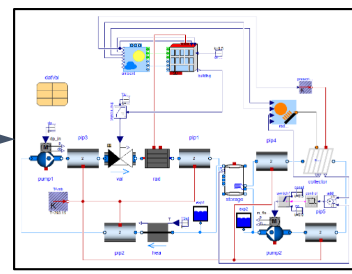
Engineering Use

- Modelica is complex and challenging to use in the factory
- FMI + Excel makes models accessible

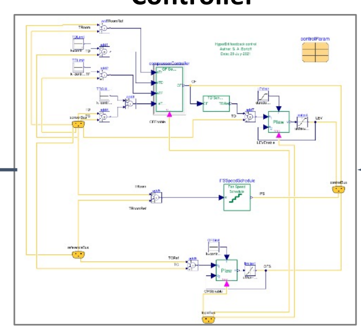
System



Modelica Model

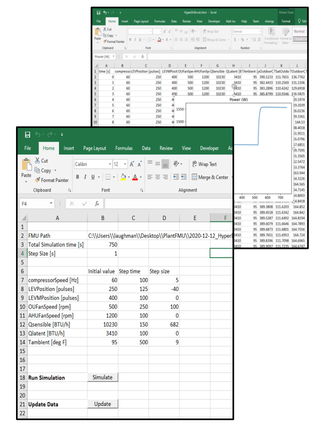


Controller

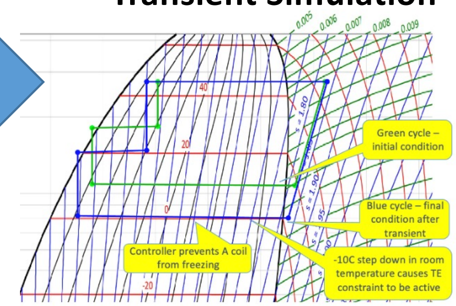


Functional Mock-Up Interface

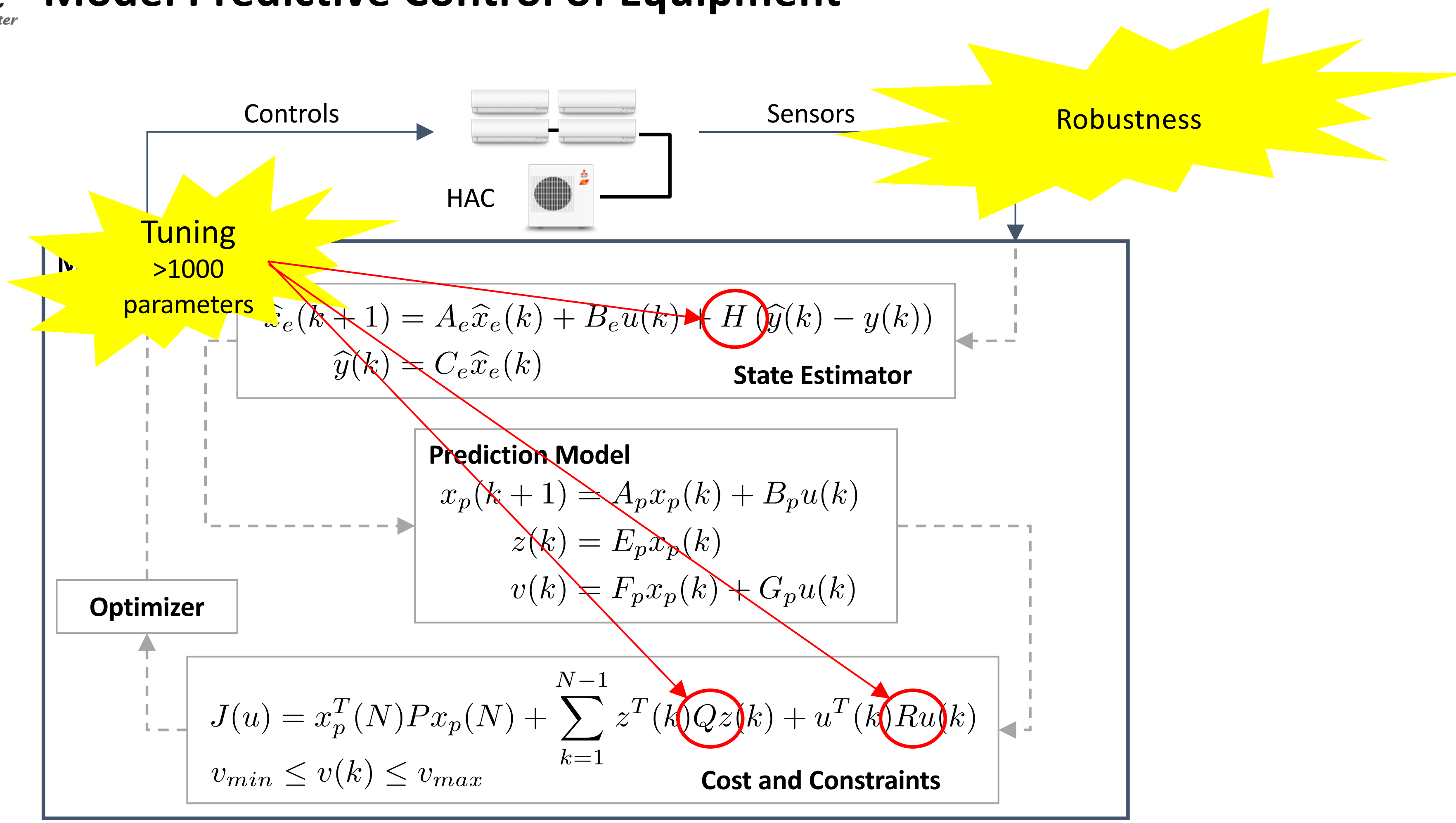
MS Excel Interface



Steady State and Transient Simulation

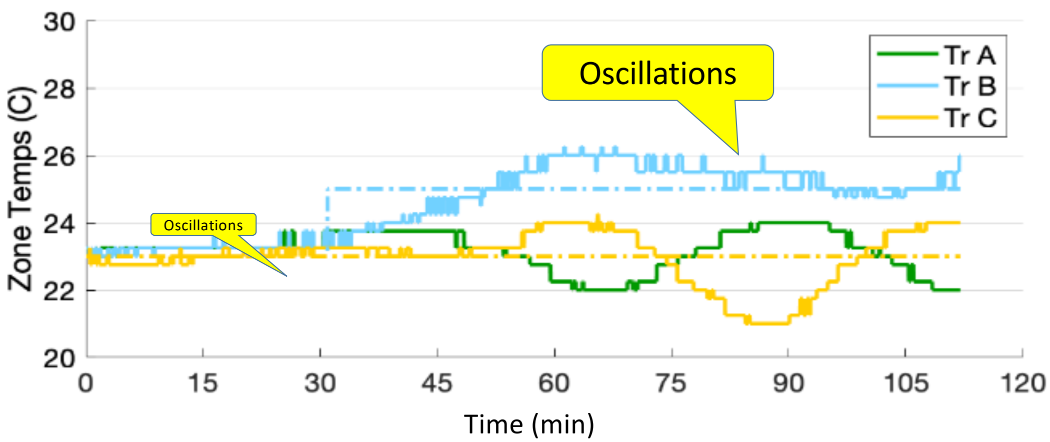


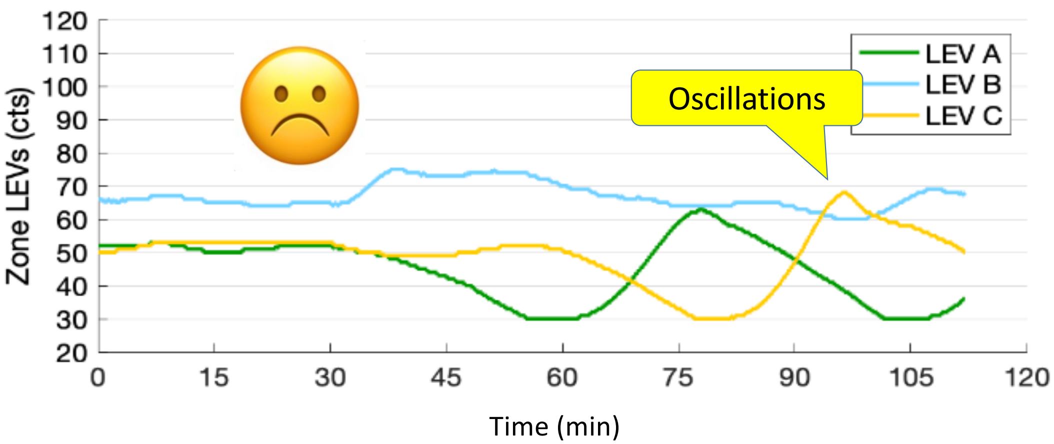
Model Predictive Control of Equipment



MITSUBISHI ELECTRIC
Changes for the Better

First Attempt with MPC (2017)



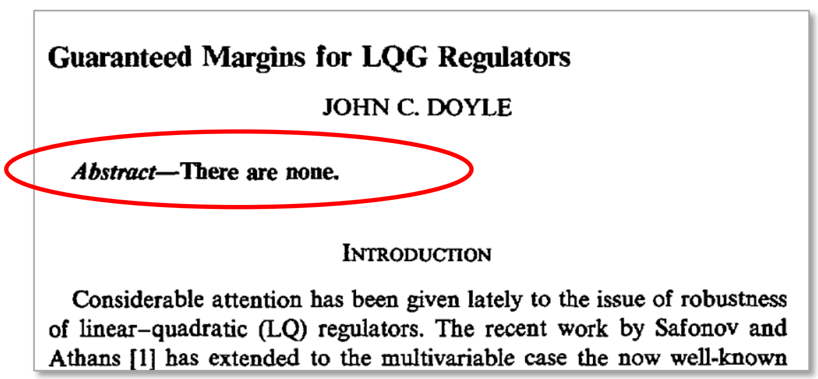


- This MPC is based on Linear Quadratic Regulation
- Estimator is Luenberger Observer

$$\widehat{x}_e(k+1) = A_e\widehat{x}_e(k) + B_e u(k) + H\left(\widehat{y}(k) - y(k)\right)$$
$$\widehat{y}(k) = C_e\widehat{x}_e(k)$$

- Cost is Quadratic

$$J(u) = x_p^T(N)Px_p(N) + \sum_{k=1}^{N-1} z^T(k)Qz(k) + u^T(k)Ru(k)$$



Guaranteed Margins for LQG Regulators

JOHN C. DOYLE

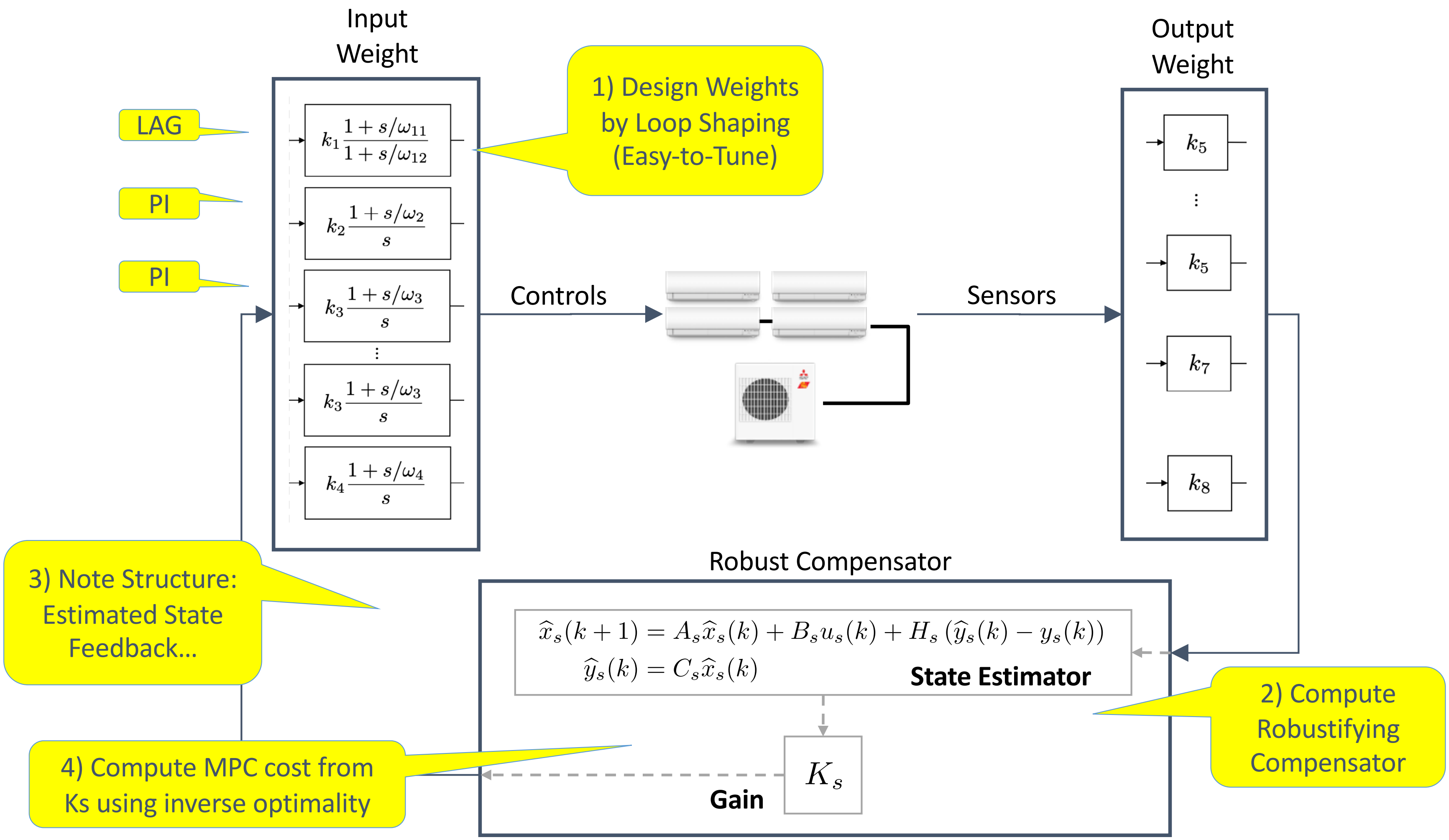
Abstract—There are none.

INTRODUCTION

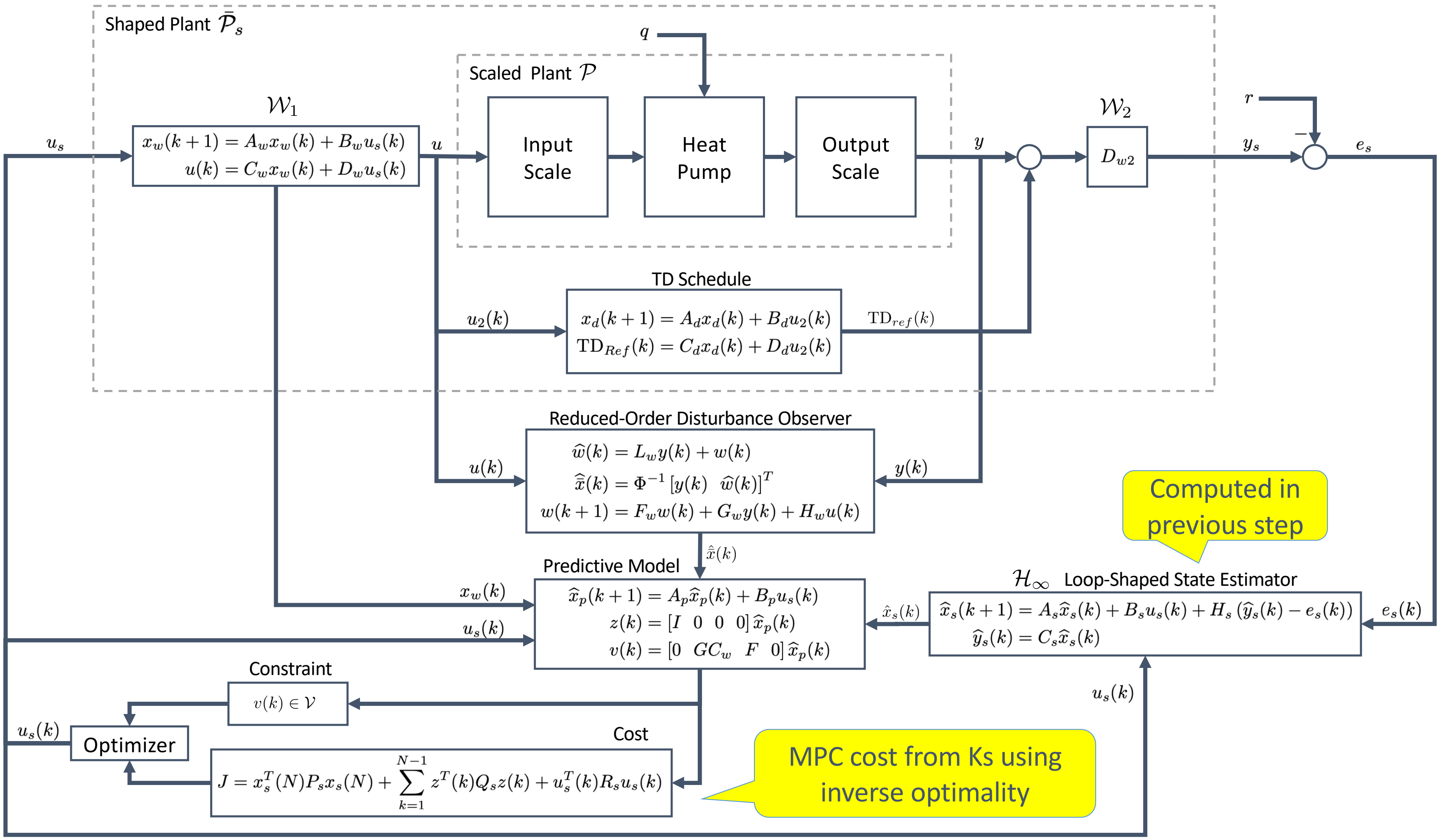
Considerable attention has been given lately to the issue of robustness of linear–quadratic (LQ) regulators. The recent work by Safonov and Athans [1] has extended to the multivariable case the now well-known

(1978)

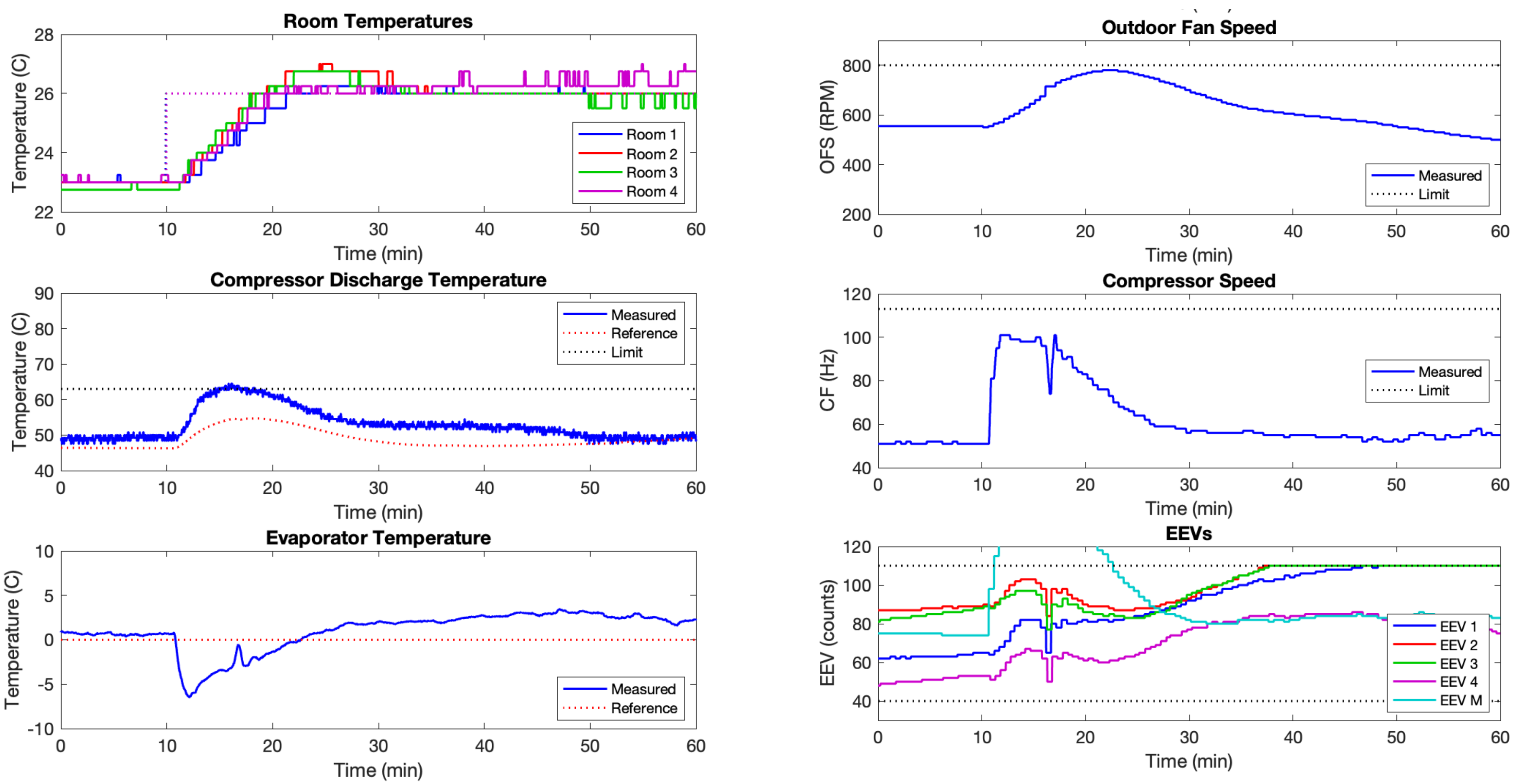
H-Infinity Loop Shaping for Robust Performance



H-Infinity Loop Shaped MPC

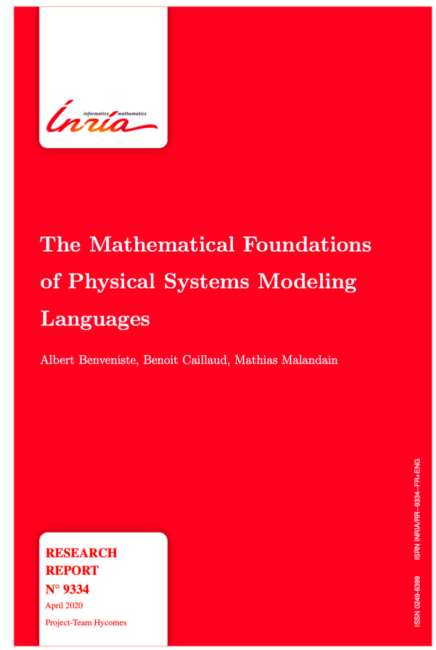


First Successful Experiments (2019-2020)



Research Problems at Equipment Level

- Goal: Robust operation → Energy efficiency.
- Other goal: Reduce refrigerant charge.
- Modeling and Simulation of multi-model (hybrid) systems
  - On-off valves, different modes of operation (heating, cooling, defrost, off)
- Nonlinear model reduction
  - Not black box. Retain the structure. Symbolic.
  - A math + computation + computer science problem.
- Model Predictive Control
  - Robustness in the sense of feedback loops
  - Mode switching
  - Gain scheduling
  - Embedded Realizations



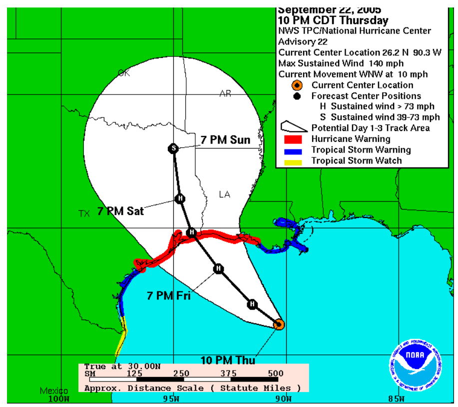
What is a ``Digital Twin'' ?

- A virtual (computer simulation) model of a process or product
- Used in (real-time) operation
- Combining real-time data with a (set of) model(s), used throughout the product lifecycle
- A proven and effective technology e.g. weather forecasting

Past

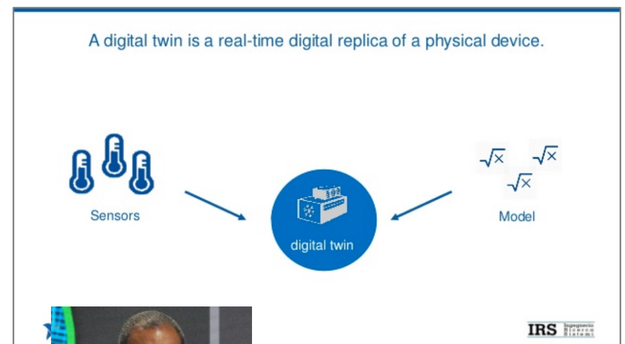
"Houston, we have a problem"

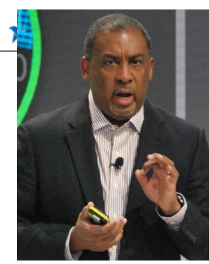
Present



- Modeling
- Data Assimilation
- Estimation

Marketing



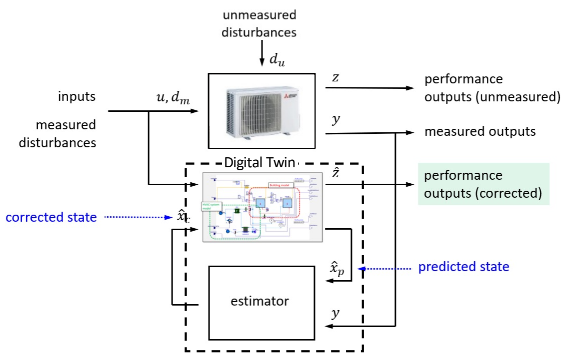


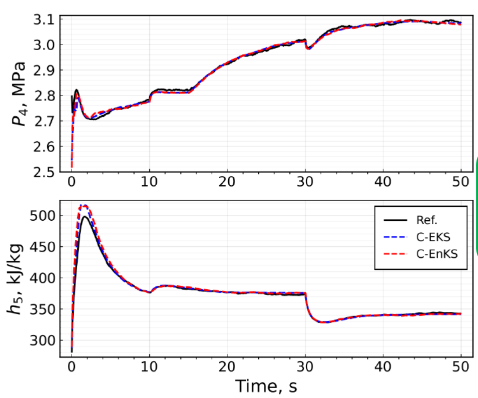
"Big Data"
"Internet of Things"
YouTube Videos

Opportunities for Digital Twins

- Target 1: Estimate refrigerant charge + HEX heat flux for equipment in operation
- Target 2: Estimate heat loads, heat flows in buildings

Equipment Digital Twin



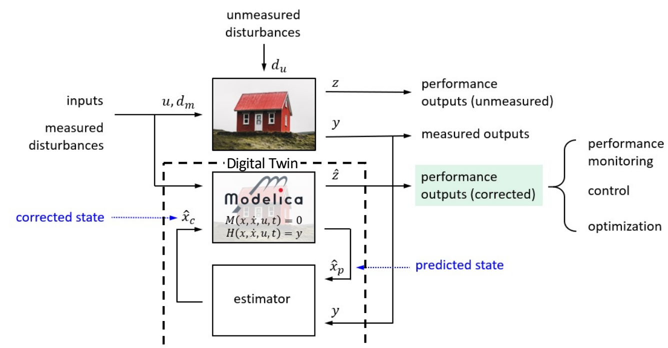


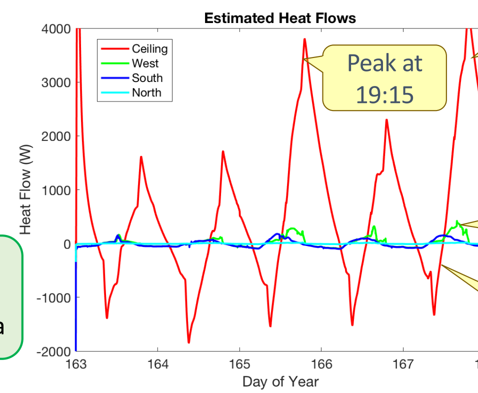
Estimating unmeasured or unmeasurable **equipment variables** from measured data

IT Platform

Estimating unmeasured or unmeasurable **building variables** from measured data

Building-Level Digital Twin





Peak at 19:15

Ceiling heat flow is dominant

West wall heat flow in evening

Negative heat flow at night

Naïve Attempt #1: Open Loop Model

A model ≠ A Digital Twin

- Inputs are uncertain, and initial conditions are unknown
- Dynamics are very, very slow – errors in initial conditions take <u>many days</u> to converge
- Poor robustness to model uncertainty
- Poor use of measurements

Physical

Weather
Internal Loads
Usage

Measurements
Performance Variables

Digital

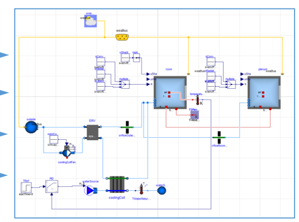
What if these are unknown?

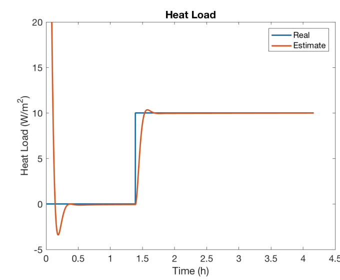
Assume ☹

Weather
Internal Loads
Usage
Initial Conditions

How to compute these?

Guess ☹





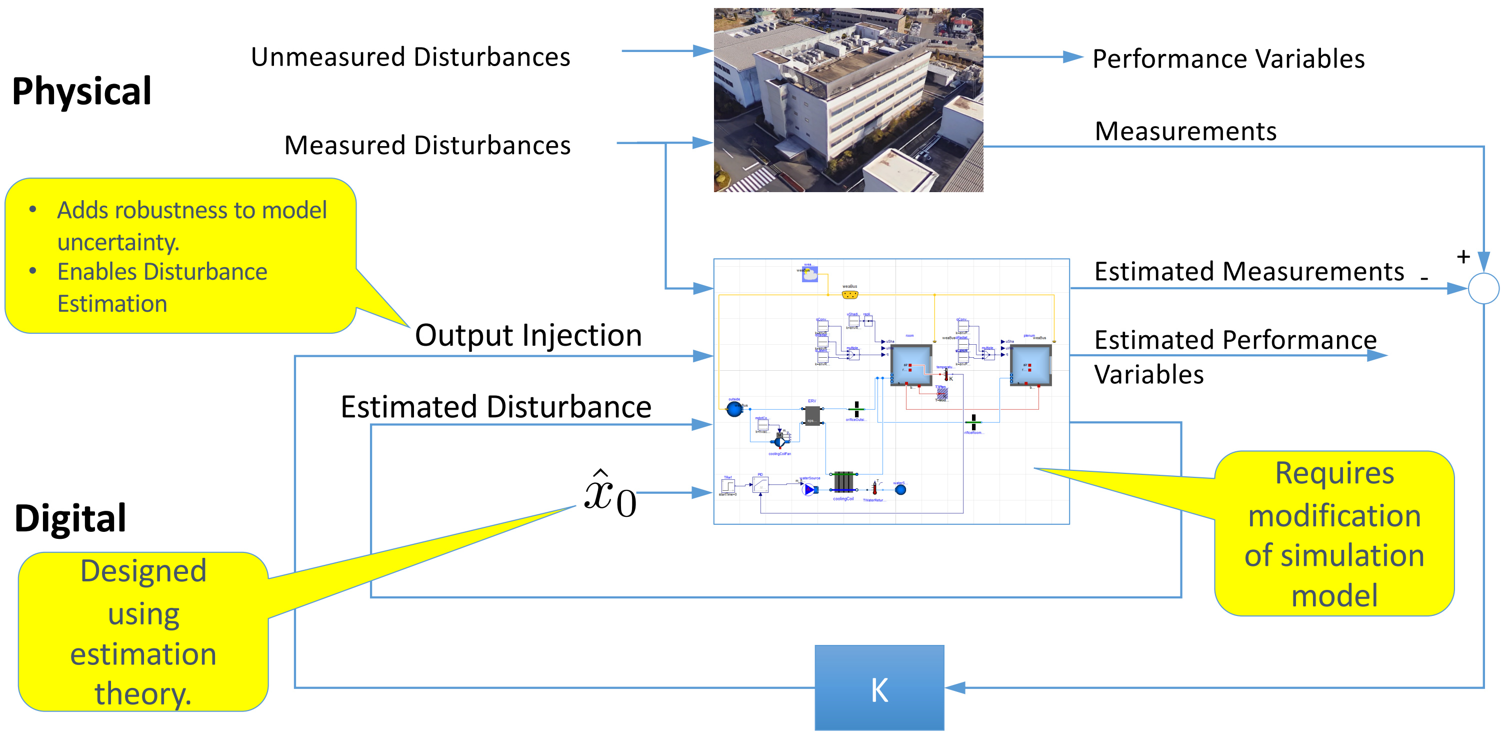
Math

Control input $u(t)$
Measured Input $d(t)$
Unmeasured Input $q(t)$
Initial Condition x_0

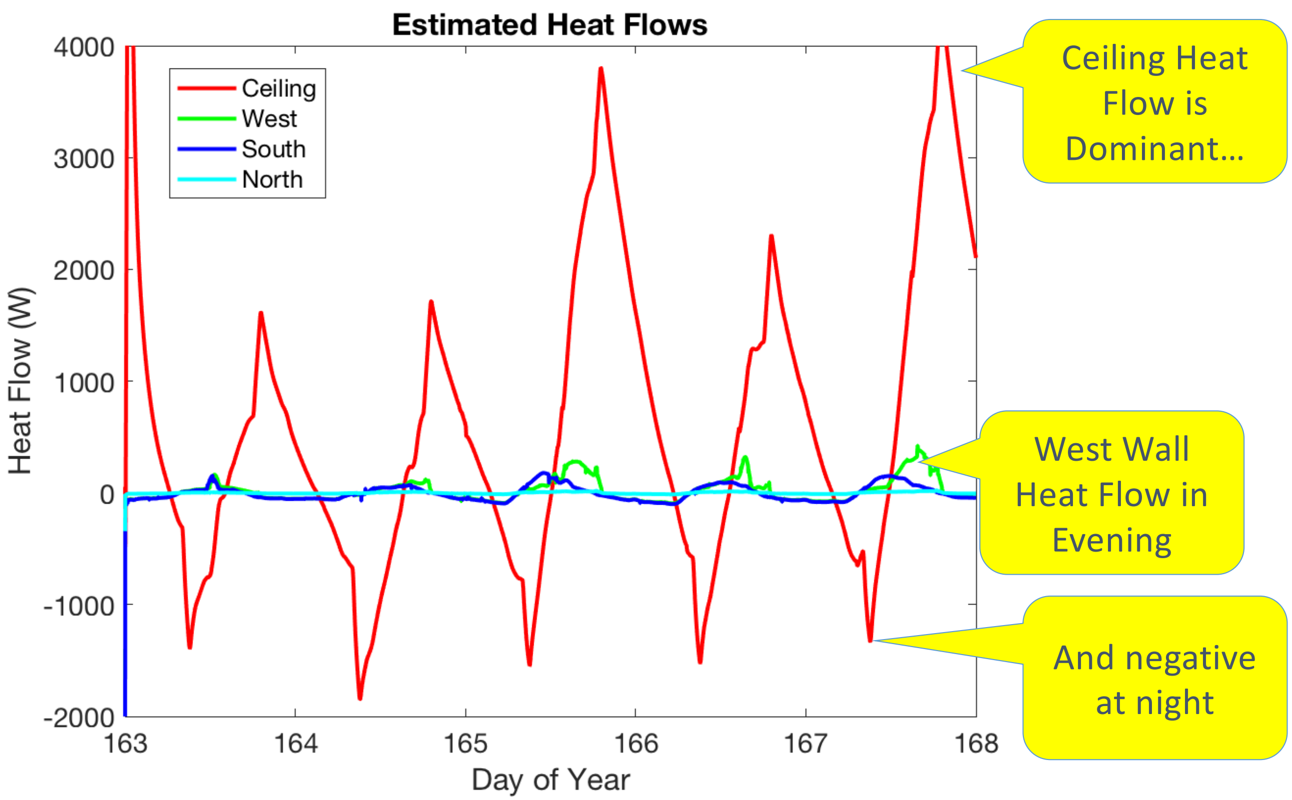
$$\boxed{\begin{aligned} &\dot{x} = f(x,u,d,q) \quad x(t_0) = x_0 \\ &y = h(x,u,d,q) \\ &z = g(x,u,d,q) \end{aligned}}$$

Naïve Attempt #2: Use feedback (EKF + FMU)

- Uncertain boundary conditions are *estimated* by feedback
- Measurement error is fed back through gain K – EKF or observer
- Initial Conditions are *designed* to avoid exciting very slow dynamics



It worked well enough write a paper, but…



But…

Correction step causes constraint violations.

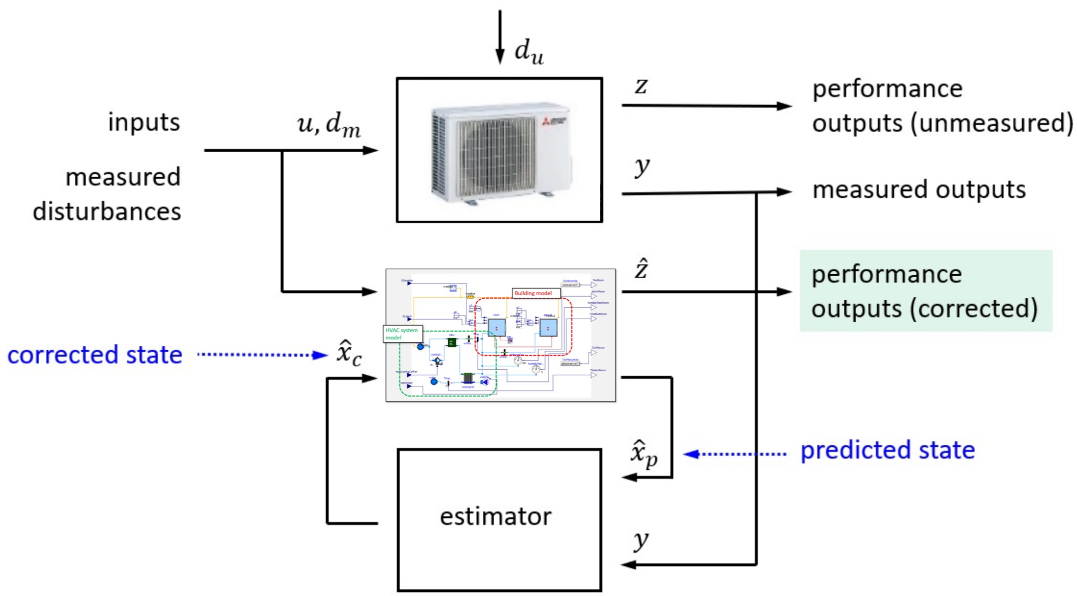
Solver crashes.

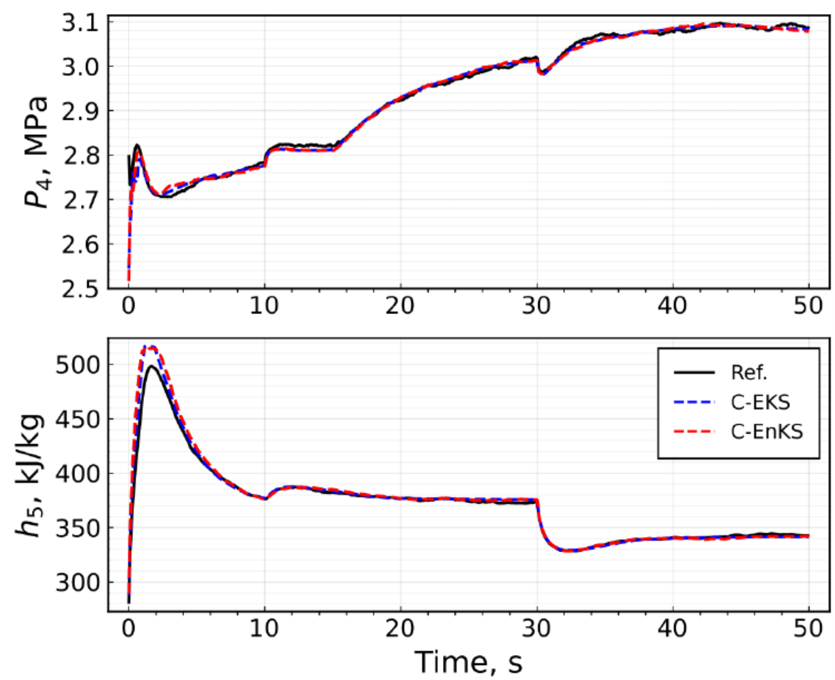
Modelica models were not designed for this.

Even as FMUs

Slightly Less Naïve Attempt #3

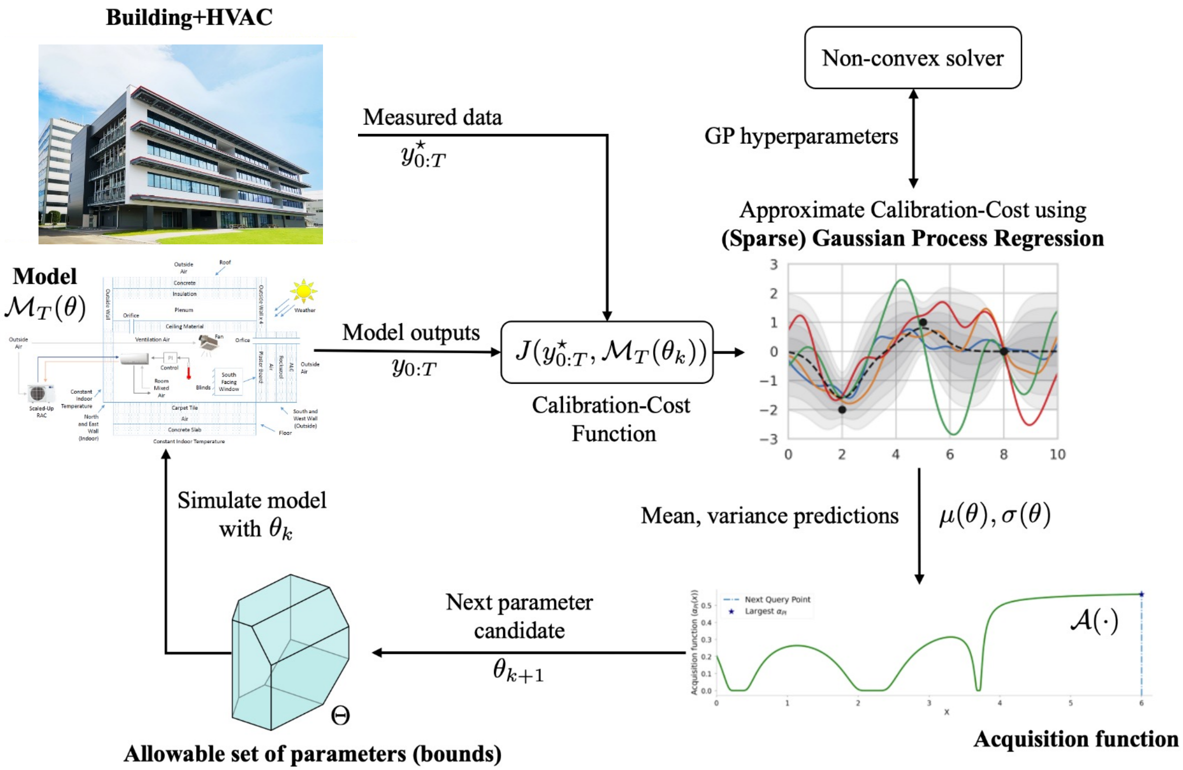
- Constrained Estimation EKF (and related varieties)
- Model Reduction + Symbolic Model (Julia) – Symbolic Jacobian helps
- But…Model is still very stiff. Is there a better formulation?





Building Model Calibration for Digital Twin

- Objective: Calibrate integrated building/equipment models using measurement data to improve predictions
- Use Bayesian optimization employing sparse Gaussian processes to identify 17 model parameters
- All parameters identified within range of ASHRAE Guideline 14, 70% are greater than 95% accuracy



Parameter	True Value	Est. Value	Accuracy
Airflow infiltration rate	0.0337	0.0327	97.1%
Outer IR roof emissivity	0.9	0.863	95.8%
Outer solar roof emissivity	0.9	0.935	96.1%
Outdoor HEX vapor HTC	500	518	96.3%
Outdoor HEX 2-phase HTC	3000	3251	91.6%
Outdoor HEX liquid HTC	700	738	94.6%
Indoor HEX 2-phase HTC	2000	1958	97.9%
Indoor HEX liquid HTC	700	712	98.3%

Challenges for Digital Twin

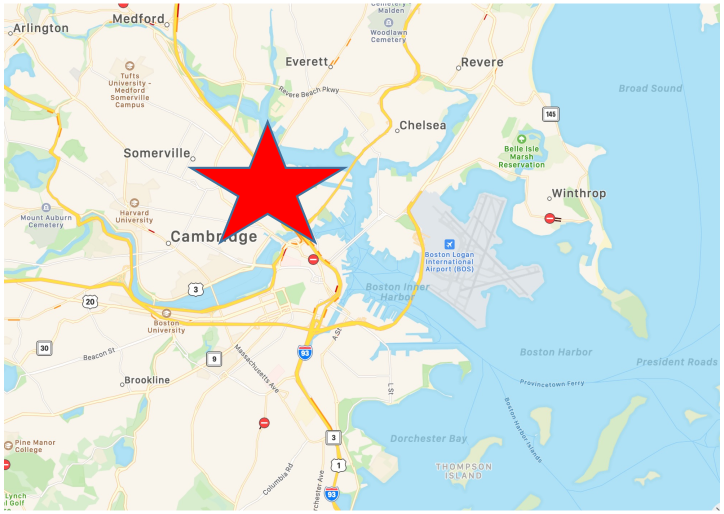
- What is its purpose? And for whom?
  - Estimation of charge – of interest to multiple parties (alignment of incentives)
- Data assimilation involves state modification (output injection)
  - Modelica models / libraries were not intended for this purpose.
  - FMU has limitations – no Jacobian wrt parameters
  - Models are stiff and nonlinear. Is there an implicit formulation?
- How can we use feedback to make a digital twin robust?
  - Full state estimation is a brute force solution.
- Consider refrigerant charge estimation.
  - Charge is not a state. It is an output.
  - Charge is not conserved in a simulation. It can change during simulation. Good? Bad?
  - Mathematics problem first.
- How does this scale up?

Changes for the Better

Conclusions

- Modelica (tools + community) can play leading role in development of sustainable HVAC
  - Play the long game, maintain a sustained effort
  - Align incentives
- There are terrific research problems to be solved
  - Great Ph.D. topics for many backgrounds (math, software, modeling)
  - Great topics for government – university – industry collaboration
- If you find yourself in Boston, please visit MERL!

Cambridge, MA, USA



MITSUBISHI ELECTRIC

Changes for the Better