CERN

Energy Consumption Optimisation using Advanced Control Algorithms

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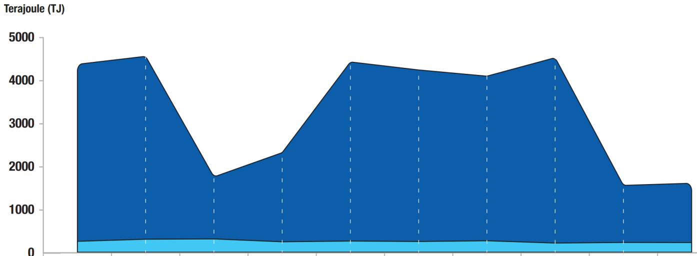
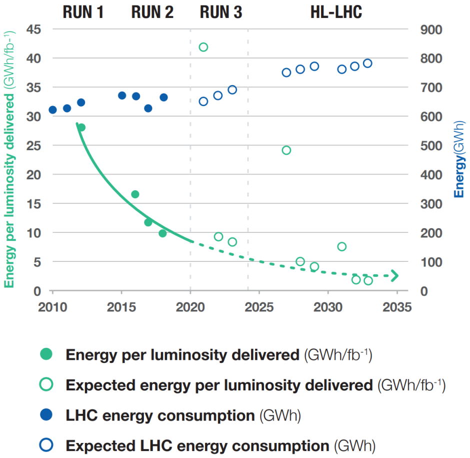
Introduction



	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Electricity	4350	4536	1738	2300	4405	4219	4075	4504	1541	1591
Gas (heating)	252	301	308	241	259	248	235	212	226	224
Diesel (heating and generators)	0	10.1	2.3	0.4	1.8	1.9	16.5	5.3	1.6	1.3
Renewable energy	0	0	0	0.1	0	0.1	0.1	0.1	0.1	0.2
Petrol (transportation)	18	18	20	20	26	16	13	15	18	12

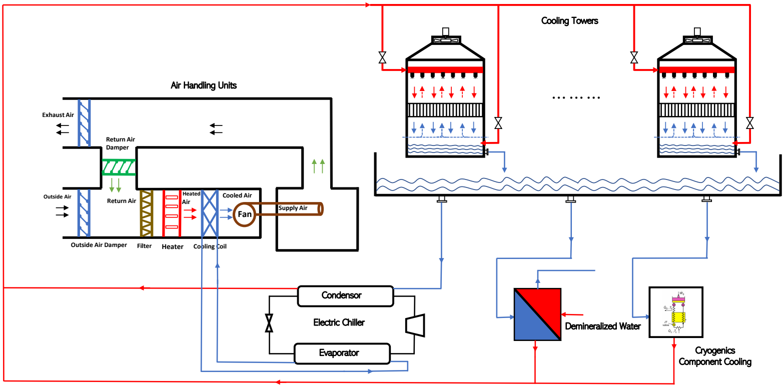
CERN's energy consumption is high (1.3 TWh per year), and costs are rising

Energy Efficient Operation



- Focus on energy consumed per luminosity delivered GWh/fb^{-1}
- Running accelerators less saves money, but doesn't help this metric
- Need to be able to reduce consumption while continuing to operate as normal
- **Improved controls for infrastructure can help!**

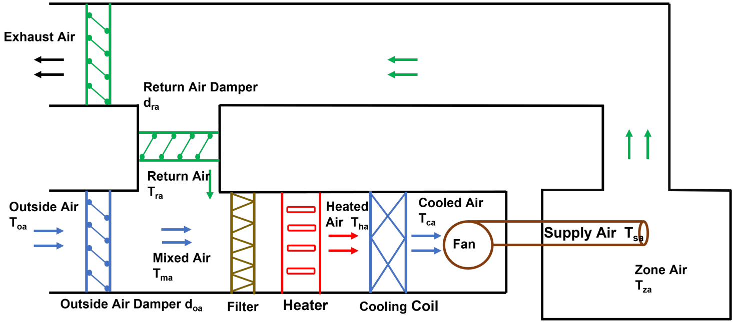
Cooling and Ventilation



Cooling and ventilation at CERN consumes considerable energy (66 GWh in 2019)

Pilot Project: Air Handling Units (AHU)

AHU Control Problem



Controlled Variables

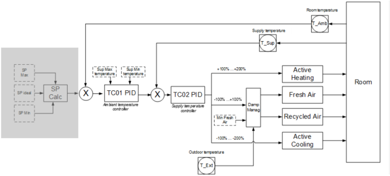
- Zone air temperature (range 15-24 degrees)
- Supply air temperature (15-30 degrees)

Manipulated Variables

- Outside and return air dampers
- Fan speed
- Heating and cooling coils

AHU Control Problem

A classical controls approach would be to use cascaded PID controllers:



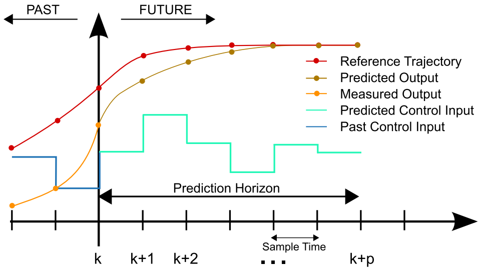
We are forced to choose specific setpoints (which we can try to vary to minimize energy consumption). However, this is not easy to do without introducing dynamic interactions.

We would like to have a controller that:

- Can express the control objectives in terms of ranges and constraints
- Can explicitly take into account energy consumption
- Can easily take into account present and even future process disturbances (for example, via a weather forecast)

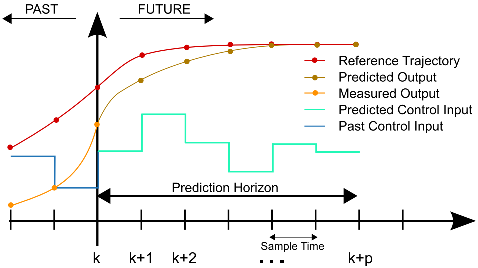
Model Predictive Control (MPC)

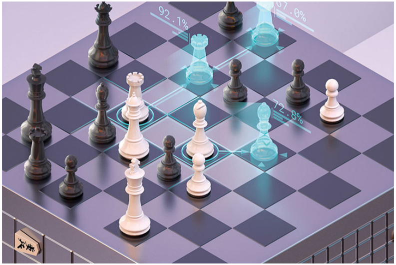
What is MPC?



- Want to find a set of control actions that minimizes some cost over a fixed horizon, while respecting some constraints
- Need to have some kind of dynamic plant model to predict future behavior
- Leads to an optimization problem which must be solved
- **Apply the first of the sequence of control actions, then repeat the process!**

Open loop or Closed loop?





Feedback comes from repeating the entire process once new information arrives.

Formulation of the MPC problem

$$\min_{\mathbf{d},\boldsymbol{\omega},\boldsymbol{\epsilon},\mathbf{T}} \sum_{k=0}^{N} P_f(\omega_k) + P_h(T^{ha}_{k+1}) + P_c(T^{ca}_{k+1}) + r_{sp}(T^{za}_k - T^{za}_{sp})^2 + \mathbf{r}^T\boldsymbol{\epsilon}^2$$

$$\begin{aligned}
\text{s.t} \quad & T^{za}_{k+1} = f_{za}(T^{za}_{,k}, T^{sa}_k, T^{oa}_k, \omega_k), T^{ma}_{k+1} = f_{ma}(T^{za}_k, T^{oa}_k, d^{oa}_k), T^{sa}_{k+1} = f_{fan}(T^{ca}_k) \\
& T^{ca}_{k+1} - \epsilon_{ha} \le T^{ha}_{k+1} \le T^{max}_{ha} + \epsilon_{ha}, T^{min}_{ca} - \epsilon_{ca} \le T^{ca}_{k+1} \le T^{ha}_{k+1} + \epsilon_{ca} \\
& T^{min}_{sa} - \epsilon_{sa} \le T^{sa}_{k+1} \le T^{max}_{sa} + \epsilon_{sa}, T^{min}_{za} - \epsilon_{za} \le T^{za}_{k+1} \le T^{max}_{za} + \epsilon_{za} \\
& d^{min}_{oa} \le d^{oa}_k \le d^{max}_{oa}, \omega^{min} \le \omega_k \le \omega^{max} \\
& -\dot{d}_{oa} \le d^{oa}_{k+1} - d^{oa}_k \le \dot{d}_{oa}, -\dot{\omega} \le \omega_{k+1} - \omega_k \le \dot{\omega} \\
& -\dot{T}^{ca} \le T^{ca}_{k+1} - T^{ca}_k \le \dot{T}^{ca}, -\dot{T}^{ha} \le T^{ha}_{k+1} - T^{ha}_k \le \dot{T}^{ha} \\
& T_{za}[0] = T^{init}_{za},\ T^{ma}[0] = T^{init}_{ma}, T_{ha}[0] = T^{init}_{ha}, \\
& T_{ca}[0] = T^{init}_{ca},\ \epsilon_{sa} > 0, \epsilon_{za} > 0, \epsilon_{ca} > 0, \epsilon_{ha} > 0,\ \mathbf{r} > 0
\end{aligned}$$

Complete formulation for the AHU

Formulation of the MPC problem

$$\min_{\mathbf{d},\boldsymbol{\omega},\boldsymbol{\epsilon},\mathbf{T}} \sum_{k=0}^{N} P_f(\omega_k) + P_h(T_{k+1}^{ha}) + P_c(T_{k+1}^{ca}) + r_{sp}(T_k^{za} - T_{sp}^{za})^2 + \mathbf{r}^T \boldsymbol{\epsilon}^2$$

$$\begin{aligned}
\text{s.t} \quad & T_{k+1}^{za} = f_{za}(T_{,k}^{za}, T_k^{sa}, T_k^{oa}, \omega_k),\, T_{k+1}^{ma} = f_{ma}(T_k^{za}, T_k^{oa}, d_k^{oa}),\, T_{k+1}^{sa} = f_{fan}(T_k^{ca}) \\
& T_{k+1}^{ca} - \epsilon_{ha} \leq T_{k+1}^{ha} \leq T_{ha}^{max} + \epsilon_{ha},\, T_{ca}^{min} - \epsilon_{ca} \leq T_{k+1}^{ca} \leq T_{k+1}^{ha} + \epsilon_{ca} \\
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\end{aligned}$$

Cost function: Energy consumption

Formulation of the MPC problem

$$\min_{\mathbf{d},\boldsymbol{\omega},\boldsymbol{\epsilon},\mathbf{T}} \sum_{k=0}^{N} P_f(\omega_k) + P_h(T^{ha}_{k+1}) + P_c(T^{ca}_{k+1}) + r_{sp}(T^{za}_k - T^{za}_{sp})^2 + \mathbf{r}^T\boldsymbol{\epsilon}^2$$

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\end{aligned}$$

Evolution of system states (based on model)

Formulation of the MPC problem

$$
\begin{aligned}
\min_{\mathbf{d},\boldsymbol{\omega},\boldsymbol{\epsilon},\mathbf{T}} \sum_{k=0}^{N} & P_f(\omega_k) + P_h(T^{ha}_{k+1}) + P_c(T^{ca}_{k+1}) + r_{sp}(T^{za}_k - T^{za}_{sp})^2 + \mathbf{r}^T \boldsymbol{\epsilon}^2 \\
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\end{aligned}
$$

Actuator constraints (hard) and state constraints (soft)

Formulation of the MPC problem

$$
\begin{aligned}
\min_{\mathbf{d},\boldsymbol{\omega},\boldsymbol{\epsilon},\mathbf{T}} \sum_{k=0}^{N} & P_f(\omega_k) + P_h(T^{ha}_{k+1}) + P_c(T^{ca}_{k+1}) + r_{sp}(T^{za}_k - T^{za}_{sp})^2 + \mathbf{r}^T\boldsymbol{\epsilon}^2 \\
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& T^{min}_{sa} - \epsilon_{sa} \le T^{sa}_{k+1} \le T^{max}_{sa} + \epsilon_{sa}, T^{min}_{za} - \epsilon_{za} \le T^{za}_{k+1} \le T^{max}_{za} + \epsilon_{za} \\
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& -\dot{T}^{ca} \le T^{ca}_{k+1} - T^{ca}_k \le \dot{T}^{ca}, -\dot{T}^{ha} \le T^{ha}_{k+1} - T^{ha}_k \le \dot{T}^{ha} \\
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\end{aligned}
$$

Rate of change constraints

Formulation of the MPC problem

$$\min_{\mathbf{d},\boldsymbol{\omega},\boldsymbol{\epsilon},\mathbf{T}} \sum_{k=0}^{N} P_f(\omega_k) + P_h(T_{k+1}^{ha}) + P_c(T_{k+1}^{ca}) + r_{sp}(T_k^{za} - T_{sp}^{za})^2 + \mathbf{r}^T \boldsymbol{\epsilon}^2$$

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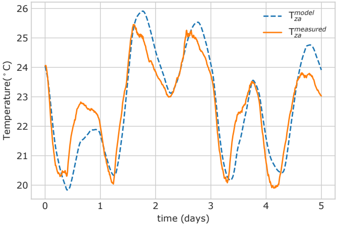
\end{aligned}$$

Initial conditions: the latest process value samples

AHU Model Derivation

Plant dynamics are first-principles models based on mass and energy balances. For example, zone air f_{za}:

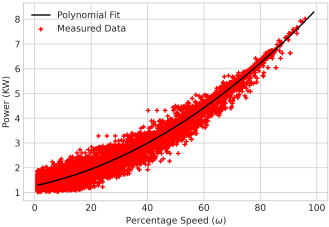
$$C_z \frac{dT_{za}}{dt} = \dot{m}_{sa}^{in} C_{pa} T_{sa} - \dot{m}_{sa}^{out} C_{pa} T_{za} + \alpha (T_{oa} - T_{za}) + q(t)$$



Actuator power consumption also based on simple models, for example cooling coil power:

$$P_c = \frac{\dot{m}_{sa} C_{pa} (T_{ha} - T_{ca})}{\eta_c COP_c}$$

Fan power model:

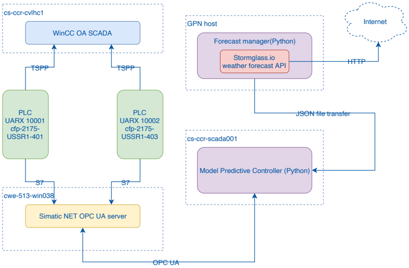


Implementation

Implementation

The process models are simple and continuous, but nonlinear. The MPC optimization problem is a Nonlinear Program (NLP)
Not realistic to implement solver on classic PLC. Instead, implement in Python and run on remote server.
Solve with CasADI and IPOPT

CasADi

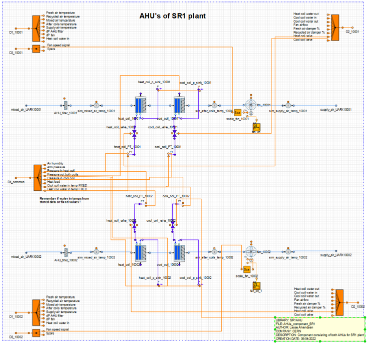


Communication between PLC and MPC is through OPC UA. We keep cascade PID, and add tracking mode for bumpless switch to/from MPC

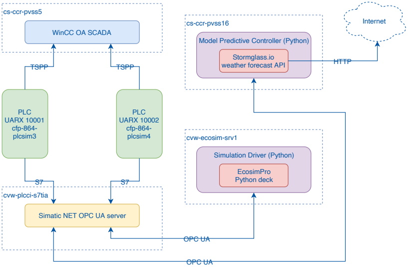
Virtual Commissioning

Virtual Commissioning

Need a more realistic model to reliably develop and test the new controller. Created in EcosimPro:



Recreate the production setup in the lab:



Lab setup includes PLCs, SCADA and Python simulation driver application.

Results

Simulation Studies

- Using the virtual commissioning lab setup, we can simulate periods based on historical data, and compare MPC to the existing controls
- Results are conservative, as they do not account for changes in operational parameters that MPC provides (such as using wider allowable temperature ranges)

Region	**Energy Consumption**		
	MPC	Actual	Savings
Summer	3178	4008	20.7%
Autumn	1185	1557	23.9%
Spring	942	1064	11.4%

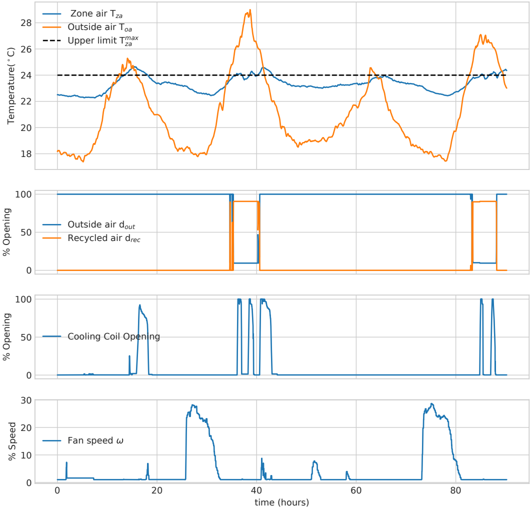
Results indicate around 20% savings could be achieved

Operational Deployment

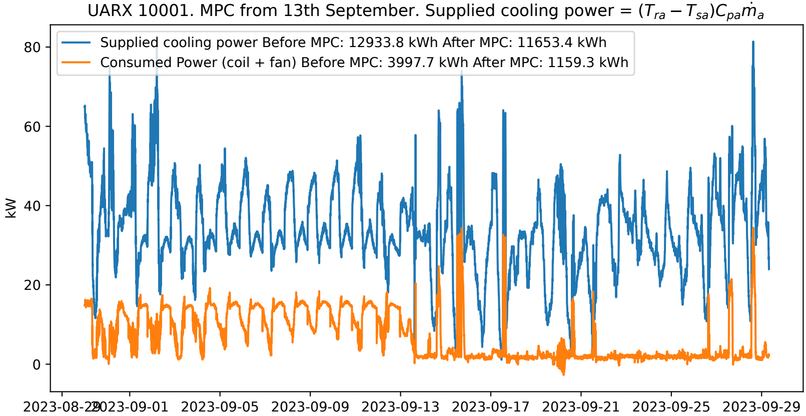
HVAC for SR1 (Point 1)

- One of two AHUs in the building will be controlled by MPC
- The other retains existing controls
- Deployed mid-September 2023
- Practically no commissioning: less than 2 hours from intervention start to MPC running

Operational Results: Control

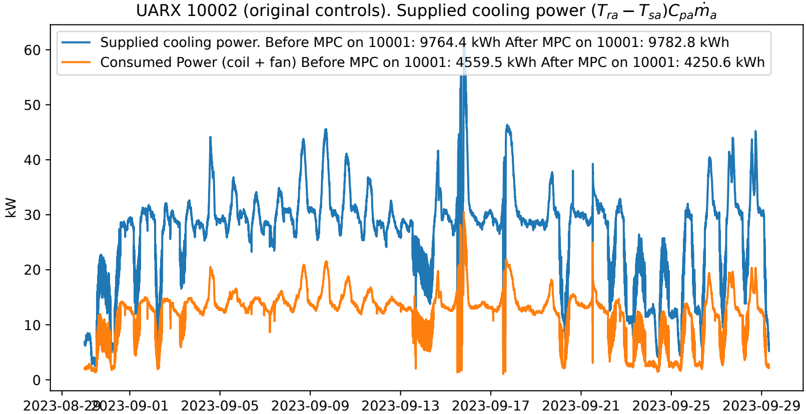


Operational Results: Energy Usage



The two AHUs interact somewhat, and temperatures have decreased since deploying MPC, but energy savings are considerable (∼70%)

Operational Results: Comparison



Not a fair comparison as there is an issue with the dampers on this AHU!
Nevertheless overall energy consumption is reduced with MPC (∼35%)

Conclusions

Energy savings potential

- Early results show that MPC is very good at using ‘free’ cooling
- Difficult to achieve this with classical setpoint regulation
- Still much scope for tuning MPC parameters and changing operational parameters (thanks to tighter control)
- Need to gather more operational data, but savings of at least 20% seem achievable

Scalability

- Once initial modeling is done, easy to apply to other similar plants
- In this case, tuning with a process model seemed to be sufficient for good results on the real plant
- Computational complexity for this class of problem (NLP) not very high. Also uses open source solvers and framework, so no license costs

Operation

- Keeping existing, well-proven controls, with bumpless transfer to MPC control, was important for acceptance
- Virtual Commissioning setup crucial for smooth deployment.

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