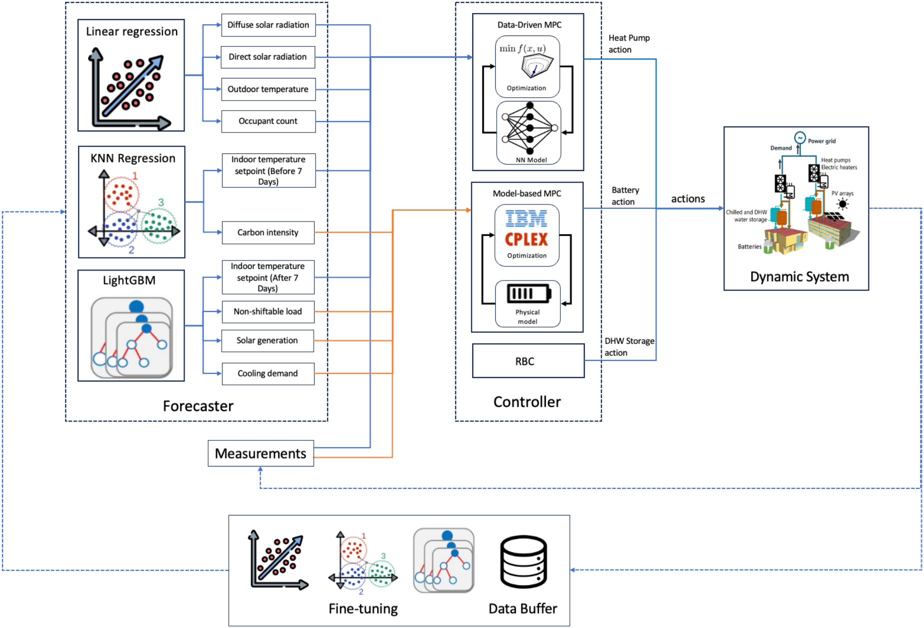
Optimizing building energy system for grid-interactivity, resilience, and comfort

Wanfu Zheng   Zhe Wang

Team: HKUST_Smart_Building

The Hong Kong University of Science and Technology

Integrated Energy System Management Framework



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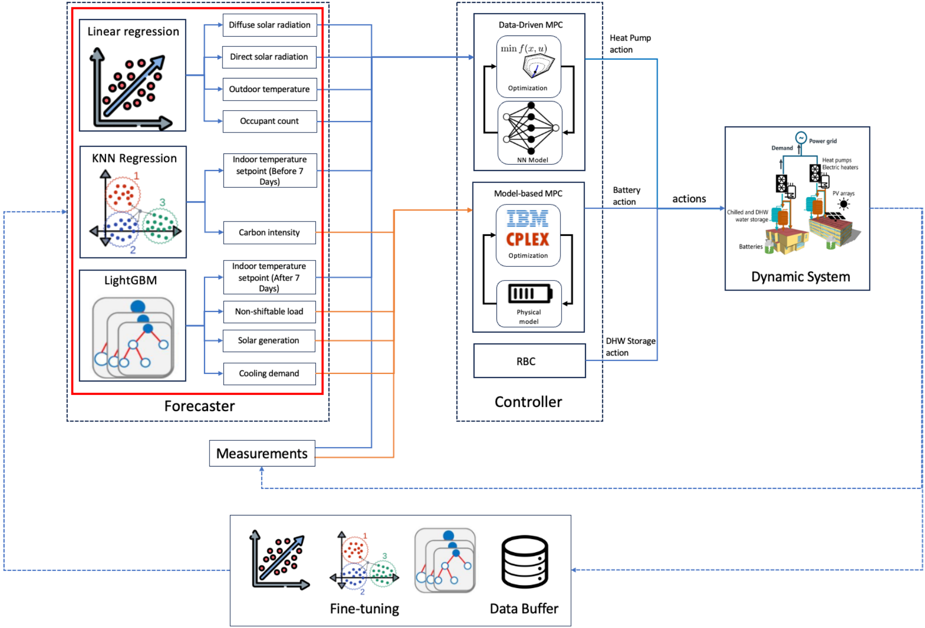

Data-Driven MPC for Cooling: **Prediction Models**

Target Variables (24h Prediction)	**Model**	**Input Features**
Diffuse Solar Radiation	Linear Regression	Hour, Day type Outdoor temperatures (current, 6h, 12h, 24h leads) Diffuse solar radiation (current, 6h, 12h, 24h leads, 1-24h lags) Direct solar radiation (current, 6h, 12h, 24h leads)
Direct Solar Radiation	Linear Regression	Hour, Day type Outdoor temperatures (current, 6h, 12h, 24h leads) Diffuse solar radiation (current, 6h, 12h, 24h leads) Direct solar radiation (current, 6h, 12h, 24h leads, 1-24h lags)
Outdoor Temperature	Linear Regression	Hour, Day type Outdoor temperatures (current, 6h, 12h, 24h leads, 1-24h lags) Diffuse solar radiation (current, 6h, 12h, 24h leads) Direct solar radiation (current, 6h, 12h, 24h leads)
Indoor Temperature Setpoint	KNN Regression (First 7 days) LightGBM (After 7 days)	KNN Regression: Hour, Day type, Weekday, Office hour Indoor temperature setpoint(1-24h lags) LightGBM: Hour, Day type, Weekday, Office hour, Indoor temperature setpoint(1-168h lags)
Occupant Count	Linear Regression	Hour, Day type, Weekday, Office hour, Occupant (1-24h lags)

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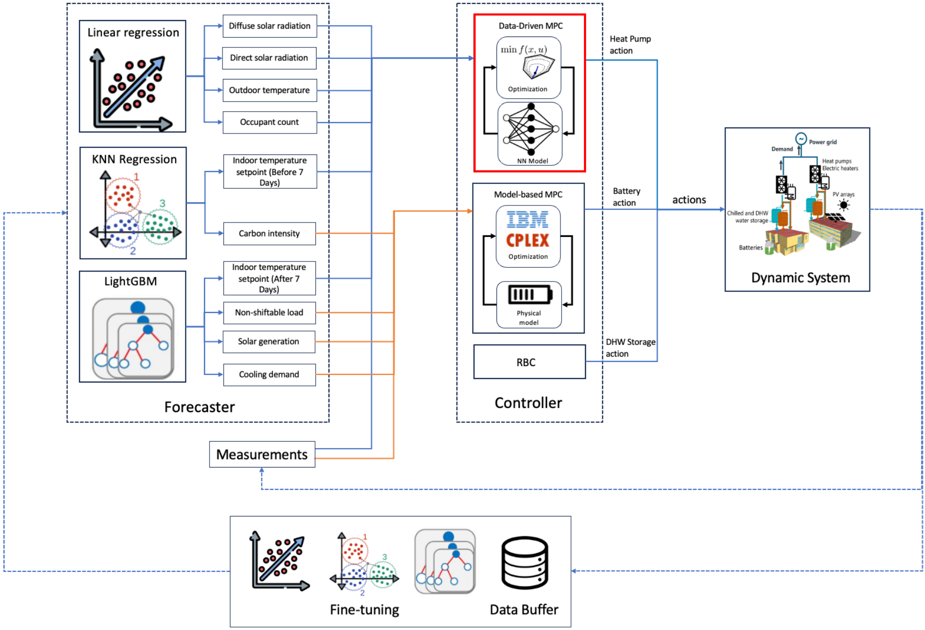

Data-Driven MPC for Cooling: **Optimization Problem**

$$
\begin{aligned}
\underset{u_t, u_{t+1}, \ldots, u_{t+N-1}}{\text{minimize}} \quad & \mathrm{J} = \sum_{k=1}^{N} (x_{t+k} - \hat{x}_{t+k})^2 \\
\text{subject to} \quad & \hat{x}_{t+1} = f(x_t, u_t, d_t), \\
& \hat{x}_{t+k+1} = f(\hat{x}_{t+k}, u_{t+k}, d_{t+k}), \quad k = 1, \ldots, N-1, \\
& u_{t+k}^{\min} \leq u_{t+k} \leq u_{t+k}^{\max}, \quad k = 0, \ldots, N-1.
\end{aligned}
$$

- $N = 24$: Control horizon.
- $f(\cdot)$: Function representing the building's temperature dynamics modeled by LSTM neural network.
- $\hat{x}$: State variable, representing controlled indoor temperature.
- x: Indoor temperature setpoint.
- u: Control variable, representing cooling demand.
- d: Disturbances including diffuse solar radiation, direct solar radiation, outdoor temperature, indoor temperature setpoint, occupant count, and cyclical time variable (sine/cosine of month, hour, and day type).
- $u^{\min} = 0$: Minimum cooling demand.
- $u^{\max}$: Maximum cooling demand.

- Calculation of maximum cooling demand u^{max} for the heat pump:

$$COP^{c}_{t+k} = \eta_{\text{tech}} \cdot \frac{T^{c}_{\text{target}}}{T^{outdoor}_{t+k} - T^{c}_{\text{target}}}^{1},$$

$$u^{\text{max}}_{t+k} = COP^{c}_{t+k} \cdot P_{\text{nominal}}^{2}$$

- How to optimize the objective function? Stochastic Gradient Descent (SGD).

- Applies the first element of the optimal actions of heat pump:

$$a_t = \frac{u_t}{COP^{c}_{t} \cdot P_{\text{nominal}}}$$

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[1] COP^{c}: Coefficient of Performance for cooling, η_{tech}: Efficiency of heat pump, T^{c}_{target}: Target cooling temperature, $T^{outdoor}$: Outdoor temperature

[2] P_{nominal}: Nominal power of the heat pump

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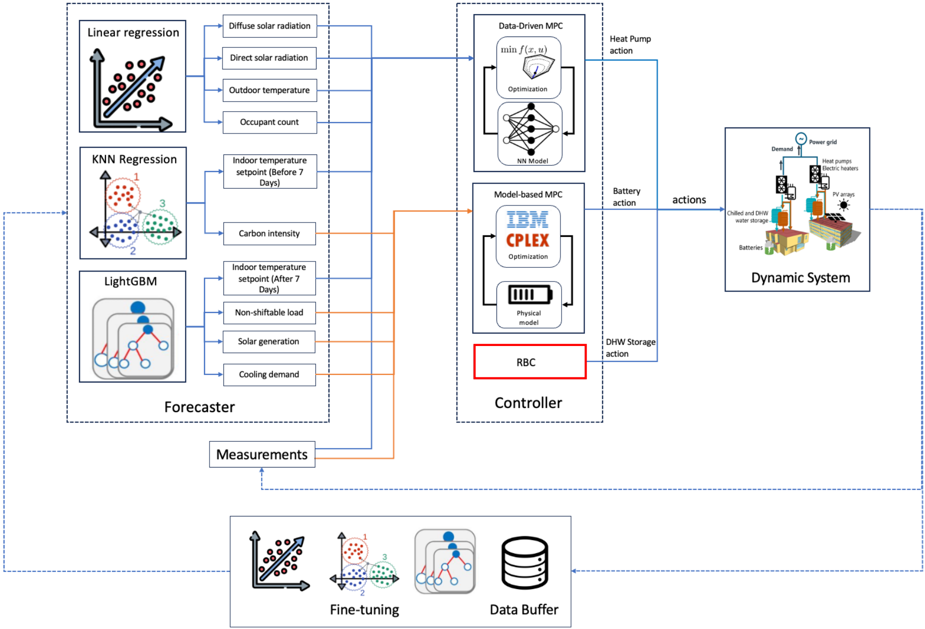
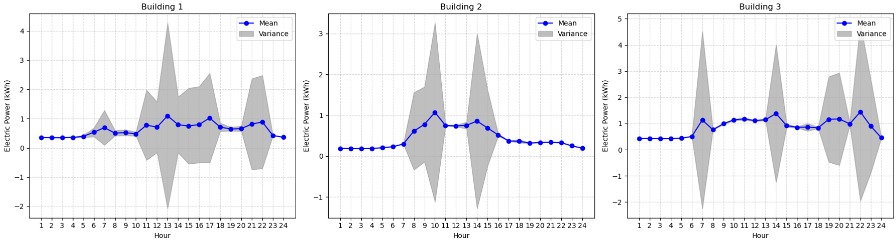
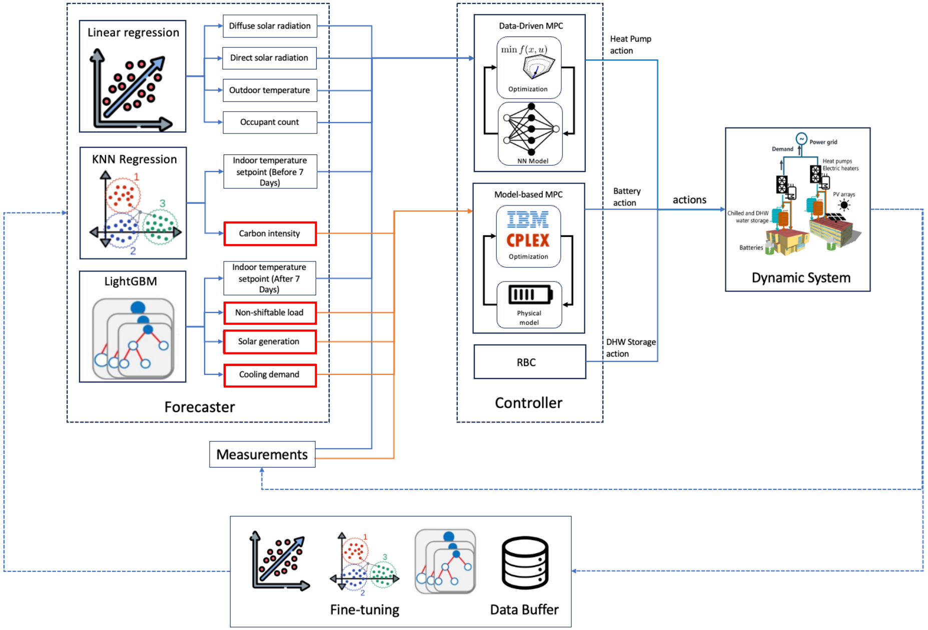


RBC for DHW Storage



- **Storage Phase (Hour 1 to 5):**
  - Charging action of 0.2 for each hour.
- **Release Phase (Hour 6 to 24):**
  - Release DHW as needed and supply with grid electricity if stored DHW is insufficient (*action* = -*1*).

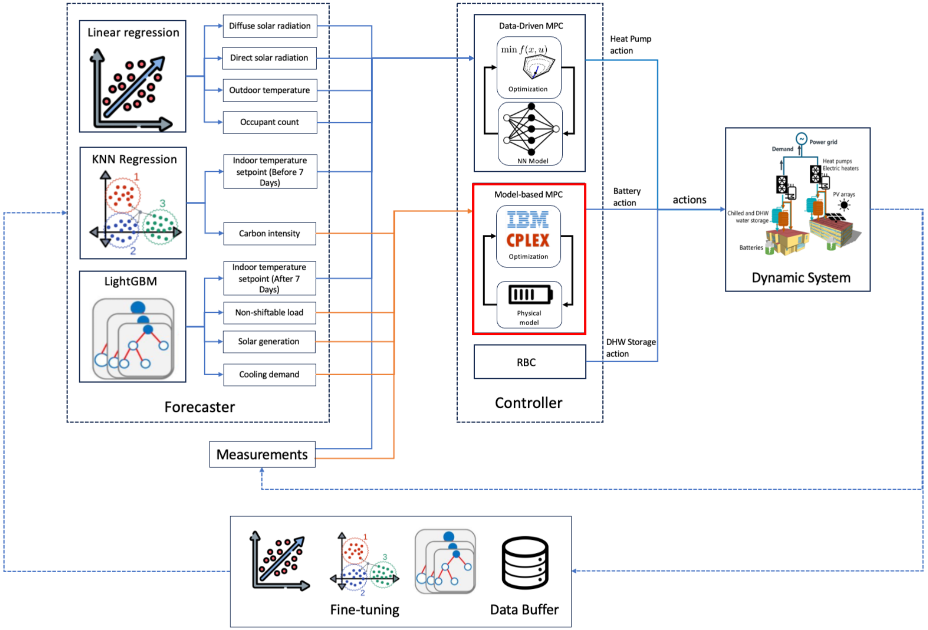
Integrated Control Framework



MPC for Battery: **Prediction Models**

Target Variables (24h Prediciton)	**Model**	**Input Features**
Non-shiftable load	LightGBM	Hour, Day type Outdoor temperatures (current, 6h, 12h, 24h leads) Diffuse solar radiation (current, 6h, 12h, 24h leads) Direct solar radiation (current, 6h, 12h, 24h leads) Indoor temperature, Solar generation Non-shifitable load (current, 1-24h lags)
Solar generation	LightGBM	Hour, Day type Outdoor temperatures (current, 6h, 12h, 24h leads) Diffuse solar radiation (current, 6h, 12h, 24h leads) Direct solar radiation (current, 6h, 12h, 24h leads) Solar generation (current, 1-24h lags)
Cooling demand	LightGBM	Hour, Day type Outdoor temperatures (current, 6h, 12h, 24h leads) Diffuse solar radiation (current, 6h, 12h, 24h leads) Direct solar radiation (current, 6h, 12h, 24h leads) Indoor temperature, DHW demand Indoor temperature Setpoint (current, 1-24h leads) Cooling demand (current, 1-24h lags)
Carbon Intensity	KNN Regression	Carbon Intensity (current, 1-24h lags)

Integrated Energy System Management Framework



MPC for Battery: **Variables**

Variable	Description	Range	Note
$x_{i,t}$	Charging action	$\left[0, \frac{\text{Nominal Power}^{(i)}}{\text{Capacity}^{(i)}}\right]$	$i \in [1, n] \cap \mathbb{Z}, t \in [1, 24] \cap \mathbb{Z}$
$y_{i,t}$	Discharging action	$\left[-\frac{\text{Nominal Power}^{(i)}}{\text{Capacity}^{(i)}}, 0\right]$	$i \in [1, n] \cap \mathbb{Z}, t \in [1, 24] \cap \mathbb{Z}$
$soc_{i,t}$	State of charge	$[0.2, 1]$	$i \in [1, n] \cap \mathbb{Z}, t \in [1, 24] \cap \mathbb{Z}$
$soc1_{i,t}$	State of charge part1	$[0.2, 0.8]$	$i \in [1, n] \cap \mathbb{Z}, t \in [1, 24] \cap \mathbb{Z}$
$soc2_{i,t}$	State of charge part2	$[0, 0.2]$	$i \in [1, n] \cap \mathbb{Z}, t \in [1, 24] \cap \mathbb{Z}$
$building\_e_{i,t}$	Single building energy consumption	$[0, +\infty]$	$i \in [1, n] \cap \mathbb{Z}, t \in [1, 24] \cap \mathbb{Z}$
agg_e_t	Aggregated energy consumption of all buildings at each time step	$[0, +\infty]$	$t \in [1, 24] \cap \mathbb{Z}$
w_t	Grid ramping	$[0, +\infty]$	$t \in [2, 24] \cap \mathbb{Z}$
$w0$	First grid ramping	$[0, +\infty]$	
max_e	Maximum aggregated energy over the horizon	$[0, +\infty]$	
$over\_threshold\_e$	Energy exceeding the defined maximum threshold	$[0, +\infty]$	
avg_e	Average aggregated energy over the horizon	$[0, +\infty]$	
$load_{i,t}$	The sum of non-shiftable loads, cooling demand, DHW demand, and solar generation	$[0, +\infty]$	$i \in [1, n] \cap \mathbb{Z}, t \in [1, 24] \cap \mathbb{Z}$
C_t	Carbon intensity	$[0, +\infty]$	$t \in [1, 24] \cap \mathbb{Z}$
$init\_soc_i$	Initial state of charge	$[0, +\infty]$	$i \in [1, n] \cap \mathbb{Z}$
$init\_agg\_e$	Initial aggregated energy consumption of all buildings	$[0, +\infty]$	

MPC for Battery: **Objective Function and Constraints**

$$\text{Objective} = \frac{1}{\text{emission\_base}} \times \sum_{i=1}^{\text{agent\_num}} \sum_{t=1}^{24} \left(building\_e_{i,t} \times C_t \times \text{weight\_factor}[t] \right)$$

$$+ \frac{1}{\text{grid\_base}} \times (w0 + \sum_{t=1}^{23} w_t \times \text{weight\_factor}[t]) + over\_threshold\_e^2 + avg\_e$$

- $agg\_e_t \geq \sum_{i=1}^{\text{agent\_num}} \left(x_{i,t} * capacity^{(i)} + y_{i,t} * capacity^{(i)} + \text{load}_{i,t} \right) \quad \text{for } t = 1, 2, \ldots, 24$
- $max\_e \geq agg\_e_t \quad \text{for } t = 1, 2, \ldots, 24$
- $over\_threshold\_e \geq max\_e - threshold\_value$
- $w0 \geq (agg\_e_0 - init\_agg\_e)$
- $w0 \geq (init\_agg\_e - agg\_e_0)$
- For $t = 1, 2, \ldots, 23$:
  - $w_t \geq agg\_e_{t+1} - agg\_e_t$
  - $w_t \geq agg\_e_t - agg\_e_{t+1}$
- For every i, t :
  - $soc_{i,t} = soc1_{i,t} + soc2_{i,t}$
  - $x_{i,t} \leq \frac{\text{Norminal Power}^{(i)} \times (1 - 4 \times soc2_{i,t})}{\text{Capacity}^{(i)}}$
  - $y_{i,t} \geq -\frac{\text{Norminal Power}^{(i)} \times (1 - 4 \times soc2_{i,t})}{\text{Capacity}^{(i)}}$
  - If $t = 1$:

$$soc_{i,1} = init\_soc_i + x_{i,1} \times \eta_1 + y_{i,1} \times \eta_2$$

$$y_{i,0} \geq -(init\_soc_i - \text{soc\_limit\_wrt\_dod}_i) \times \text{round\_trip\_efficiency}_i$$

else:

$$soc_{i,t} = soc_{i,t-1} + x_{i,t} \times \eta_1 + y_{i,t} \times \eta_2$$

$$y_{i,t} \geq -\left(soc_{i,t-1} - \text{soc\_limit\_wrt\_dod}_i\right) \times \text{round\_trip\_efficiency}_i$$

  - $building\_e_{i,t} \geq x_{i,t} * capacity^{(i)} + y_{i,t} * capacity^{(i)} + \text{load}_{i,t}$

Control during the power outage

- **Pre-Outage Battery Preparation:** Maintain a higher battery SOC (up to 1) before the outage to provide more energy during the power interruption.

- **Precise Power Allocation:** Adjust cooling demand Q'_{cool} and manage battery discharge D given the the expected cooling demand Q_{cool} and the available power (solar generation E_{sol} and maximum battery discharge D_{max}) in the next step:
  - If $Q_{cool} \leq E_{sol}$, no battery discharge is required $\Rightarrow D = 0$ & Q'_{cool} =Q_{cool}.
  - If $E_{sol} < Q_{cool} \leq (E_{sol} + D_{max}) \Rightarrow D = Q_{cool} - E_{sol}$ & Q'_{cool} =Q_{cool}.
  - If $Q_{cool} > (E_{sol} + D_{max})$, deploy maximum battery discharge and limit cooling demand$\Rightarrow D = D_{max}$ & $Q'_{cool} = E_{sol} + D_{max}$.

- **Temperature Setpoint Adjustment:** Increase indoor temperature setpoints by 0.5 $^{\circ}$C to conserve energy, given that the comfort band is within ± 1 $^{\circ}$C of the setpoint.

Tranfer to the unknown building thermal dynamics