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Performance quantification: Key Performance Indicators

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Expert meeting: Paris, Oct 1st 2018

THERMAL SYSTEMS SIMULATION

KU LEUVEN

Objectives

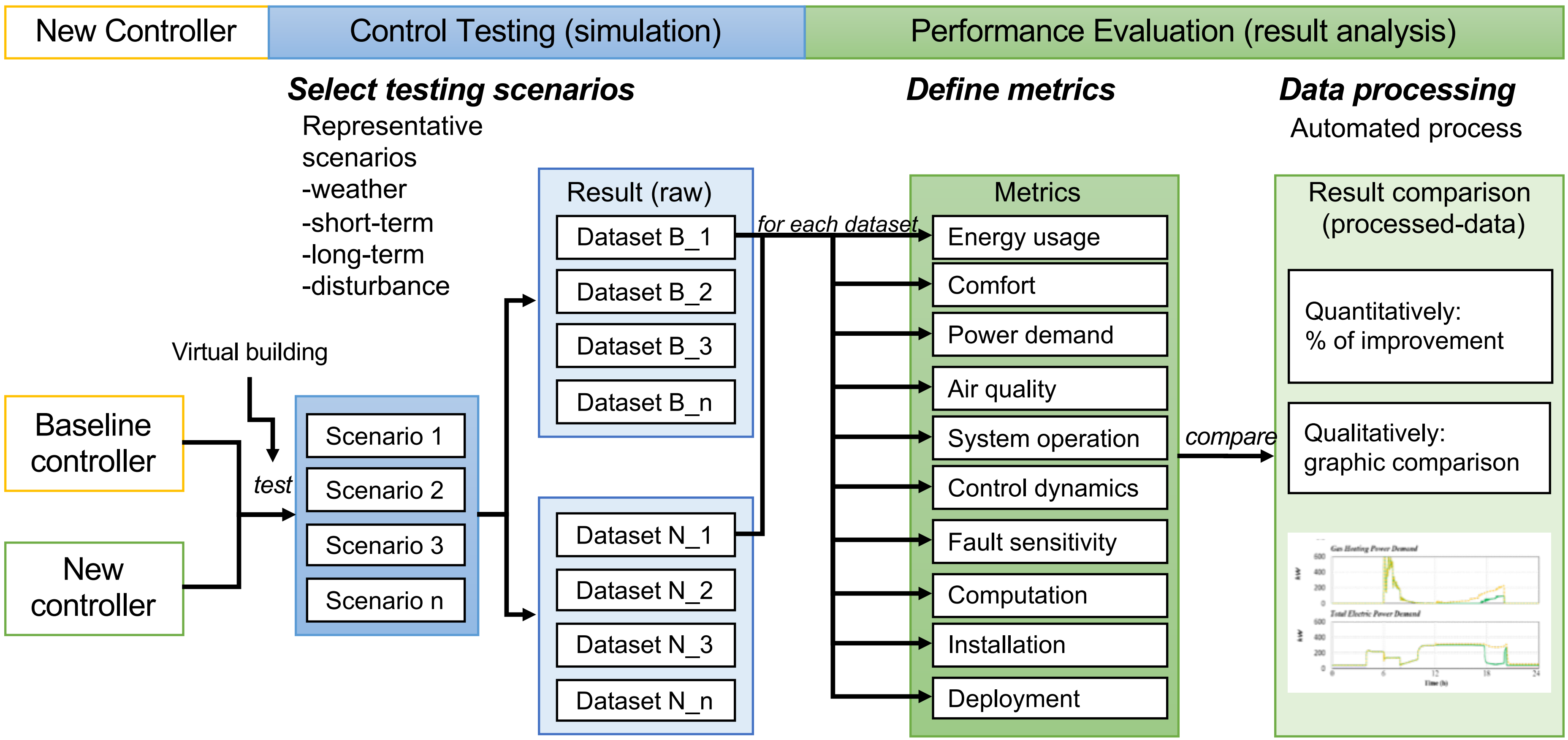
Berlin

- Define a set of KPIs to assess control algorithms performance
  - Group KPIs in categories
  - Choose those that are necessary or nice-to-have for a fair comparison
  - Avoid redundancy

Paris

- Performance evaluation process
- KPI computation/evaluation
- Discussion topics
  - Solver and emulator KPIs
  - Dependencies on developer, region or availability of data
  - KPI implementation: emulator/solver/docker/users
  - Annual test or representative weeks
  - Next steps

Control Performance Evaluation Process



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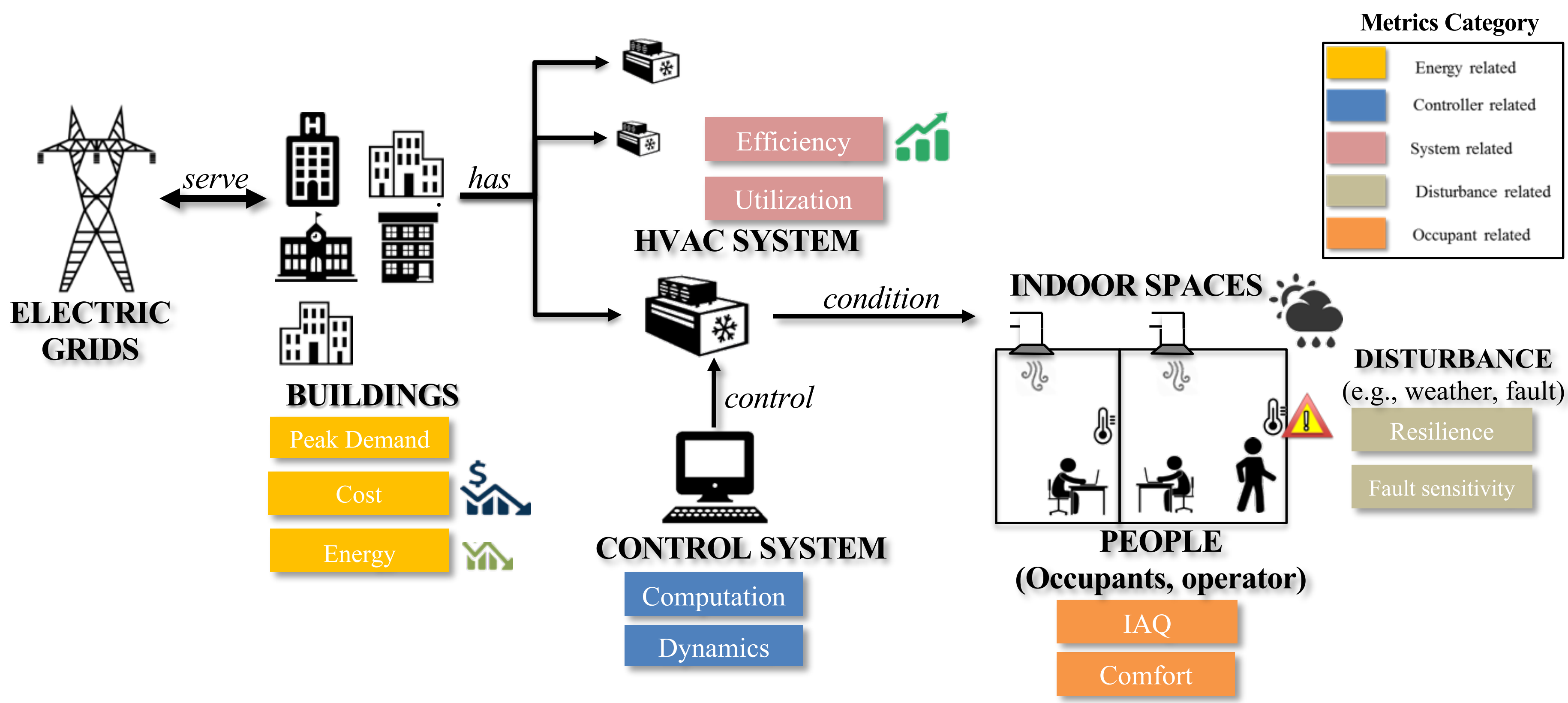
Performance Evaluation in Existing Studies

References	HVAC System type	Study type	Location	Simulation Software	Testing scenarios	Simulation/ and periods	Evaluation (quantitative)	Evaluation (qualitative)
(Rehrl and Horn 2011)	Single duct single zone	Simulation, and lab experiment	Austria	Matlab/Simulink MPC-Toolbox	Use step changes of supply air temperature	(1 day)	None	Control dynamics
(Ma, Qin et al. 2012)	Single duct multi-zone	Simulation	Chicago	EnergyPlus, BCVTB, Matlab SID toolbox	Use pre-designed T setpoint constrain for one day, and then one week in July	(8 days)	Energy, Cost	Zone temperature (thermal comfort)
(Prívara, Široký et al. 2011)	Water-based system (ceiling radiant heating and cooling)	Experiment	Czech Republic	NA	Use real-time weather	Heating season (30 days)	Energy	Control dynamics
(Moroşan, Bourdais et al. 2010)	Three zones, individual zone heating control, no central AHU.	Simulation	Rennes, France	Matlab /SIMBAD	Use historic weather	Heating season (1 day)	Energy, Comfort, Computation Time	Control dynamics
(Huang 2011)	Single duct single zone	Simulation	Not specified	Matlab /SIMBAD	Used step change of the set point	(1-4 hours)	None	Control dynamics
(Xi, Poo et al. 2007)	Single duct single zone	Simulation	Not specified	Not specified	Use step changes of T setpoint, and RH% setpoint.	(2 hours)	None	Control dynamics
(Yuan and Perez 2006)	Single duct multi-zone	Simulation	Miami, Phoenix, Nashville, Chicago	Matlab /Simulink	Use historic weather	Cooling season (60 days)	None	Control dynamics, Comfort, Energy, Indoor Air Quality (Ventilation)

Lack of standardized selection of testing scenarios

Lack of standardized metrics for control performance evaluation

Control Performance Metrics – Overview



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Matrix of Metrics - Input and Output Requirements

KPI Category	Individual KPIs	Fuel price (peak demand)	Fuel price (regular)	Boiler power demand (timestep)	Chiller power demand (timestep)	Fan power demand (timestep)	Lighting power demand (timestep)	Plug load power demand (timestep)	Pump power demand (timestep)	Fan speed control output (timestep)	AHU static pressure setpoint (timestep)	Mixing box temperature control output (OA damper)	Mixing box temperature control output (return damper)	Mixing box temperature control setpoint	Supply air temperature control output (cooling coil)	Supply air temperature control output (heating coil)	Supply air temperature setpoint	Local control output Note	Local control setpoint Note	Occupant activity (timestep)	Occupant clothing factor (timestep)	Zone temperature measurement (timestep)	Zone temperature setpoint (bound) (timestep)	Simulation timestamp (timestep)	Zone CO2 concentration (timestep)	Zone humidity (timestep)	VAV box control output (damper)	VAV box control output (Reheat coil)	Real building system operation time length	Model simulation time length	Controller prediction time	Performance under fault condition	Performance under fault-free condition
Air Quality	Average CO2 concentration																							•								
Air Quality	Maximum CO2 concentration																							•								
Air Quality	CO2 Unmet time fraction																							•								
Computation	Model simulation time																						•									
Computation	Prediction-Simulation time Ratio																												•	•	•		
Computation	Modeling-Operation time ratio																												•	•	•		
Computation	Controller prediction horizon																						•									
Control Dynamics	Control loop performance index - Harris index									•	•	•	•	•	•	•	•	•	•				•				•	•					
Control Dynamics	Control loop response speed - absolute speed									•	•	•	•	•	•	•	•	•	•				•				•	•					
Control Dynamics	Control loop response speed - relative speed									•	•	•	•	•	•	•	•	•	•				•				•	•					
Energy Cost	Cost of energy		•	•	•	•	•	•	•																								
Energy Cost	Cost of energy with peak demand charges	•	•	•	•	•	•	•	•																								
Energy Usage	Energy consumption - equipment			•	•	•	•	•	•																								
Energy Usage	Energy consumption - HVAC			•	•	•	•	•	•																								
Energy Usage	Energy consumption - Non HVAC			•	•	•	•	•	•																								
Energy Usage	Energy consumption - total building			•	•	•	•	•	•																								
Energy Usage	Energy consumption fraction			•	•	•	•	•	•																								
Fault sensitivity	Performance sensitivity to fault																															•	•
Integrated Performance	Weighted performance factor	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•			•	•	•	•	•	•	•	•	•	•	•	•	•	•
Power Demand	Diversity Factor			•	•	•	•	•	•																								
Power Demand	Equipment power demand fraction			•	•	•	•	•	•																								
Power Demand	Load Factor			•	•	•	•	•	•																								
Power Demand	Power peak demand			•	•	•	•	•	•																								
Equipment Utilization	Equipment operational capacity - average			•	•	•	•	•	•																								
Equipment Utilization	Equipment operational capacity - maximum			•	•	•	•	•	•																								
Equipment Utilization	Equipment operational efficiency - average			•	•	•	•	•	•																								
Equipment Utilization	Equipment operational time			•	•	•	•	•	•																								
Thermal Comfort	Maximum deviation of temperature unmet																					•	•										
Thermal Comfort	Predicted Percent of Dissatisfied (PPD)																			•	•					•							
Thermal Comfort	Temperature Unmet occurrence																					•	•										
Thermal Comfort	Temperature Unmet time fraction																					•	•										
Thermal Comfort	Temperature Unmet total time																					•	•										

Cost calculation depending on fuel price and peak demand schedules

Energy usage and **Equipment usage** are estimated based on power data from each equipment

Thermal comfort is calculated based on temperature setpoint and actual measured zone temperature for each time step

Note: Local control setpoint and output such as the following.
-static pressure setpoint vs. fan speed
-mixing box temperature setpoint vs. outdoor air damper, return air damper
-supply air temperature setpoint vs. AHU heating coil, AHU cooling coil
-zone air temperature setpoint vs. VAV box airflow, VAV box reheat coil

KPIs

Starting point:

- Berlin → Agreed core metrics
- Yan Chen et. al. → Specific formulation

ENERGY INDICATORS	**COST INDICATORS**	**COMPUTATION INDICATORS**
Achieved energy savings	Development time (TO BE CALCULATED)	Computation time (TO BE CALCULATED)
Energy use (TO BE CALCULATED)	Cost (TO BE CALCULATED)	Compilation time
Energy efficiency	Extra hardware costs	Flexibility of supported formulations
Primary energy use	Data requirements (TO BE CALCULATED)	Compactness
ENVIRONMENTAL INDICATORS	Payback period (TO BE CALCULATED)	Usability
CO_2 emissions (TO BE CALCULATED)	**IEQ INDICATORS**	Scaling of computation time
Share of RES	Thermal discomfort (TO BE CALCULATED)	Scalability
Flexibility provided to grid (TO BE CALCULATED)	IAQ (dis)comfort	Robustness/Fault tolerance
		Optimality

Energy use

- Energy consumption of equipment "e" during [t_0, t_N]

$$\sum_{t_i=t_0}^{t_N} P_e(t_i)$$

- Energy consumption fraction of equipment "e" during [t_0, t_N]

$$\frac{\sum_{t_i=t_0}^{t_N} P_e(t_i)}{\sum_{t_i=t_0}^{t_N} \sum_{e\in E} P_e(t_i)}$$

- Total building energy consumption during [t_0, t_N]

$$\sum_{t_i=t_0}^{t_N} \sum_{e\in E} P_e(t_i)$$

- HVAC system energy consumption during [t_0, t_N]

$$\boxed{\sum_{t_i=t_0}^{t_N} \sum_{e\in E} P_{e,AC}(t_i)}$$

- Non-HVAC system energy consumption during [t_0, t_N]

$$\sum_{t_i=t_0}^{t_N} \sum_{e\in E} P_e(t_i) - \sum_{t_i=t_0}^{t_N} \sum_{e\in E} P_{e,AC}(t_i)$$

CO_2 Emissions

- We have to identify source factor to quantify
  - Kg of CO_2 / KWh of electricity consumed
  - Kg of CO_2 / Kg of fuel consumed
- Work with a fixed source factor data. Which one? It depends on location and time.
- One factor per national level with possibility to specify location
- Allow the controller developer to use the source factor as an input

Flexibility provided to grid

- Smart control response metrics

Indicator of controller response time to external request (e.g., peak load reduction from grid) and internal demand (e.g., personalized heating or cooling demand), detection of zone occupy status, and utilization of occupant account information for demand control ventilation, etc.

- Look into Annex 67

Installation metrics

- Engineering effort
  - Installation time
  - Installation knowledge level/training requirement
  - Installation cost

- Richness of data
  - Business as usual or Required extra-excitements
  - Required extra sensors or not

Total cost

- Total Energy cost:

$$\boxed{\sum_{t_i=t_0}^{t_N} \sum_{e \in E} P_e(t_i) c(t_i)}$$

- Should the cost depend on location?
- Compute payback period based on:
    - Installation metrics → Need to quantify them
    - Energy cost difference with baseline controller

Thermal discomfort and air quality

- Predicted Percent of Dissatisfied people

$$PPD = 100 - 95e^{-0.03353*PMV^4 - 0.2179*PMV^2}$$

$$PMV = (0.303e^{-0.036M} + 0.028)(H - L)$$

- Number of excursions outside the comfort zone

$$|\{t \mid T_t^n \in S_c \wedge T_{t+1}^n \notin S_c\}|$$

- Total time when the comfort indicator T is outside comfort

$$t_{u,n} = \sum_{t_i=T_0}^{T_n} c(t_i)$$

… By the magnitude of the deviation [K*h]

Where

$c(t_i) = 1$, if $T_t^n \notin S_c$, at time t_i; $c(t_i) = 0$, if $T_t^n \in S_c$, at time t_i

Thermal discomfort and air quality

- Percent time that T is outside comfort

$$\frac{|t_{u,n}|}{t_N - t_0}$$

- Maximum deviation from comfort

$$max\{T^n_{min} - T_l, T_u - T^n_{max}\}$$

Where

$$T_u = \max\{T^n_t \mid T^n_t > T^n_{max}\} \text{ and } T_l = \min\{T^n_t \mid T^n_t < T^n_{min}\}$$

Thermal discomfort and air quality

- Average CO_2 concentration per zone during $[t_0, t_N]$

$$\frac{1}{t_N - t_0}\sum_{t_i=t_0}^{t_N} A_n(t_i)$$

- Maximum CO_2 concentration per zone during $[t_0, t_N]$

$$max\{A_n(t_i) \mid t_i \in \{t_0, t_N\}\}$$

- Percentage of time that CO_2 concentration exceeds the ASHRAE requirements for zone n during $[t_0, t_N]$

$$\frac{\sum_{t_i=t_0}^{t_N}(A_n(t_i) - A_r) \mid t_i \in \{t_0, t_N\}\}}{t_N - t_0}$$

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Computational time

- Controller prediction time

$$t_p(i) = t_{p1}(i) - t_{p0}(i)$$

- Model simulation (or real building operation)

$$t_s(i) = t_{s1}(i) - t_{s0}(i)$$

- Real building operation time

$$t_r(i) = t_{r1}(i) - t_{r0}(i)$$

- Total model simulation over a time period of [t_0, t_N]

$$t_s = \sum_{t_i=t_0}^{t_N} t_s(i)$$

- Total real building operation time

$$t_r = \sum_{i=t_0}^{t_N} t_r(i)$$

- Total prediction-simulation time ratio $\frac{t_p}{t_s}$
- Total modelling-operation time ratio $\frac{t_s}{t_r}$

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Other

- Power demand metrics:
  - Diversity factor

$$\frac{\sum_{e\in E} \max\limits_{t_0<t<t_N} P_e(t_i)}{\max\limits_{t_0<t<t_N} \sum_{e\in E} P_e(t_i)}$$

  - Equipment power demand fraction (At time ti)

$$\frac{P_e(t_i)}{\sum_{e\in E} P_e(t_i)}$$

  - Load factor

$$\frac{\operatorname*{mean}\limits_{t_0<t<t_N} P_e(t_i)}{\max\limits_{t_0<t<t_N} P_e(t_i)}$$

  - Power peak demand

$$\max_{t_0<t_i<t_N} \sum_{e\in E} P_e(t_i)$$

Other

- Fault sensitivity metrics
- System and equipment utilization metrics
- Control infrastructure complexity metrics
- Control dynamics metrics

- Integrated Overall Performance

$$c = MW^T$$

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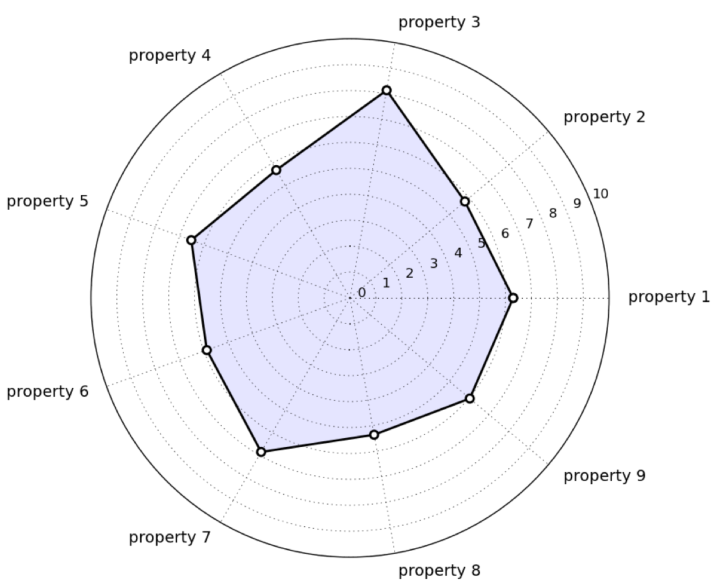
Visualization

- Comparison to a reference controller (to be defined on a case by case basis)
- Comparison to total population (relative position and range)

Radar plot



Box plot