Summary of the EMPA DC and RL-Based Control

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1 Layout of the DC

The schematic layout of the EMPA DC and its front view are shown in Figure 1. The fans directly provide cool air to the both server groups numbered as 0 and 1.

2 Measurements and Control Switches

Various parameters from the DC can be measured and some the parameters can be adjusted based on a control algorithm. These are shown in Figure 2 and summarized below:

T_{sup} : Temperature of the air supplied by the cooler to the server racks or simple rack intake temperature. In the EMPA DC, the supply temperature can be adjusted. ~~In a typical DC scenario, where cool air is supplied to a cold aisle and collected from a hot aisle, T_{sup} may differ for each server in a row of servers. In EMPA DC, it can be assumed that the temperature of the cold air supplied by the cooler is equal to the rack intake temperature.~~

v_{f} : Velocity of the cooler fan. Fan is used to vary the supply air flow rate. In EMPA DC, fan velocity can be adjusted.

T^i_{ret} : Temperature of the air measured at the location of air returning to the cooler. ~~In EMPA DC, T^i_{ret} is assumed to be equal to the temperature of the hot air leaving the servers.~~

T^i_{in} : Inlet temperature of the i^{th} server. This temperature is measured at the air inlet location of the server.

T^i_{out} : Outlet temperature of the i^{th} server. This temperature is measured at the air outlet location of the server.

T^i_{CPU} : The temperature of the CPU of the i^{th} server. This temperature is measured and reported by the server.

P^i_{s} : Power consumption of the i^{th} server. This value is measured and reported by the server.

P_{IT} : Total power consumption of the overall IT system.

P_{c}: Power consumption of the cooling system. This is represented in terms of power consumption of the servers.

u_i : Utilization of the i^{th} server. Utilization directly dictates the the power consumption of the server. In EMPA DC, if utilization is smaller than 50%, power consumption follow a rule and it follows a different rule if it is larger than 50%.

2.1 Modelling of the Server Power Consumption

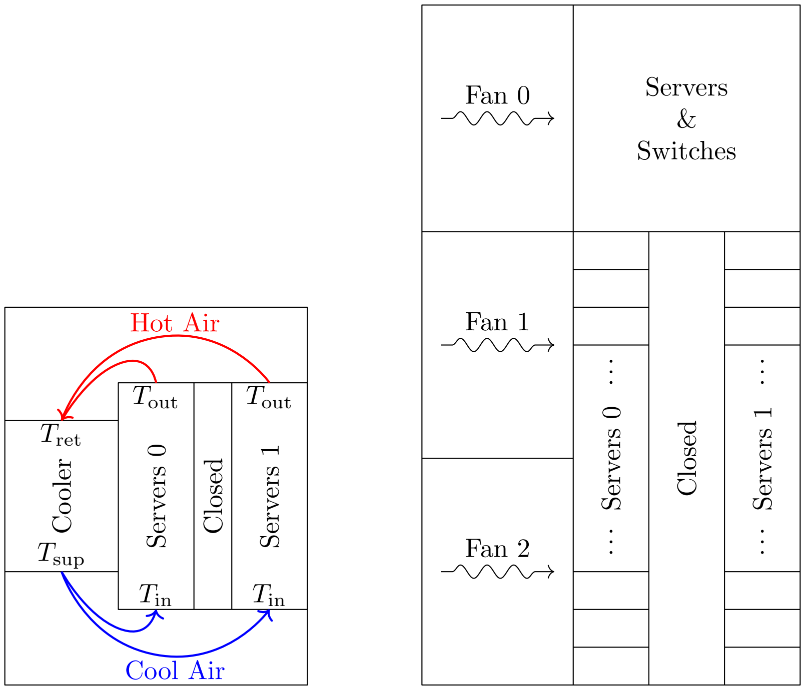
Utilization is the percentage utilization of the CPU computational capacity. For the i^{th} server utilization is defined as u_i and $0 < u_i < 1.0$. Total utilization is defined as:

$$U_{\text{total}} = \sum_{i=1}^{N} u_i \tag{1}$$

Utilization is adjusted by a scheduler, depending on the workload and the performance of the cooling system.

P_{IT} is the power consumed by the IT equipment (e.g. servers) and defined as

$$P_{\text{IT}} = \sum_{i=1}^{N} P^i_{\text{s}} \tag{2}$$



(a) Layout (plan)

(b) Front view

Figure 1: Schematic layout and front view of the EMPA DC

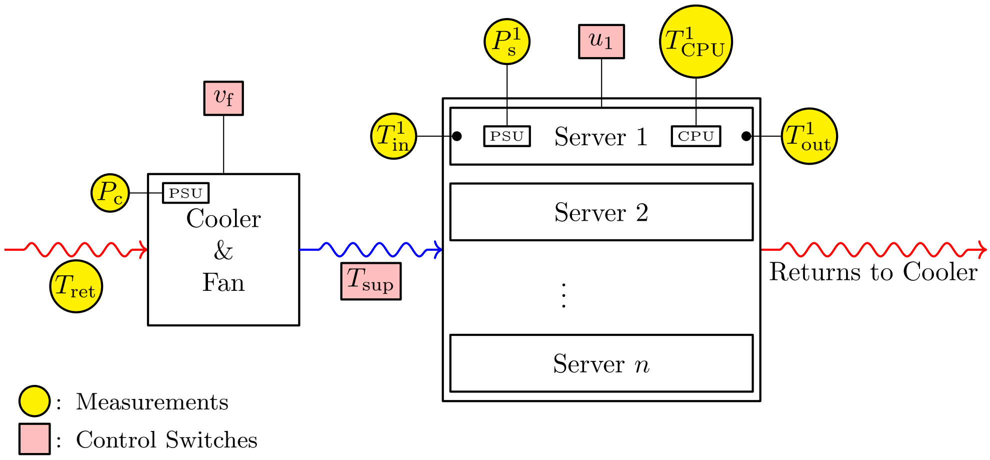


Figure 2: Measurements and control switches of the EMPA DC

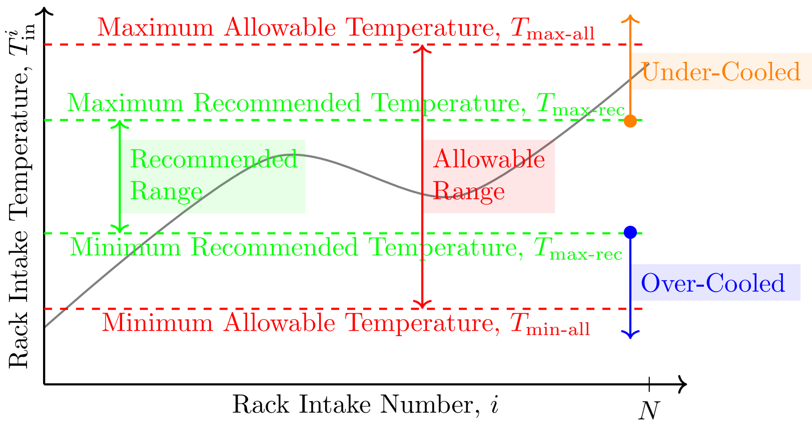


Figure 3: Cooler supply temperature distribution along the racks

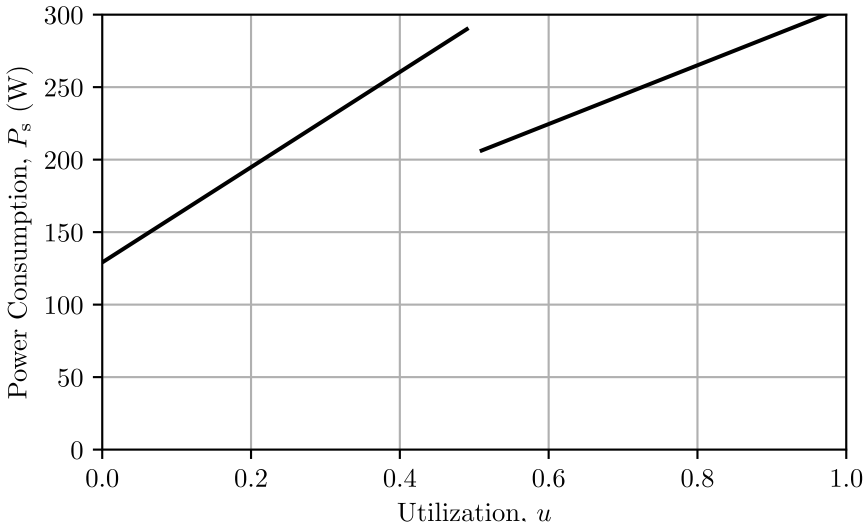


Figure 4: Power consumption function of servers

The power consumption of each server is measured and modelled by [REF]. The power consumption is given by the following equations:

$$\begin{aligned} P_{\mathrm{s}}^{i} &= 69 + 328.338u_i + 60.1008, \qquad u_i \leq 0.5 \\ P_{\mathrm{s}}^{i} &= 69 + 328.338u_i + 60.1008, \qquad u_i > 0.5 \end{aligned} \tag{3}$$

where u_i is utilization of server i. Power consumption function is shown in Figure 4.

2.2 Modelling of the Return and Supply Temperatures

A model to estimate the relation between supply and return temperatures for a given workload is developed by [REF]. [UNDER PROGRESS]

2.3 Modelling of Power Consumptions

An index for evaluating the power usage performance of a DC is Coefficient of Performance (COP), which is defined as:

$$COP = \frac{P_{\mathrm{IT}}}{P_{\mathrm{c}}} \tag{4}$$

where, P_{IT} is the power consumed by the IT equipment (e.g. servers), and P_{c} is the power consumed by the cooling system. P_{IT} can be represented as:

$$P_{\mathrm{IT}} = \sum_{i=1}^{N} P_{\mathrm{s}}^{i} \tag{5}$$

COP is a characteristics of the cooling system and the DC and is fixed for given temperatures. For EMPA DC, COP function is given by [REF] and summarized as below: [UNDER PROGRESS].

The total power usage of the DC is given by:

$$P_{\mathrm{total}} = P_{\mathrm{IT}} + P_{\mathrm{c}} \tag{6}$$

It is convenient to represent the total power consumption in terms of only P_{IT} as follows:

$$P_{\mathrm{total}} = \left(1 + \frac{1}{COP}\right) P_{\mathrm{IT}} \tag{7}$$

Therefore, the problem of minimization of total power consumption can be represented as:

$$\min\left(P_{\mathrm{total}}\right) = \min\left[\left(1 + \frac{1}{COP}\right) P_{\mathrm{IT}}\right] \tag{8}$$

3 Performance Evaluation

Performance of the EMPA DC is evaluated on several basis. These are summarized in this section.

3.1 CPU Temperature

The maximum temperature of the CPU should be 73°C. CPU temperatures higher than this value may result reduced performance of the CPU and poss a certain level of risk of failure. CPU temperatures below this level may not be optimal for energy efficiency without contribution any advantage to the CPU performance.

3.2 Cooler Supply Temperature

ASHRAE recommends that cooler supply temperature should be within a certain range for the cooling system to provide adequate cooling environment for the servers. It is considered that prolonged exposure to supply temperatures may result failures or unnecessary use of energy. For this purpose two sets of ranges for the cooling system supply temperature are defined:

- Recommended maximum and minimum temperatures
- Maximum and minimum allowable temperatures.

These are summarized in Figure 3. It is recommended that the cooler supply temperature stay in the recommended range. It is, however, normal that the temperature may exceed the maximum recommended temperature or fell below the minimum recommended temperature. In these cases, temperature should stay in the allowable range. Under-cooling may result in the failure of the servers, and over-cooling may result inefficient use of energy. Recommendations of the suggestions of the ASHRAE is given in Table 1.

Two indices are frequently used to evaluate the performance of the cooling system: Rack Cooling Index (RCI) and Return Temperature Index (RTI). These are discussed next.

Table 1: ASHRAE recommendations of the supply temperatures

Temperature	Notation	Recommendation
Maximum Allowable Temperature	$T_{\text{max-all}}$	32°C
Maximum Recommended Temperature	$T_{\text{max-rec}}$	27°C
Minimum Recommended Temperature	$T_{\text{min-rec}}$	18°C
Minimum Allowable Temperature	$T_{\text{min-all}}$	15°C

Rack Cooling Index, RCI

Rack Cooling Index (RCI) is proposed by Herrlin (2005) and measures how well the cooling temperature follows the recommendations. RCI is defined for both under-cooling and over-cooling.

Rack cooling index is defined for under-cooling as:

$$RCI_{\text{HI}} = \left(1 - \frac{\text{Total Over-Temp.}}{\text{Max. Allowable Over-Temp}}\right) \times 100, \qquad \text{unit:\%} \tag{9}$$

According to this definition, RCI_{HI} is a measure pof the absence of over-temperatures. 100% means no over-temperature exists. RCI_{HI} values lower than 100% shows that over-temperature occurred at some of the racks. Equation 9 can be written for $N-$racks as follows:

$$RCI_{\text{HI}} = \left(1 - \frac{\sum_{i=1}^{N} \left(T_{\text{in}}^{i} - T_{\text{max-rec}}\right)_{T_{\text{in}}^{i} > T_{\text{max-rec}}}}{\left(T_{\text{max-all}} - T_{\text{max-rec}}\right) \times N}\right) \times 100, \qquad \text{unit:\%} \tag{10}$$

Rack cooling index is defined for over-cooling as:

$$RCI_{\text{LO}} = \left(1 - \frac{\text{Total Under-Temp.}}{\text{Max. Allowable Under-Temp}}\right) \times 100, \qquad \text{unit:\%} \tag{11}$$

According to this definition, RCI_{HI} is a measure of the absence of over-temperatures. 100% means no over-temperature exists. RCI_{HI} values lower than 100% shows that over-temperature occurred at some of the racks. Equation 11 can be written for $N-$racks as follows:

$$RCI_{\text{LO}} = \left(1 - \frac{\sum_{i=1}^{N} \left(T_{\text{min-rec}} - T_{\text{in}}^{i}\right)_{T_{\text{in}}^{i} < T_{\text{min-rec}}}}{\left(T_{\text{min-rec}} - T_{\text{min-all}}\right) \times N}\right) \times 100, \qquad \text{unit:\%} \tag{12}$$

Table 2 shows the rating for both of the RCI indices.

Table 2: Rating of RCI indices

RCI	Rating
RCI = 100%	Ideal
RCI ≥ 96%	Good
91% ≤ RCI ≤ 95%	Acceptable
RCI ≤ 90%	Poor

Return Temperature Index (RTI)

Return Temperature Index (RTI) is proposed by Herrlin (2008) and is a measure of how effectively the air supplied to the rack is take flow through the server and returned back to the cooler. Two important definitions are important to understand the RTI: by-pass air and re-circulation air.

By-pass air is defined as the supplied air that does not participate in the cooling of the servers. In this case, the cool air finds its way to the hot aisle without passing through the interior of the server rack due to probably the poor construction quality or high levels of supply airflow.

Re-circulation air is defined as the air that directly goes back to the cold aisle, possibly several times, instead returning to the cooler. This increases the temperature of the supply air. Re-circulation may be caused by low levels of supply airflow or poor construction quality.

RTI is the ratio of the air actually taken by the server and is used for the cooling of the servers to the air supplied by the coolers:

$$RTI = \frac{\dot{M}_{\text{equip}}}{\dot{M}_{\text{sup}}} \times 100, \qquad \text{unit:\%} \tag{13}$$

where $\dot{M}_{\text{equip}}$ is the mass air flow actually taken by the IT equipment, and $\dot{M}_{\text{sup}}$ is the mass air flow supplied by the cooler. RTI can be expressed for the i^{th} rack using the temperature measurements as follows:

$$RTI = \frac{T_{\text{ret}} - T_{\text{sup}}}{T_{\text{out}}^{i} - T_{in}^{i}} \times 100, \qquad \text{unit:\%} \tag{14}$$

For $N-$racks, an average RTI can be expressed as follows:

$$RTI = \frac{\left(T_{\text{ret}} - T_{\text{sup}}\right) \times N}{\sum_{i=1}^{N} \left(T_{\text{out}}^{i} - T_{in}^{i}\right)} \times 100, \qquad \text{unit:\%} \tag{15}$$

Interpretation of the RTI is given in Table 3.

Table 3: Interpretation of the RTI indices

RTI	Interpretation
RTI = 100%	Target
RTI > 100%	Re-Circulation
RTI < 100%	By-Pass

4 Reinforcement Learning for Control of Cooling System

Reinforcement Learning (RL) is being considered for control of the cooling system for both optimal performance of the servers and optimal energy usage. The following components are the basic elements of a RL-based control system:

- Environment: Environment is the system that is controlled.
- States: States define the environment, which is represented by the measured parameters. These parameters cannot be adjusted directly (e.g. CPU temperature).
- Actions: Actions are controllable parameters.
- Reward/Penalty: Reward/Penalty function is a type of index that feedback positive reward when the control action results recommended temperatures and vice versa.

In the EMPA DC, the components of the RL control system is proposed as shown in Table 4. Reward/Penalty function is proposed to be:

Table 4: Proposed components of the RL control of the EMPA DC

RL Component	Parameters
Environment	Server Racks
States	T^i_{in} , T^i_{out} , T^i_{CPU} , P^i_{s} , u_i
Actions	T_{sup} , v_{f}

$$R = \alpha(EER) + \beta(PM) - (\gamma(OP) + P) \tag{16}$$

where EER is the energy efficiency ratio, PM is the performance metric, OP is the overhead penalty, and P is a general penalty term based on the successful realization of the recommended temperatures.

In the current scenario of the RL-based control, workload distribution is not considered to be an action. It will be included as an action parameter in the following stages of the study.

4.1 Training of the Algorithm

For training purposes, a simulation model of the environment will be developed. In this model, server CPU temperatures will be approximated by the model developed by [REF] and summarized in Section 3.1. Furthermore, the model developed by [REF] will be used to estimate the supply and return temperatures. In the simulation model, randomly generated workloads, u_i will be used.

References

Herrlin, Magnus K. (2005). “Rack Cooling Effectiveness in Data Centers and Telecom Central Offices: The Rack Cooling Index (RCI)”. In: *ASHRAE Transactions* 111.DE-05-11-2, pp. 725–731.

— (2008). “Airflow and Cooling Performance of Data Centers: Two Performance Metrics”. In: *ASHRAE Transactions* 114.SL-08-018, pp. 182–187.