EFFICACITY - Energy efficiency for a sustainable city


PÔLE GARE
A Microgrid

Optimization of a subway station microgrid

energy and climate management

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Outline

1. A subway station microgrid
    - Subway stations energy and climate characteristics
    - There is room for optimization
    - A subway station Microgrid prototype
2. Dynamic modelling of the station
    - Supply/demand balance
    - Building thermal dynamics
    - Battery dynamics
    - Economic criterion
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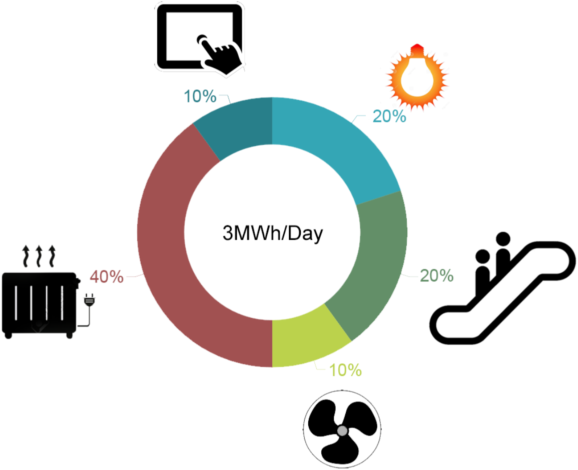
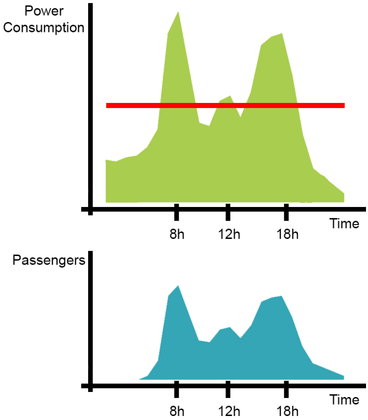
Outline

Subway stations energy consumption

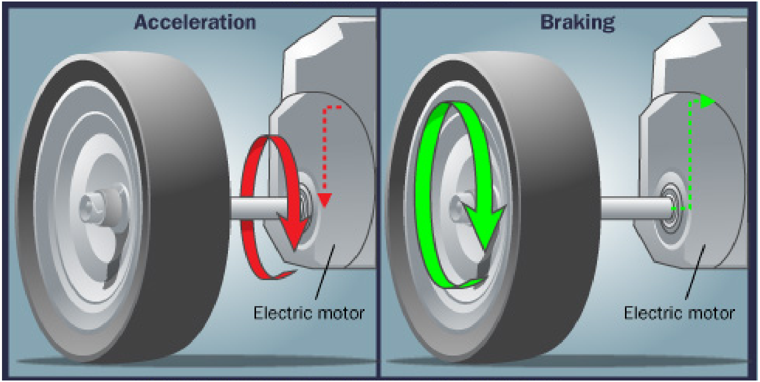


Daily consumption and passengers traffic are correlated

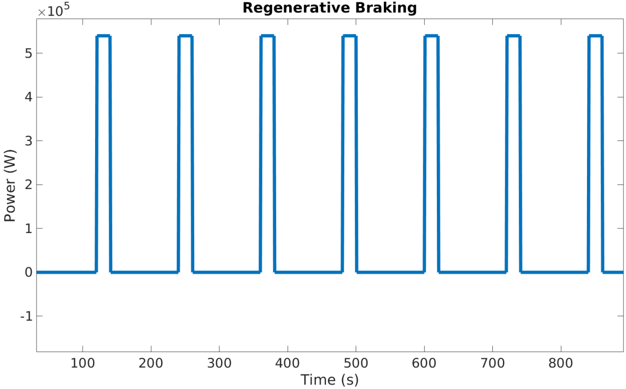


Subway stations produce electricity

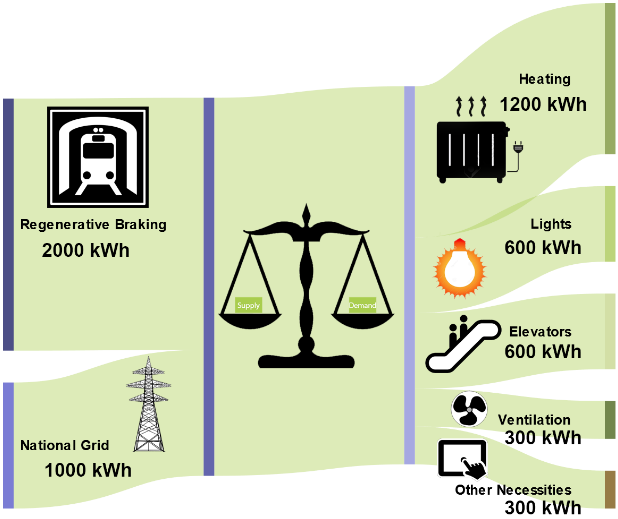
- Electrical power produced by regenerative braking of the trains : 100 - 700 kW (20 seconds of braking)



Subway stations produce electricity

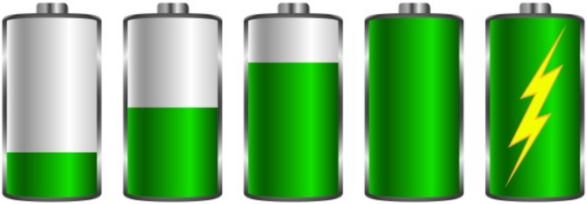


Supply/Demand balance over a day (MWh)



Buffer needs

- A battery can store the braking power excess

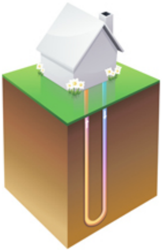


A subway station is a thermal buffer

- Aeraulics & thermal inertia

Subway stations produce heat

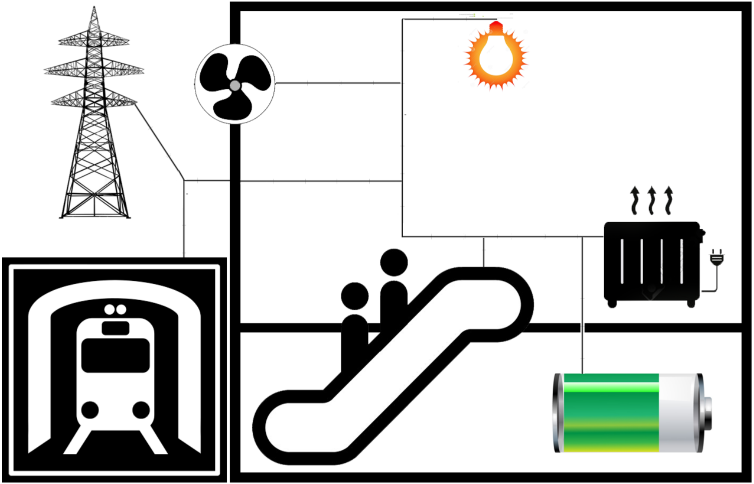
- Waste heat produced by the station technical facilities and by mechanical brakings of the trains
- Geothermal heat / Canadian well (or earth pipe or provence well)



There is room for optimization

In the new electrical grid paradigm
a subway station becomes an energy deposit
and
an energy deposit becomes an Efficacity opportunity

A subway station Microgrid prototype



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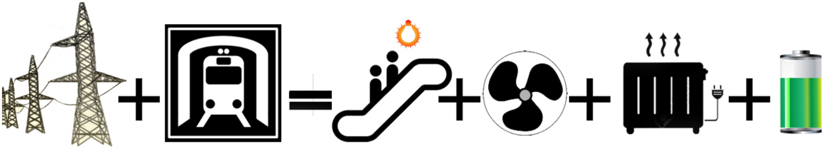
Supply/Demand balance

Over $\tau = 24$ hours we have to ensure :

$$\underbrace{P_G(t)}_{\text{Main Grid Power}} + \underbrace{P_{Train}(t)}_{\text{Brakes Power}} = \underbrace{P_L(t)}_{\text{Lights, Elevators}} + \underbrace{P_V(t)}_{\text{Ventilation}} + \underbrace{P_H(t)}_{\text{Heating}} + \underbrace{P_B(t)}_{\text{Battery}}$$



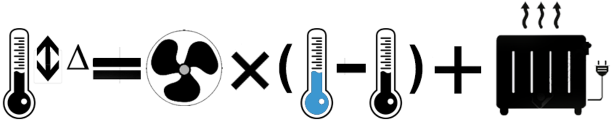
Building Thermal Dynamics

We have to ensure the occupants thermal comfort :

$$\boxed{Tmin < T(t) < Tmax}$$

Knowing the temperature dynamics :

$$\underbrace{\overbrace{C_v}^{\text{Zone Heat Capacity}} \quad \frac{dT}{dt}(t)}_{\text{Temperature Dynamics}} = \underbrace{\overbrace{r_v P_V(t)}^{\text{Fan Air Flow}}\ (T_e(t) - T(t))}_{\text{Ventilation}} + \underbrace{r P_H(t)}_{\text{Heating}}$$



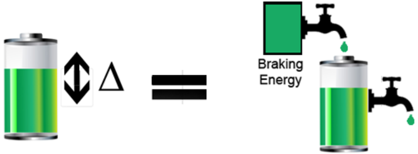
Battery Dynamics

We can control the battery knowing its dynamic :

$$\frac{dS_{OC}}{dt}(t) = \frac{\overbrace{\rho_B}^{\text{Charge/Discharge Efficiency}}}{\underbrace{V_0 Q_{max}}_{\text{Tension} \times \text{Maximum Charge}}} \times \underbrace{P_B(t)}_{\text{Charge/Discharge Power}}$$

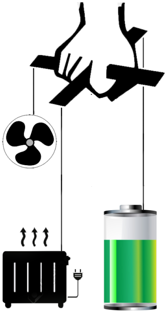
Which are valid between bounds that ensure good ageing of the battery

$$\boxed{S_{OC\,min} \leq S_{OC}(t) \leq S_{OC\,max}}$$



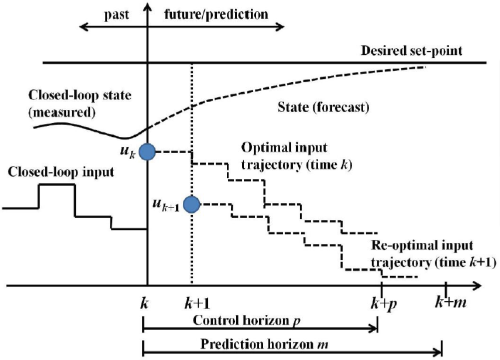
We have three control variables

$$u(t) = \begin{pmatrix} P_V(t) \\ P_H(t) \\ P_B(t) \end{pmatrix}$$



We want trajectories

$$u(t) = \begin{pmatrix} P_V(t) \\ P_H(t) \\ P_B(t) \end{pmatrix}$$



Here is the criterion :

$$J(u(.)) = \overbrace{\int_0^T \underbrace{C(t)}_{\text{Cost } (\text{€}/\text{ Watt})} \times \underbrace{P_G(t)}_{\text{Main Grid Power}} \, dt}^{\text{Total cost of consumed electricity}}$$

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Dynamic optimization problem

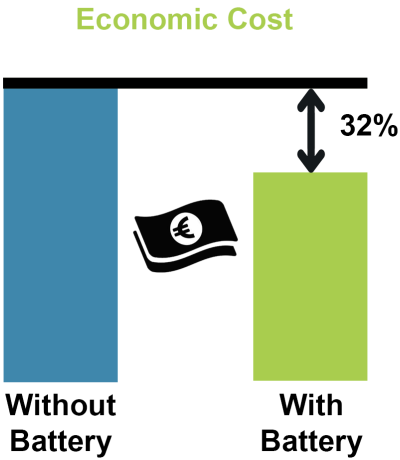
$$\min_{u(.)} J(u(.)) = \int_0^{\tau} C(t) P_G(t) dt$$

s.t

$$\begin{cases} P_G(t) + P_{Train}(t) = P_L(t) + P_V(t) + P_H(t) + P_B(t) \\ C_v \dfrac{dT}{dt}(t) = r_v P_V(t)(T_e(t) - T(t)) + r P_H(t) \\ \dfrac{dS_{OC}}{dt}(t) = \dfrac{\rho_B}{V_0 Q_{max}} P_B(t) \\ \\ T_{min} \leq T(t) \leq T_{max} \\ S_{OC\,min} \leq S_{OC}(t) \leq S_{OC\,max} \\ P_V(t), P_H(t) \geq 0 \\ \\ T(0) = T_0, S_{OC}(0) = S_{OC0} \end{cases}$$

No battery vs. Battery controlled

We could save 32% of money everyday with a battery



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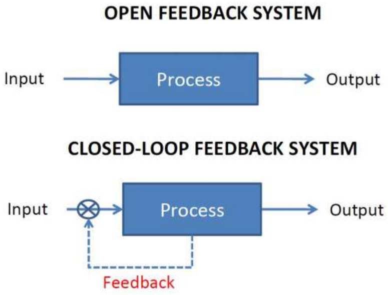
For a dynamic optimization problem there are two kinds of solutions :

- Open Loop : providing a control trajectory depending on time u(t)
- Closed Loop : providing a control policy depending on the state variables feedback u(x(t))

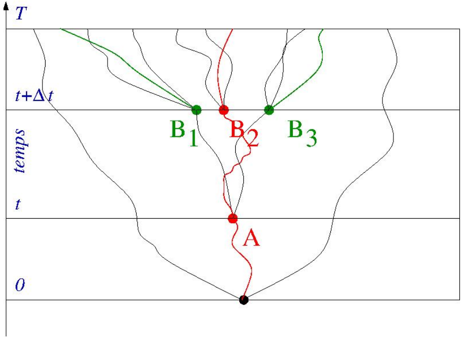


(DfE)

Methods for a dynamic optimization problem

For a deterministic dynamic optimization problem there exists methods :

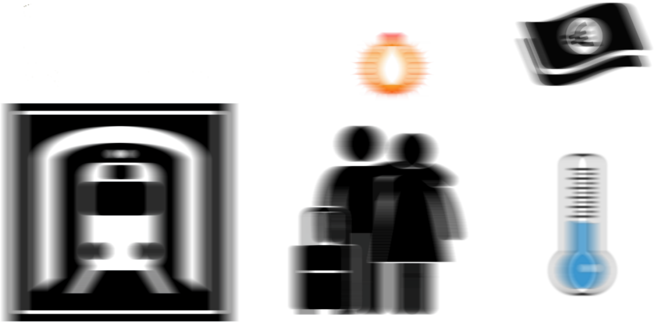
- Pontryagin Maximum Principle (open loop)
- Dynamic Programming (closed loop)



(Brêves de maths)

And there are several uncertainties

$T_e(t)$, $P_L(t)$, $P_{Train}(t)$, $C(t)$



And there are several uncertainties

$$\min_{u(.)} J(u) = \int_0^{\tau} C(t) P_G(t) dt$$

s.t

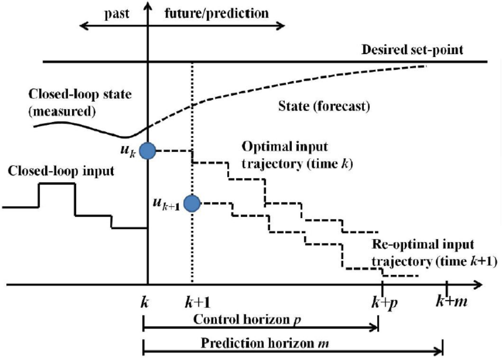
$$\begin{cases} P_G(t) + P_{Train}(t) = P_L(t) + P_V(t) + P_H(t) + P_B(t) \\ C_v \dfrac{dT}{dt}(t) = r_v P_V(t)(T_e(t) - T(t)) + r P_H(t) \\ \dfrac{dS_{OC}}{dt}(t) = \dfrac{\rho_B}{V_0 Q_{max}} P_B(t) \\ \\ T_{min} \leq T(t) \leq T_{max} \\ S_{OC\,min} \leq S_{OC}(t) \leq S_{OC\,max} \\ P_V(t), P_H(t) \geq 0 \\ \\ T(0) = T_0, S_{OC}(0) = S_{OC0} \end{cases}$$

Outline

Model Predictive Control

MPC rolling horizon strategy

Frequent monitoring and online reoptimization to prevent uncertainty and provide open loop feedback



(Dai et al. 2012)

Model Predictive Control merits and demerits

- Advantages : feedback by reoptimization, computationally feasible, handle non linearities and state constraints
- Drawbacks : suboptimal, open loop, uncertainties

Conclusion

- There exists substantial potential energy savings
- Work in progress to apply MPC solutions to simulations and real data
- Work in progress to compare MPC policies to other closed loop policies
- Work in progress to compute these strategies on more accurate thermal, electrical and aeraulic models
- Electrical sizing of the battery, electrical simulation and economic model

Perspectives