# A coupled geo-spatial energy-air quality assessment model for the Grand Duchy of Luxembourg

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# Outline

Problem definition

Integration of the models

Optimization

Results and perspectives

# Introduction

## Rationale

The control and mitigation of local air pollution ($NO_x$, VOC, $O_3$) in urban region is an important problem that can benefit from an integrated approach.

## Objective

To couple two models:

- an energy model which optimizes the energy system;
- an air quality model which simulates ozone episodes,

and to perform a cost-benefit assessment.

# Decomposition Problem

$$\min_{\bar{\mathbf{e}},\mathbf{p}}\{\gamma(\bar{\mathbf{e}}) + \mathcal{V}(\mathbf{p}) : \mathrm{AOT}(\bar{\mathbf{e}}) - \mathbf{p} \leq 0\}$$

- $\gamma(\bar{\mathbf{e}})$: Energy system cost function (euros)
- $\mathcal{V}(\mathbf{p})$: Impact cost function
- $\mathrm{AOT}(\bar{\mathbf{e}})$: AOT level function

- $\bar{\mathbf{e}}$: sectoral emissions (kt)
- $\mathbf{p}$: AOT level

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# ETEM: Energy model

- ETEM model (`http://www.ordecsys.com`)
- Implementation of MARKAL/TIMES in GMPL (LP)
- Energy system of Luxembourg ($\sim$ 100'000 rows/columns)
- Time horizon: 9 periods of 5 years (2005–2050)
- Minimize the total discounted energy cost s.t.
  - the demands in energy services are satisfied,
  - the commodity flows balance is respected;

$$\min_{\mathbf{x}}\{\mathbf{c}'\mathbf{x} \mid \mathbf{A}\mathbf{x} = \mathbf{b}, \mathbf{x} \geq 0\}$$

# Energy cost function

Emissions are computed using stoichiometric coefficients $\mathbf{s}$ :

$$\mathbf{s}'\mathbf{x} = \mathbf{e}.$$

Sectoral emission $\bar{\mathbf{e}}$ constrain the model:

$$\gamma(\bar{\mathbf{e}}) = \min_{\mathbf{x}} \{\mathbf{c}'\mathbf{x} \mid \mathbf{A}\mathbf{x} = \mathbf{b}, \mathbf{s}'\mathbf{x} = \mathbf{e} \leq \bar{\mathbf{e}}, \mathbf{x} \geq 0\},$$

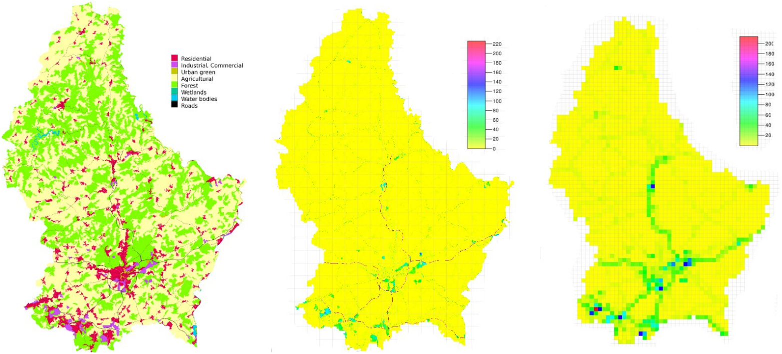
By construction, dual values of the added constraints define a subgradient $\frac{d\gamma(\bar{\mathbf{e}})}{d\bar{\mathbf{e}}}$.

**Calculation time using GLPK solver**

ETEM $<$ 1 min

# Emission allocation

Sectoral emissions $\bar{\mathbf{e}}$ are distributed over space and time to provide emissions rates at sources using land-use maps and spots.




land-use (20mx20m) $\Rightarrow$ sources (20mx20m) $\Rightarrow$ sources (1kmx1km)

$$\bar{\mathbf{e}} = \int_{S \times T} \mathbf{E}(t, s) \mathrm{d}s \mathrm{d}t$$

# AYLTP: Air quality model

AYLTP is a fast air quality calculator based on

- AUSTAL2000: lagrangian transport model
- $O_3$ photochemical reactions: lookup table generated from OZIPR
- Input: Emissions rates at sources $\mathbf{E}(t, s)$
- Output: $O_3$ concentration $\mathbf{C}_{O_3}(t, s)$

# AOT calculation

AOT: Average Over Threshold (60 ppb)

$$\mathrm{AOT}(\bar{\mathbf{e}}) = \frac{1}{\mid S \mid} \frac{1}{t} \int_{S \times T} \mathbf{C}_{O_3}(t, s; \bar{\mathbf{e}}) \mathrm{d}s \mathrm{d}t$$

**Calculation time**

Emission allocation + AYLTP + AOT calculation = 5 min

# Impact function

Disability adjusted life years (DALY) due to 1 ppb of ozone:

$$\mathrm{DALY} = \mathrm{imp}_{O_3} \times \frac{m_{O_3}}{V_{\mathrm{air}}} \times \mathrm{air} \times \mathrm{nbdays} \times \mathrm{expos} \times 10^{-9}$$

Monetarise the DALY using budget constraint:

$$\mathcal{V}(\mathbf{p}) = \mathbf{p} \times \mathrm{pop} \times \mathrm{pp} \times \mathrm{DALY}$$

| | | |
|---|---|---|
| $\mathrm{pop}$ | population in Luxembourg in 2010 | 502'500 |
| $\mathrm{pp}$ | potential annual economic production per capita at full well-being[a] | 74'000 €/y |
| $\mathrm{imp}_{O_3}$ | ozone impact factor[b] | 0.31 $y/kg_{O_3}$ |
| $\mathrm{air}$ | daily breathing air of a person | 10'800 L |
| $\mathrm{nbdays}$ | yearly average ozone episode duration | 10 days |
| $\mathrm{expos}$ | daily exposure duration to ozone | 0.25 |
| $V_{\mathrm{air}}$ | volume of 1 mole of air (20°C,1015 hpa) | 24 L/mol |
| $m_{O_3}$ | ozone molar mass | 48 g/mol |

[a](Weidema,2009),[b](Goedkoop,2008)

# OBOE

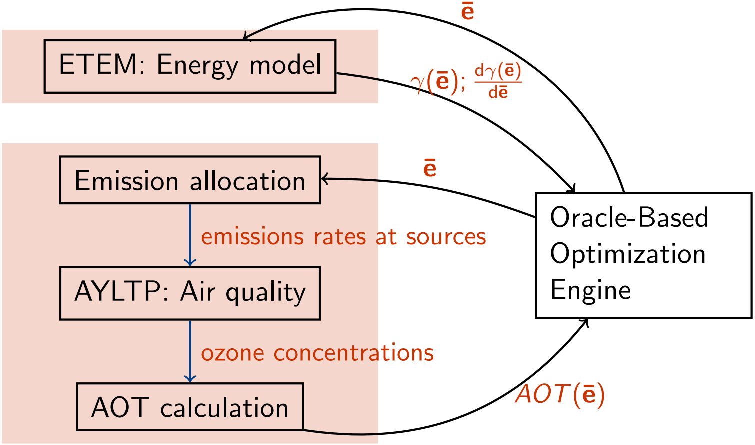
Implementation of an oracle-based optimization method (Babonneau, 2006).

- Proximal-ACCPM (Vial, 2002):
  - cutting plane method
  - choose the Analytic center as the next query point
- OBOE: oracle-based optimization engine.
- Implementation in C available at COIN-OR.

# Algorithm

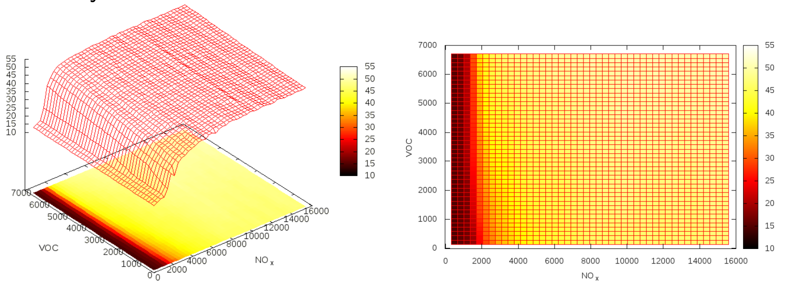
1. Initialize OBOE
2. Get the query point $(\bar{\mathbf{e}}, \mathbf{p})$ in the current localization set
3. if LHS $> 0$
   - Compute a feasibility cut
     - value: LHS
     - subgradient: finite-differences on $\mathrm{AOT}$
4. else
   - Compute an optimality cut
     - value: $\gamma(\bar{\mathbf{e}})$
     - subgradient: $\frac{d\gamma(\bar{\mathbf{e}})}{d\bar{\mathbf{e}}}$
5. go to 2., if the stopping criterion is not meet

# Optimization Framework



# AOT response

The AOT response in function of $\bar{\mathbf{e}} = (e_{\mathrm{NOx}}, e_{\mathrm{VOC}})$ is close to convexity:



# First results and future perspectives

- To converge, some restarts are needed (when a new cut gives an empty localization set)
- 20 iterations and 1 restart.

| | Baseline | Cost-benefit |
|---|---|---|
| Energy cost (M€) | 58.119 | 64.323 |
| Impact cost (M€) | 141.925 | 129.475 |
| $NO_x$ 2010 (t) | 14 456 | 10 379 |
| $NO_x$ 2015 (t) | 14 784 | 10 420 |
| VOC 2010 (t) | 6 570 | 5 388 |
| VOC 2015 (t) | 6 637 | 5 427 |
| AOT 2010 (ppmb) | 53 | 44 |
| AOT 2020 (ppmb) | 55 | 44 |

# Future perspectives

- SUNleaq project: handle spatial error in emission allocation
- Non-convexity: smooth $AOT$ function using a statistical emulation.
- Spatial AOT to choose the healthier place for new residential areas.
- Calibration of the impact function

**Thank you for your attention !**

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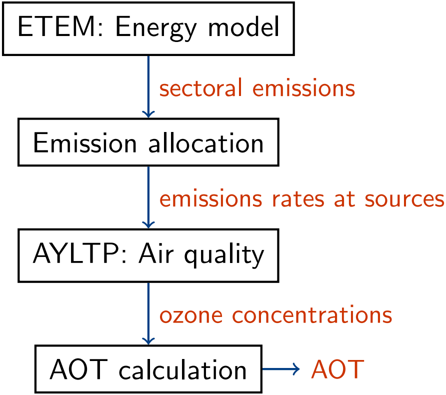
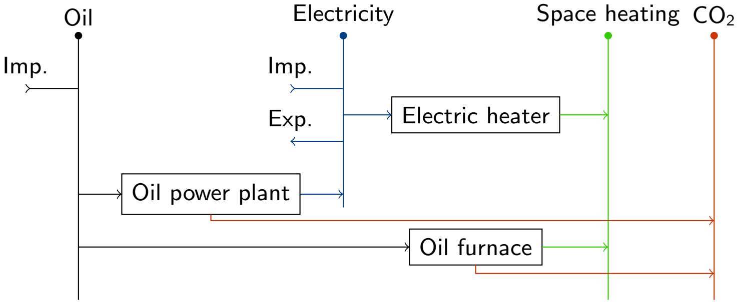
# Simulation Framework



# Example of an Energy System




- Technologies
- • Commodities (Fuels, energy services demands, emissions)
- ⟶ Commodity flows