Development and Application of an Asymptotic Level Transport Pollution Model for Luxembourg Energy Air Quality Project

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Outline

Air Quality - A Major Concern

- The London smog disaster 1952, brought attention to the damaging effects of air pollution.

- There is a negative relation of air pollution with human health, resulting in an increase of morbidity and mortality.

  [Ström et al., 1994; Solé et al.,2007; West et al., 2007; Laaidi et al., 2011; Rückerl et al., 2011; Tzivian, 2011].

- *"Urban outdoor air pollution is estimated to cause 1.3 million deaths worldwide per year."* [World Health Organization, 2011].

Need of Integrated Solutions for Air quality

- *"Indeed air pollutant concentrations are still too high and harm our health and the ecosystems we depend on."* [European Environment Agency, 2012].
- Ozone (O_3) is one of the most problematic and harmful pollutants. Exposure to O_3 has generally not decreased since 2001. [European Environment Agency, 2012].
- European legislation on air quality has been developed and is becoming more and more strict.
- ***"European policies and measures increasingly seek to maximise co-benefits, managing air pollutant and greenhouse gas emissions at the least cost to society."*** [European Environment Agency, 2011].

Objectives

- Develop an air quality model, with the focus on the pollutant ozone, for an optimization integrated assessment model.
  - Build a photochemical air quality module which can be included in the LEAQ framework.
  - Develop of an emission allocation module.
- Evaluate the developed air quality model.
- Apply the developed air quality model within the LEAQ integrated assessment model.

Integrated Assessment Models for Air Pollution

Integrated assessment model

Combines knowledge from different scientific fields in order to study a problem that cannot be studied by a single disciplinary approach.

- Modelling approaches:
  - Simulation mode → Scenario evaluation
  - Optimization mode → Optimal strategy
- Mathematical problem:
  - Cost-benefit → based on the total cost (Economic + Impacts)
  - Cost-effectiveness → imposes an environmental constraint

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Integrated Assessment Models for Air Pollution

Name	Emission model	Air quality model	Scale	Reference
Simulation mode				
MERG	MARKAL	SCA	regional	James et al. (1985)
RAINS	PRIMES	EMEP	regional	Alcamo and Hordijk (1990)
ASAM	EMEP/CASM	RAINS	regional	ApSimon et al. (1994)
SAMI	EMS-95/Mobile5b	URM-1ATM,...	regional	Odman et al. (2002)
USIAM	Inventory	ADMS-Urban	urban	Mediavilla and ApSimon (2003)
IMPAQT	ADMS inventory	ADMS-Urban	urban	Lim et al. (2005)
EC4MACS	GAINS	TM5,EMEP,...	regional	EC4MACS (2007)
SIMCA	CEP/SMOKE	CMAQ	regional	Borge et al. (2008)
BRUTAL	iMOVE	ADMS-Urban,...	urban	Oxley et al. (2009)
MINNI	RAINS-Italy	FARM	regional	D'Elia et al. (2009)
Mexico2050	E3MG	p-TOMCAT	regional	Barker et al. (2010)
SEA	Projection	MUAIR	urban	Nguyen and Coowanitwong (2010)
Finish IAM for PM	FRES,EMEP	SILAM	regional	Tainio et al. (2010)
Global Health Impacts	MESSAGE	TM5	global	Rao et al. (2012)
Optimisation mode				
Shih	Projections	Isopleths	urban	Shih et al. (1998)
RAINS	PRIMES	EMEP	regional	Amann et al. (2001)
UKIAM	NAEI	FRAME,PPM	regional	Oxley et al. (2003)
GENEVA	MARKAL-lite	TAPOM-lite	urban	Carlson et al. (2004)
OMEGA	EMEP	EMEP	regional	Reis et al. (2005)
MERLIN	EMEP	OFIS	regional	Reis et al. (2005)
GAMES	EMEP	TCAM	regional	Carnevale et al. (2008)
GAINS	GAINS	EMEP	regional	Amann et al. (2011)
LEAQ	ETEM	TAPOM-lite	urban	Zachary et al. (2011)

Reduction Techniques used Integrated Assessment Models for Air Pollution

- **Artificial neural networks**: non-linear relationship linking air quality indicator and precursor emissions.
- **Source-receptor**: used in emission reduction strategies, store information about the contribution of emissions by a source to the concentration levels in a receptor point
- **Model reduction**: reduce the order of the equation of the problem. For example using linear relationships to relate ozone levels to its precursors levels.

Develop innovative solutions that can reproduce the complex relations between ozone and its precursors, and at the same time simple enough to keep the uncertainties at a minimum. [Carnevale et al, 2008].

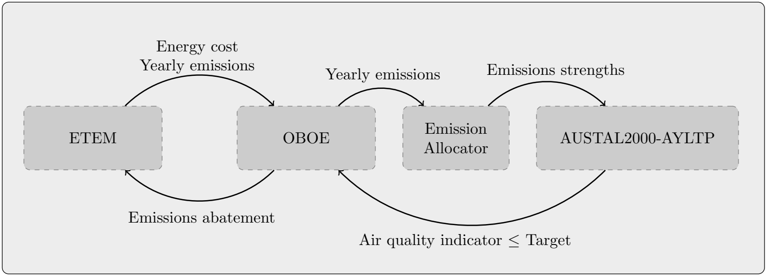
LEAQ

Integrated assessment model for air quality designed for Luxembourg Grand-duchy. It consists of an Energy Techno-economic Model (ETEM) and an Air quality Model (AUSTAL2000-AYLTP) coupled in an optimization problem.

- Long-term energy use and air quality planning.
- Energy technologies related not only to emissions but, more importantly, with AQ levels.
- May be applicable to other regions/cities.
- Open-source software.
- Inclusion of secondary pollution → ozone.

The Luxembourg Energy and Air Quality Model

Goal: Find the optimal energy arrangement which complies with a given ambient ozone level standard.



The optimisation framework requires a fast Air quality model.

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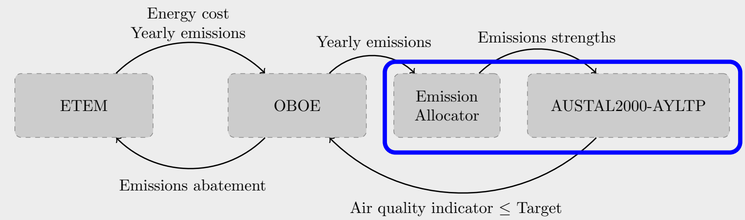

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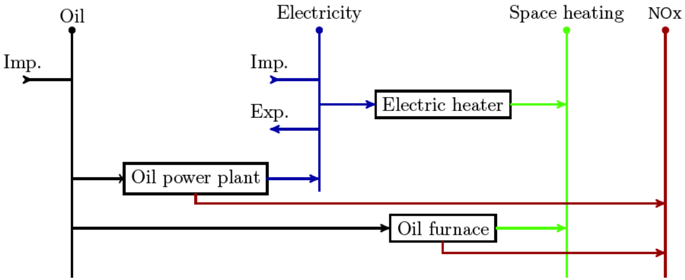
The ETEM Luxembourg Model

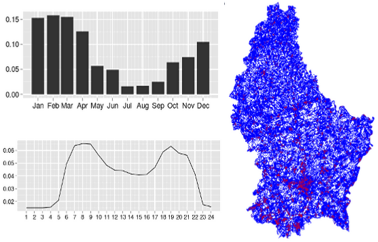


† Simplified example of a reference energy system.

- The ETEM model implemented for the Luxembourg country
- Total cost of the energy system.
- Air pollutants (NO_x, VOC) $\rightarrow$ Ozone precursors

The Emission Allocation Module

- Disaggregation of the annual emissions by sector:
  - Land-use maps
  - Temporal profiles: monthly, weekly and hourly.
- Time series maps of emissions' strengths
- AUSTAL2000 format

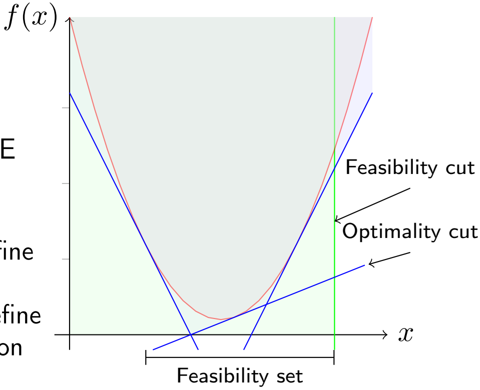


Time profiles

Spatial distribution

The Oracle Based Optimisation Engine (OBOE)

- Optimisation engine
- Iterative analytic centre cutting plane method: ACCPM
- At each iteration, OBOE solves the optimisation problem based on cuts:
  - Feasibility cut to define the feasible set
  - Optimality cut to define the problem's function



Ozone Behaviour

- Secondary pollutant $\rightarrow$ not emitted.
- The relation of ozone with its precursors is not linear.
- There are two ozone regimes: NO_x -Limited and NO_x -Saturated.
- A decrease of NO_x might lead to an increase of O_3. depending on the VOC/NO_x ratio.

Modelling Photochemistry

The air quality model desirable characteristics:

- Include topography
- Include meteorology
- Flexible
- Open-source
- Secondary pollutant: ozone

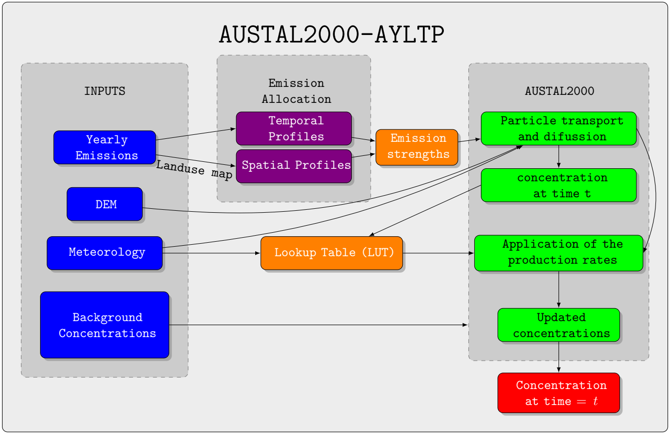
The AsYmptotic Level Transport Pollution (AYLTP)

Find a compromise between CPU time and accuracy

It is assumed that under a certain number of restricted conditions a linear pollutants' production rate holds.

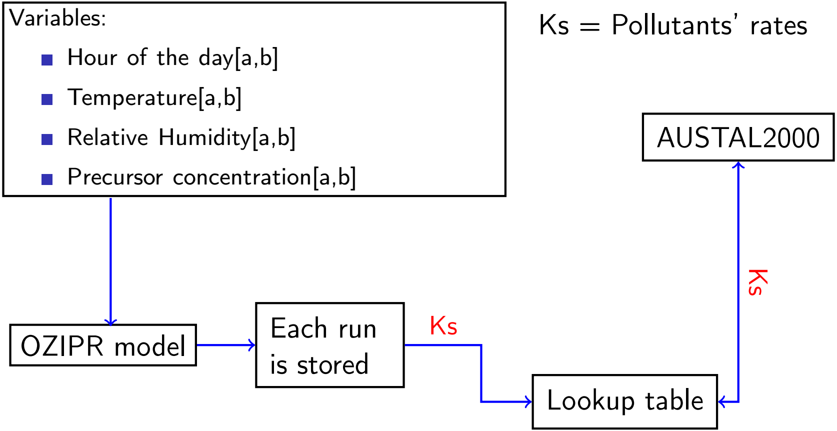
The LEAQ Air Quality Model

Use AUSTAL2000 Lagrangian particle model as the transport calculator and implement a photochemical module through LUT.



The LookUp-Tables (LUT)

Ks = Pollutants' rates



The Production Rates

The use of quasi-linear production ozone rates allows the fast simulation of ozone production/depletion in AUSTAL2000.

$$Ks_p(c_p(t),\Omega) = \frac{c_p(t+\Delta t; c_p(t),\Omega) - c_p(t)}{\Delta t},$$
$$p \in \{NO_{\mathrm{x}}, VOC, O_3\},$$

- c is concentration
- t is time period
- Ω are the meteorological variables
- final concentration $c_p(t+\Delta, c_p(t),\Omega)$ is calculated by OZIPR.

The Production Rates

The rates Ks are applied as follows:

$$m'_{p,i,j,k}(t) = m_{p,i,j,k}(t) + Ks_p(c_p(t), \Omega)\Delta t V, \; \forall(i,j,k) \in E,$$

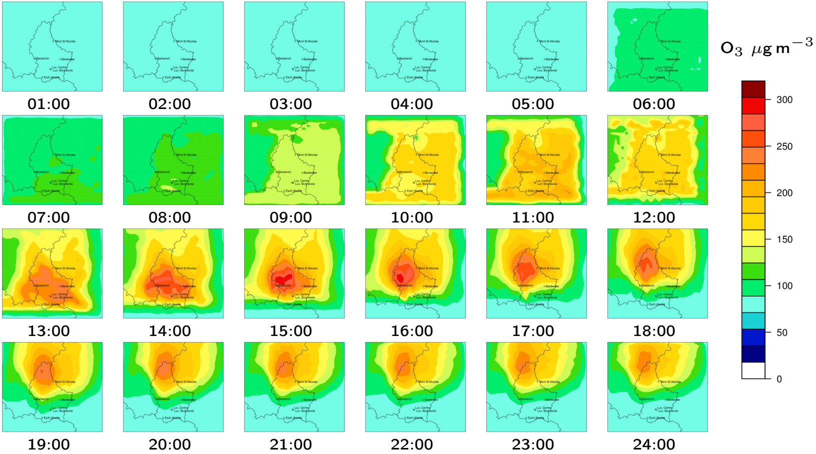
where E is the calculation domain.

- The new mass is then applied over the particles located in the cell, by distributing equally the mass.

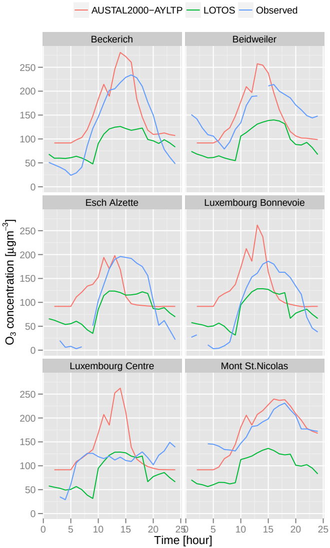
AQ Model Results

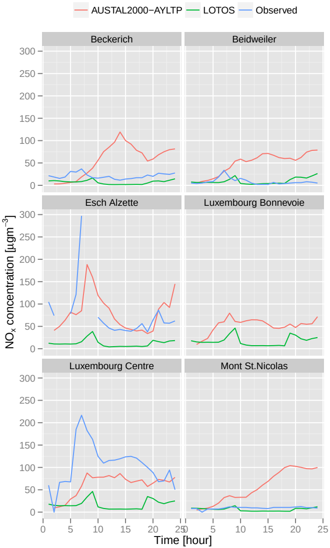
Day: - July 19th 2006

- high ozone concentration day
- ETEM emissions calibrated for 2006

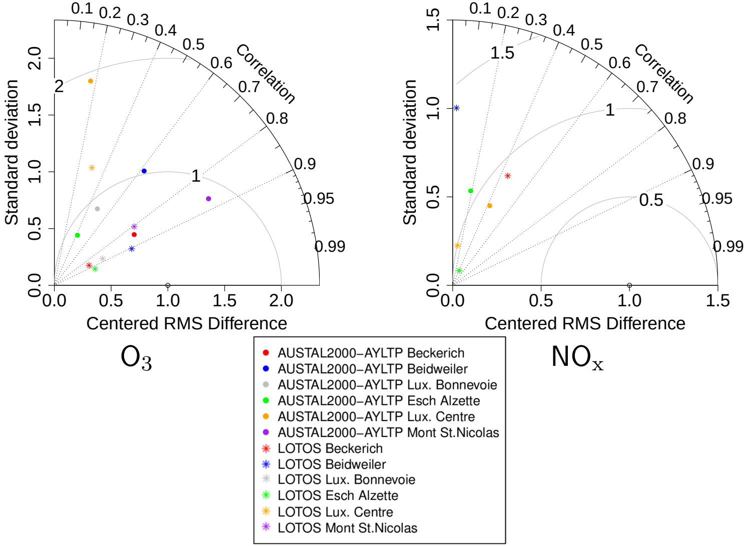


Air Quality Qualitative Evaluation





Air Quality Quantitative Evaluation



The LEAQ Convex Optimization Problem

Find the optimal energy arrangement which complies with a given ambient ozone level standard.

$$\min_{\hat{\mathbf{e}}} \left\{ \gamma(\hat{\mathbf{e}}) : p(\hat{\mathbf{e}}) - \hat{p} \leq 0 \right\},$$

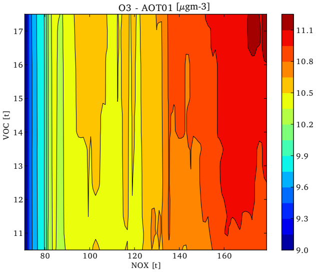
where

- $\hat{e}$: pollutant's annual emission bounds.
- $\gamma(\hat{\mathbf{e}})$: energy system cost.
- $p(\hat{\mathbf{e}})$: air quality indicator on ozone.
- $\hat{p}$: air quality indicator target.

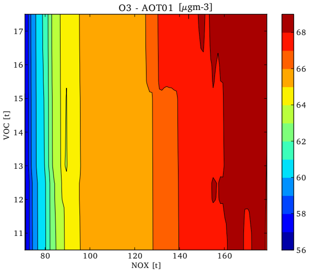
OBOE requires a convex problem.

Convex Optimization Approach Limitations

AOT: Accumulated Ozone exposure over a Threshold



Realistic meteorology



Theoretical worst meteorological case

Air Quality Model Uncertainty

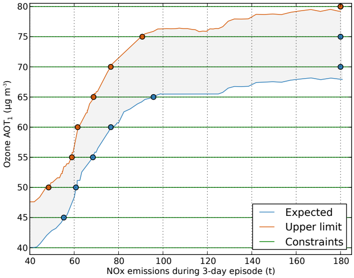
- The number of Lagrangian particles used in the simulations is much smaller than the number of particles in reality $\rightarrow$ sampling error.
- Turbulent velocities in AUSTAL2000 are simulated using a random velocity.

$$\varepsilon_c = \frac{\sigma_c}{\bar{c}} \tag{1}$$

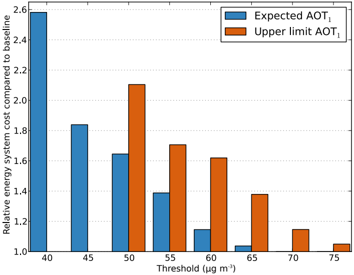
- σ_c standard deviation between the groups.
- $\bar{c}$ average of the groups.

The Luxembourg Country:

- Scenario 1: NO_x national emissions.
- Uncertainty of the air quality model, using 95% of the upper limit of the confidence interval.



Optimal emissions vs AOT_1-indicator

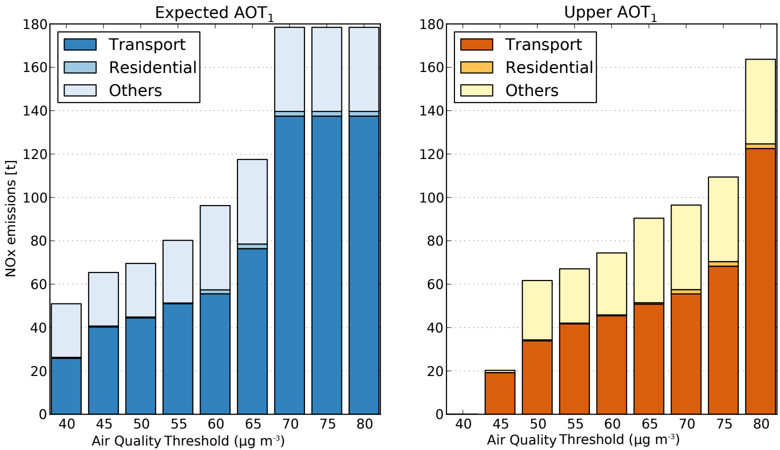


Relative cost vs AOT_1-indicator

The LEAQ Application - The Luxembourg Country: Scenario 2

The Luxembourg Country:

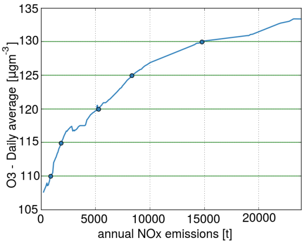
- Scenario 2: NO_x sectoral emissions.



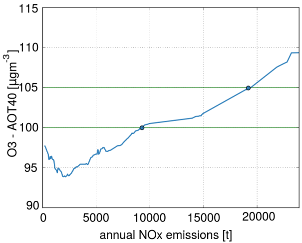
The LEAQ Application- The Luxembourg Region

The Luxembourg Region:

- NO_x national emissions.



Daily average



AOT_{40}

Conclusions part I

- The AUSTAL2000-AYLTP has been developed and implemented into LEAQ.
- The emission allocator has been developed and implemented.
- The use of Lookup tables and production rates fastens the model.
- The results of the AUSTAL2000-AYLTP model are satisfactory for this modelling framework.

Conclusions part II

- Luxembourg's energy system has limited flexibility.
- Smaller sized countries like Luxembourg are more dependent on regional and international air quality policy plans.
- The convexity restriction imposed by the optimisation approach limits the air quality model.

Future Work

- Include new pollutants.
- The LEAQ policy results can be improved by increasing the impacted period, and using other (yearly) air quality indexes.
- Include exposure impacts (DALY) in the decision, started in [Zachary, D. et al, 2011].
- Further expansion into a cost-benefit analysis.
- Application in other urban areas.
- The LEAQ framework could be further augmented to be used as a spatial tool.

Thank you!

Thank you!

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