Air pollution source term estimation using self-adaptive Evolutionary multiobjective optimization

TECHNION Israel Institute of Technology

Shai Kendler[#,1,2], Asaf Nebenzal[3], David Gold[4], Patrick. M. Reed[4], Barak Fishbain[1]

1. Dept. of Environmental, Water and Agricultural Engineering, Faculty of Civil & Environmental Engineering, Technion – Israeli Institute of Technology, 2. Environmental physics department, Israel Institute for Biological Research, 3. Department of Mathematics, Technion – Israeli Institute of Technology, 4. School of Civil and Environmental Engineering, Cornell University

Corresponding authors: Prof. Shai Kendler - ikendler@gmail.com, Asaf Nebenzal - asaf.n@technion.ac.il

Introduction

Source term estimation

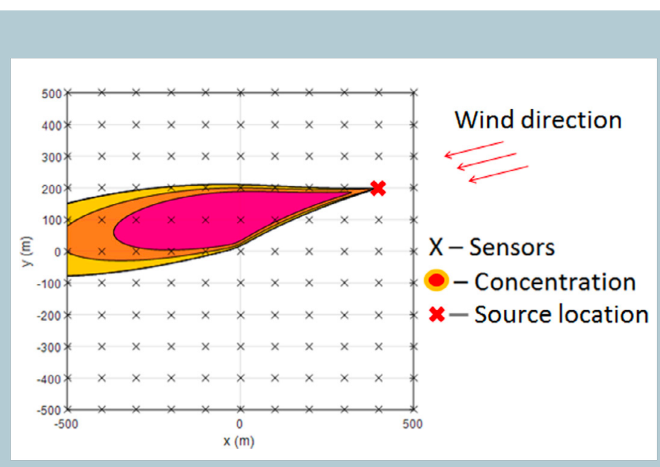


Figure 1. Example of a source and a network of sensor (Hutchinson et. al., 2017).

- A leak of various chemicals from industrial activity may harm humans and the environment.
- The first line of defense, before prioritizing any mitigating steps, is detection of the resulted plume and mapping the contamination level, using a network of sensors.
- Large number of sensors are typically needed for achieving concentration maps of high spatial and temporal resolution.
- An alternative approach is to locate the leak source and flow rate (i.e., source term), and use it as input to an atmospheric dispersion model to generate spatial dense pollution maps.

Research objective

Using simulations of a flat industrial site, our objective is to estimate the source term in the case of multiple leaks and a sparse network of sensors, using a state of the art evolutionary multiobjective search coupled with a Gaussian plume dispersion model.

Methodology

What is a multi-objective optimization?

- More than one objective function is optimized simultaneously.
- Tradeoffs exist between two or more conflicting objectives, for example – error rate and cost (Fig. 2).
- A Pareto frontier is the set of non-dominated solutions, being chosen as optimal, if no objective can be improved without harming at least one other objective.

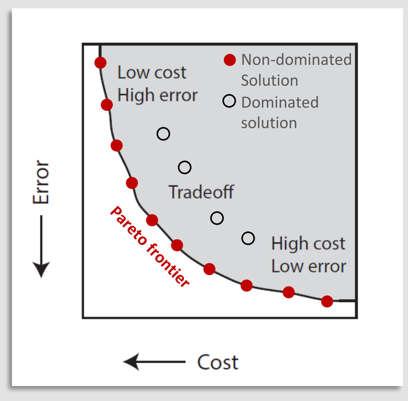
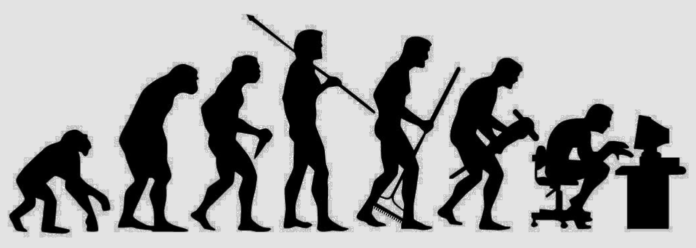


Figure 2. Example of tradeoff between two objectives and the Pareto frontier

What are Evolutionary Algorithms (EAs)?



- Inspired by biological Evolution, EAs are given a population of individuals (= a set of candidate solutions) (Fig.3).
- The environmental pressure causes natural selection and according to a fitness measure (= objective function), the better candidates have a higher chance to survive and reproduce.
- Recombination is applied to two or more selected parents (= selected solutions) and results in one or more offsprings (= new solutions) that may undergo a mutation.
- Based on their fitness, the offsprings compete with the old candidates for a place in the next generation.
- The process is iterated until a candidate with sufficient quality (= a non-dominated solution) is found.

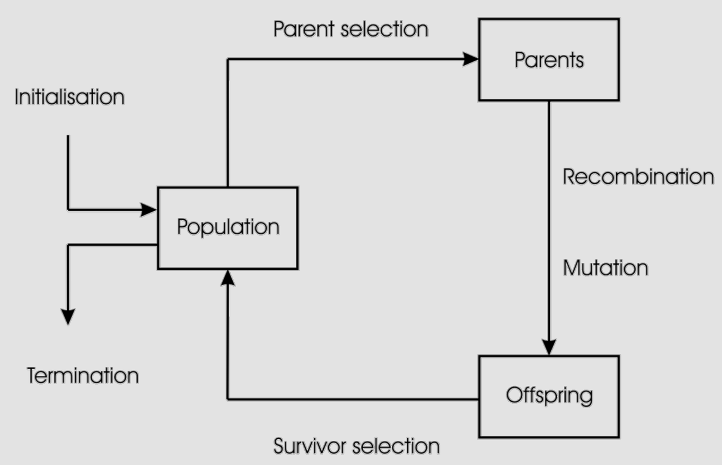


Figure 3. A general scheme of an Evolutionary Algorithm

Problem formulation

Objective-1: Minimize the difference between the sensors' actual and computed readings:

$$\Psi_{error} = \min_{\{S\}} \sum_{r\in\{R\}} \left| \boldsymbol{c_r(t)} - \sum_{s\in\{S\}} \boldsymbol{m_{sr}} \cdot \boldsymbol{q_s(t)} \right|$$

Objective-2: Minimize the number of active sources (NAS):

$$\Psi_{\#S} = \min_{\{S\}} |S|_0$$

Simulation set

- 600*600 m^2 flat area, with constant west-wind (5 m/s) and slightly unstable conditions.
- Leak rates of 0-1000 kg/s from varying number of leaks, between 0-9.
- Leak heights of 5 m above ground level.
- Six configuration sets, four of them are shown in Fig.4a-d.
- Configuration "Co9/9" (Fig.4a) is an arrangement of nine sources and nine sensors, each sensor located 50 m downwind from a leak.

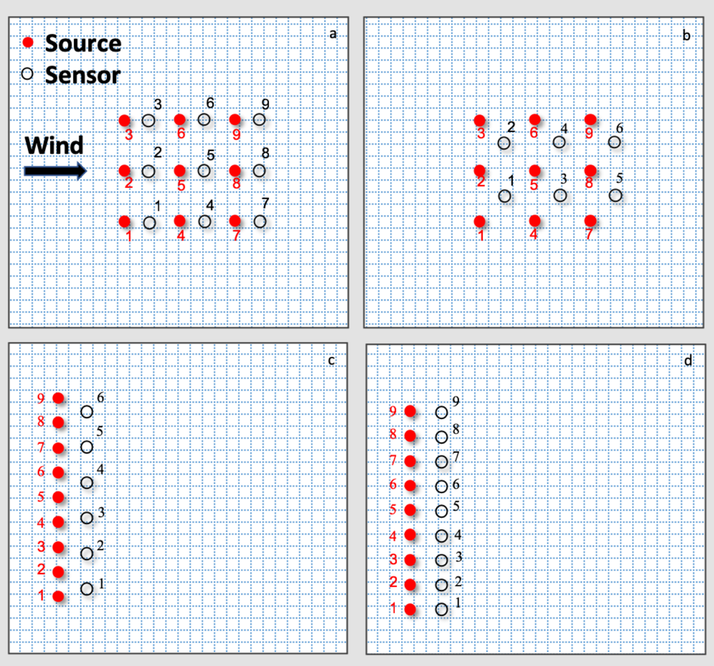


Figure 4. Source-sensors arrangements. the term "source" refers to both active and non-active sources. a) ("Co9/9") - nine sources and sensors in a compact group, 50 m apart b) ("Co9/6") - same as Co9/9, using six sensors, c) ("L9/6")- nine sources arranged in a line 50 m apart and a line of sensors 50 m downwind, sensors are 65 m apart, d) ("L9/9") same as 'c' using nine sensors, each sensor is in line with one of the sources.

Results

- Figure 5 shows the Pareto frontiers calculated by the Borg for the co9/9 arrangement, for an increasing number of leaks, $|S|_0 = \{1, \cdots, 9\}$.
- The minimum Ψ_{error} is achieved for the correct number of leaks.

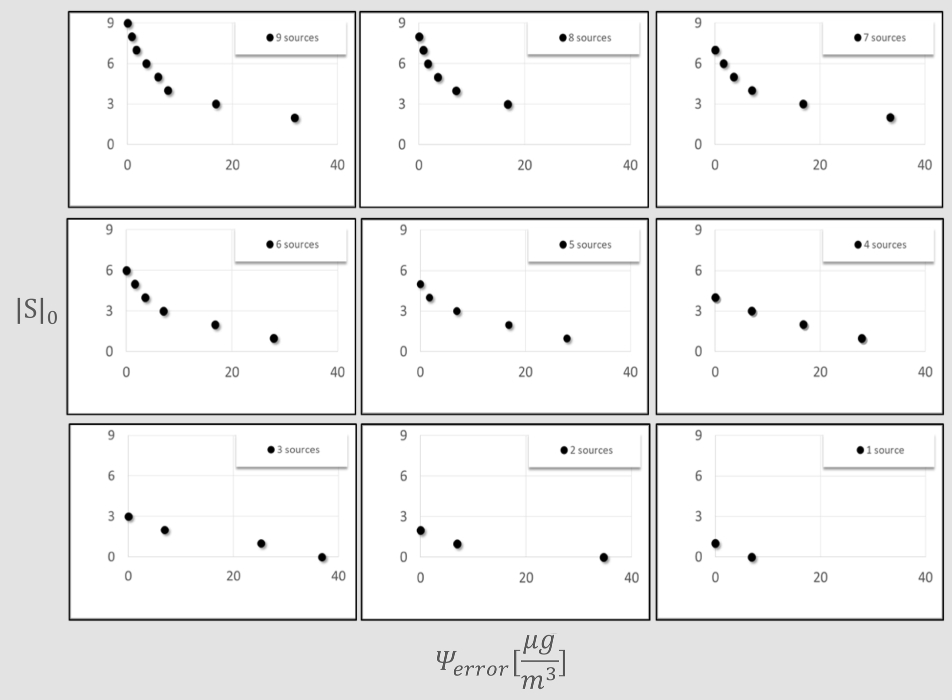


Figure 5. Pareto frontiers calculated for the "Co9/9" arrangement for several $|S|_0$.

- Figure 6 shows a comparison between the preset leak rates (at the 'x' axis) and the calculated leak rates (at the 'y' axis)
- Excellent agreement is seen, due to the relatively convenient sensing configuration.

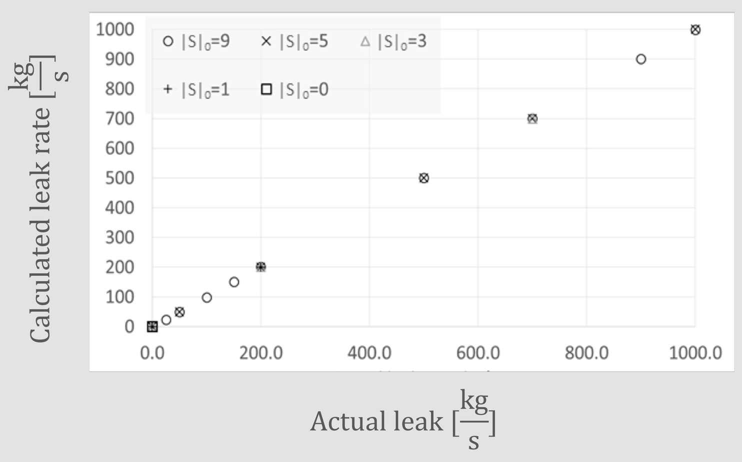


Figure 6. A comparison between the calculated and the actual leak rate in Co9/9 arrangement for several $|S|_0$.

Scenario complexity estimation

- PED = pairwise Euclidean distance for the sensor network observed readings between two sets of active sources with different sizes {S}' and {S}":

$$PED_{\{S'\},\{S''\}} = \sqrt{\sum_{r=1}^{|R|} \left(c_r^{\{S'\}} - c_r^{\{S''\}}\right)^2}$$

- Figure 7 shows the calculated color maps of PEDs for $|S|_0 = 1 - 9$ of all configurations.
- Figures 7a and b exhibit high PED values = simple scenarios
- Figures 7c and d exhibit low PED values = complex scenarios

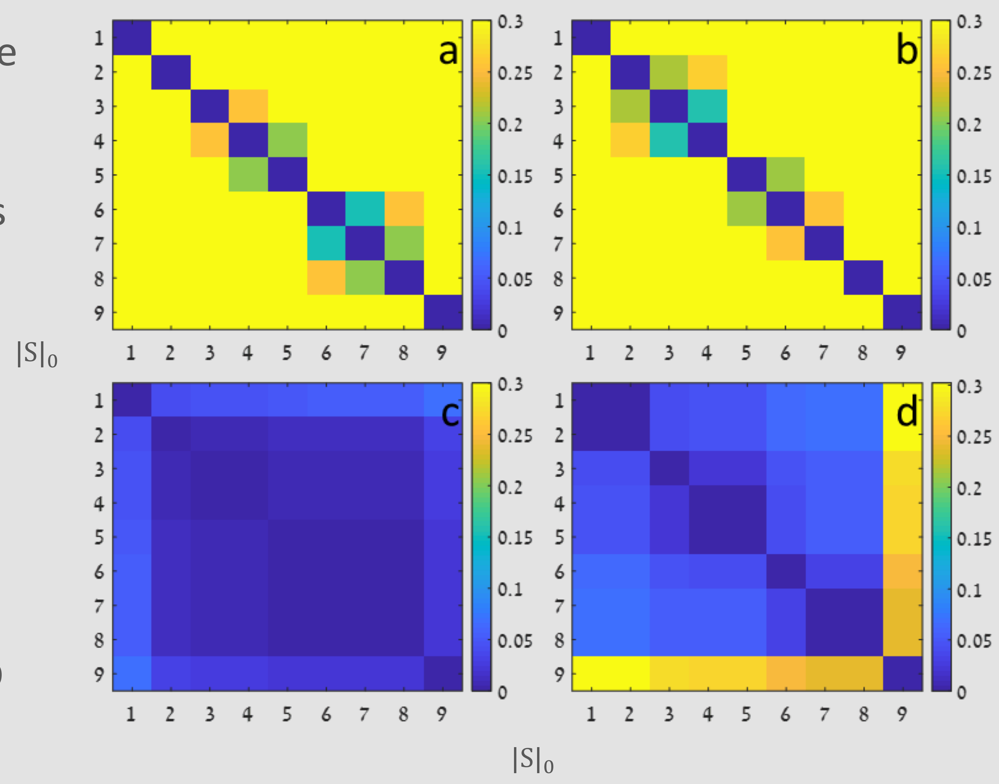


Figure 7. Color map for calculated PED as a function of $|S|_0$. a) "L9/9", b) "Co9/9", c) "Co9/6", d) "L9/6". High PED values presented in yellow color are a result of a large effect of NAS on the sensor network readings. Figures are truncated at $PED = 0.3 \cdot 10^6 ppm$, to allow comparison complex and simple situations

Summary & Conclusions

- This work presents a multiobjective scheme for estimating the source term in the case of multiple gas leaks.
- The method consists of coupling self-adaptive Borg multiobjective evolutionary algorithm (MOEA) framework with a dispersion model, relying on the readings from a sparse network of sensors.
- Two objectives are considered – minimizing the error of the estimated contamination level and the number of active sources, the letter corresponds to a simpler solution.
- The method is tested in a simulated flat terrene with 0-9 sources, and results show the method is effective, with the main limitation being the number of sensors and their locations relative to the leaks.
- A new measure to quantify the ability to resolve a specific configuration is presented – the PED criteria. This criteria, along with the findings of this work, will be used in future work to find the optimal deployment of sensors and their attributes.

Acknowledgements