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Design of an Urban Monitoring System for Air Quality in Smart Cities

Andrea Marini[1], Patrizia Mariani[2], Alberto Garinei[1,2], Stefania Proietti[2], Paolo Sdringola[3]
Massimiliano Proietti[1], Lorenzo Menculini[1], Marcello Marconi[1,2]

[1] Idea-Re S.r.l., Perugia, Italy
[2] Department of Sustainability Engineering, Guglielmo Marconi University, Rome, Italy
[3] ENEA Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Rome, Italy

Motivations

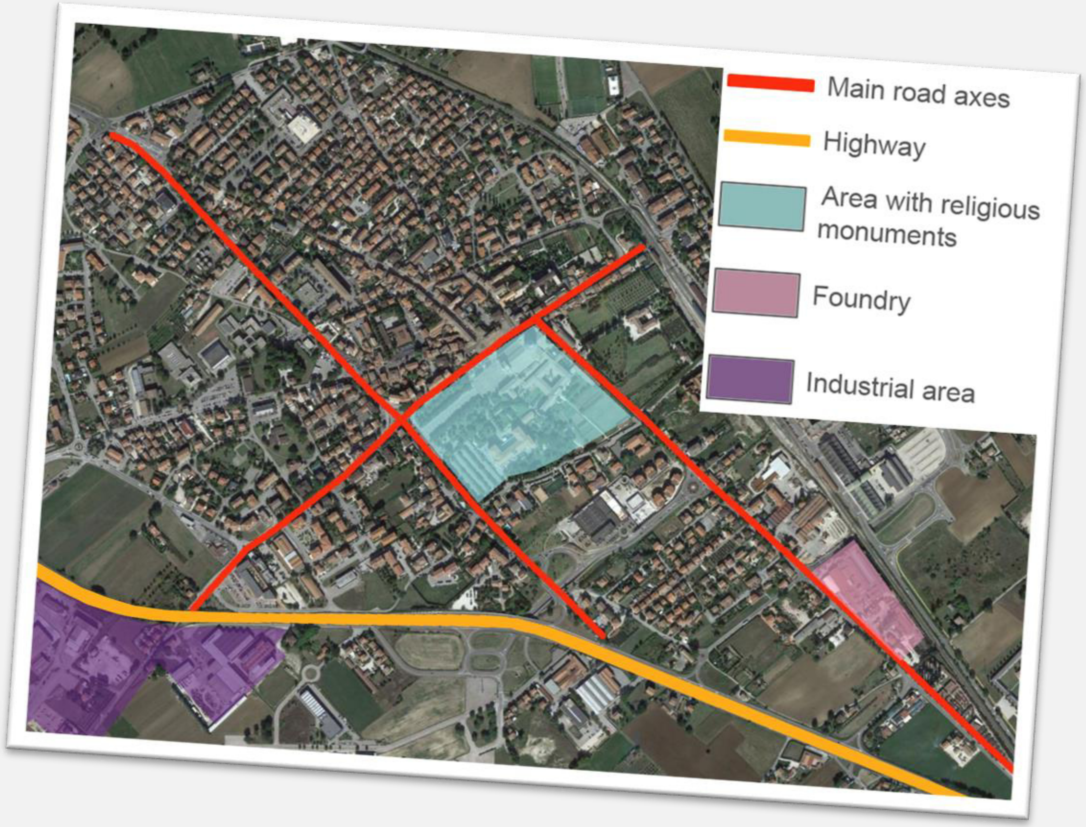
- Pollution is one of the main problems faced by cities
  - increase in emissions from anthropogenic sources resulting from economic, industrial and demographic development
- High values of pollutants (*e.g.* atmospheric particulate matter) lead to adverse effects on the environment and human health
  - spread of respiratory, cardiovascular and neurological problems
  - connection between the spread of the Covid-19 pandemic and environmental pollution? [Setti et al., 2020] [Wu et al., 2020] [Fattorini and Regoli, 2020]
- Urban monitoring of pollutants can allow to evaluate and perform actions aimed at reducing pollution in order to safeguard citizens' health

Overview

- This study proposes a method to design a low-cost urban air quality monitoring system that can be implemented in any small-to-medium-sized smart city
- The monitoring concerns atmospheric particulate matter (PM10 and PM2.5)
- Sensors are connected through a LoRaWAN network
- Location of the sensors are determined in two steps
    1. Analytic Hierarchy Process (AHP) multi-criteria decision-making technique
    2. Cellular Automaton model in order to ensure the best overall coverage of the polluted areas

Case study

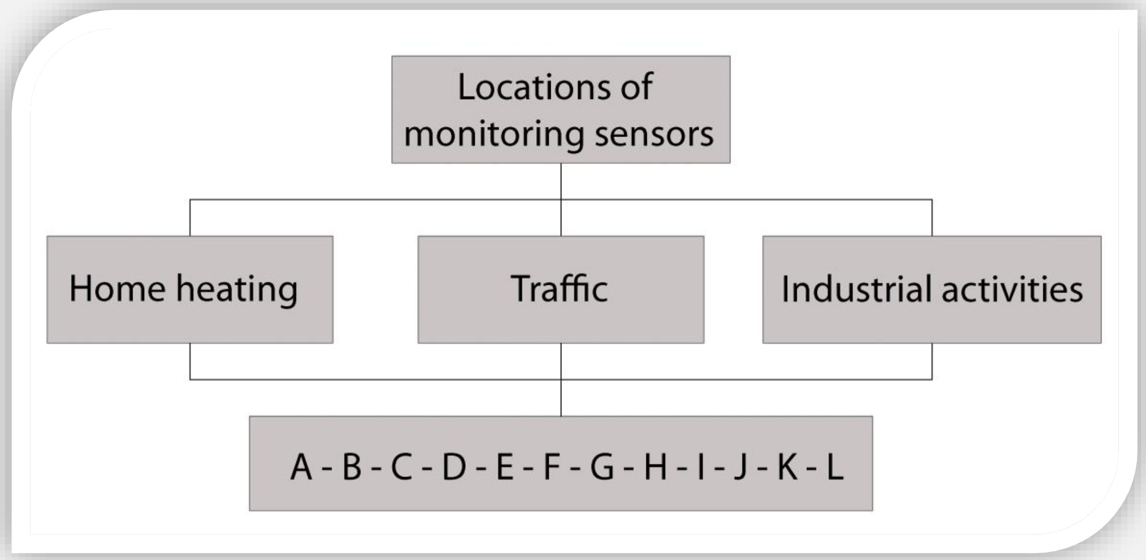
- Santa Maria degli Angeli
  - (43°03′32″N 12°34′41″E)
  - Municipality of Assisi (Italy)
  - 8470 inhabitants
- Over the years, the area has experienced an important urban development
  - residential settlement
  - industrial activities (concentrated in the south-west area)
- LoRaWAN network consists of six sensors



Analytic Hierarchy Process (AHP)

- Analytic Hierarchy Process (AHP) is a multi-criteria decision-making technique [Saaty]
- AHP allows to assign priorities to a series of decision-making alternatives and define them on a single scale, relating also parameters that are not directly comparable
- The method is made of three steps:
  - definition of a hierarchy of the problem (final objective, criteria, alternatives)
  - for each hierarchy layer definition of the matrices of pairwise comparisons and computation of the priority vector
  - hierarchical recomposition

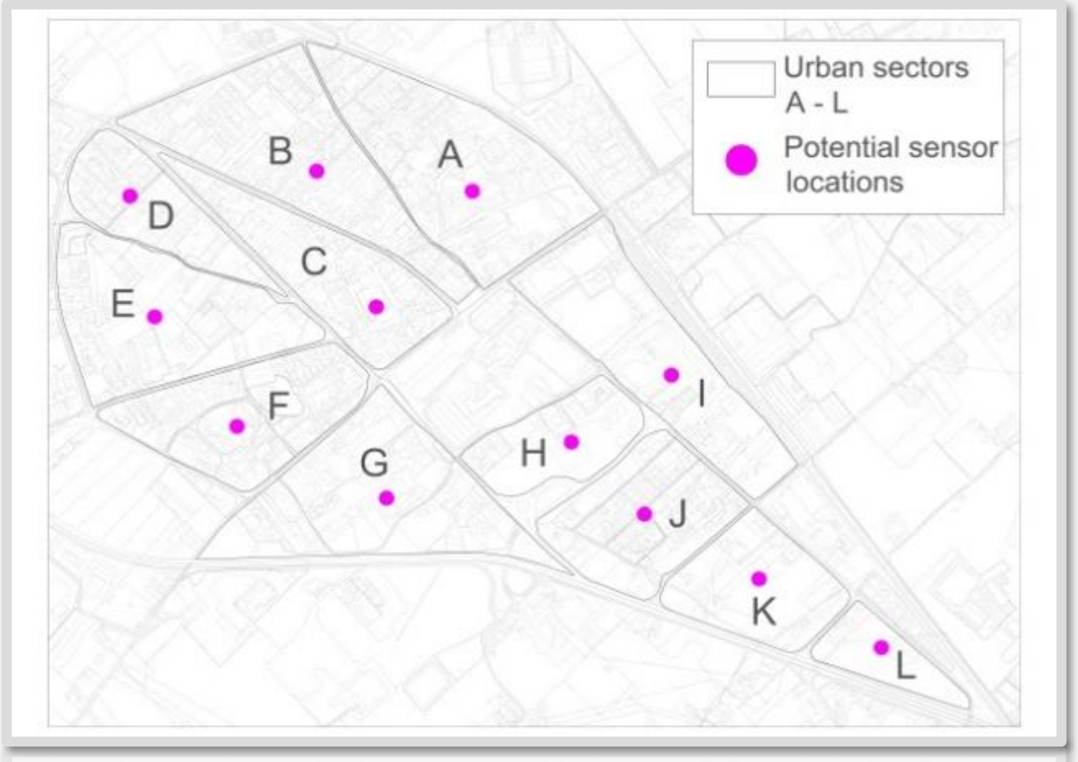
AHP hierarchy



- Final objective: locations of sensors for air quality monitoring
- Criteria layer: three main sources of pollution [Samad & Vogt, 2020]
  - Evaluation through a participatory process with the direct involvement of citizens (survey)
- Alternatives layer: twelve candidates locations for the sensors
  - Evaluation through a more objective method using available data

AHP: candidate sensors locations

- Twelve urban sectors (A-L) identified by the three main roads axes and the other main roads



AHP: questionnaires

- Questions:
  - which is the main source of atmospheric pollution among home heating, traffic and the presence of industrial activities?
  - how much the indicated source of pollution is more decisive than the other two, expressing a value in the scale from 1 to 9?
  - subjective assessment of the air quality in the various areas of the town (polluted or clean?)
- The anonymous questionnaires were distributed to a heterogeneous sample of citizens, inhabitants of the study area, of different ages and gender
- 38 questionnaires were collected

AHP: criteria comparison

- Collected values aggregated by means of the geometric mean and approximated to the nearest integer number yielding the pairwise comparisons matrix

	Home heating	Traffic	Industrial activities
Home heating	1	1/7	1/8
Traffic	7	1	1/5
Industrial activities	8	5	1

- Priority vector = normalized principal eigenvector

$$\begin{pmatrix} 0.0545 \\ 0.2331 \\ 0.7125 \end{pmatrix} \begin{array}{l} \longleftarrow \text{ home heating} \\ \longleftarrow \text{ traffic} \\ \longleftarrow \text{ Industrial activities} \end{array}$$

AHP: alternatives comparison

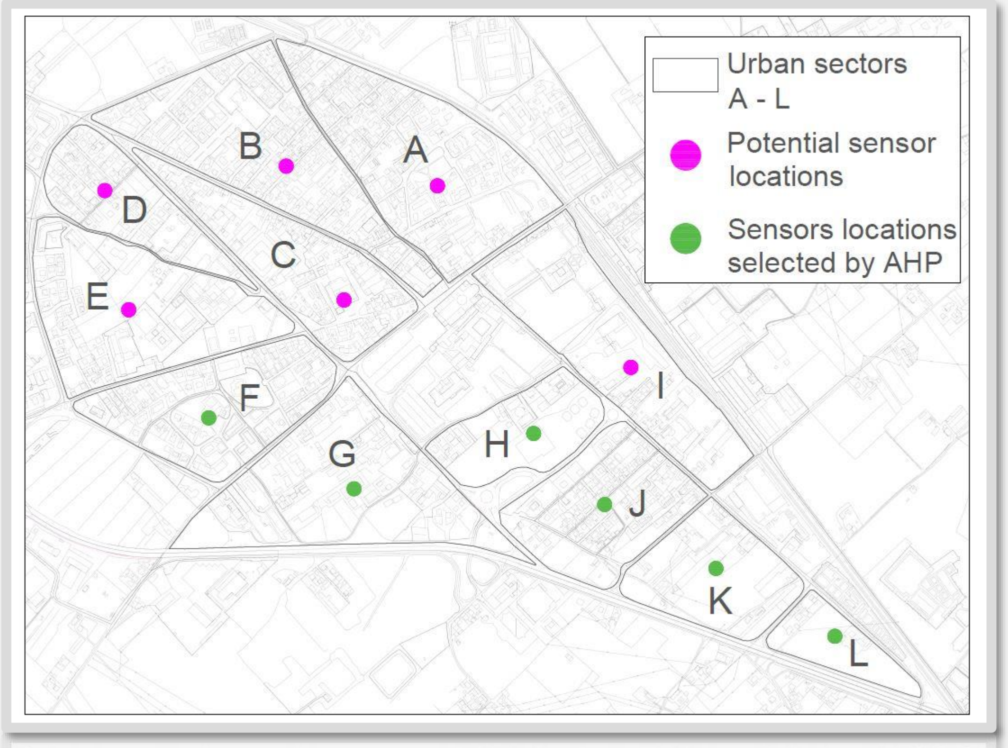
- Home heating criterion: on the basis of the population data in each sector as recorded in the Municipality database
- Traffic criterion: considering how each sector is enclosed by main roads
- Industrial activities criterion: considering the average distance of each sector from the foundry and the industrial area to the south-west of the town

AHP: hierarchical recomposition

Ranking	Sector	Home heating (0.0544)	Traffic (0.2331)	Industrial activities (0.7125)	Global weights
1	G	0.1034	0.2832	0.2008	0.2147
2	J	0.0431	0.0689	0.2008	0.1614
3	H	0.0156	0.0271	0.1515	0.1151
4	K	0.0156	0.1685	0.1017	0.1126
5	F	0.08	0.0346	0.129	0.1043
6	L	0.0127	0.2128	0.0275	0.0698
7	I	0.0482	0.0546	0.0674	0.0634
8	C	0.1315	0.0546	0.0434	0.0508
9	E	0.0251	0.0159	0.0411	0.0344
10	B	0.3174	0.0149	0.0114	0.0288
11	A	0.171	0.0214	0.0141	0.0244
12	D	0.0364	0.0434	0.0114	0.0202

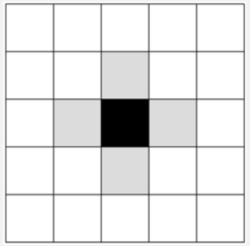
Sensors positions as selected by AHP analysis

AHP: sensors locations

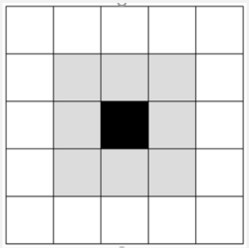


Cellular automaton (CA)

- A cellular automaton is a discrete dynamic system
- It consists of a set of elements, called cells, organized in a regular spatial grid and taking on a finite number of states
- The state of each cell at a certain moment evolves according to a given transition rule depending on the present state of the cell itself and the states of the neighborhood
- The neighborhood can be defined in many ways



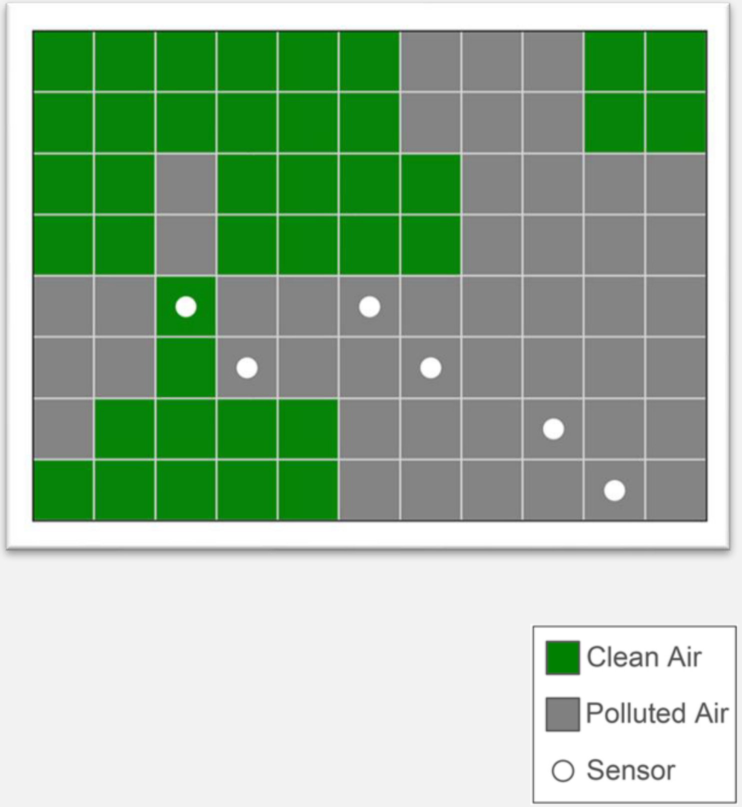
Von Neumann



Moore

CA for locations optimization

- Goal: optimizing the configuration obtained with the AHP method
- 11 × 8 grid superimposed on the study area
  - Cell dimensions 200 × 200 m
- Two binary variables associated to each cell:
  1. Absence (0) / presence (1) of a sensor (dynamical)
  2. Unpolluted (0) / polluted (1) area, as derived by the survey (fixed)
- CA initialized with the sensors placed in the position determined by AHP



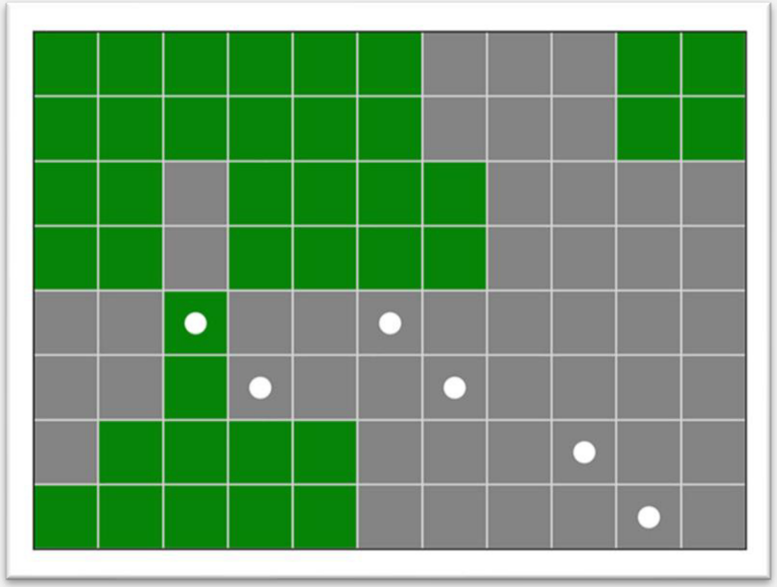
CA dynamics

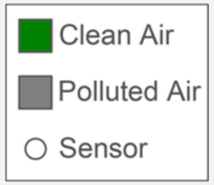
- At every iteration step each sensor moves in its Moore's neighbourhood (or remains in the current position) according to a stochastic dynamics:
  - A probability is assigned to every possible movement of the sensor reflecting the coverage of the polluted areas that the movement will determine
  - The actual movement of the sensor is randomly extracted according to movements probabilities
- The new configuration is accepted if it results in an increase of global coverage, otherwise it is discarded and the system remains in the previous configuration
- The system evolves till it reaches a stable configuration…

Results

1st step

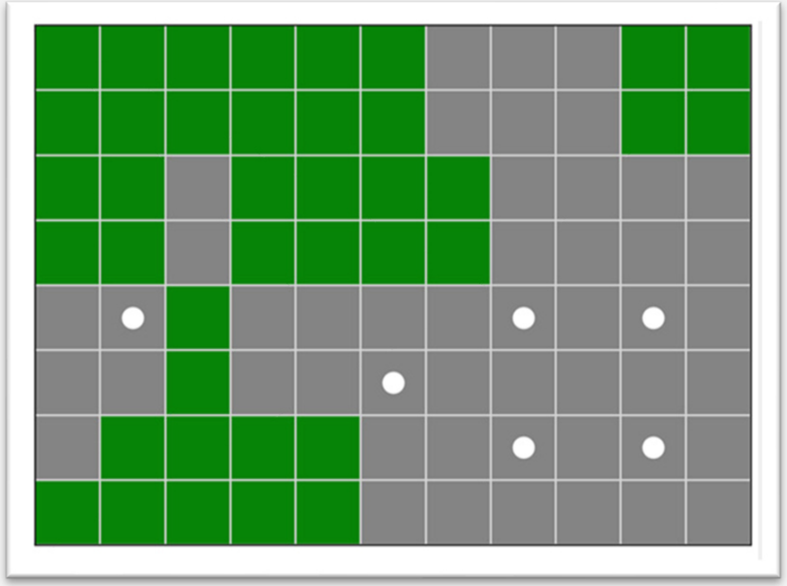
Sensors locations resulting from AHP





Final configuration

Sensors locations resulting from CA



Outlook

- A real air quality monitoring system is going to be implemented in Santa Maria degli Angeli
- A more refined optimization of the sensors positioning, considering levels of pollution determined using not only surveys but also
  - the measurements detected by the sensors
  - the epidemiological data regarding respiratory and cardiovascular diseases associated with long-term exposure to high levels of pollution
- When the sensors will be installed and when a significant amount of data will have been collected the cellular automaton step will be run again in order to possibly improve the configuration

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