

PM10 dispersion model in quarrying activities: a comparison of an ISC3 approach to a mono/multivariate geostatistical estimation

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Abstract

Airborne particulate matter represents one of the most pollutant factors in quarrying activities. The present study, developed in an Italian limestone quarry, pursues the aim of comparing different modelling and forecasting techniques for local atmospheric dispersion of PM10. In particular, after the preliminary characterization of dust sources according with an active monitoring system, dust concentration is sampled together with the most important environmental parameters such as pressure, temperature, atmospheric humidity, wind direction and speed. Then emission rate for each mining activity is determined. In particular typical mining activities are characterized with particular care of crushing, drilling, riddling, materials loading and unloading, transport and haul road. Therefore from this variety of sources associated with quarrying activities, the assessment of PM10 concentration is realized according with an ISC3 model. The second part of the work consists in the prediction of spatial variability of dust concentration according with a geostatistical approach. In particular, sampled values represent the input data grid used to obtain a continuous map of PM10 concentration in the quarry itself. For the monovariate approach, after a preliminary analysis based on variograms computation, the Kriging method is used. In the multivariate approach, taking into consideration the two variables PM10 and PTS, the Co-Kriging technique is used. In the final part a comparison of these two different methods is given in order to define the more suitable one in the exposed conditions.

Keywords: air pollution, particulate matter, dispersion, geostatistics.



1 Site selection

The study was developed in a limestone quarry that sells crushed limestone for bituminous conglomerates (400-500 m³/day). The flow chart of quarrying activities can be represented as it follows:

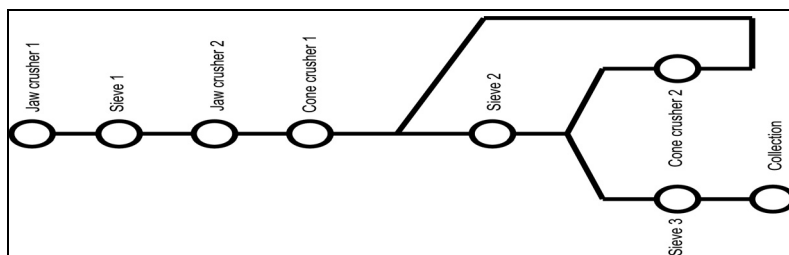


Figure 1: Quarrying activities: flow chart.

2 Dust sources and their classification

As for the exposed aim, the first step is represented by dust source individuation and classification. In particular, dust sources can be classified as ordinary or extraordinary sources, depending on the nature of activity that implies dust emission. They can be located in a specific position or distributed over a large area. Moreover, dust emission could last for the entire eight hour working day or just for a short period. In this classification it is important to find, according to a non-specific observation site, all the process activities connected with airborne dust emission independently from the intensity, which will be sampled afterwards. Also, in particular, we define point linear and area sources, but also uniform and not uniform emission sources.

3 Dust source characterization: Upwind-downwind method

This method allows one to calculate the amount of dust from a particular source. The dust concentrations upwind and downwind of the pollutant source are measured. The upwind sample is used for defining the degree of isolation of the source, while the downwind one is used to define the emission rate according to the application of the inverse formula of Gaussian Equation

4 The ISC model

The ISC3 is used for modeling dust dispersion in mining operations. It is based upon the Gaussian Equation for point source emissions

$$C = \frac{Q K V D}{2 \pi u_s \sigma_y \sigma_z} \exp \left[-\frac{1}{2} \left(\frac{y}{\sigma_y} \right)^2 \right] \quad (1)$$



where

Q = pollutant emission rate (g/s)

K = Conversion factor

V = Vertical term (include the images method)

D = Decay term

$\sigma_y \sigma_z$ = Standard deviation of lateral and vertical concentration distribution

u_s = Mean wind speed at release high:

C = hourly concentration at downwind distance x

y = crosswind distance from source to receptor

5 Field studies

5.1 Crushers

These sources are handled as volume sources as shown in the following figures.

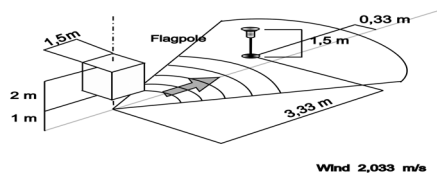


Figure 2: Volume source as handled by the ISC3 Model.

The results of the sampling procedure are summarized in the following table. The emission rate in order to obtain the sampled concentration in the sampling position is 40,77 mg/s.

Table 1.

Unsampled weight filter (1h)	0,0585 g
Sampled weight filter (1h)	0,0628 g
Air sampled volume	2,998 m ³
Standard Volume	2,966 m ³
Temperature	293,25 °K
Wind velocity	2,033 m/s
Dust concentration	1448,094 ug/m ³

5.2 Conveyor belts

In order to consider topographical features of the site we have considered adjacent volume sources at different heights. The sampling results are in the table, every single source is characterized by an emission rate of 2,21 mg/s.



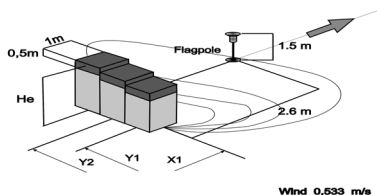


Figure 3: Line and uniform sources as handled by the ISC3 model.

The emission rate in order to obtain the sampled concentration ($1303,84 \text{ mg/m}^3$) is defined according to the inverse Gaussian form of the equation.

Table 2.

Unsampled weight filter (1h)	0,0583 g
Sampled weight filter (1h)	0,0615 g
Sampling time.	2,5 h
Air sampled volume	$2,499 \text{ m}^3$
Temperature	$299,15 \text{ }^\circ\text{K}$
Wind velocity	$0,533 \text{ m/s}$
Dust concentration	$1303,849 \text{ ug/m}^3$

5.3 Road dust emission

A receptor to characterize the emission of haul trucks has been defined in order to estimate this source type. This application creates a constant uniform distribution of emissions over this specified area. In real life this source is not uniform, but it is handled like a uniform one to obtain the measured concentration.

A first sampling has been carried out with a watered area while the second one has been carried out with the real conditions.

Table 3.

Dust mass	0,0014 g
Sampling time	3 h
Temperature	$300,81 \text{ }^\circ\text{K}$
Wind speed	$2,700 \text{ m/s}$
Dust concentration	482.91 ug/m^3

In case of area sources the rate emission is defined by surface unit $Q = 0,729 \text{ mg/s.m}^2$.

5.4 Two dimensional graph of dust concentration

The field data of each source was input into the ISC3 model to obtain a two dimensional map of dust concentration in the quarry itself (1,7 m flagpole).

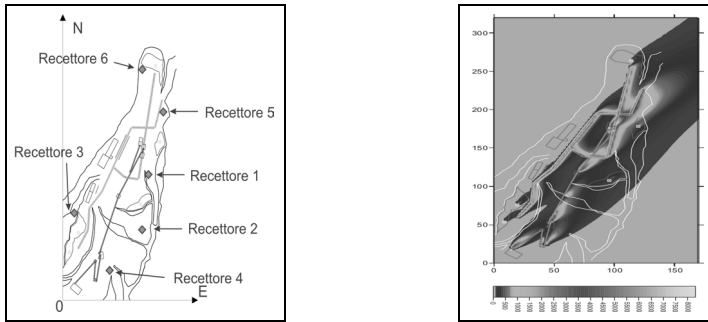


Figure 4: Receptors and complete simulation.

6 Geostatistical application

Geostatistics might be viewed as a methodology for interpolating data on an irregular pattern. Each data value is associated with a location in space and there is at least an implied connection between the location and the data value. It may be useful to introduce some geostatistical definitions for an exact interpretation of topics. In particular it is important to define:

6.1 Variogram

It is a geostatistical function used in characterizing the spatial variability of a local phenomenon.

Let S be a domain of definition of FA $z(x)$ and given x_0 and x_0+h a couple of S points h distant.

$[z(x_0 + h) - z(x_0)]$ is defined as a new variable called accretion, its half variance is for definition the variogram:

$$\gamma(x_0, h) = \frac{1}{2} \text{Var} \{ [z(x_0 + h) - z(x_0)] \} \quad (2)$$

The variogram estimation is realized according to experimental samples: it is shown the sampling points map on an irregular grid with different concentration values. As for stationary and semi-stationary functions, the accretion $z(x+h) - z(x)$ does not change, so the value to be calculated will be:

$$\gamma^*(h) = \sum_{i=1}^{N_R} [z(x_{i+r}) - z(x_i)]^2 \quad (3)$$

where: N represents the number of couples whose distance on X direction is r .

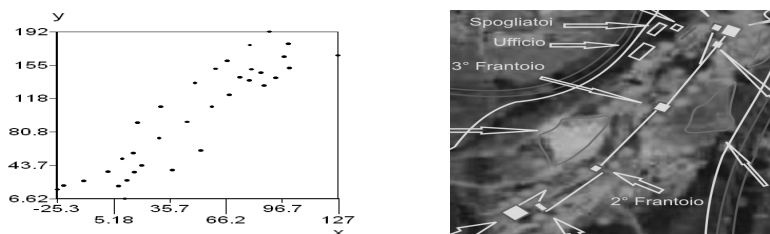


Figure 5: Input data grid and sampled points.

6.2 Model of regionalization

In order to create a variographic model, an experimental variogram of the C variable is realized. On such experimental evidence a model of two nested structures has been developed:

- Hole component
 - Period 57
 - Range 10
- Gaussian component
 - Range 110

In order to fit the theoretical variogram with two nested structures only one direction (0°) has been considered because of the phenomenon's isotropy.

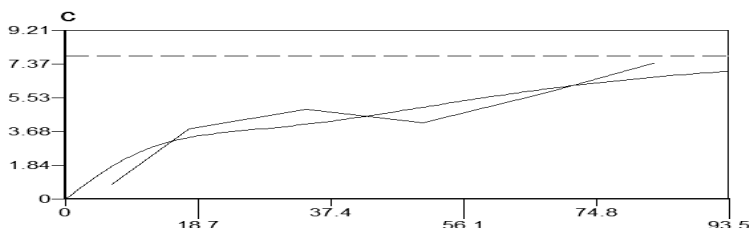


Figure 6: Variogram/model.

6.3 Linear approach in geostatistical analysis: Ordinary Kriging

$Z(x)$ is an aleatory stationary function used to study the phenomenon in a probabilistic way, and $C(h)$ and $\gamma(h)$ are covariance and variogram functions, respectively. N is the number of points required to estimate x_0 , x_α and $z(x_\alpha)$ are with $\alpha = 1, n$ respectively their position and their corresponding variable values. $Z(x_0)$ is the unknown value in x_0 , $z^*(x_0)$ is the linear estimator considered. It is showed in the following form

$$Z^*(X_0) = \sum_{\alpha=1}^N \lambda_\alpha Z(X_\alpha) \quad (4)$$

where λ_α are the coefficients of a linear combination

On this evaluation an associated estimation error, ε , is defined as the difference between the sampled value and the estimated value:

$$\varepsilon = Z(X_0) - \sum_{\alpha=1}^N \lambda_{\alpha} Z(X_{\alpha}) \quad (5)$$

However, it is also to be considered that

$$E \left[Z(X_0) - \sum \lambda_{\alpha} Z(X_{\alpha}) \right] = 0$$

$$\text{So} \quad \sum_{\alpha=1}^N \lambda_{\alpha} = 1 \quad (6)$$

An important parameter to evaluate estimation quality is that of considering estimation variance, defined as

$$\sigma_s^2 = 2 \sum_{\alpha} \lambda_{\alpha} \gamma(x_{\alpha} - x_0) - \sum_{\alpha} \sum_{\beta} \lambda_{\alpha} \lambda_{\beta} \gamma(x_{\alpha} - x_{\beta}) \quad (7)$$

In order to obtain the best estimation, it will be necessary to minimize the estimation variance so:

$$\frac{\partial \sigma^2}{\partial \lambda_{\alpha}} = 0 \quad \forall \alpha = 1, n$$

With the exactness condition the system becomes:

$$\begin{cases} \sum_{\beta} \lambda_{\beta} \gamma_{\alpha\beta} + \mu = \gamma \\ \sum_{\beta} \lambda_{\beta} = 1 \end{cases} \quad \forall \alpha = 1, n \quad (8)$$

The associate estimator is called Kriging and the system is called **Kriging system**. The coefficient's matrix does not depend on entity to be estimated but they are exclusively dependent on the sampled points position and on variographic function.

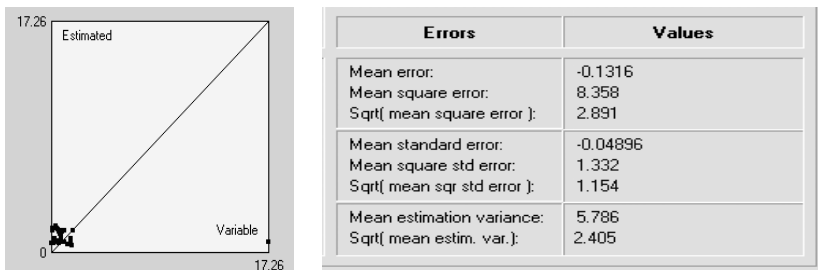


Figure 7: Scatterplot and error table.

6.4 Cross validation

The model has been tested using a cross validation method called “leave one out”. This methodology estimates the variable’s value in the known points and provides to delete from time to time the measured value. The error’s report is shown below and geostatistical analysis is then completed according with the evaluation of scatterplot estimated/sampled values.

6.5 Multivariate approach

Co Kriging is an interpolation technique that allows one to use a more intensely sampled covariate in the estimation of values for a related variate. Because of the primary variate ($L_{EQ(A)}$) correlation with a more available covariate (L_p at different emission frequencies), the Co Kriging technique is developed in order to improve interpolation estimates.

Let $Z_{i0}(x_0)$ be the value to estimated, the Co Kriging estimator $Z_{i0}^*(x_0)$ becomes

$$Z_{i0}^*(x_0) = \sum_{i=1}^{NV} \sum_{\alpha=1}^{n_i} \lambda_{\alpha}^i z_i(x_{\alpha}) \quad (9)$$

The set of weights λ_{α}^i can be defined according to the following two conditions:

Correctness condition

$$E[Z_{i0}^*(x_0)] = E[z_{i0}(x_0)]$$

that becomes

$$m_{i0} \sum_{\alpha=1}^{n_{i0}} \lambda_{\alpha}^{i0} + \sum_{i \neq i_0} m_i \sum_{\alpha=1}^{n_i} \lambda_{\alpha}^i = m_{i0}$$

This equation is satisfied by the following conditions

$$\sum_{\alpha=1}^{n_{i0}} \lambda_{\alpha}^{i0} = 1 \quad \text{and} \quad \sum_{\alpha=1}^{n_i} \lambda_{\alpha}^i = 0 \quad (10)$$

that together with the condition of minimizing estimation function

$$\sum_{j=1}^{NV} \sum_{\alpha=1}^{n_j} \lambda_{\alpha}^j \gamma_{i,j}(x_k - x_{\alpha}) + \mu_i = \gamma_{ii_0}(x_k - x_0) \quad (11)$$

constitute the Co Kriging system.

6.6 Variogram and regionalization model

On experimental evidence it is developed a model based on one structure:

- Spherical component
 - Sill 5,25
 - Range 40



6.7 Estimation map

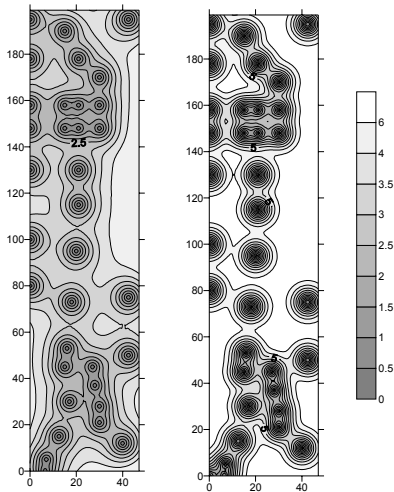


Figure 8: Estimation variance Map: Co Kriging (left)/ Kriging (right).

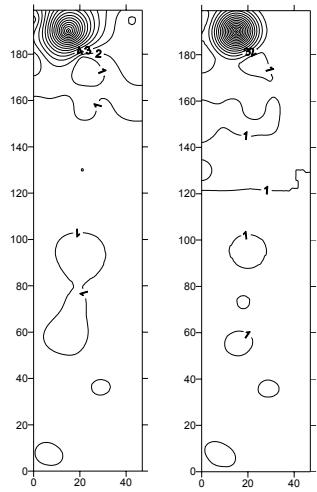


Figure 9: Concentration Map: Co Kriging (left)/ Kriging (right).

6.8 Cross validation

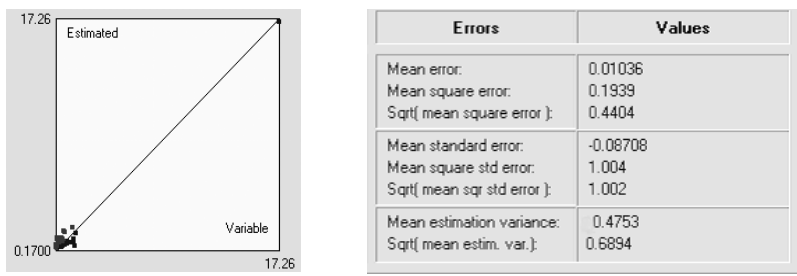


Figure 10: Scatterplot.

7 Testing both models

The final step is represented by the comparison between the ISC3 and the geostatistical approaches. These two sets of dust concentration values are tested according to the choice of six receptors in which samples are compared with the two model results. Two contour maps of the PM10 concentrations surrounding the quarry are shown. Data comparison shows the over prediction of PM 10 concentration by the ISC3 model (on the right). This result may occur because the model applies the total emission of mobile sources to a specific area source.

This application creates a constant uniform distribution of emissions over this area that does not correspond to the real case.

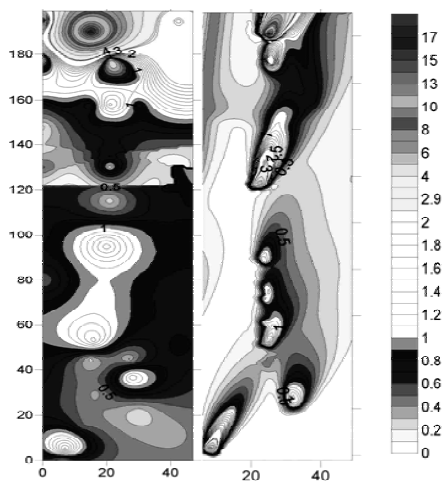


Figure 11: Comparison between estimation (left) and ISCST output (right).

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