A multicriterial geographical approach for the environmental impact assessment of open-pit quarries

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ABSTRACT: The paper shows an application of distribute modeling techniques using a GIS package, together with multicriteria analysis (MCA) for decision support, in the environmental impact assessment of asurface quarry in Tuscany. A comparison is drawn with more traditional techniques now widely in use, such as matricial lumped judgements, thus highlighting the advantages of coupling a geographical approach with MCA in order to minimize the bias due to subjective evaluation.

1 INTRODUCTION

In quarrying activities, strategic impact assessment (SEA) tools are not very commonly used at present. In addition, most environmental impact assessments[1], [2] use simple, synthetic matrix methods[3], strongly influenced by the subjective judgement of the analyst. According to a broad class of these methods, the impact score is assigned through a single score representing the judgement about the effects of an action on the environment. As a consequence, the full range of intensities of the effects, and their spatial distribution in the study area are lost[4].

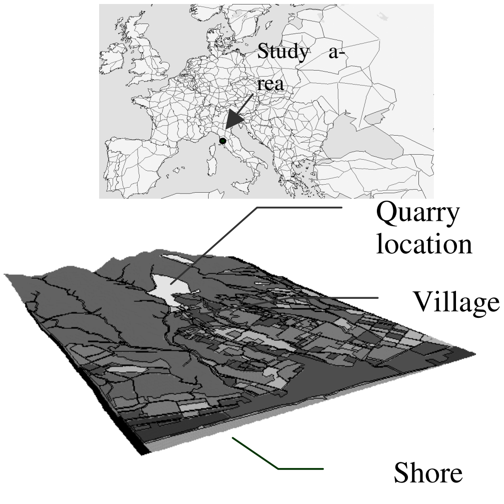


Figure 1

It seems a major issue to characterize the spatial features of the effects due to a quarry, both for a better choice of its location, and for the mitigation of its impacts in the areas where they're more intense, given a geographical location of the activity.

The advances in information technologies during the last decades have made widely available GIS tools that allow to cope with such spatial analysis issues, by forming up a spatial decision support system (SDSS). The construction of a SDSS asks for integration of [5]:

a) A database management system (DBMS);
b) A digital cartographical representation of data;
c) A mathematical model to describe all relevant physical phenomena deriving from choices assumed in the planning process.

Traditional distributed models try to describe reality through a set of complex differential equations to be integrated numerically (using i.e. finite element or finite difference techniques); on its side, GIS-based modeling uses close-form, simple mathematical relations, capitalizing on elementary spatial features of the variables, such as distance, contiguity, gradients and variations, within the conceptual and formal computing environment of map algebra[6].

2 DESCRIPTION OF PHYSICAL PHENOMENA, AND IMPACT ASSESSMENT

It seems pretty useful to point out that it is common practice to draw impact assessments directly based on the planned actions, while a more appropriate approach to impact assessments would require evaluation of the effects of such actions before defining their impacts on the environment. It is in fact quite clear that the evaluation of effects is very often easier to be achieved in objective, or at least shareable terms, while a more subjective judgement, also more difficult to be shared, lies in the assignment of impacts.

Table 1 shows the main effects of open pit quarrying activities on the environment, and helps to highlight how available methods for the description of these effects are quite limited in number, and in cases where no single 'objective' method exists also – as in economical evaluations-. It is relatively easy to achieve a shareable perspective of the actions on the effects themselves.

The judgement on impacts, on its side, always introduces subjectivity due to the ethical choices of the evaluators, the social context and political addresses of the decision makers, and the force equilibria between opposite parts. At present, it must be said that no single method can be indicated for optimal solution of multicriterial evaluation problems[7].

Figure 2

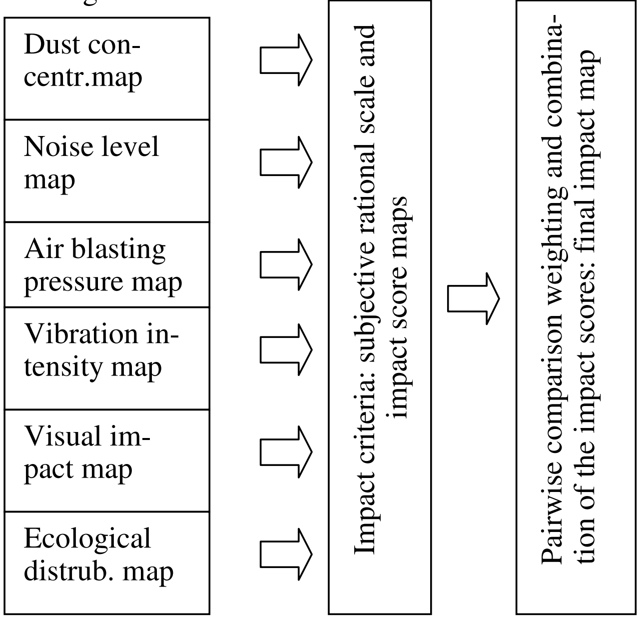


Table 1 – Physical effects of quarrying activities on the environment

Issue	Physical effects	Available methods for the description
Noise	Noise production by excavation and transport; air blasting	Empirical distance-based algorithms, analytical models or numerical integration of the wave equation (for non-impulsive sources); acoustical equivalence modeling for impulsive sources
Air pollution	Production and dispersion of particulate	Box models, gaussian models, lagrangian or eulerian integration of the dispersion-advection parabolic equation
Surface- and groundwater	Hydrological and hydromorphological effects; increase in sediment load to streams; potential pollution due to wastewater from mineral treatment plants	Empirical models(e.g. Universal Soil Loss Equation);mass balances; distributed physical models in hydrology; quality models in surface and groundwater (e.g. QUAL2E, MT3D)
Lithosphere	Slope instability in waste disposal and excavation sites, induced slope instability due to morphological modifications; vibrations	Geomechanical models for slope stability (probabilistic, deterministic); empirical vibration propagation models (es. IRSM)
Landscape perception	Visual impacts due to excavation fronts and plants	DTM analysis and viewshed extraction; projective geometrical analysis; photographic simulation and virtual reality
Landscape ecology	Ecological disturbance due to modifications in landscape pattern	Analysis of landscape ecological patterns and their modifications based on synthetic indicators;disturbance and resilience predictive modeling; multicriterial transformation evaluation
Socio-economics	Employment and socio-economical induced effects	Ad hoc analyses, descriptive statistics.
Stock of natural resources	Reduction of local stocks (soil, geomass, biomass…)	Mass balances, ad hoc evaluations

The environmental impact assessment case study hereby presented has been faced using:

- A set of descriptive-predictive models based on GIS analysis tools in order to define the effects of quarrying activities;
- A set of 'impact laws', in order to assign each pixel of the study area an impact score based on (subjective) judgement for each effect separately;
- A priority scale, so to assign weights of relative importance to the various elementary impacts. The weights are drawn from a pairwise comparison technique (Saaty [4]).

Figure 2 describes the overall flowchart of the study.

3 CASE STUDY DESCRIPTION

The above considerations have been kept in account during the construction of a decision support system for an open pit quarry in Tuscany, Italy. Such open pit produces limestone.

The excavation method (blasting the entire highwall lenght at one time with reversing of the highwall front) allows mitigation of the morphological impacts on the area (hilly region with elevation range 150-500 m a.s.l.), and to make progressive rehabilitation of the landscape possible during the excavation itself.

Physical effects of the excavation can be listed as follow: noise, dust, ground vibrations and air blast, visual impacts, landscape ecological disturbance. Figure 1 shows the general structure of the study.

3.1. Noise

The most relevant noise sources are the mineral treatment plant, the different material transport phases, both within the quarry and around the cable line used for transfering limestone to the railroad downslope, for further transport.

A noise level map has been computed from the LeqA (equivalent noise level according to the standard weighting curve A [8]) of each elementary source, taking in account the attenuations due to different environmental factors [8]: geometrical divergence, attenuation due to air, ground, and diffraction.

Equivalent noise level (dBA) is given by:

$$\mathrm{LeqA}\ [\mathrm{dBA}] = 10\log\left\{\sum_{i=1}^{n}\left[\sum_{j=1}^{8} 10^{0,1\left[L_{p(ij)} + A_{f}(j)\right]}\right]\right\} \quad (1)$$

Where:

n = n° of sources;

j = index for each of the 8 standard mean values of frequency (63 Hz - 8 kHz) [8];

A_f = weight according to curve A for frequency f [8];

Lp(i,j)= elementary pressure level.

Attenuation (dBA) is given by the sum:

$$\mathrm{Att} = \mathrm{Att}_1 + \mathrm{Att}_2 + \mathrm{Att}_3 + \mathrm{Att}_4 \quad (2)$$

where Att_1 represents geometrical divergence, Att_2 accounts for the effect of air, Att_3 gives the absorption of ground, Att_4 is used to take in account diffraction due to acoustical barriers. The following relations show:

$$\mathrm{Att}_1 = 20\log(r) + 11 \quad (3)$$

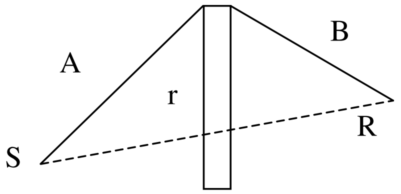
$$\mathrm{Att}_2 = a\, r/1000 \quad (4)$$

$$\mathrm{Att}_3 = \mathrm{Att}\,\sigma + \mathrm{Att}\,\mu + \mathrm{Att}\,\rho \quad (5)$$

$$Att_4 = 5 + 20\log\frac{\sqrt{2\pi|N|}}{\tanh\sqrt{2\pi|N|}} \quad (6)$$

Where r= geometrical straight line distance from the source, α = air absorption coefficient (dB/m), λ=wavelength (m); the terms in (5) depend on the distance from the source and can be found in all details in [8]; N is an index given by eq. (7) (where symbols refer to figure 3, representing a barrier between source S and receptor R, and A, B, r are segment lengths):

Figure 3



$$N = \frac{2}{\lambda}(A + B - r) \quad (7)$$

3.2. Dust production and dispersion

Dust production can be regarded basically as due to the movement of material in the quarry site and along the cable line from the quarry to the railway.

Dust distribution can be estimated using geostatistical techniques provided an appropriate number of sampling points and measures of dust concentration in air. For exploratory purposes, this case study chose to use literature values for dust production in cases very similar to the one in question. The estimates used for the case study are as follows: Highwall Removal- 80 kg/h; Material

Loading and Movement- 25 kg/h; Stockpiling Material- 0.0275 kg/h.

In a first approximation dust dispersion has been studied using a box model, in order to obtain screening level indication of the atmospheric dilution processes, using the following hypotheses:

- The system is assumed in simplified form as a regular volume of atmosphere where a mass input rate m_k of pollutant A_k is prescribed; the volume expands isotropically in all directions;
- Air in the volume is considered completely mixed (air density is constant, as well as dust concentration);
- Wind velocity u is constant, and directed perpendicular to one side which is long B (a first estimate of $u = 3$ m/s has been assumed on the basis of general meteoclimatological considerations over the area, while experimental surveys are being carried at present);
- Stationarity is assumed about overall fluxes of dust across the volume boundary (mass input rate equals gravitational deposition);
- There's no chemical reaction;
- Base level of dust concentration is zero.

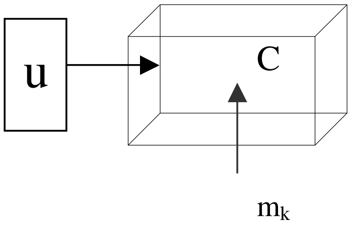


Figure 4

Computing for the volume in figure 2 the mass balance, and the concentration (in µg/m^3) results:

$$\rho_k = \frac{m_k}{u * B * H} \quad (8)$$

where B and H are the base side and the height of the volume, or mixing height (in m).

If we assign B as the distance from the source, and we assume the mixing height as H=100 m above ground surface (considering that meteorological surveys on atmospheric stability were not available for the case study), equation (8) allows us to evaluate, at a first screening level, the atmospheric dilution effect which dust is subject after production to.

It is apparent how the simple model discussed here leads to an isotropic prediction of dust concentration. This model needs to be replaced with a more detailed one, once data become available for a gaussian or higher approach.

3.3 Ground vibrations

According to most theoretical and experimental research, the best parameter representing the impact of vibrations is the maximum soil particle velocity at the structures' location. The maximum velocity criterion is assumed in many regulatory acts, as discussed in literature [10], and in the ISRM recommendations [11].

The experimental laws linking the distance from the explosion, and the mass of explosive in use, can be represented in exponential form as follows:

$$V_{\max} = K \cdot R^{-n} \cdot Q^{b} \quad (9)$$

Where:

- K, n, b are parameters depending on the kind of explosive, explosion geometry and rock type;
- R is the distance from the explosion (m);
- Q is the explosive mass (kg).

Many values have been proposed for b and n[10]. Using the "preset distance" parameter, eq. 9 can be rewritten as:

$$V_{\max} = K \cdot \left(\frac{R}{Q^{c}}\right)^{-b} \quad (10)$$

where R/Q^c is the preset distance, that will be indicated with D_s.

According to literature, c ranges from 0.33 to 1.

Existing regulations give the minimum safety distance R as a function of the preset distance D_s, and the explosive mass, Q:

$$\frac{R}{Q^{c}} > D_{s} \quad (11)$$

Coefficients K and b can be expreimentally valuated or taken from literature. Table 2 gives the values of K and b assumed for each velocity vector component, in the case of hard limestone.

Land can be classified according to land use, as in [13], so that a specific impact can be assigned to vibrations in dependence on the building type vulnerability.

3.4 Air blast

Explosions also generate air blast, which can be linked with high acoustic disturbance. Process analysis is very complex, and theoretical difficulties emerge in describing the sound pressure peak, due to the impulsive nature of the acoustic wave source, that makes the phenomenon clearly different from previously treated noise aspects. The following empirical equation has been proposed [14, 15, 16, 17]:

$$P = K \cdot \left(\frac{D}{\sqrt[3]{Q}} \right)^{-n} \quad (12)$$

Where:
P = instant noise pressure (Pa);
D = distance from explosion (m);
Q = instant explosive mass (kg);
K, n = experimental coefficients.

In this case study, it has been assumed that atmospheric conditions are isotropic. In reality, many different anisotropic atmospheric features can affect propagation. The topic is undergoing further research, but the needs of environmental impact assessment can justify the use of this simplified model.

Table 2 – Coefficients for the vibration velocity equation [12]

Velocity component	B	K
V_v	1,553	37,042
V_l	1,632	68,905
V_t	1,654	56,517

3.5 Landscape ecological disturbance

All previous phenomena have impacts over both the human and natural environment, but this section describes the specific effects given by the quarry on the spatial pattern of ecosystems in their landscape organization.

It has been chosen to evaluate an index (the Btc index, [18]) representing a measure of resistance stability of the landscape, prior and posterior to the quarry excavation. The Btc index, expressed in Mcal/m^2/year, can be computed from site specific biomass measures, respiration and primary gross productivity. For exploratory analysis the Btc index has been computed from literature values suggested for mean conditions in the most common ecological settings of southern Europe [18]. It must be reminded that site specific surveys at an initial qualitative analysis level might allow for a better index characterization according to a simplified methodology [18-bis].

Another point was to cope with gradual variation of the index across the ecological patch boundaries in the landscape. This has been managed with by dividing the patches into a core and a buffer, and prescribing a linear variation of the index between two adjacent patch values. In this way, a Btc map prior and posterior to the quarry has been computed, and the Btc value variation has been assumed as an indicator of the impact.

3.6 Visual Impacts

Visual impacts have been evaluated from the ratio between the total area of the quarry visible from each point, and the human visual field in the direction of the quarry. The total visible area of the quarry has been computed through a viewshed analysis [19], after dividing the quarry front into constant height vertical stripes, and summing up for each pixel the indicator variable (0/1) derived from the viewshed analysis and referred to all stripes, weighted with the area of the stripe. The human visual field has been computed by assigning standard visual angles and using the distance of each point from the quarry.

4 EVALUATION AND COMBINATION OF THE IMPACTS

There is no unique rule to move from the indicators of impact (the intensity of the phenomena) to the impacts themselves. In this study, it has been chosen to assign conventional impact values to specified thresholds of the phenomenon intensity value, and to link these points in the (intensity, impact) plane with an 'impact law' [20]. Impact values have been assigned individually for each phenomenon in a scale ranging between 0 and 10.

As a general rule, the score 10 is assigned to regulatory values, since regulations for the phenomena in study are drawn keeping the safe side, thus assuming that being close to the limits gives rise to impacts but not yet to risk. The score 5 is assigned to guideline values and the score 0 is given to null intensity of the phenomenon. In cases where no reference regulation is available, or thresholds are senseless, the overall values have been normalized into the range 0-10.

As an example, the impact assessment of the dust production is reported. Italian regulation [21] gives the quality thresholds referred to dust concentration in atmosphere, that amounts for dust to 50 (guideline value) and 150 (imperative limit value) ug/mc, respectively.

Impact scores are assigned considering that dust concentration values should not overpass the guide value (50 $\mu g/m^3$), assumed already present in the atmosphere.

Table 3 – Impact indexes for dust concentrations

Impact index (y)	Dust concentration due to quarrying works($\mu g/m^3$)	Presumed total concentration ($\mu g/m^3$)
0	0	50
5	50	100
10	≥ 90	≥ 140

The impact scores assigned to relevant points are:

- Concentration =0 ug/mc: impact score= 0
- Concentration =50 ug/mc: impact score= 5
- Concentration ≥ 90 ug/mc: impact score= 10

As noticed here, impact is maximum when concentration approaches the imperative limit value. The scores between two points have been drawn using the best-fit linear regression curve over the points. In the specific case, the impact law assigning the score y to concentration x is:

$$y_p = 0.0003 \cdot x^2 + 0.0861 \cdot x \quad (13)$$

All elementary impact scores have been computed in an analogous way.

The overall impact has been extracted via weighted sum of the scores, using the Analytical Hierarchy Process [23] multicriteria decision analysis technique, performed as well known via pairwise comparison of alternatives.

According to this approach, a reciprocal matrix is constructed, assigning to position (i, j) an integer value between 1 and 9 (Table 3) according to relative importance of impact i over impact j. When impact j is more important than impact i, position (i, j) receives the reciprocal of position (j, i). For the case study, the matrix is shown in table 4.

It can be shown [22] that the vector of weights is the normalized eigenvector associated to the only non-zero eigenvalue of the matrix, that was in this case $\lambda_{max} = 6.1378$

The obtained weights are:

- Noise: 0.1630;
- Dust: 0.0816;
- Air blast: 0.0500;
- Vibrations: 0.0326;
- Visual Impacts: 0.4271;
- Ecological Disturbance: 0.2457.

In order to check for the consistency of the judgement, the consistency index can be computed [22]: this must be less than 1 and as close to 0 as consistency increases. In case this index is greater than 1, inconsistencies in the judgement cannot be disregarded and the matrix must be re-examined. The consistency index for the matrix shown in table 6 is μ = 0.0276, that is a very low value. The pairwise comparison technique has been chosen among the many existing multicriterial methods because of its simplicity and the possibility to get an easier and wider agreement of the stakeholders in this elementary stepwise judgement, with respect for other alternative ranking methods.

5 THE USE OF IMPACT INDEXES IN DECISION MAKING

The aim of an environmental impact assessment is to detect critical areas of the region where the effects of the project are more intense. A major issue is the use of impact indicators in driving the design of mitigative actions and their location.

This allows to chose, on a participative and negotiative basis, the more sustainable alternative and its implementation modalities. In this attitude, the simulation of the material phenomena deriving from different actions allows us to draw the indicators for many design alternatives.

Figure 4 shows the mitigation of impacts obtained with the construction of a noise and visual barrier, and is the result of the previously described computations, including in the input data the presence of the barrier itself.

Table 4 – pairwise comparison impact scores

Level of importance	Definition
1	Same importance
3	Moderately higher importance
5	Higher importance
7	Very higher importance
9	Absolute predominance
2,4,6,8	Intermediate values

6 CONCLUSIONS

The use of GIS based modeling techniques for impact assessment supports optimal exploitation of:

a) Knowledge of distributed parameters;
b) Predictive modeling of the different case-specific phenomena.

GISs form the ideal computing environment due to their capability in the management of distributed variables through the simple conceptualizations of map algebra, rather than sophisticated and detailed data- exigent numerical models [24].

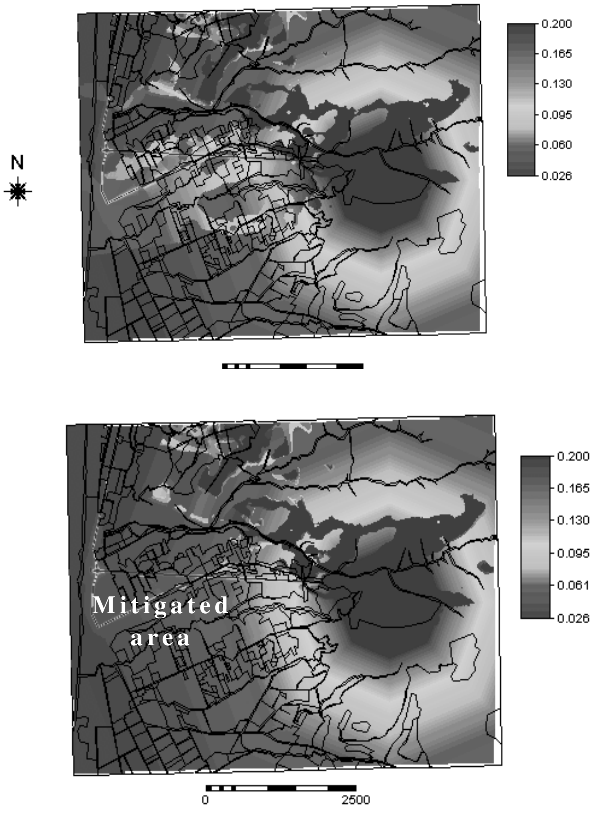
Table 5 – pairwise comparison reciprocal matrix

	Noise	Dust	Air blast	Vibrations	Visual Impacts	ecological disturbance
Noise	1	3	4	5	1/4	½
Dust	1/3	1	2	3	1/5	1/3
Air blast	¼	1/2	1	2	1/7	1/5
Vibrations	1/5	1/3	½	1	1/9	1/7
Visual Impacts	4	5	7	9	1	2
ecological disturbance	2	3	5	7	1/2	1

Further improvements in the case study here presented will concern the integration in the procedure of a more complex algorithm for dust dispersion.

At present, the procedure allows a complete description and characterization of the impacts of a quarry over its context, and it constitutes an expert-system-like environment in which further improvements can be easily integrated in an open and easily adaptable structure which is conceived as a support for social negotiation and rational discussion of the alternatives both at a technical and a political level.

Figure 4



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