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INDUSTRIAL ECOLOGY: AN APPLICATION OF GIS AND QUANTITATIVE COMMUNITY METHODS FOR THE ANALYSIS OF INDUSTRIAL PATTERNS

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Abstract. In modern industrial societies, all development must be planned in the light of its probable impact on the environment. In this context, industrial ecology has evolved with the aim of studying the interactions between industry and basic environmental systems in a systematic way. This paper aims to demonstrate how Geographic Information Systems and certain spatial pattern analysis methods, namely the nearest-neighbour and spatial autocorrelation techniques, can be used to assess the dynamics of industrial systems, facilitating industrial planning and environmental control.

Introduction

It is evident that in modern industrial societies, human activity is interacting with basic environmental systems in a way never before experienced. It is in this context that industrial ecology (IE; Graedel 1994) has evolved as a branch of ecology with the specific aim of systematically analyzing these interactions. The best way to define industrial ecology is by way of analogy to traditional ecology. Within both industrial and natural ecosystems, each process or network of processes is viewed as an interrelated part of a larger whole. In other words, manufacturing processes are not performed in isolation from their surroundings but are influenced by them and, in turn, have their own influence on the environment.

Ecology has shown that sustainable ecosystems have cyclic processes rather than linear ones. On the contrary, many present-day industrial processes, being essentially dissipative, follow linear models, in which materials are degraded, dispersed and lost. Industry is under pressure to move away from this linear model towards cyclicity in order to achieve sustainable development. Industrial ecology is intended to facilitate this by offering tools for managing industrial development. For practical and economic reasons, it is impossible to achieve complete cyclicity in a short time. For this reason, it is necessary to develop an integrated system useful for planning industrial development in such a way as to control as far as possible industrial pollution. The use of Geographic Information Systems (GIS) and spatial pattern analysis should be implemented to help with industrial siting and to measure and control the impact that industrial activities should have at different territorial levels. GIS is by definition "a technology designed to capture, store, manipulate, analyse and visualize the diverse sets of georeferenced data that are required to support accurate modelling of the Earth's environmental processes" (Goodchild et al. 1993). However, GIS is also a technology for integrating data coming from different sources such as data bases and maps. It is in the context of industrial ecology that GIS has been applied in this paper by implementing certain spatial pattern methods used in ecological community analysis (Feoli & Orlóci 1991). The aim of this paper is to show how the GIS can be integrated with external packages of data analysis to test the aggregation pattern of industrial typologies, and how it can be used to assess a system useful for environmental control based on the knowledge of the spatial arrangement of industries.

Materials and methods

The study area

Sampling was carried out in the administrative area of Monfalcone, which has an area of 20.2 km^2 and a population of 27000. This area falls within the province of Gorizia in the Friuli-Venezia Giulia region (North-East Italy). The area is bounded by the Adriatic Sea in the south, the River Isonzo in the west and the Carso hills and the River Timavo in the east. The area is flat and it constitutes the most eastern part of the Friulan plain.

Monfalcone, as well as being a busy port, is the industrial centre of the province of Gorizia. Central to the industrial development of the area have been an important shipyard, established in 1907 and currently employing 1876 workers, an engineering company specialising in the manufacture of electric motors and an oil and coal-fired power station producing 976 MW, which represents a considerable source of potential pollution.

Data set and GIS

The data set, relating to 1993, consists of the location coordinates, the number of employees, the activity and seven principal factors of internal risk of 73 factories. The technical regional map (1:25000) was used as a geographic reference system. For the environmental control assessment, the following risk factors of the industries are considered: chemicals, noise, dust and fibre, smoke and steam, solvents, temperature, and electrical fields. A digitized map of the sewer network of the principal outlets used both for civil and industrial waste was considered in order to relate water pollution to the position of the industries. Chemical-physical analyses of water samples, taken periodically by the local environmental control body along the coast and the internal canals close to the discharge points, were used to show how the GIS can be used to assess the pollution levels in the area. In this specific case the output of GIS was interfaced with a statistical package (Altobelli 1996) to perform the non parametric analysis of variance of Kruskal-Wallis.

For the creation of the GIS the software MapInfo 3.0 (MapInfo Corp. 1995) for Windows was used. The files of data for spatial analysis were created directly by means of the SQL (Structured Query Language) functions of the relational data base of MapInfo.

Spatial pattern analysis

The spatial pattern analysis of the factories was carried out by clustering their positions (latitude, longitude) based on Euclidean distance and average linkage method (program FIVEPA in Feoli & Orlóci 1991). The nearest-neighbour technique (Clark & Evans 1954, Ebdon 1977) and spatial autocorrelation technique (Cliff & Ord 1973, Ebdon 1977) using the program PATTERN (Ganis 1985) were applied to test the aggregation pattern of the factories and of the other data. The data for FIVEPA and PATTERN were provided directly by MapInfo.

In the case of the nearest-neighbour technique a positive index value indicates a dispersed pattern, whereas a negative value indicates a clustered pattern, the opposite in the case of the spatial autocorrelation index. The significance for both indices can be checked by reference to the table of critical values of a standard normal deviate (Z).

Results and discussion

GIS performance

Through the GIS it is possible to visualize the position of factories and their characteristics. The map in Figure 1 shows where the factories are located, as well as showing the results

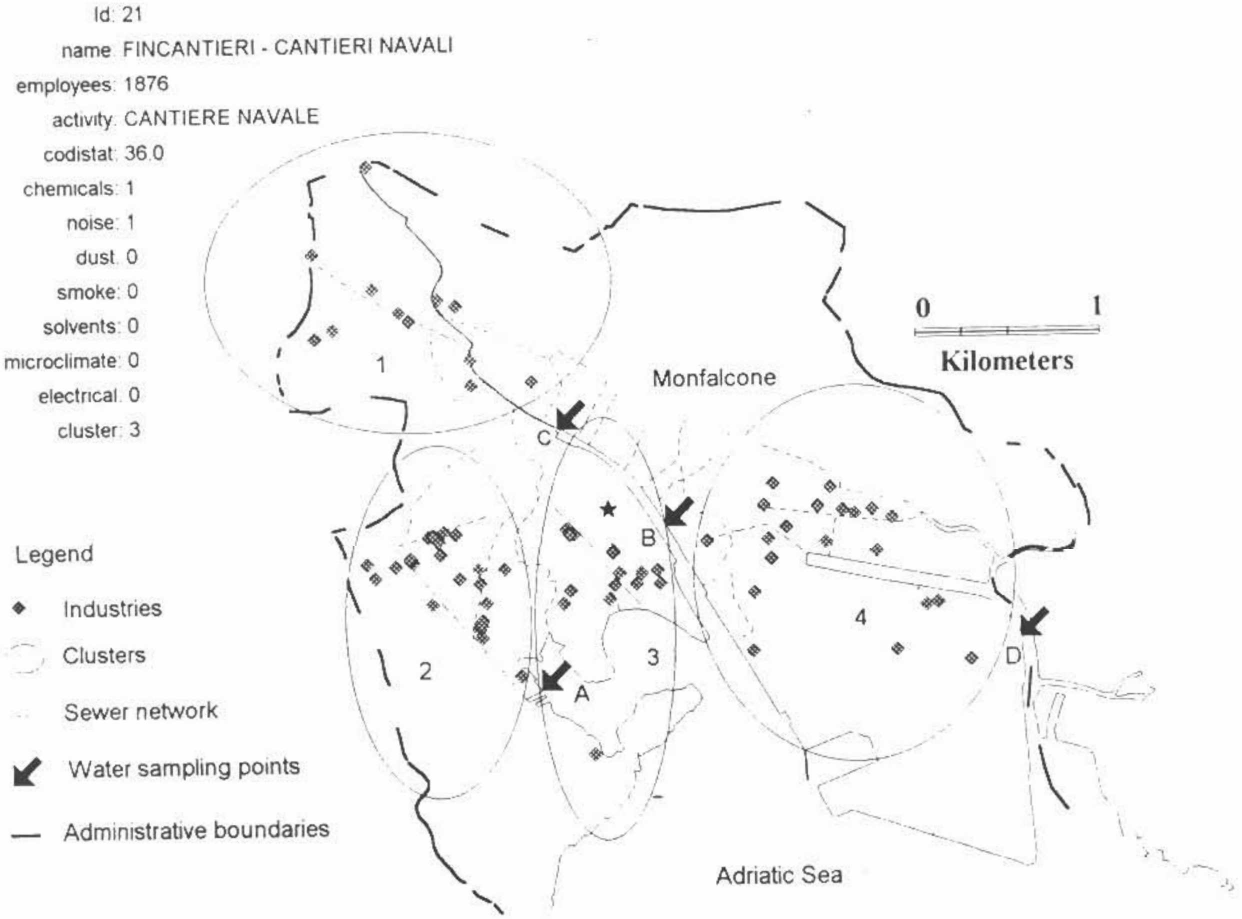

Figure 1. In the map the study area with the position of the factories is shown. On the left listed the parameters, stored in Mapinfo data base, relating to a selected factory (★).

Table 1. The most important types of industrial activity in the study area. The data given for each cluster refer to the number of employees and, in parentheses, the number of factories.

Industrial activity	Cluster 1	2	3	4	Total
Shipbulding	-	8 (1)	1876 (1)	12 (1)	1896 (3)
Engineering	32 (1)	543 (8)	450 (2)	-	1025 (11)
Metalworking	22 (3)	288 (9)	142 (4)	72 (4)	524 (20)
Port actvity	-	-	-	500 (1)	500 (1)
Power station	-	-	-	366 (1)	366 (1)
Plastics	-		-	208 (1)	208 (1)
Cereal processing	-	71 (1)	-	-	71 (1)
Other activities	28 (8)	73 (5)	91 (9)	207 (12)	470 (34)
Total	82 (12)	983 (25)	2559 (16)	1365 (20)	4989 (73)

of cluster analysis by ellipses, the sampling points for the chemical analysis of water (indicated by arrows) and the sewer network. In the lower window the information stored in the MapInfo data base regarding the factories is displayed.

In Figure 2, the distribution of factories with more than 50 employees is given as an example of another GIS facility, while Figure 3 presents an example of water pollution data stored in MapInfo.

Spatial pattern analysis of industrial factories

The spatial distribution of the 73 factories analyzed by the nearest-neighbour index shows a very significant clustered pattern (c = –15.5, 99% probability).

From the dendrogram obtained by applying cluster analysis, four main groups of industries, corresponding to four areas, are identified (Figure 1). The first group is located

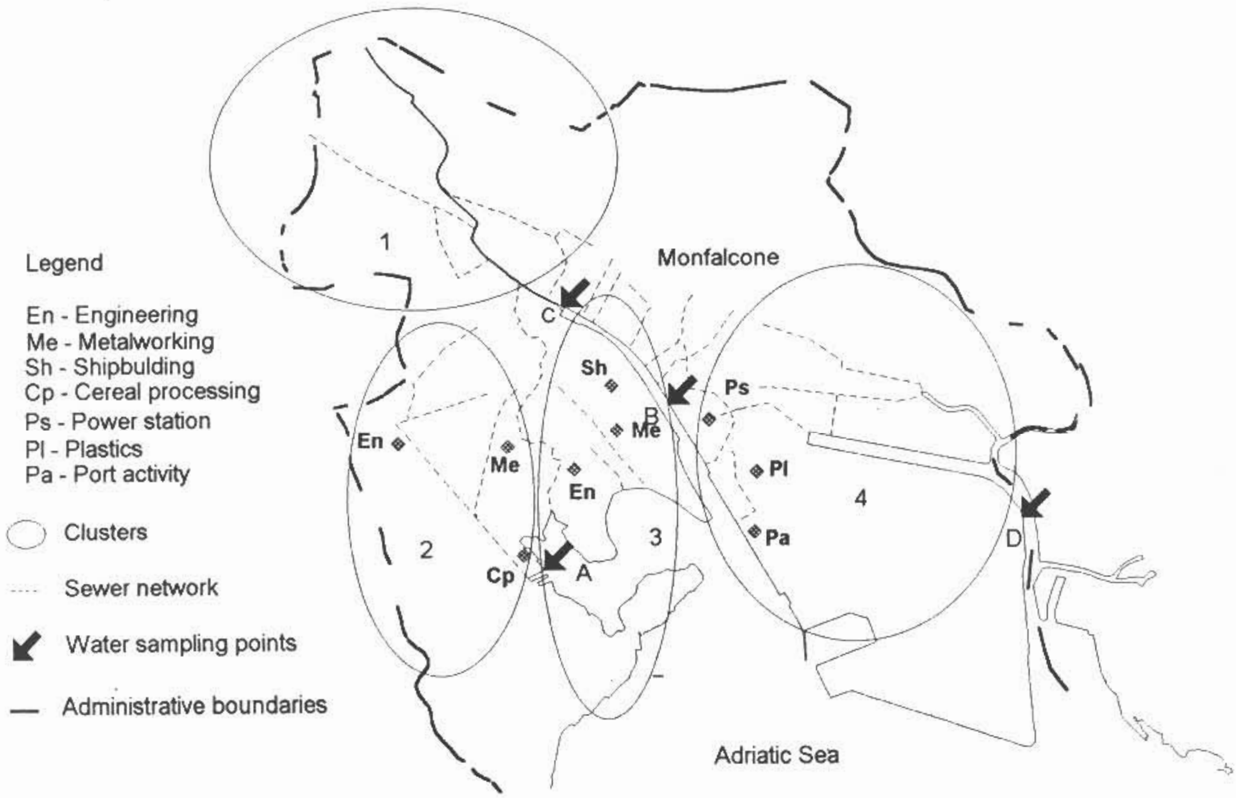

Figure 2. Distribution of factories with more than 50 employees.

Table 2. Spatial autocorrelation analysis for the seven factors of internal risk. If the value of z is greater than 1.645 (or –1.645) the result obtained is significative with 95% of probability.

Internal risk	z
Chemicals	-0.77
Noise	0.06
Dust and fibre	-1.32
Smoke and steam	1.23
Solvents	0.53
Microclimate	0.23
Electrical fields	0.05

the furthest inland and coincides with the residential part of the area, the second in an industrial zone not far from the sea and the third and fourth on the coast. The third and the fourth groups are divided only by a canal. The spatial distribution of the industrial workforce ($Z = -0.041$), which is an indirect measure of the dimensions of an industry, indicates that in the total area there is no clustered pattern of this parameter.

The four clusters obtained by cluster analysis evaluated according to the type of industrial activity are described in Table 1, where the most important types of industrial activity in the area are listed.

From Table 1 it can be seen that the companies belonging to cluster 1 are all small enterprises. Cluster 2 is characterized by engineering and metalworking companies. Cluster 3 is characterized by the shipyard. In cluster 4 there is the port, the power station and a chemical company manufacturing plastics.

The spatial autocorrelation index applied to the most frequently occurring industrial activities in the area, namely engineering and metalworking (Table 1), weighted by the number of employees, shows that both types of activity tend to have a clustered pattern. However the value is significant ($Z = 1.73$; 95% probability) only for the metalworking companies. The engineering companies, notwithstanding being concentrated in a single zone (cluster 2), do not form significant groups. In the case of the metalworking companies, on the other hand, there is a concentration of larger companies in the two central clusters (2,3), while small enterprises are concentrated in cluster 1 and medium-sized ones in cluster 4 (see Table 1).

Spatial pattern of the risk

The GIS allows us to show the pattern distribution of the risk associated with each industry. The spatial autocorrelation analysis applied to the seven factors of risk occurring

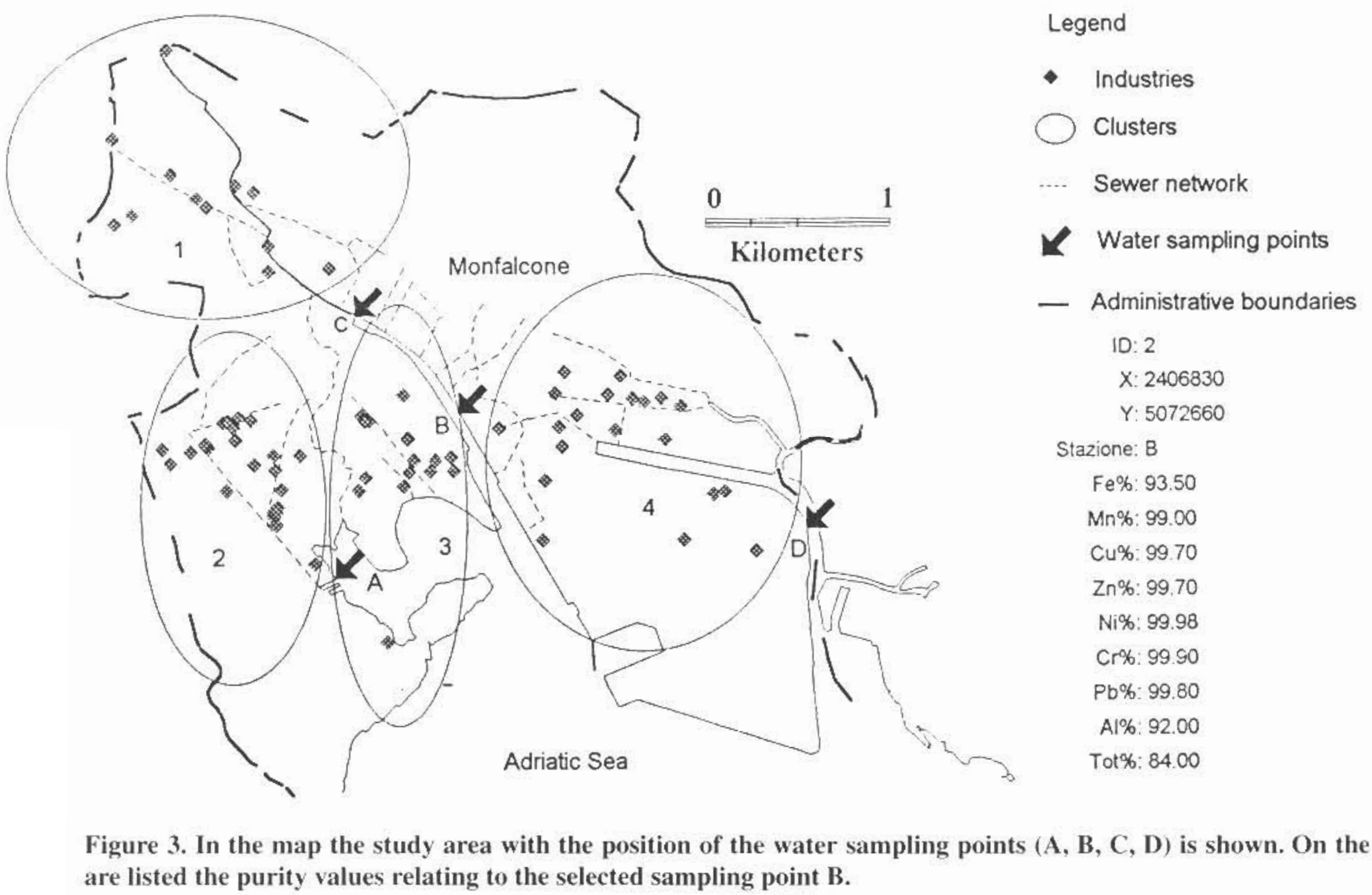

Figure 3. In the map the study area with the position of the water sampling points (A, B, C, D) is shown. On the rig are listed the purity values relating to the selected sampling point B.

Table 3. Results of Kruskal-Wallis Test (df=3) between the parameters relative to the four sampling points in three different periods (10/2, 30/6 and 10/11/93). The results in bold are significant. MS = material in suspension. OS = oily substances. FR = fixed residue. TU = turbidity, BOD = biochemical oxygen demand.

Parameters	T°	MS	FR	TU	pH	O_2	BOD	Al	Cr	Fe	Mn	Ni
Chi-square	0.58	4.02	**8.43**	3.50	**8.90**	5.77	3.77	2.08	0.97	1.02	4.46	2.00
Parameters	Pb	Cu	Sr	Zn	Cl	SO_4	F	P	PO_4	NH_4	NO_3	OS
Chi -square	1.37	5.20	8.13	4.50	**9.39**	**9.36**	5.28	6.76	5.30	**9.88**	7.42	5.64

Table 4. Average values and the corresponding purity indices of the parameters that are considered indicative of industrial pollution, relative to the sampling points (A, B, C, D) in Figure 3.

METALS	A		B		C		D	
	mg/l	Purity %	mg/l	Purity %	mg/l	Purity %	mg/l	Purity %
Iron (Fe)	0.043	95.70	0.065	93.50	0.088	91.20	0.074	92.60
Manganese (Mn)	0.006	99.40	0.01	99.00	0.011	98.90	0.021	97.90
Copper (Cu)	0.007	99.30	0.003	99.70	0.0007	99.93	0.004	99.60
Zinc (Zn)	0.002	99.80	0.003	99.70	0.004	99.60	0.001	99.90
Nickel (Ni)	0.0001	99.99	0.0002	99.98	0.0001	99.99	0.003	99.97
Chromium (Cr)	0.001	99.90	0.001	99.90	0.0004	99.96	0.0009	99.91
Lead (Pb)	0.0009	99.91	0.002	99.80	0.001	99.90	0.0009	99.91
Aluminium (Al)	0.03	97.00	0.08	92.00	0.09	91.00	0.06	94.00
Total	0.09	91.00	0.16	84.00	0.20	80.00	0.16	98.00

most frequently (Table 2) demonstrates no significant pattern.

Surface water pollution assessment

Having defined the position and the aggregation pattern of the factories it is possible, by the analysis of the sewer network, to identify the water sampling points corresponding to each group of industries.

The non-parametric analysis of Kruskal-Wallis for the pollution differences is presented in Table 3. Significant differences were found only for parameters that are not strictly related to industries. In Table 4 the average values of the parameters that, according to the international standard, are considered indicative of industrial pollution, and the corresponding purity index are given. The purity index is calculated by subtracting the concentration of a metal (or metals), present in water samples, from 1 and multiplying this value by 100 to produce a percentage; pure water having the value of 100%.

From this table it appears that the total purity index is lower for sample point C which receives pollution from group 1. This means that in this study area the small industries, distributed in the residential area, are more dangerous than the bigger industries located in specific industrial areas where they are forced to use systems for reducing the emission of pollutants in the water.

Conclusion

The analogy between ecology and industrial ecology should not be confined to the production process of a single factory, but should be extended to the industrial system that can be developed in a specific area. The industrial system has to be seen as an assemblage of different kinds of enterprises, as the ecological community is seen as an assemblage of different species. Each type of industrial enterprise should be interpreted as a species niche while an industrial system of a specific area should be interpreted as a community niche (Feoli et al. 1988). Consequently, all the techniques that have been developed in community analysis can be applied to industrial ecology. The industrial system interpreted as an ecological system is a dynamic entity: as the species composition can change in a community according to successional or other trends, the typology of an industrial system can change owing to changes in technology and changes in market demand. Like ecological systems, industrial systems also follow different trajectories in the multidimensional space defined by technological, economical and environmental variables (Tewolde 1981).

This paper shows that GIS can be used to describe the pattern of an industrial system and also its environmental impact. GIS can be applied to all the methods of community ecology to assess the dynamics of industrial systems and is therefore an indispensable tool for developing industrial ecology.

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