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Utilizing multiobjective analysis to determine an air quality monitoring network in an industrial district

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Abstract

An industrial district with polluting factories operating inside poses a potential threat to the air quality in the surrounding areas. Therefore, establishing a proper air quality monitoring network (AQMN) is essential for assessing the effectiveness of imposed pollution controls, strategies, and facilities in reducing pollutants. The geographic layout of such an AQMN should assure the quality of the monitored data. Monitoring stations located at inappropriate sites will likely affect data validity. In this study, a multiobjective approach was explored for configuring an AQMN for an industrial district. A dispersion model was employed to simulate hourly distribution of pollutant concentrations in the study area. Models optimizing pollution detection, dosage, coverage, and population protection were established. Alternative AQMNs with varied station numbers and spatial distributions were obtained using the models. The resulting AQMNs were compared and evaluated for effectiveness in monitoring the temporal and spatial variation of pollutants. Discussion of the differences among the AQMNs is provided. This multiobjective analysis is expected to facilitate a decision-making process for determining an appropriate AQMN.
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1. Introduction

Air pollutants emitted from factories located in industrial districts are potentially hazardous to surrounding environments, affecting human health, materials, agriculture, forestry, etc. Establishing a proper air-quality monitoring network (AQMN) to evaluate the spatial and temporal distribution of pollutants and the effectiveness of pollution control

strategies at industrial facilities is critical to ensure the health of the residents and environment in the area surrounding an industrial district.

The effectiveness of an AQMN depends primarily on the suitability of monitoring sites. Unsuitable sites cannot effectively reflect the characteristics of pollution. In the early days, monitoring site planning was done based on empirical judgment or simple qualitative rules, such as distance of polluters to neighboring residential areas and population density. Systematic approaches were developed in the 1970s. For instance, Nakamori et al. (1979) designed a monitoring network to obtain the best

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estimation of overall mean pollutant concentrations. Graves et al. (1981) adopted detection and protection capabilities as the major objectives in designing an AQMN. Noll et al. (1977) applied statistical analyses in developing a planning method for an AQMN by targeting large point pollution sources, while detecting violations of air-quality standards was used as the primary objective. Noll and Mitsutomi (1983) further proposed a dosage index in designing an AQMN. Most studies have considered only a single objective. Such designs may be flawed. For example, if detecting violations of air-quality standards is used as the primary objective, monitoring stations would likely be located the leeward of the prevailing wind direction, and, thereby, be unable to determine the spatial and temporal variations of airborne pollutants. Although increasing the number of monitoring sites enlarges coverage area, cost also increases. Therefore, properly locating monitoring sites using a multiobjective model for AQMN planning is potentially a superior approach.

In a previous multiobjective study, Modak (1985) planned an AQMN for Taipei City, Taiwan, based on the objectives of maximum coverage and maximum violation detection for monitoring single and multiple pollutants. Trujillo-Ventura and Ellis (1991) proposed a model using the objectives of spatial coverage, violation detection, and data validity, and a weighting method was applied to find the most suitable network. Arbeloa et al. (1993) established a multiobjective planning method for AQMNs based on a hypothetical case and attempted to find the optimal solution based on a utility function. Although these studies considered multiple objectives, their models are not directly applicable for planning an AQMN for an industrial district. For example, if detection of maximum average concentration is the primary objective, then monitoring sites would likely be over-concentrated, located around the high average concentration spots. Other objectives, such as maximizing population coverage, should also be considered when resident safety is a concern. The multiobjective mixed-integer programming model proposed in this study utilizes four objectives: maximum detection capability of pollution potential, maximum dosage detection capability, maximum detection area, and maximum population protection.

Given that wind speed and directions vary over time, these uncertainties should be taken into account. Therefore, this study used the ISCST3 (USEPA, 1995) model to simulate pollutant distributions of under hourly wind fields for a whole year in order to assess the uncertainty in pollutant distribution affected by wind speed and direction. Based on the results obtained from the simulation model and multiobjective models established, this study compared the effects of various objectives on selection of monitoring sites in a case study, with the intention to devise a suitable monitoring network and to demonstrate the applicability of the established model.

2. Multiobjective model development

Potential zone, detection coverage areas, and meteorological uncertainty are first explained. Description of the applied models, with objective formulations and relevant constraints, then follows.

2.1. Potential zone

A monitoring site is generally located where it can best measure the pollution distributions. Given that pollutants spread throughout the atmosphere, surface pollutant levels between a location and a pollution source have a distribution relationship as depicted in Fig. 1 which shows different potentials of pollution for the areas surrounding a pollution source. Noll et al. (1977), who pointed out that a monitoring station should be located in a potential zone, defined such a zone as having pollutant concentrations larger than 90% of the maximum. However, the maximum concentration of a plume can be excessively high, and by taking 90% of the maximum to define a potential zone may exclude some other potential areas. Therefore, as shown in Fig. 1, this study demarcated detection areas based on concentrations greater than 100 ppb, the domestic standard limit for daily average concentration of SO_x.
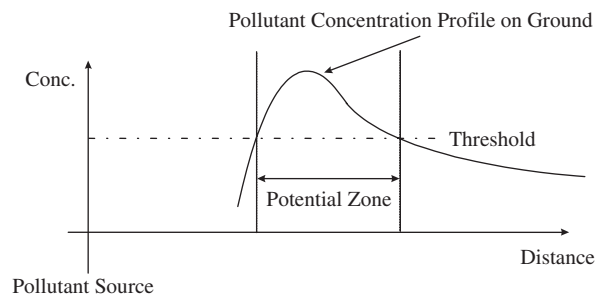

Fig. 1. Potential zone.

2.2. Detection coverage areas

According to the method described by Modak (1985), the detection area covered by a monitoring site can be determined using the spatial correlation analysis (SCA). The SCA is based on the pollution correlation coefficient between a monitoring site and a covered location. If the correlation coefficient is higher than a pre-defined cut-off value, the location is considered as correlated and is covered. The correlation coefficient is computed as follows:

$$R_{mj} = \frac{\sum_{i=1}^{n}(C_{mi} - \overline{C_m})(C_{ji} - \overline{C_j})}{\sqrt{\sum_{i=1}^{n}(C_{mi} - \overline{C_m})^2 \sum_{i=1}^{n}(C_{ji} - \overline{C_j})^2}}, \tag{1}$$

where m is the index of a monitoring site under evaluation for its coverage, j is a location index under evaluation, i is the index of a concentration data pair and n is the number of data pairs, C_{mi} and C_{ji} are the concentrations of data pair i at the monitoring site m and the location j, respectively, and $\overline{C_m} = (1/n)\sum_{i=1}^{n} C_{mi}$ and $\overline{C_j} = (1/n)\sum_{i=1}^{n} C_{ji}$ are the average concentrations at the monitoring site m and the location j, respectively.

By applying this relationship, the detection area covered by a monitoring site can be defined as an area in which the correlation coefficients between the site and the locations in the area are higher than a cut-off value. This approach was also applied by Liu et al. (1986), Langstaff et al. (1987), and Arbeloa et al. (1993) to determine coverage areas.

2.3. Meteorological uncertainty

Wind speed and wind direction are meteorological factors that vary significantly. Pollutant distribution in the atmosphere varies under different meteorological conditions. Fig. 2 shows the annual windrose diagram for the study area. Wind speed and directions change markedly in different months, which imposes some uncertainty on the distribution of pollutants. This study employed whole-year hourly meteorological and wind field data in simulations. These data were also utilized to assess the efficiency of the planned monitoring network based on simulation results.

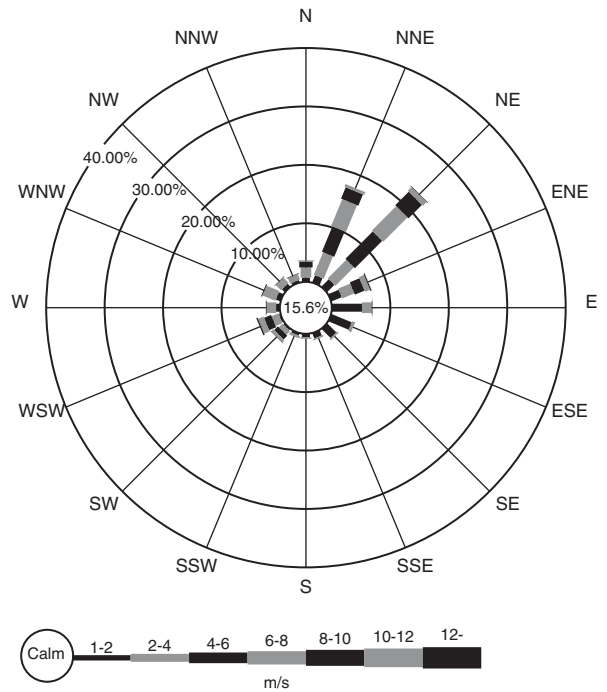The multiobjective model in this study is based on four objectives. The following subsection defines the

Fig. 2. Windrose for the study area.

objectives and describes how the relevant models were established.

2.4. Maximum detection capability (DC)

Detection capability is defined as the number of significant plumes captured by an AQMN. The zone of each plume is defined according to the aforementioned potential zone, a set of land grids with pollutant levels exceeding the threshold value of 100 ppb. The model, based on this objective, is established as follows:

$$\text{Max } o_{\text{DC}} = \sum_{i=1}^{I} d_i \tag{2a}$$

S.T.

$$d_i \leqslant \sum_{j \in M_i} y_j \quad \forall i, \tag{2b}$$

$$0 \leqslant d_i \leqslant 1 \quad \forall i, \tag{2c}$$

$$\sum_{j=1}^{J} y_j \leqslant Q, \tag{2d}$$

$$y_j = [0, 1] \quad \forall j, \tag{2e}$$

where d_i is the variable indicating whether plume i is detected, y_j is a binary integer that indicates whether a monitoring site is placed in grid j, M_i is the set of grids in plume i with a pollutant level greater than the threshold of 100 ppb, and Q is the upper limit of the number of monitoring sites in an AQMN.

2.5. Maximum dosage detection capability (DDC)

Some areas may have a low incidence of high-level pollution but a large dosage due to long-term exposure. Thus using the previous objective, DC, alone when planning an AQMN may be inadequate for assessing long-term exposure. The objective and the model for maximum dosage detection capability can be formulated as follows:

$$\text{Max } o_{\text{DDC}} = \sum_{j=1}^{J} \left(\sum_{i=1}^{I} C_{ij} \right) * y_j \qquad (3)$$

S.T. same as constraints (2d) and (2e) where C_{ij} is the pollutant level at grid j of plume i.

2.6. Maximum detection area (DA)

When planning an AQMN, one major goal is to cover the maximum detection area with a minimum number of monitoring stations. The total detection area can be defined as follows:

$$a_1 \cup a_2 \cup \cdots \cup a_j \cup \cdots \cup a_Q, \qquad (4)$$

where a_j is a site's detection area as defined using the SCA (Modak, 1985) method. When the detection areas of monitoring sites do not overlap, the total detection area is greater than when they overlap. The model established based on this objective can be presented as follows:

$$\text{Max } o_{\text{DA}} = \sum_{j=1}^{J} t_j \qquad (5a)$$

S.T.

$$t_j \leqslant \sum_{j \in N_j} y_j, \qquad (5b)$$

$$0 \leqslant t_j \leqslant 1 \quad \forall j, \qquad (5c)$$

same as constraints (2d) and (2e) where N_j is the set of grids in which the detection area of each such grid, if a monitoring site is established at the grid, can cover grid j, and t_j is the variable indicating whether grid j is covered.

2.7. Maximum population protection (PP)

Population protection is an important objective when developing an AQMN. The model based on this objective is as follows:

$$\text{Max } o_{\text{PP}} = \sum_{j=1}^{J} P_j * y_j \qquad (6)$$

S.T. same as constraints (2d) and (2e) where P_j is the total population within grid j.

2.8. The multiobjective model

Of these four single objective models described above, the DC and DDC ones can be applied independently. However, if either of the DA or PP model is used alone, the derived sites may fall outside the potential zone and, therefore, not detect the significant pollutant distribution. The DA and PP objectives should be used together with one or both of the DC and DDC objectives. A general multiobjective formulation for all objectives is expressed as follows:

$$\text{Max } W_{\text{DC}} o_{\text{DC}} + W_{\text{DDC}} o_{\text{DDC}} + W_{\text{DA}} o_{\text{DA}}$$
$$+ W_{\text{PP}} o_{\text{PP}}, \qquad (7)$$

where W_{DC}, W_{DDC}, W_{DA} and W_{PP} are the respective weights of the four objectives. The multiobjective model can improve the deficiency of considering only the DC or DDC objective. In the following section, the multiobjective model with varied weight-sets is applied in a case study for planning an AQMN for a local industrial district. Results obtained with varied weight-sets are discussed and compared.

3. Illustrative case

The study area is the Toufen Industrial District in Miaoli County, Taiwan. The district, originally planned as a petrochemical industrial zone, is 95 ha. Fig. 3 shows the major emission sources, modeling grids and meteorological monitoring station in the study area. There are a total of 58 major sources within the study area accounting for more than 90% of total emissions. Based on simulation results using the ISCST3 model (USE-PA, 1995), locations with high pollutant concentrations are situated mostly within a 5 km radius of the industrial zone. One purpose in setting up the industrial district is to facilitate the management,
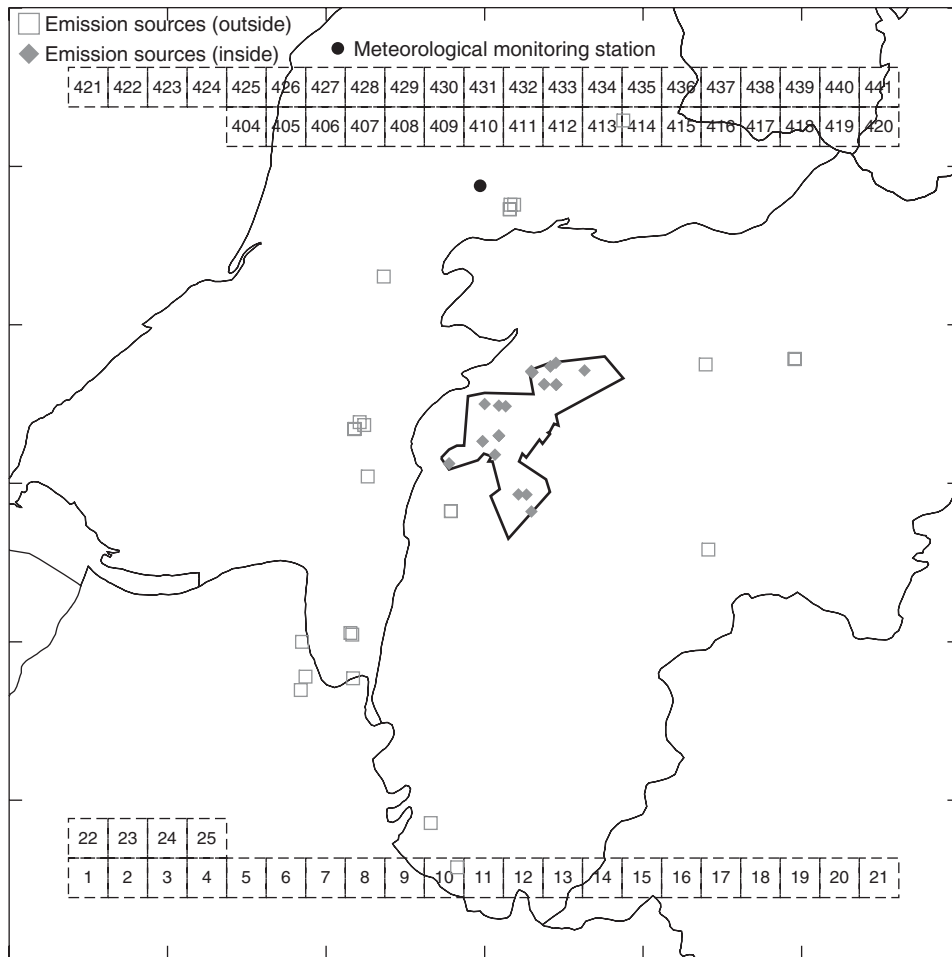
Fig. 3. Major emission sources, modeling grids, and meteorological monitoring station in the study area.

monitoring and control of pollution. However, at the Toufen Industrial District, some factories have not yet moved into the district, that is, some pollution sources are located outside the district. In light of this situation, this study addressed pollutant emissions based on two scenarios. The goal of Scenario I was to investigate possible distributions of monitoring sites under current source distribution. Scenario II only considered the sources inside the industrial zone to explore the planning of sites when the sources are all converged inside the zone. This study discusses the possible effects of different objectives on site selection results for these two scenarios.

To compare and analyze the differences in results obtained under different objectives, this study applied the following five test sets:

1. Constant cut-off value and single objective: to learn about the differences in solutions obtained with different single objectives.
2. Constant cut-off value, single objective and different numbers of monitoring sites: to investigate the performance of different monitoring networks with varied numbers of sites under the same objective.
3. Varied cut-off values and single objective: to analyze the effect of various cut-off values on site distribution.
4. Trade-off relationship between two objectives: to identify the trade-off relationship between two objectives by adjusting their respective weights.
5. Multiobjective results: to evaluate the effects of multiple objectives on planning a monitoring network by using several sets of weights for the multiple objectives.

4. Result and discussion

4.1. Constant cut-off value and varied single objective

Fig. 4(a) shows the distribution of sites under Scenario I using DC, DDC, DA, and PP as single objectives and under the constraints of cut-off value 0.8 and 5 sites. The values of objectives, the used single objective and others, for each solution are listed in Table 1. When DC or DDC is the single objective used, the selected sites are distributed in the southern region of the industrial zone. The region was selected because the prevailing north wind and northeastern winds in the area disperse the majority of pollutants south. However, a slight site distribution difference existed between the results for DC and DDC. This difference can be explained by the fact that some grids frequently exceeded the threshold, but their cumulative dosages were not high (e.g., grids 52 and 75), whereas some grids had few pollutant levels exceeding the threshold, but had high dosages in a few significant events. The cut-off value, which is mainly determined by numerical correlation, may not be related to the concentration level. Therefore, in a high-concentration area the correlation coefficient can be low due to substantial variations, and the detection area associated with the high-concentration area may, thus, be small.

Consequently, when the AQMN is planned based on the DA objective, sites may not be distributed in high-concentration areas. Furthermore, an AQMN design typically avoids overlap of detection areas, thus selected sites may not be located in high-pollution areas and fail to achieve the purpose of detection. These findings indicate that DA should not be considered alone, together with either DC or DDC, or both. When maximum population protection, the PP objective, is considered, sites were generally spread throughout the northern region of the industrial zone, which is close to significant concentration of residents. Similarly, using this objective alone cannot effectively measure pollutant sources and, therefore, it should be combined with DC, DDC or both during analysis.

In Scenario II, only the sources within the industrial district were considered. As illustrated in Fig. 4(b), the patterns of sites selected based on different objectives are similar but with some variation to those obtained for Scenario I.

4.2. Constant cut-off value, varied number of monitoring sites

Table 1 lists the results obtained for different single objectives and various limits on the desired
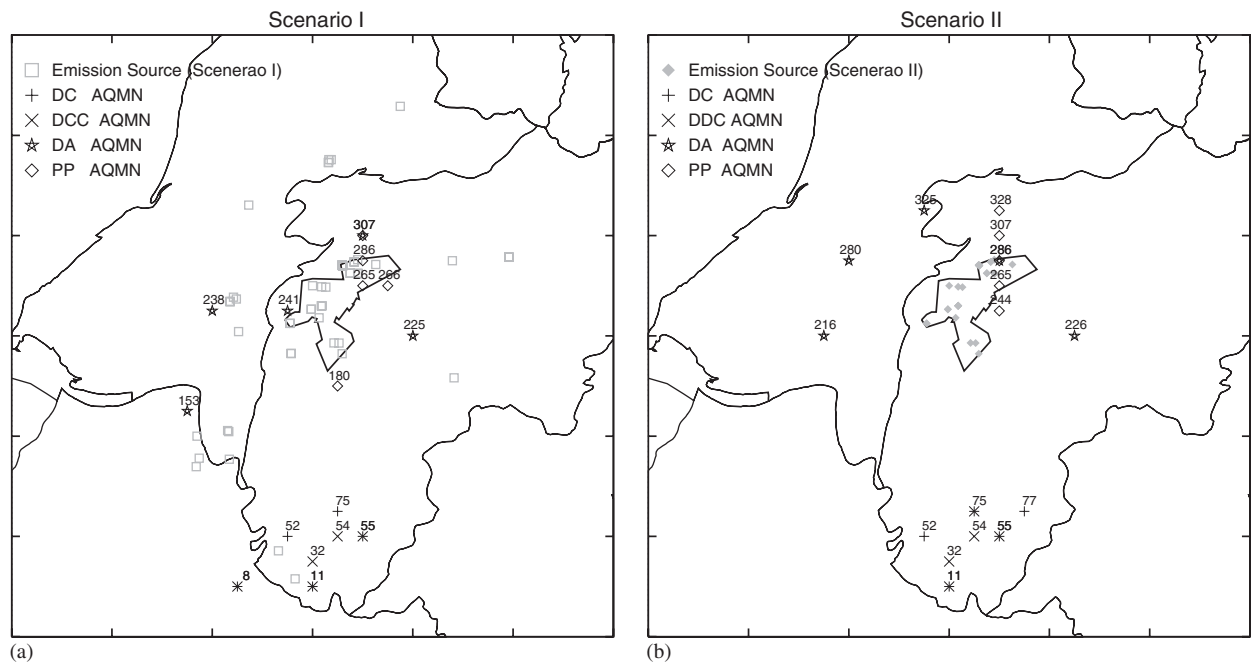

Fig. 4. Constant cut-off value (0.8) and varied single objectives.

Table 1
Results for cut-off value = 0.8, single objectives, varied numbers of stations

[#]	DC	DDC	DA	PP	Selected sites (grid numbers)
Scenario I					
Objective: DC					
4	2,256	495,214	4	408	8, 11, 55, 75
5	2,501	551,718	5	509	8, 11, 52, 55, 75
6	2,731	583,882	6	610	8, 11, 52, 55, 75, 77
7	2,907	634,428	7	711	8, 11, 52, 55, 74, 75, 77
Objective: DDC					
4	1,753	559,752	4	408	8, 11, 32, 54
5	2,112	653,787	5	509	8, 11, 32, 54, 55
6	2,576	735,127	6	610	8, 11, 32, 54, 55, 75
7	2,594	802,784	7	711	8, 11, 32, 34, 54, 55, 75
Objective: DA					
4	44	30,301	181	98,553	225, 238, 241, 307
5	83	46,963	213	104,416	153, 225, 238, 241, 307
6	118	53,870	238	117,496	132, 221, 225, 257, 301, 307
7	120	56,588	258	123,716	132, 221, 225, 257, 271, 301, 307
Objective: PP					
4	11	22,939	55	141,056	265, 266, 286, 307
5	61	39,570	55	175,462	180, 265, 266, 286, 307
6	61	42,797	58	209,593	180, 265, 266, 286, 307, 330
7	61	47,313	58	243,333	180, 265, 266, 286, 307, 328, 330
Scenario II					
Objective: DC					
4	1,805	385,225	4	404	11, 52, 55, 75
5	2,052	413,056	5	505	11, 52, 55, 75, 77
6	2,275	460,437	6	606	11, 52, 53, 55, 75, 77
7	2,426	578,284	7	707	11, 32, 52, 53, 55, 75, 77
Objective: DDC					
4	1,469	492,114	4	404	11, 32, 54, 55
5	1,928	572,613	5	505	11, 32, 54, 55, 75
6	1,989	642,270	6	606	11, 32, 33, 54, 55, 75
7	1,999	706,708	7	707	11, 32, 33, 34, 54, 55, 75
Objective: DA					
4	22	17,827	148	78,963	216, 226, 280, 286
5	22	20,864	178	94,043	216, 226, 280, 286, 325
6	35	28,365	204	98,828	173, 226, 257, 280, 286, 325
7	46	33,583	228	118,839	173, 226, 245, 257, 263, 280, 282
Objective: PP					
4	10	16,286	45	128,374	244, 265, 286, 307
5	10	19,419	45	159,874	244, 265, 286, 307, 328
6	10	22,281	45	191,233	244, 265, 286, 307, 328, 349
7	10	24,905	45	222,592	244, 265, 286, 307, 328, 349, 370

[#]Desired number of stations; DC: detection capacity; DDC: dosage detection capacity; DA: detection area; PP: population protection.

number of monitoring sites under a cut-off value of 0.8. The values of other objectives in each single objective solution were also computed and listed in the table. Generally, when few sites are desired, the marginally best one would be selected from candidates for each additional site. Such a greedy

characteristic was the primary reason why Modak (1985) and Arbeloa et al. (1993) employed the Minimum Spanning Tree method. However, as the number of monitoring sites increases, this characteristic is no longer applicable. For example, when DA is the objective, the best DA candidate may not

be the optimal choice, as its detection grids overlap with the DAs of sites already selected. Moreover, this greedy approach is not suitable when considering multiple objectives.

4.3. Varied cut-off values, single objective

The varied cut-off values mainly affect the DA size of a selected site. As DA changes, the size of PP and site distribution will be affected. Thus, the variation in cut-off values primarily affects the results obtained under DA and PP, and not those for DC and DDC. Therefore, only DA and PP are discussed here. Fig. 5 illustrates the site selection results under different cut-off values and a 5-station constraint. When DA is the objective, the results derived under both scenarios show dispersed distribution as the cut-off value decreases. When PP is the objective, Scenario I results obtained under cut-off values 0.9 and 0.8 are close, and are significantly different when the cut-off value is 0.7. This difference is due to significantly different detection areas derived from various cut-off values, thereby producing a different coverage of the population. Similar results are observed for Scenario II. As described earlier, using DA or PP as a single objective cannot effectively grasp the pollution picture, as the size of the effective coverage area and population size may have no specific relationship with pollution concentrations. Thus, it is crucial that DC and/or DDC also be factored in as well.

4.4. Trade-off analysis between two objectives

This study employed the NISE method proposed by Cohon (1978) to examine the trade-off relationship between two objectives. Fig. 6 depicts such trade-off relationships at a cut-off value of 0.8 and 5 sites. The results show that DC vs. DA, PP vs. DC and DA vs. DCC conflict. That is, to have one objective value better, the other objective must be sacrificed. Considering trade-off relationships can improve the quality of decision-making. Further analyses are required to find a compromise solution between two objectives. For example, a utility function can be derived, and then the compromise solution can be obtained by incorporating the trade-off curve. However, such a decision analysis process is beyond the scope of this work.

4.5. Multiobjective results

In the above analyses and comparison of results, one or two objectives were considered when determining solutions. When three or more objectives were considered, the analysis becomes complicated. In this study, several sets of weights are defined, as listed in Table 2. These weight sets are substituted into the multiobjective model to seek solutions. To ensure that the monitoring network can measure the background pollutant concentrations and function as a population protection tool, the following two constraints are added into the multiobjective model:

1. At least one site must be located in a densely populated area. This study defines population density > 5000 as densely populated areas, as shown in Fig. 7(a).
2. At least one site must be located in the background (not significantly affected by the industrial district). The cumulative concentration of each grid and that of the entire study area are calculated from the whole-year data of simulation. Grids are then ranked, and those with a cumulative concentration accounting for less than 1% of the total cumulative concentration of the study area are taken as background candidates, as shown in Fig. 7(a).

Fig. 7 illustrates the grids with high population densities, background grids, and partial typical results when considering multiple objectives. As influenced by the DC and DDC objectives, sites are located leeward (main pollution receiving area) of the sources as the number of sites increase. The solutions derived are similar under the cut-off values of 0.9 and 0.8, and are significantly different under a cut-off value of 0.7. This difference occurs because the detection area obtained with this cut-off value differs, to a certain extent, from that under the other two sets, which leads to different results in the calculation of PP and, hence, site selection. When the number of objectives increases, the complexity of the decision-making process also increases. It is necessary to weigh the compromise relationships between various objectives to decide an appropriate weight assignment.

5. Conclusion

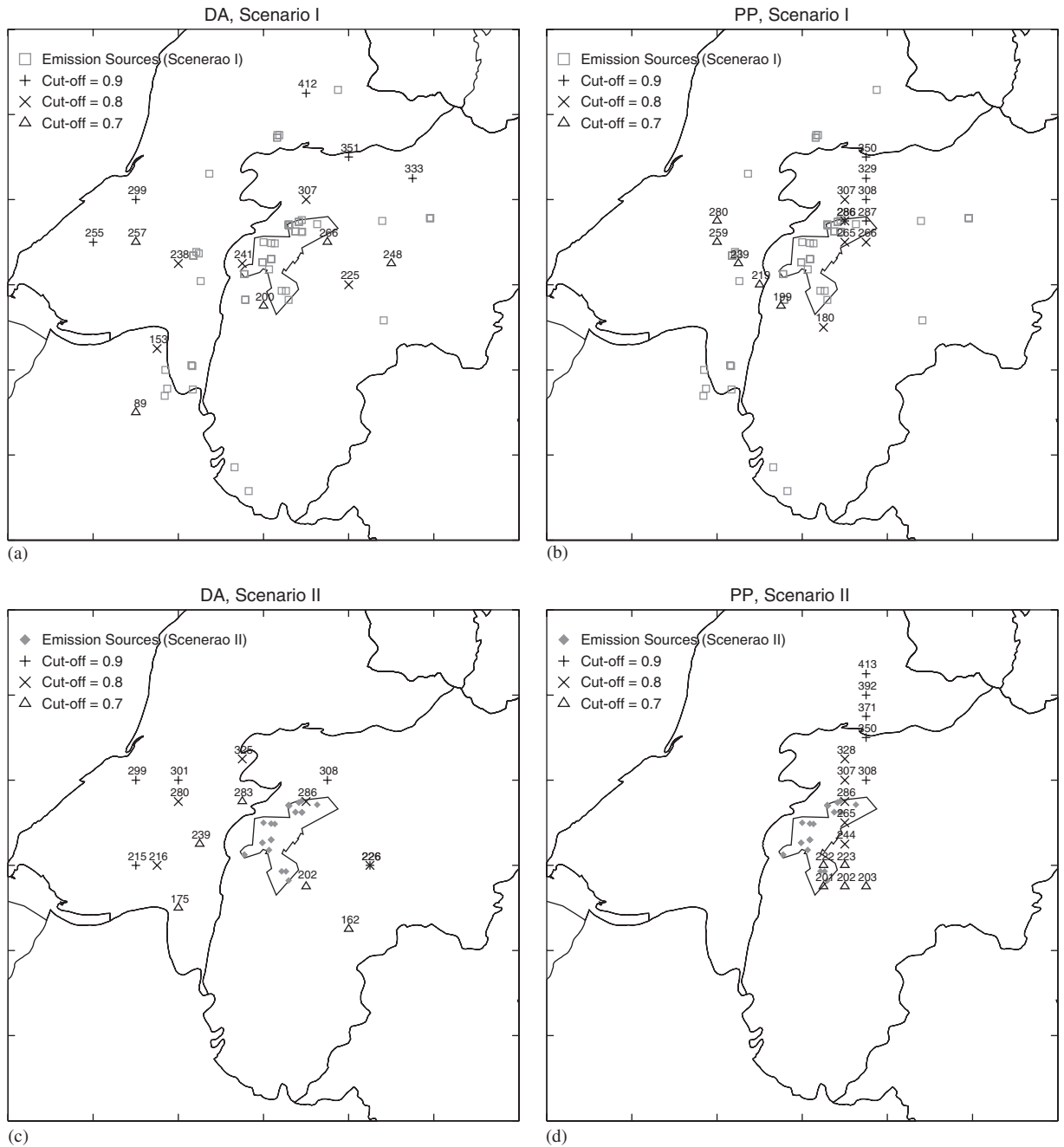This study proposed and demonstrated the effectiveness of a multiobjective model for selecting

Fig. 5. Varied cut-off values and single objectives.

proper sites to establish a suitable AQMN for assessing the temporal and spatial distribution of pollutants emitted from an industrial zone. Four objectives of DC, DDC, DA and PP as well as the uncertainty of wind velocity and directions were accounted for when developing the multiobjective model. By applying the model to the case of the local Toufen industrial zone, essential findings are summarized as follows:

1. When DC or DDC is the objective and determining the dominant pollution sources is emphasized, the resulting sites are spread mainly leeward of the prevailing wind direction. However,
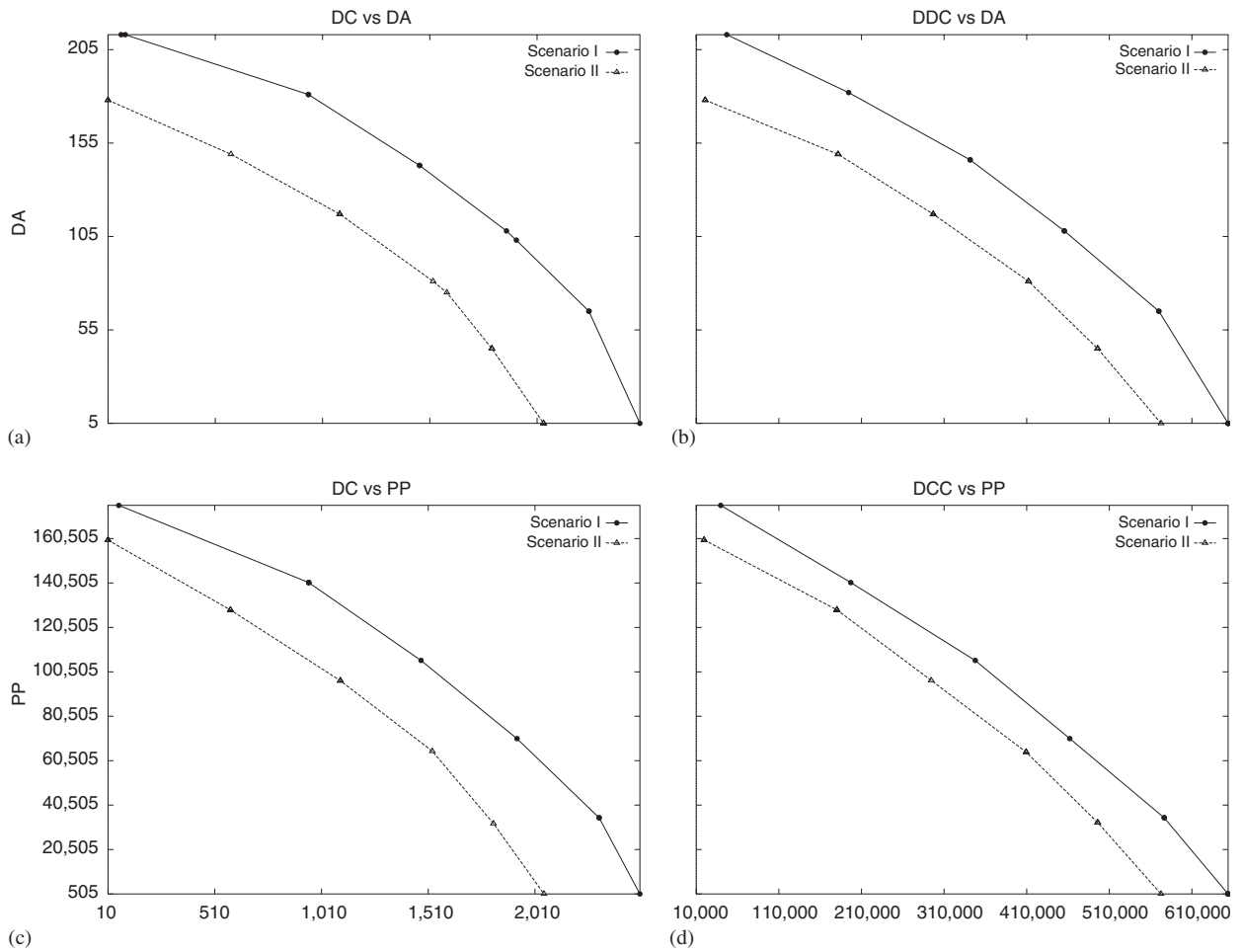
Fig. 6. Tradeoffs between objectives.

Table 2
Weight sets for tested multiobjective cases

Cases	DC	DDC	DA	PP
1	1	1	0.5	0.5
2	1	1	0.5	0
3	1	1	0.25	0.25

analytical results from the two models differed slightly because some areas may not have high cumulative dosages, even when their levels exceeded frequently the cut-off value and, in other cases, some areas may have levels that exceeded infrequently the cut-off value, but exposed to a relatively high cumulative dosage.

2. When only DA or PP is considered, the resulting network might cover a maximum detection area or protect the largest population respectively. However, both DA and PP solutions may fail to over

high pollution areas. Therefore, these two objectives should not be considered alone, but rather with DC or DDC or with DC and DDC together.

3. Based on analytical results obtained under different numbers of monitoring sites, when the number of sites is few, the sites obtained generally have a greedy characteristic. In such a case, a simple approach, such as the Minimum Spanning Tree suggested by Modak (1985) and Arbeloa et al. (1993), can be employed to find solutions. However, when the number of sites increases or the trade-off relationship between objectives is factored in, the greedy characteristic is eliminated, and an optimization model is appropriate for identifying a solution.

4. When different cut-off values are applied, the resulting site selections are similar to those obtained under the cut-off values of 0.8 and 0.9, and are significantly different under the
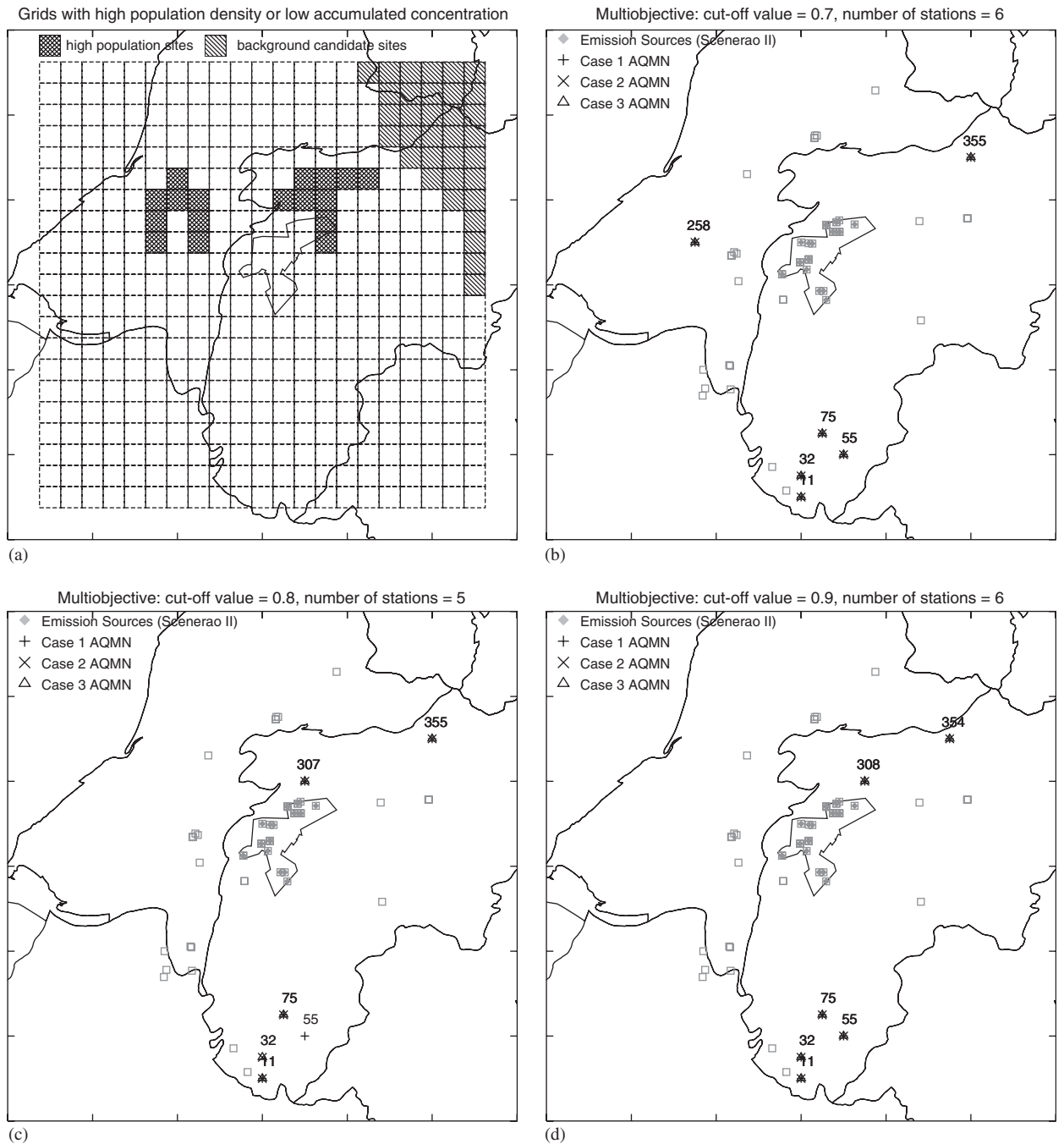
Fig. 7. Multiobjective results.

cut-off value 0.7. This difference stems from the fact that when the cut-off value is less than 0.8, the detection area of the sites increases substantially, thereby resulting in different solutions.

5. The two sets of objectives—DC or DDC vs. DA or PP—conflict, as illustrated in Fig. 6. That is, to get a better value for one objective, the other must be sacrificed. Thus the trade-off relationship between objectives should be considered in the decision making process to obtain the best compromise solution.

6. When multiple objectives are considered simultaneously, the weighted combination and interrelationship among objectives become complicated.

Thus, it is necessary to carry out a proper decision-making procedure to determine the proper weights of all objectives.

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