Statistical Approach for Environmental Problems
based on Spatial Structure

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1. Introduction
The increased level of interest is the concern in society for environmental issues and their relation to the health of individuals. It is important to investigate the areas of significant risk (hotspot) about the effect on the human health status to make early warning for infectious diseases and so on. Most environmental phenomena investigated by sampling geographic space have spatial components. The important role of statistical analysis for spatial data is to build a model and to make clear the structure of data based on spatial information. There are some typical problems of spatial analysis for geostatistical data, lattice data and point patterns. We focus on lattice data over a fixed subset $D$ of $d$-dimensional Euclidean space. We deal with the 0/1 event data over the entirety of a partitioned spatial region. Data can be collected directly within each region. These data are known as a kind of spatial epidemiological data, cellular data, irregular lattice data and so on. Several methods have been proposed to detect the hotspots areas. From the perspective of the spatial autocorrelation, Anselin (1995) proposed a local Moran's $I$ statistics which was able to locate spatial associations. Recently, the hotspot detection by scan statistics based on the likelihood ratio is a popular method. Kulldorff (1997) detected the hotspots, significant cluster (zone) for the lattice data, based on spatial scan statistic with Binomial and Poisson models. The circular window zone for scanning is defined around one lattice (county) seat. The zone consists of counties whose county seat exists within the circle. Thus we can only detect the circular cluster based on this circular scan. Echelon analysis (Myers et al. 1997) is useful to investigate the cellular surface analysis by systematically and objectively determining topological structure and change. The echelon dendrogram represents the surface topology of lattice data and hierarchical structure of these data. Regional features such as hotspots and trends are shown in an echelon dendrogram. The candidates of hotspots are given as the top echelon in the dendrogram, and some extended approaches are proposed for health and environmental data (Ishioka et al. (2007), Kurihara (2004), Kurihara et al. (2000, 2006), Myers et al. (2006), Tomita et al. (2008)). Therefore we can detect the hotspots of any size and shape for spatially aggregated lattice data based on proposed technique with spatial scan statistic and echelon analysis. The purpose of this paper is to classify any types of lattice data based on their spatial hierarchical structure and to detect the hotspots with regional features. In section 2, we explain the spatial scan statistics. In section 3, we introduce echelon analysis.
for some types of lattice data. In section 4, we demonstrate the proposed technique with some illustrations on environmental and epidemiological data.

2. Spatial Scan Statistics

The spatial scan statistics is a test statistics to detect the areas with significantly high or low rates. There is one area $Z$, which is a subset of whole area $G$. Individuals within area $Z$ have population probability $p_1$ of the attribute, whereas the population probability for individuals outside of the area $Z$ is $p_2$. The probabilities for all individuals are mutually independent. The null hypothesis is $H_0$: $p_1 = p_2 = p$, and the alternative hypothesis is $H_1$: $p_1 > p_2$, then we have a high attribute rate in an area $Z$. Let $n(G)$ be the total population in whole area $G$, and $n(Z)$ be the population within area $Z$. The $c(G)$ is the total number of attributes in all of area $G$ and $c(Z)$ is the number of the attributes within area $Z$. Then we consider the model based on the Poisson distribution. The probability of the study area is given by

$$f(Z) = \exp[-p_1n(Z) - p_2(n(G) - n(Z))]
\frac{[p_1n(Z) + p_2(n(G) - n(Z))]^{c(G)}}{c(G)!}.$$  \hspace{1cm} (2.1)

The density function $f(x)$ of a specific point being observed at location $x$ is

$$f(x) = \begin{cases} 
\frac{p_1n(x)}{p_1n(Z) + p_2(n(G) - n(Z))} & \text{if } x \in Z \\
\frac{p_2n(x)}{p_1n(Z) + p_2(n(G) - n(Z))} & \text{if } x \not\in Z
\end{cases}.$$  \hspace{1cm} (2.2)

We can therefore write the likelihood function as

$$L(Z, p_1, p_2) = \exp[-p_1n(Z) - p_2(n(G) - n(Z))]
\frac{[p_1n(Z) + p_2(n(G) - n(Z))]^{c(G)}}{c(G)!}
\prod_{x \in Z} \frac{p_1n(x)}{p_1n(Z) + p_2(n(G) - n(Z))}
\prod_{x \not\in Z} \frac{p_2n(x)}{p_1n(Z) + p_2(n(G) - n(Z))}.$$  \hspace{1cm} (2.3)

$$= \frac{\exp[-p_1n(Z) - p_2(n(G) - n(Z))]\prod_{x}n(x)}{c(G)!} \frac{1}{p_1^{c(Z)} p_2^{c(G)-c(Z)}} \prod_{x \not\in Z} n(x)$$

To maximize the likelihood function (2.3), we calculate the maximum likelihood function conditioned to area $Z$. The maximum likelihood estimator $\hat{p}_1 = \frac{c(Z)}{n(Z)}$ and $\hat{p}_2 = \frac{(c(G)-c(Z))}{(n(G)-n(Z))}$ are substituted.
The likelihood ratio $\lambda(Z)$ is maximized over all subset areas of whole areas to detect the hotspots.

$$\lambda(Z) = \text{Max } L(Z) / L_0 = \frac{\left(\frac{c(G)}{n(G)}\right)^{c(G)} \left(\frac{c(G) - c(Z)}{n(G) - n(Z)}\right)^{c(G) - c(Z)}}{\left(\frac{c(G)}{n(G)}\right)^{c(G)}}.$$  \hfill (2.5)

Here, $L_0$ is the following likelihood function under the null hypothesis.

$$L_0 = \sup_{p} \frac{\exp[-p n(G)]}{c(G)!} p^{c(G)} \prod_{x_i} n(x_i) = \frac{\exp[-c(G)]}{c(G)!} \frac{c(G)}{n(G)} \prod_{x_i} n(x_i).$$  \hfill (2.6)

The test statistics $\hat{\lambda}(Z)$ is also written as

$$\hat{\lambda}(Z) = \left(\frac{c(Z)}{e(Z)}\right)^{c(Z)} \left(\frac{c(G) - c(Z)}{e(G) - c(Z)}\right)^{c(G) - c(Z)},$$  \hfill (2.7)

where $e(Z)$ is the expected value of the attribute within area $Z$, and $e(G)=c(G)$. An area $Z$, where the value of $\hat{\lambda}$ becomes the maximum, is suitable as the hotspot.

3. Echelon Analysis

3.1 Basic idea

The echelon approach aggregates the areas in which the values have identical topological structure and produce a hierarchically related structure of these areas based on connective (neighbor) information among cells. One-dimensional spatial lattice data has the position $(i)$ and the value $h_i$ on the horizontal and vertical lines, respectively. For $D_1$ divided lattice (interval) data, data are taken at the interval $l_i(i) = (i-1,i), i=1,2,\ldots,D_1$. Table 1 shows the 25 intervals named from A to Y in order and their values (e.g., A=1 and Q=7).

| i | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 |
|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| ID| A | B | C | D | E | F | G | H | I | J | K | L | M | N | O | P | Q | R | S | T | U | V | W | X | Y |
| h(i)| 1 | 2 | 3 | 4 | 5 | 4 | 3 | 2 | 3 | 4 | 5 | 6 | 5 | 6 | 5 | 6 | 7 | 6 | 5 | 4 | 3 | 2 | 1 | 2 | 1 |

At first, we define the neighbor information of spatial lattice data $l_i(i)$, say $NB(i)$. The $NB(i)$ indicates the spatial positions between each cell, and it is given by
We can make the cross sectional view of topographical map like Figure 1, based on $NB(i)$ and value of each cell. There are nine numbered parts with same topological structure in these hills. These parts are called echelons. These echelons consist of peaks, foundation of peaks and foundation of foundation. The numbers $1, 2, 3, 4$ and $5$ are the peaks of hills. The numbers $6$ and $7$ are the foundations of two peaks. The number $8$ is the foundation of two foundations. The number $9$ is the foundation of foundation and peak and also called as the root. The graphical representation is given by the following dendrogram shown in Figure 2.

Figure 1: The hypothetical set of hillforms in one-dimensional spatial lattice data.

Figure 2: The echelon dendrogram for one-dimensional spatial lattice data.

3.2 Echelon analysis for two and three dimensional spatial lattice data

Two dimensional spatial lattice data, such as remote sensing data or mesh data, are given as the cells of digital value $h_{i,j}$ over the $D_1 \times D_2$ array data:

$$l_2(i, j) = \{(x, y) \mid x_{i-1} \leq x \leq x_i, y_{j-1} \leq y \leq y_j \} \quad i = 1, 2, \ldots, D_1, \; j = 1, 2, \ldots, D_2$$

The neighbor information of cell $l_2(i, j)$ is given as
\[
NB(l_2(i,j)) = \{(a,b) | i \leq 1 \leq a \leq i+1, j \leq b \leq j+1\} \cap \{(a,b) | 1 \leq a \leq D_1, 1 \leq b \leq D_2\} - \{(i,j)\} 
\]

where \( A - B = A \cap \{B^c\} \) for the sets of \( A \) and \( B \). Here, \( B^c \) denotes the complement of \( B \). For such 2D data with a digital value over a \( 5 \times 5 \) array shown in the left side of Figure 3, the echelon dendrogram shown in the right side of Figure 3 is produced by the following steps.

**Algorithm-E:** To find the peaks and foundation of echelon

**Step E-1) Find the peaks**

The digital values in the peak are greater than the values of neighboring cell of same peak. There are four peaks in this 5-by-5 array. The maximum value in this array is 25. The value of 25 belongs to the fist peak. The maximum value among connected data to 25 is 23. The value of 23 is greater than the values of neighboring cell of 25 and 23. Thus the value of 23 belongs to the fist peak. The maximum value among connected data to 25, 23 and 22 is 22. The value of 22 is greater than the values of neighboring cell of 25, 23 and 22. Thus the value of 22 belongs to the fist peak. The maximum value among connected data to 25, 23, 22 and 21 is 19. But the value of 21 is greater than the values of neighboring cell of first peak. As a result, the first peak consists of the values of 25, 23 and 22, and its echelon number is 1. These values are greater than the values of neighboring cell of first peak. In the same manner, second peak consists of 24, and third peak consists of 21 and 20, and the fourth peak consists of 18. These echelon numbers are 2, 3 and 4, respectively.

**Step E-2) Find the foundations of the peaks and foundations**

The maximum value except the values of four peaks is 19. The value of 19 is greater than the values of neighboring cell of first peak. In the same manner, second peak consists of 24, and third peak consists of 21 and 20, and the fourth peak consists of 18. These echelon numbers are 2, 3 and 4, respectively.
The echelon number 5 is a parent of echelon numbers of 1 and 3. This relationship is expressed as 5(1 3) using echelon numbers. Similarly, we can find the foundation 6 for echelon numbers 4 and 5, and foundation is 7 for echelon numbers of 2 and 6. These relationship is expressed as 7(2 6(5(1 3) 4)) using echelon numbers.

Three dimensional spatial lattice data consist of overlapped two-dimensional (2D) spatial data. These data are also considered as cubic data that consist of \( D_1 \times D_2 \times D_3 \). Therefore, neighbor information of cell \( l(i, j, k) \) is given as

\[
NB(l(i, j, k)) = \{(a, b, c) \mid i - 1 \leq a \leq i + 1, \ j - 1 \leq b \leq j + 1, \ k - 1 \leq c \leq k + 1\} \\
\cap \{(a, b, c) \mid 1 \leq a \leq D_1, \ 1 \leq b \leq D_2, \ 1 \leq c \leq D_3\} - \{(i, j, k)\}
\]  

(3.4)

where \( i=1,2,...,D_1 \), \( j=1,2,...,D_2 \), and \( k=1,2,...,D_3 \).

For 3D data with a digital value over a \( 4 \times 4 \times 3 \) array shown in the left side of Figure 4, the echelon dendrogram shown in the right side of Figure 4 is also produced by the similar steps of Algorithm-E.

![Figure 4: Digital data over 4×4×3 array and their echelon dendrogram.](image)

We use the echelon technique to seek areas \( Z \) where the test statistics is maximized. Through scanning based on echelon, we can detect the candidates of hotspots using the following procedures.

**Algorithm-H: To detect the candidate of hotspots**

**Step H-1)** Draw the echelon dendrogram for specified spatial data

**Step H-2)** Scan the areas from the upper echelon to the bottom, based on the hierarchical structure determined in Step H-1.

**Step H-3)** Detect the candidate of hotspots, which takes the maximum natural logarithm of test statistics \( \hat{\lambda}(Z) \).
3.3 Echelon analysis for multivariate spatial data using PCA

Echelon analysis has been applied only to univariate spatial data. As a result, it is impossible to detect the hotspots on the multivariate spatial data. We propose a technique of echelon analysis for multivariate spatial data with principal component analysis (PCA) which is the one of the multivariate dimension reduction techniques. We can detect the candidate of hotspots for multivariate spatial data using the following procedures.

<table>
<thead>
<tr>
<th>Algorithm-M: To detect the candidate of hotspots for multivariate spatial data</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Step M-1)</strong></td>
</tr>
<tr>
<td><strong>Step M-2)</strong></td>
</tr>
<tr>
<td><strong>Step M-3)</strong></td>
</tr>
<tr>
<td><strong>Step M-4)</strong></td>
</tr>
<tr>
<td><strong>Step M-5)</strong></td>
</tr>
</tbody>
</table>

4. Applications

4.1 Hotspot detection for 3D lattice data in the event of leachate-leaking accident

At final-disposal sites, the possibility exists of a leachate accident of waste material to groundwater because of liner sheet rupture. As an application of our study, we detect the hotspot with statistically significant pollution area for the simulated process of leachate advection-diffusion in the event of a leachate leaking accident. Figure 5 shows expected processes of leachate advection-diffusion in the event of a leachate-leaking accident at the three time points.

![Simulation results of leachate advection-diffusion in the event of a leachate-leaking accident at the three time points.](image)

This consists of the physical space \((x, y, z)\). Therefore, it can be said that these are 3D lattice data. These data consist of
Each cell has leachate concentration \( C \) computed by solving the advection-diffusion equation. Because the volume of the leachate concentration data is huge, i.e. \( 61 \times 101 \times 41 = 252601 \), we grouped the cells as

\[
\{ D_1 \times D_2 \times D_3 \mid D_1 \in \{1,2,\ldots,61\}, D_2 \in \{1,2,\ldots,101\}, D_3 \in \{1,2,\ldots,41\}\};
\]  \( (4.1) \)

and detected statistically significant pollution area (hotspot) based on echelon structure using spatial scan statistics. Table 2 shows the calculated result of the spatial scan statistics and the number of hotspot cells in each time.

Table 2: Result of hotspot detection for each time.

<table>
<thead>
<tr>
<th>( \log \lambda(Z) )</th>
<th>Number of hotspot cells</th>
<th>Ratio of hotspots</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t=1 )</td>
<td>137.27</td>
<td>40</td>
</tr>
<tr>
<td>( t=2 )</td>
<td>183.86</td>
<td>47</td>
</tr>
<tr>
<td>( t=3 )</td>
<td>310.54</td>
<td>104</td>
</tr>
</tbody>
</table>

4.2 Hotspots detection for 5 leading causes of death of Korea

We detect the candidate of hotspots for the 5 leading causes of death among the 16 counties of Korea in 2001. It is collected to promote national prosperity and to formulate the policy for health by Korea National Statistical Office in 2001. The mortality statistics were compiled in accordance with the World Health Organization (WHO) regulations, which specify that member nations classify causes of death. The 5 leading causes of death of Korea in 2001 are shown in Table 3.

(1) Malignant diseases (i.e. Cancer)
(2) Cerebrovascular diseases
(3) Diseases of heart
(4) Diabetes mellitus
(5) Chronic lower respiratory diseases

Thus we shall limit ourselves to these 5 leading causes in this study. We calculate the standardized mortality ratio (SMR) as a common intensity measurement and then apply the principal component analysis (PCA). We detect hotspots on the first principal component (PCA). Eigen values and vectors of PCA are shown in Table 4.

As the coefficients of the first component are all positive, it can be interpreted as an overall measure of the five variables. The echelon dendrogram using the score of the first component is shown in the left side of Figure 6. We calculate the spatial scan statistics according to Poisson model by aggregating regions for the echelon from the upper county in each peaks. The area \( Z \) with the maximum \( \log \lambda(Z) \) becomes the candidates of hotspots. The result of hotspots for the PC1 are six counties (Busan, Ulsan, Gyeongnam, Gyeongbuk, Daegu and Jeonnam) in the first peak, where the spatial statistics \( \lambda(Z) \)
Using the spatial scan statistics, we can detect the candidates of hotspots which take maximum likelihood. We can also detect various shapes of hotspots. The second component represents a contrast between habitual disease (Heart diseases and Diabetes mellitus: positive sign) and the remaining variables (Cancer, Cerebrovascular diseases and Chronic lower respiratory diseases; negative sign). Thus the habitual disease in PC2 can be interpreted as the main cause of death. In similar manner, the hotspots for PC2 turned out Seoul and Gyeonggi in the second peak, where the spatial statistics \( \lambda(Z) = 319.51 \) in the right side of Figure 6.

Table 3: The 5 leading causes of death of Korea in 2001.

<table>
<thead>
<tr>
<th>counties</th>
<th>Total population</th>
<th>Cancer</th>
<th>Cerebrovascular diseases</th>
<th>Diseases of hearts</th>
<th>Diabetes mellitus</th>
<th>Chronic lower respiratory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Seoul</td>
<td>10263336</td>
<td>10077</td>
<td>5573</td>
<td>2823</td>
<td>1911</td>
<td>1139</td>
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<tr>
<td>Busan</td>
<td>3770536</td>
<td>4789</td>
<td>2853</td>
<td>1916</td>
<td>1000</td>
<td>688</td>
</tr>
<tr>
<td>Daegu</td>
<td>2525109</td>
<td>2903</td>
<td>1634</td>
<td>718</td>
<td>586</td>
<td>416</td>
</tr>
<tr>
<td>Incheon</td>
<td>2564598</td>
<td>2629</td>
<td>1813</td>
<td>724</td>
<td>518</td>
<td>373</td>
</tr>
<tr>
<td>Gwangju</td>
<td>1383765</td>
<td>1389</td>
<td>661</td>
<td>325</td>
<td>292</td>
<td>174</td>
</tr>
<tr>
<td>Daejeon</td>
<td>1403164</td>
<td>1370</td>
<td>868</td>
<td>352</td>
<td>250</td>
<td>217</td>
</tr>
<tr>
<td>Ulsan</td>
<td>1055618</td>
<td>915</td>
<td>557</td>
<td>281</td>
<td>209</td>
<td>167</td>
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<tr>
<td>Gyeonggi</td>
<td>9544494</td>
<td>9408</td>
<td>5953</td>
<td>2747</td>
<td>1870</td>
<td>1424</td>
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<tr>
<td>Gangwon</td>
<td>1552407</td>
<td>2274</td>
<td>1573</td>
<td>633</td>
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<td>389</td>
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<tr>
<td>Chungbuk</td>
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<td>1511</td>
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<td>365</td>
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<td>3230</td>
<td>1981</td>
<td>740</td>
<td>553</td>
<td>514</td>
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<tr>
<td>Jeju</td>
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<td>624</td>
<td>331</td>
<td>172</td>
<td>98</td>
<td>91</td>
</tr>
</tbody>
</table>

Table 4: Eigen values and vectors of PCA.

<table>
<thead>
<tr>
<th></th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cancer</td>
<td>0.4396</td>
<td>-0.5579</td>
<td>-0.2744</td>
<td>-0.4609</td>
<td>0.4559</td>
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<tr>
<td>Cerebrovascular</td>
<td>0.4212</td>
<td>-0.1571</td>
<td>0.8764</td>
<td>0.1515</td>
<td>0.0824</td>
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<tr>
<td>Diseases of hearts</td>
<td>0.4156</td>
<td>0.6428</td>
<td>0.0400</td>
<td>-0.6086</td>
<td>-0.2053</td>
</tr>
<tr>
<td>Diabetes mellitus</td>
<td>0.4599</td>
<td>0.4085</td>
<td>-0.2898</td>
<td>0.5714</td>
<td>0.4596</td>
</tr>
<tr>
<td>Chronic lower respiratory</td>
<td>0.4951</td>
<td>-0.2900</td>
<td>-0.2664</td>
<td>0.2604</td>
<td>-0.7294</td>
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<tr>
<td>Eigen values</td>
<td>3.2463</td>
<td>0.7269</td>
<td>0.5166</td>
<td>0.3556</td>
<td>0.1547</td>
</tr>
<tr>
<td>Cumulative contribution ratio</td>
<td>0.6493</td>
<td>0.7946</td>
<td>0.8980</td>
<td>0.9691</td>
<td>1.0000</td>
</tr>
</tbody>
</table>
5. Conclusion

It is important to investigate the areas of significant risk (hotspots) about the effect on the human health status to make early warning for infectious diseases and so on. We can easily find the candidates of hotspots for any types of spatial data based on spatial scan statistics and echelon spatial hierarchical structure.

References


