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Assessment of sewer system using PROMETHEE and GAIA methods

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ABSTRACT

In this work, determination of the conditional ranking of aging sewer pipes was discussed using PROMETHEE and GAIA method. Pipe density in a drainage area, hydraulic capacity, flow velocity, and defect rate in each sewer section were considered as factors affecting the conditional ranking of the existing sewer pipes by PROMETHEE, which was compared with the sewer rehabilitation priority previously used in Seoul, Korea. In addition, GAIA plane was discussed as a tool to enable to visualize the correlation of alternatives, evaluation items, and weights. A method of so called 'GAIA cube', three dimensional extension of GAIA plane, was also suggested to reduce much loss of information from the original data set.

Keywords: Sewer pipes; Conditional ranking; PROMETHEE; GAIA plane; GAIA cube; Sewer rehabilitation

1. Introduction

Deterioration of existing sewer pipes results in their functional degradation, which would increase the risk of flooding and road subsidence following sewer collapse, resulting in impairing benefits of the sewer system. Accordingly, in order to maintain its intrinsically intended normal condition, it is needed to implement comprehensive and systematic inspections and thereafter sewer rehabilitation programs. Since it costs a lot and takes years in implementing a sewer rehabilitation program, investment priority should be decided based upon key factors affecting the condition of a sewer system. In recent years, aging infrastructure rehabilitation market has largely increased worldwide and researches on evaluating rehabilitation priority of sewer pipes have been actively conducted based on the multiple criteria decision method [1–13]. An [14] and Kessili and Benmamar [13] applied AHP-PROMETHEE II ranking method for prioritization of sewer rehabilitation projects. They determined weights of the selected criteria in their application using Analytic Hierarchy Process (AHP) and Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) II method. PROMETHEE method was suggested by Brans [15], which is a method to find the best alternative or ranking of some alternatives by pairwise comparison among them. Brans and Vinker [16] proposed a modified approach based upon extended notion of a criterion, which could easily be built by decision-makers. Brans and Mareschal [17–19] developed an interactive decision support system based on PROMETHEE and GAIA methodology including newer developments such as PROMETHEE III (ranking based on intervals), IV

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(representation of the human brain), and V (multi-criteria optimization under constraints) and GAIA visual modeling methods.

In this work, conditional ranking of sewer pipes is discussed using PROMETHEE and GAIA method. Evaluation items such as sewer pipe density in a certain drainage area, insufficient hydraulic capacity, gentle hydraulic gradient or low flow velocity, and defect rate in a sewer section are selected as decision criteria in this work. With such criteria, PROMETHEE and GAIA method are used to evaluate conditional ranking of sewer pipes at a drainage area in Seoul, Korea. Quantitative visualization of decision actions and criteria can be provided and weights are represented by a vector in GAIA plane and GAIA cube as well.

2. PROMETHEE and GAIA methodology

PROMETHEE method was suggested by Brans and Vinker [16], which is one of the decision making methods. It is similar to AHP in terms of pairwise comparison between actions or alternatives and similar to fuzzy approach in terms of using preference functions. The peculiar advantage of PROMEHEE is that each decision action or alternative and its relation to others can be visualized in so called GAIA plane and quantitative reasoning for flexible decision making can be provided.

In PROMETHEE, the degree *a* preferred to *b* for two alternatives *a* and *b* can be written as:

$$\pi(a,b) = \sum_{j=1}^{k} P_j(a,b) w_j \tag{1}$$

where k is the number of decision criteria and w_j is the weight factor of decision criterion j for each j = 1, 2, … k. $P_j(a,b)$ ranging from 0 to 1 represents the preference of a over b about decision criterion j, which is usually defined as:

$$P_j(a,b) = F_j\left[d_j(a,b) = g_j(a) - g_j(b)\right] \tag{2}$$

Here, $g_j(a)$ is the numeric evaluation of criterion j of a, and preference function F_j typically has the form as shown in Fig. 1.

That is, $P_j(a,b)$ has the maximum value of 1 when the degree of preference of a over b is sufficiently large and the minimum value 0 when a is not preferred to b regardless of the deviation. In this work, since all of the decision criteria can be expressed by numeric values, we let the deviation function g_j be identity function for all j.

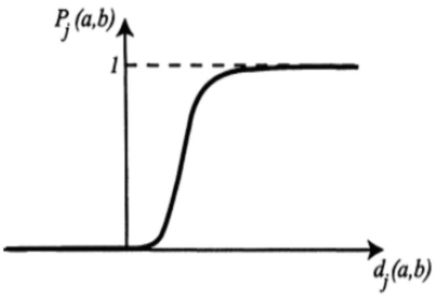

Fig. 1. Preference function.

In decision making process, the degree of 'no preference' is also important. Then it is reasonable to express the ranking of the preference of *a* as:

$$\begin{aligned}\phi(a) &= \frac{1}{n-1}\sum_{x\in A}\left(\pi(x,a) - \pi(a,x)\right)\\ &= \frac{1}{n-1}\sum_{x\in A}\sum_{j=1}^{k}\left(P_j(x,a) - P_j(a,x)\right)w_j\\ &= \frac{1}{n-1}\sum_{j=1}^{k}\phi_j(a)w_j\end{aligned} \tag{3}$$

Here, n is the number of alternatives, A is the set of the alternatives, and ϕ_j is defined as follows:

$$\phi_j(a) = \frac{1}{n-1}\sum_{x\in A}\left(P_j(x,a) - P_j(a,x)\right) \tag{4}$$

From Eq. (3), $\phi(a)$ is thought as k dimensional inner product of the two k dimensional vectors $\vec{\phi}(a)$ and $\vec{w}$ defined as:

$$\begin{aligned}\vec{\phi}(a) &= \left(\phi_1(a), \phi_2(a), \dots, \phi_k(a)\right)\\ \vec{w} &= \left(w_1, w_2, \cdots, w_k\right)\end{aligned} \tag{5}$$

Since k is generally greater than three, it is difficult to conduct geometrical interpretation of the vectors $\vec{\phi}(a)$ and $\vec{w}$ in Eq. (5). So, GAIA plane with PROMETHEE is suggested to provide quantitative visualization of the data, which is two dimensional space (plane) spun by two eigenvectors of the largest eigenvalues of the matrix A^TA defined as $A_{ij} = \varphi_i(a_j)$. Mathematically, this is obtained by spectral decomposition. The spectral decomposition tells us that any n by k real matrix A can be represented as the sum of the orthogonal bases as follows:

$$\mathrm{A} = \sum_{i=1}^{m} \lambda_i \mathrm{t}\mathrm{p}^{\mathrm{t}}, \ (m = \min(n,k)) \tag{6}$$

where t_i and p_i are called score vector and loading vector, which are the eigenvectors of the symmetric matrices AA^T and A^TA respectively, with property of $t_i \cdot t_j = p_i \cdot p_j = \delta_{ij}$. In Eq. (6), λ_i usually indexed by the size of λ ($\lambda \geq \lambda_{i+1}$) is the square root of the i^{th} eigenvalues corresponding to the i^{th} eigenvector t_i (or p_i). In most cases we're interested in only the first few terms of the equation significantly contributing to A and usually regard the remaining parts as errors or noises. So, by this process, noise filtering and dimension reduction can be conducted with maintaining as much original data as possible, which is one of the main advantages of the spectral decomposition.

GAIA method also follows the similar procedure. For example, let's consider eleven elements observing two components (for instance, pipe density and pipe condition data) as follows:

$$\mathbf{A}^{T}=\begin{pmatrix} -10 & -8 & -6 & -4 & -2 & 0 & 2 & 4 & 6 & 8 & 10 \\ -12.27 & -0.945 & -2.516 & -8.634 & -6.632 & -4.376 & -3.756 & -0.219 & -4.181 & 2.922 & 6.055 \end{pmatrix} \quad (7)$$

For simplicity, the observed data is mean centered. The spectral decomposition of $\boldsymbol{A}$ is as follows:

$$A=\lambda_1 t_1 p^T+\lambda_2 t_2 p^T=\begin{pmatrix} -15.60 \\ -6.654 \\ -6.178 \\ -8.687 \\ -5.864 \\ 2.874 \\ -0.960 \\ 2.873 \\ 1.780 \\ 7.952 \\ 11.52 \end{pmatrix}(0.754 \quad 0.657)+\begin{pmatrix} -2.687 \\ 4.541 \\ 2.042 \\ -3.885 \\ -3.688 \\ 3.300 \\ -4.148 \\ -2.791 \\ -7.093 \\ -3.050 \\ -2.00 \end{pmatrix}(-0.657 \quad 0.754) \quad (8)$$

The observed data and two loading vectors p_i are represented on the plane spun by two components 'pipe density' and 'pipe condition' as shown in Fig. 2. In geometrical point of view, the direction of the first loading vector p_1 represents the axe's direction, which has the maximum data variance. The second loading vector p_2 represents the next maximum (minimum as well in this case) variance direction. In addition, one can see that the score vector t_i represents the point of the i^{th} datum on the rectangular coordinate system spanned by two loading vectors. In GAIA method, GAIA plane is no other than this coordinate system and the original coordinate unit vectors (1,0) and (0,1) appear as the decision criterion vectors and the observed data points as alternatives in this system.

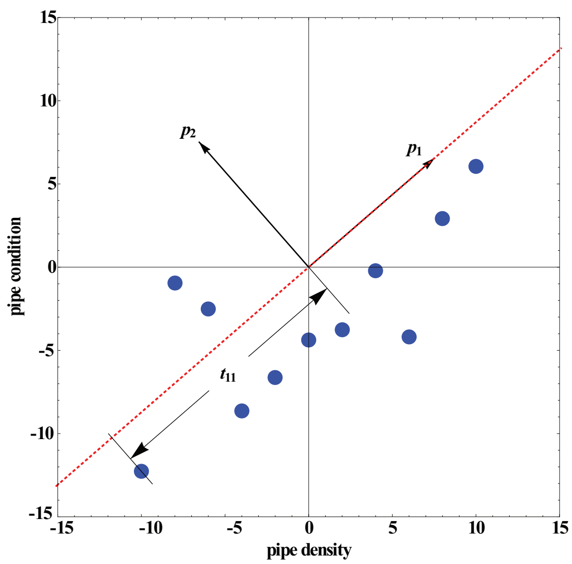

Fig. 2. Geometrical meaning of loading and score vector.

Of course, not only the alternatives and the decision criteria but the weight vectors are also projected in GAIA plane. Then it is obvious to state the following properties:

1. The longer a criterion axis in the GAIA plane is greater discriminating power this criterion has.
2. Criteria expressing similar preferences are represented by axes oriented in similar directions.
3. Criteria expressing conflicting preferences are oriented in opposite directions.
4. Criteria not related each other in terms of preferences are represented by orthogonal axes.
5. Similar alternatives are represented by points located closely each other.
6. Alternatives being good on a particular criterion are represented by points located in the direction of the corresponding criterion axis.

According to Eq. (3), the larger alternatives' component of weight direction, the higher it's ranking. In addition, a certain range of weight factors appears as a figure such as polygon or circle in GAIA plane, providing with information for more flexible decisions. Further discussion on this topic is found in section 4.

Meanwhile, though GAIA plane provides intuitive and flexible way in analyzing the conditional priority, it could not always the best choice for explaining the original data in the case that the eigenvalues following after the second one are in the same order of magnitude of the first two, meaning that more factors than two independently could contribute the data. In that case, GAIA plane could not fully reflect the original data. So, it is reasonable to investigate the data with more factors than two, which will be discussed in the section of results on 'GAIA cube'.

3. Methods

3.1. Selection of conditional factors of sewer pipes

In Seoul city [20], functional, environmental, and maintenance aspects have been considered for sewer pipe condition evaluation. The corresponding primary evaluation items are listed in Table 1.

Jin [21] suggested evaluation items of the sewer pipe condition as pollution loading, infiltration, defect rate, hydraulic capacity, pipe strength, and hydraulic gradient. Other preceding studies [13,22–25] have derived similar conclusions. Though it is desirable to consider as many items as possible referred to preceding researches, only four measurement items of sewer pipe density (expressed as the sewer pipe length per sub-catchment area), insufficient hydraulic capacity, low flow velocity (usually less than 0.6 m sec^{-1} due to the slack pipe slope and improper construction), and defect rate in a sewer section are used for this study due to the restriction of the target field data availability [26].

3.2. Target area

The research target area of this work is one of the drainage areas in Seoul, of which the plan area is 118.9 ha

Table 1
Evaluation items used in sewer inspection program implemented in Seoul [20]

Classification	Functional aspect	Environmental aspect	Maintenance aspect
Evaluation items	Water quality Hydraulic capacity Flow velocity Defect rate	Groundwater quality Sewage odor Road subsidence	Defects in sewer pipe (by CCTV inspection)

and composed of 46% woodland and 54% residential area. The city has a combined sewer system. According to an engineering consulting, a portion of the area's sewer pipe assets was inspected using closed-circuit television (CCTV) technology from 2009 to 2010. Structural and operational defects within each inspected pipe section were identified using sewer rehabilitation judgment criteria previously set by Seoul city officials [20]. This research focuses on the sub-catchment called 'region d' of this area in Fig. 3, which has 259 sewer pipes with 8.37 km total pipe length. Among them, only 98 pipes are selected for simplicity in showing the results analyzed in this study.

3.3. Preference functions of criteria

To apply PROMETHEE method, the preference functions of each criterion are to be established first. The preference functions of the criteria selected in this study are listed in Table 2 with reference to sewer rehabilitation judgment criteria of engineering consultants authorized by Seoul metropolitan city. The threshold values are 1 km ha^{-1}, 80%, 0.2 m s^{-1} and 0.6 m s^{-1}, and 30% for sewer pipe density in 'region d', the ratio of sewer pipes with insufficient hydraulic capacity in wet weather, low flow velocity in dry weather, and the rate of defects obtained by CCTV inspection conducted in each sewer pipe section, respectively [26]. The distribution of sewer pipe condition data according to the preference functions listed in Table 2 can be seen in Fig. 4 (For brevity, raw numerical data of each sewer pipe were not listed but the preference function values as graphs obtained from the raw data).

Fig. 3. Map of the target area in this study.

Table 2
Preference functions for selected criteria

Criteria	Preference function
Sewer pipe density (km ha^{-1})	$F_1(x)=\begin{cases}0, \text{ when } x\le 0\\ x, \text{ when } 0<x\le 1\\ 1, \text{ when } 1<x\end{cases}$
Ratio of sewers with insufficient hydraulic capacity (%)	$F_2(x)=\begin{cases}0, \text{ when } x\le 0\\ x/80, \text{ when } 0<x\le 80\\ 1, \text{ when } 80<x\end{cases}$
Low flow velocity (m s^{-1})	$F_3(x)=\begin{cases}0, \text{ when } 0.6<x\\ -(x-0.6)/0.4, \text{ when } 0.2<x\le 0.6\\ 1, \text{ when } x\le 0.2\end{cases}$
Defect rate (%)	$F_4(x)=\begin{cases}0, \text{ when } x\le 0\\ x/30, \text{ when } 0<x\le 30\\ 1, \text{ when } 30<x\end{cases}$

4. Results

4.1. GAIA plane analysis

Qualitative analysis of ranking of each sewer pipe deterioration level in terms of weight factors is easily conducted by GAIA plane. Generally observed *k* (the number of decision criteria) dimensional data can be represented by spectral decomposition. GAIA plane is defined by two eigen vectors (or loading vectors in Fig. 2) p_1, p_2, which have the largest eigen values among *k* ones. So it can be thought that GAIA plane is the plane with the largest variance of the data. In GAIA plane analysis, the priority of each alternative is defined by the weight factors of each criterion. As mentioned in Eq. (5), the number of weight factors is the same as that of decision criteria, it can be treated as a vector called weight vector and also represented in the GAIA plane. Fig. 5 shows the GAIA plane applying sewer pipe conditions observed in Seoul. In this figure, points represent the properties of each pipes and arrows four decision criteria. The colored area located around the axis origin represents the set of the end point of the weight vectors whose components have the range from 0.2 to 0.4. In GAIA analysis, the order of priority of each alternatives (each pipe in this case) is determined by its projection value of the line defined by its weight vector.

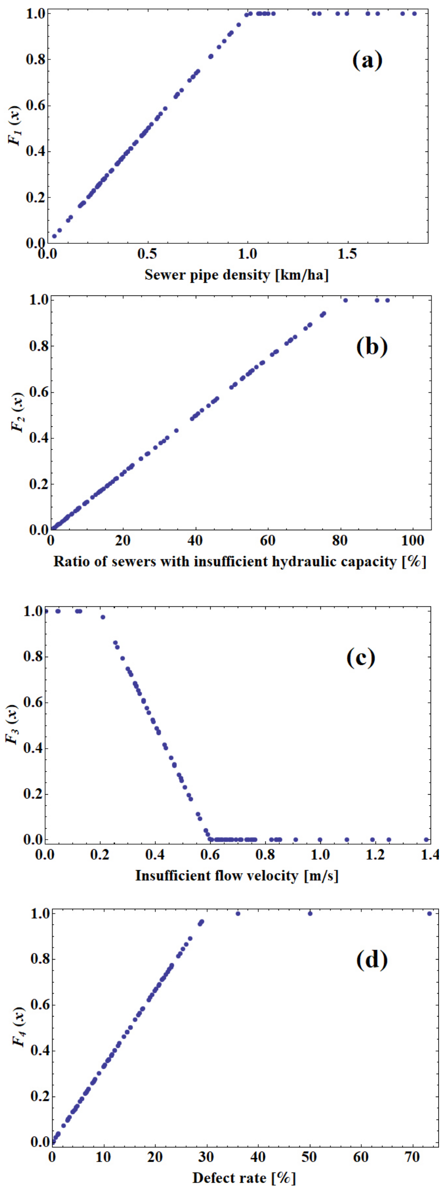

Fig. 4 Distribution of data on (a) sewer pipe density, (b) ratio of sewers with insufficient hydraulic capacity, (c) insufficient flow velocity, and (d) defect rate, according to the selected preference functions.

For example, in Fig. 5, the dashed line passes through the weight vector (0.4, 0.2, 0.2, 0.2) (lower left corner of the colored polygon) and in that figure, as one can see, the point A has the maximum projection value and thereby has the first order of priority. Likewise, the point B has the fourth order of priority and other remaining points can also be well defined.

Since we know that the longer the length of weight vector, the larger the decision power and (0.4, 0.2, 0.2, 0.2) is the most distant from the origin, a decision maker can take (0.4, 0.2, 0.2, 0.2) as a weight if he or she wants the largest decision power. In addition, Eq. (3) tells us that the pipes in quadrant 3 of Fig. 5 have high priority of ill conditional ranking regardless of the weight factors. The conditions of

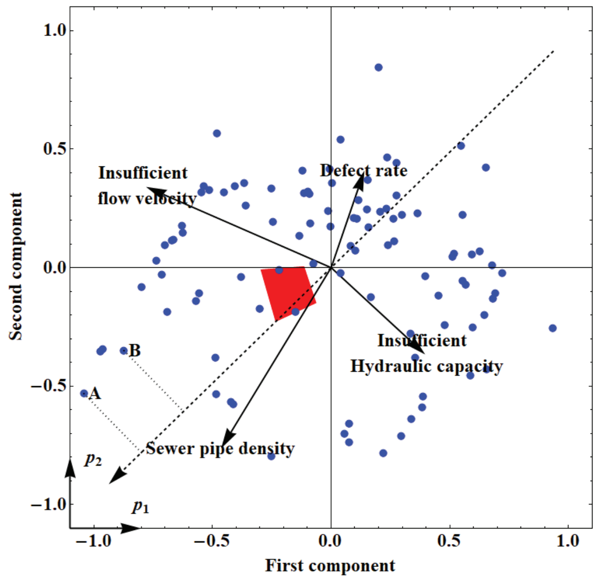

Fig. 5. Sewer pipe conditions marked as points on the GAIA plane. Four solid arrows represent four criteria, while dashed arrow represents the direction of weight vector which has the maximum decision power. Two arrows p_1, p_2 in the lower left corner represent eigenvectors (loading vectors), which define GAIA plane.

sewer pipes with low flow velocity and with insufficient hydraulic capacity is approximately conflicted each other. It makes sense in that the design of combined sewer systems should yield adequate self-cleansing velocity for a specified dry weather flow, which is nearly impossible if the capacity of the sewer must also be adequate to convey storm water runoff [27]. Sewer pipe density and defect rate are conflicted each other, too. However, this may not make sense, since it can be assumed easily that the higher pipe density in an area, the higher defect rate. It is also somewhat suspicious that the defect rate vector is oriented in the opposite direction from the weight vector, since if it be true, the higher the defect rate, the lower the priority. We will discuss this result in Section 4.2.

Among four criterion vectors, the pipe density and low flow velocity vectors have relatively longer length than the remaining ones, meaning that these two criteria are relatively highly influential in the pipe ranking on this data set. In this stage, it should be kept in mind that two criteria of pipe density and flow velocity are not more important than the remaining criteria for general pipe conditions, but only reflected that the variances of the two criteria are larger than that of the remaining ones in this data set.

4.1.1. Comparison of the conditional ranking

Fig. 6 shows the result of comparison between the previous decision (whether repair should be implemented or not) made by the engineering consultants [26] and the conditional ranking given by PROMETHEE method. In this graph, horizontal axis represents the ranking of the pipes and the ticks are marked at every 14th pipes in descending order (in worsening order) and the vertical axis represents

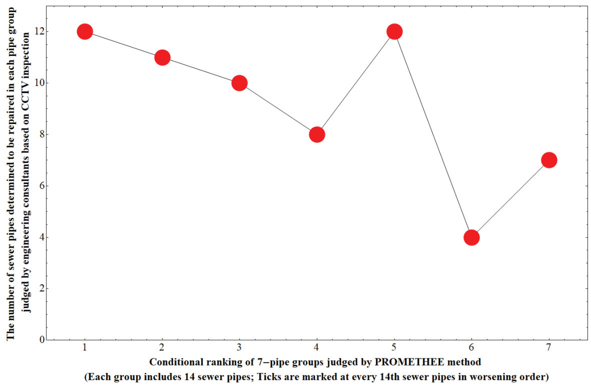

Fig. 6. Comparison between conditional rankings of seven groups among 98 sewer pipes determined by PROMETHEE and those by the engineering consultancy.

the number of sewer pipes determined to be repaired among seven groups of sewer pipes (each of which consists of 14 sewer pipes) by judgment of engineering consultants based upon CCTV inspection results including other factors. If two ways of decision are similar, the data should follow the inverse proportion function. As one can see, the data show inversely proportional tendency on the whole except the 5th and 7th groups of pipes. The reason of this discrepancy comes from the fact that engineers or CCTV inspection data interpreters considered a sewer pipe section as failed if its condition does not meet any one or a few of the criteria used in the previous decision made in Seoul [26], while the degree of defect is determined by the sum of the continuous values of each criterion in case of PROMETHEE approach.

4.2. GAIA cube analysis

As mentioned in the previous section, GAIA plane provides intuitive and flexible way in the analysis of the order of conditional priority, which is one of the main advantages of PROMETHEE method. Since only two largest eigenvalues are considered, GAIA analysis inevitably loses some information of the original data and in this case, as expected, the sum of the two largest eigenvalues is about only 60% of the total sum. Though it is known that the loss of 40% is acceptable, it would be better to reduce as much loss of the original information as possible. The main cause of evaluation with only two largest eigen system in GAIA would lie in the difficulty of visualization of over 2-D objects but human can recognize up to 3-D object. If the similar approach is used with three largest eigen system as GAIA plane with two largest eigen system, it would be better than the original one since it obviously preserves more information.

For 3-D visualization of the data, GAIA cube is suggested, which is 3-dimensional extension of GAIA plane spun by eigenvectors of three largest eigenvalues of the spectral decomposition. The result of this approach is shown in Fig. 7. The floating polygon at the center is the set of the points of weight vector, of which the values are in the range of 0.2~0.4. As the case of GAIA plane, the pipe points positioned at the weight vector direction have the high ranking ill-conditional

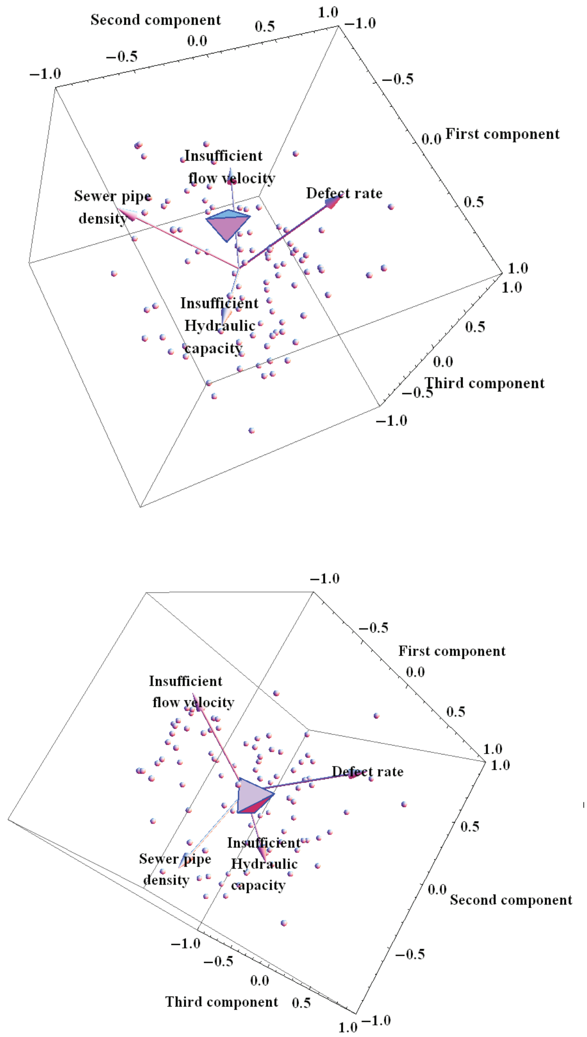

Fig. 7. Two still cut images of rotating GAIA cube.

priority. Though there is generally difficulty in identifying the properties of 3-dimensional object, it can be easily overcome with the help of such a software as 'Mathematica' used in this study, which enables the 3-D object to rotate as can be seen in Fig. 7. In this figure, it is found that pipe density and defect rate are approximately independent criteria each other while the ratio of sewers with insufficient hydraulic capacity and low flow velocity are still conflicting each other as before. In GAIA cube, the length of the pipe density vector is 0.98, the vector of the ratio of sewers with insufficient hydraulic capacity is 0.55, the low flow velocity vector is 0.85, and the defect rate vector is almost 1. In addition, the defect rate appears to be the most important criterion and the ratio of sewers with insufficient hydraulic capacity is the least one. These listed results of GAIA cube analysis are slightly different from the previous 2-D ones, suggesting that in some cases like this, the information ignored in GAIA plane analysis would not be ignorable. This result becomes more apparent through analytical method. Table 3 shows the relationship between the selected weight vectors and the criteria. As one can see, each vertices of the tetrahedron in

Table 3
Relation of weight vector with each criteria

Vertex coordinate in GAIA cube	Distance from the origin in GAIA cube	Corresponding weight vector in criterion space	Angle of each criterion between decision vector (Degree)			
			P (0.98)	*C* (0.55)	*V* (0.85)	*D* (1.0)
(–0.113,0.006,0.463)	0.477	(0.2, 0.2, 0.2, 0.4)	59.2	88.1	78.7	32.1
(–0.297,–0.007,0.278)	0.407	(0.2, 0.2, 0.4, 0.2)	49.7	111.2	50.0	59.6
(–0.234,–0.228,0.366)	0.491	(0.4, 0.2, 0.2, 0.2)	25.8	82.6	76.6	65.5
(–0.062,–0.149,0.306)	0.347	(0.2, 0.4, 0.2, 0.2)	37.7	69.5	91.9	53.4

P, *V*, *C* and *D* represent pipe density, gentle flow velocity, insufficient hydraulic capacity and defect rate. The number in parentheses in angle column is the length of the corresponding criterion in GAIA cube.

Fig. 7 can be one of the weight vectors, which are listed in the Table 3. The smaller the angle between the criterion and the weight vector, the more similar directions they are in, which implies a greater influence on the priority.

As shown in Table 3, weight vector defined by the third vertex (–0.234, –0.228, 0.366) is the longest and if it is selected as weight, then pipe density has smallest angle of 25.8 as the case of 2-D before, but the difference from the 2-D case is that the defect rate has smaller angle than other two criteria as well as not in the opposite direction from the others. Assuming that the decision power (distance from the origin) of the weight vector defined by the first vertex is the same as that by the third, if it is selected, defect rate criterion has the greatest effect on priority. This analytical approach is also possible in more than three dimensions. If one gives up conducting visual analysis, one could perform multidimensional analysis in the same way.

5. Discussion

In this work, conditional ranking of the sewer pipes selected in the area of this study is obtained by PROMETHEE method. When it is compared with the rehabilitation priority results previously determined by engineering consultants, both methods result in similar trends with some exceptions.

Through GAIA plane analysis, the most distant weight vectors (0.4, 0.2, 0.2, 0.2) from the origin of GAIA plane may be taken as weights of four criteria of pipe density, gentle flow velocity, insufficient hydraulic capacity, and defect rate, respectively, if he or she wants the largest decision power. It is also found that GAIA plane analysis may have the risk of ignoring too much information of the original data resulting in giving somewhat distorted result. To resolve this problem, visualization in GAIA cube spun by 3 dimensional analysis is suggested to preserve more information (about 80% of the original data) than GAIA plane does. Moreover, it is found that if one gives up visual analysis, higher dimensional analysis is also possible.

The main advantage of the method used in this paper is that it may help make more objective decisions and can be useful for rational persuasion of stakeholders as well as decision makers. Though only physical conditions of sewer pipes are considered as criteria in this study, non-physical and non-quantifiable criteria such as environmental or financial conditions can be easily added as one of the criteria to determine objectively the priorities of decisions.

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