Analysis of Vulnerability of Road Networks on the Basis of Graph Topology and Related Attribute Information

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INTRODUCTION

The safety of people and the security of the vital functions of society are among the core tasks of governments. Various networks, especially transportation networks, are important for human life. Much research has been done to analyse the vulnerability of road networks and most of the methods were based on analysing the topological structure of the network using graph theory. For instance, Demšar et al. presented a mathematical method for modelling the vulnerability of the elements of the network, which can be used for the identification of critical locations in a spatial network. The vertices of the line graph that correspond to critical locations have one or more of the following three properties: they are cut vertices and they have a high betweenness value or a low clustering coefficient. The risk value estimation method produced results with low accuracy because the risk value of a cut edge road is estimated on the basis of its cut edge attribute value only (Demšar et al., 2008). However, it is not always sufficient to base network vulnerability analysis only on the topological structure for crisis management. For instance, in a road network, if a bridge to an island can be considered as a cut edge, what if there is only one summer house on the island? Is this bridge more important than a minor road located inside a residential area with a high population density? If edge A has a higher betweenness centrality value than cut edge B, is edge A more vulnerable than edge B? Obviously, some non-topological attributes should also be added into consideration when analyzing the vulnerability of road network for the preparedness of crisis management. This paper introduces a multi-attribute value theory that could be used to extend the graph theory approach towards a more complementary method.

Multi-attribute value theory is useful tool of decision analysis. MAVT aggregates the alternative performance across all the criteria to form an overall assessment (Pöyhönen et al., 2001). In MAVT, alternatives, objectives and value relevant attributes should be first defined (Winterfeldt and Edwards, 1986). Value function should be created for each relevant attribute data. The value functions are the principles used for evaluation. They indicate the relative desirability of the consequence (Winterfeldt and Edwards, 1986). Alternative should be evaluated separately on each attribute and relative weights should be assigned to the attributes. After this procedure, aggregate the weights of the attributes and the single attribute evaluations of alternatives to obtain an over all value function of alternatives (Winterfeldt and Edwards, 1986).The alternative which has higher overall value is more preferred.

METHODS AND RESULTS

In this paper, MAVT is applied to the attribute data related to the road network in order to produce a more accurate overall value for each road segment. This overall value is used to compute the vulnerability of the road network for the preparedness of crisis management application. It was tested on the street network of the Helsinki area, which covers the municipalities of Helsinki, Espoo, and Vantaa, located in southern Finland. Each road segment is considered as one alternative. The road segment, which has a higher overall value, is considered more vulnerable. At beginning, alternatives, objectives and value relevant attributes should be defined. For different crisis management applications, different objectives and their relevant attributes should be selected. Figure 1 shows the normalized population size attribute map. Figure 2 shows normalised betweenness attribute value map. Figure 3 shows normalised cut edge attribute value map. In this example application population size attribute is the most important attribute. The important facilities attribute is the second most important attribute, because destroying important facilities such as power plants or water towers can cause loss of human life. Betweenness value is the least important weight, because people can still travel when some of the major roads are lost. Table 1 show a weight for those four attributes and a weight is given to those four attributes using the Swing and Smart methods. The weighting results are similar when both the SWING and SMART methods are used.

	Population size	Facility	Cut edge	Betweenness
SWING	0.42	0.33	0.17	0.08
SMART	0.47	0.35	0.11	0.05

Table 1 Weights for the corresponding attributes.

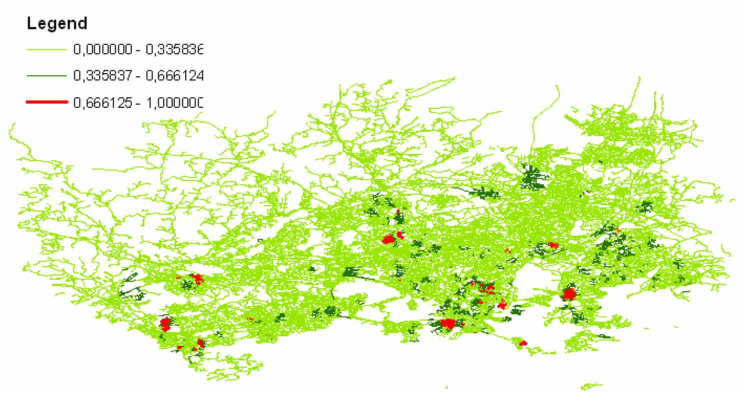

Figure 1 Normalised population size attribute map.

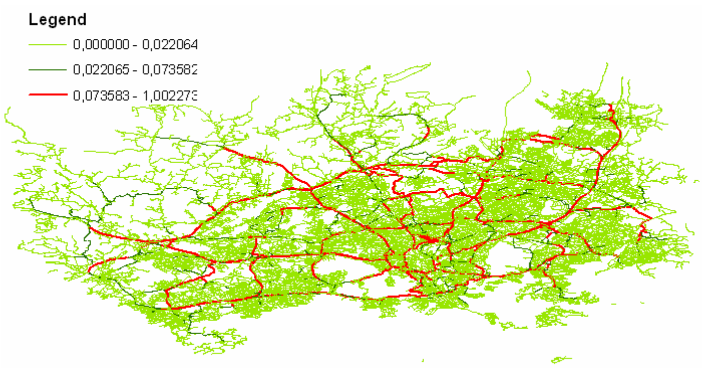

Figure 2 Normalised betweenness attribute value map.

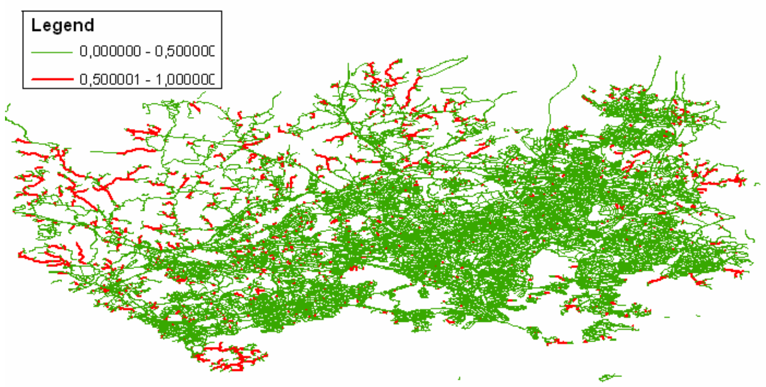

Figure 3 Normalised cut edge attribute value map.

Figure 4 shows the overall value map of this application. The blue circles represent the important facilities. Population size is the most preferred attribute. Therefore this map is similar to the population size distribution map. The places, which have the second highest population size value, have the highest overall value (Figure 4) when there are important facilities are located nearby. This is because the important facilities attribute has the second highest weigh. In Figure 1, the northern parts of the road network have a lower population size value compared to the southern part. In Figure 4, the northern parts of the network have quite a high overall value because these roads refer to the cut edges. The cut edge attribute also affects the results. The results are visualized by using graduated color in ArcGIS. The classification method for classifies the attribute data is manually computed.

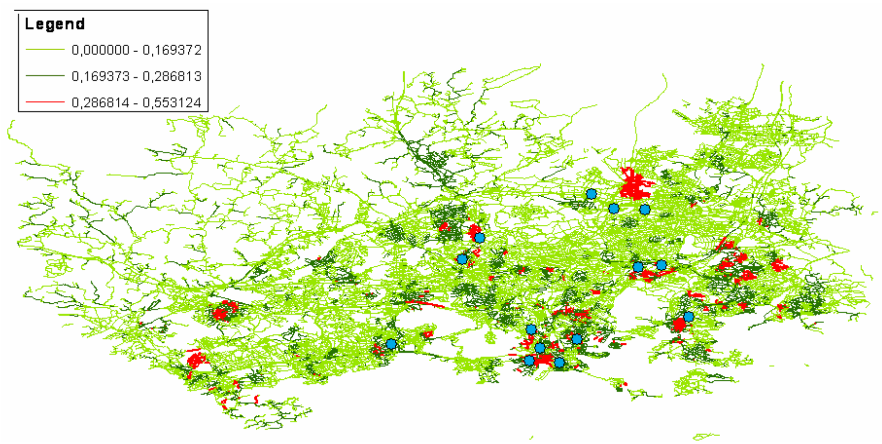

Figure 4 An Overall value map (SWING)

DISCUSSION AND FURTHER DEVELOPMENT

This method will make the analysis more flexible because various attributes can be used. The biggest benefit of combining all the attributes is to save resources in preparedness for crisis management. After the attributes have been combined into overall value, the number of roads that need to be protected is reduced, compared with adding the results together from every single attribute value vulnerability analysis map. Another advantage of using this method is to bring the decision-making knowledge to the GIS professionals. Decision making theory is a useful tool in many areas, but it is not well known by many GIS professionals as a result of their educational background. One challenging question in this method is how to give accurate weighting to different attributes. The map changes according how much the weight changes to the attributes cannot be seen in this paper. Therefore, sensitivity analysis may be needed in the further development task.

BIBLIOGRAPHY

Demšar U., Špatenková O. and Virrantaus K.: Identifying critical location in a spatial network with graph theory. Transactions in GIS, 12, pp.61-68(2008).

Pöyhönen M., Vrolijk H and Hämäläinen R.: Behavioral and procedural consequences of structural variation in value trees. European Journal of Operational Research 134, pp.216-227 (2001).

Saaty, T. L., The analytic hierarchy process. McGRaw-Hill, New York (1980).

Winterfeldt D. and Edwards W., Decision Analysis and Behavioral Research. Cambridge University press (1986)