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A multi-objective geographic information system for route selection of nuclear waste transport☆

Yuh-Wen Chen*, Chi-Hwang Wang, Sain-Ju Lin

Institute of Industrial Engineering and Management of Technology, Da-Yeh University, 112 Shan-Jeau Rd., Da-Tsuen, Chang-Hwa 51505, Taiwan

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Abstract

Nuclear power is widely used throughout the world today. Functioning nuclear power plants produce large quantities of radioactive wastes needing to be transported to safe sites for proper management. With public emphasis on environmental protection and concern for safe transport of nuclear wastes, the problem of selecting an appropriate route for transporting nuclear wastes is a vitally important issue. The aforementioned route selection problem involves conflicting objectives among interested parties; therefore, we develop a multi-objective geographic information system (GIS) with ESRI ArcView GIS 3.x interface to practically support the involved parties for such a multi-objective route selection problem in engineering practices.

Keywords: Nuclear; Route; Geographic information system (GIS); Multi-objective

1. Introduction

Currently, nuclear power is generally used worldwide; however, radioactive wastes are inevitably combined with nuclear power benefits. If produced nuclear wastes are not properly transported to safe sites for strict management, the natural environment will be destroyed from pollution. Since the public is concerned with safe transport of nuclear wastes [1–6], the problem of choosing an appropriate route for nuclear waste transport should be handled with caution.

Route selection for nuclear waste transport becomes a decision for transporting hazardous materials [7,8]: the model developed by List and Mirchandani [9] is the most similar case to what we proposed in this study. They consider three objectives: total transportation cost, total risk, and equity of the risk imposed. Although many multi-objective models for transporting hazardous materials are proposed, the multi-objective transportation decision is not widely approved among practitioners so far. This is because: (a) these models are validated by a small road-network instead of an actual road-network, and the cost of collecting *actual* road-network attributes is very high; (b) most practitioners are not familiar with the complicated models; and (c) lack of an effective interface to integrate multi-objective programming and transportation planning in practice.

The geographic information system (GIS) is specially designed to assist in finding solutions to geographic problems by computer [10,11], e.g., location problems, shortest route problems, distribution patterns of people, etc. In short, the GIS allows both practitioners and

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* Corresponding author. Tel.: +886 4 8511888 x4120; fax: +886 4 8511270.

E-mail address: profchen@mail.dyu.edu.tw (Y.-W. Chen).

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theoreticians the opportunity to grab large chunks of earth's surface and explore them around in their hands. Since GIS can effectively storage actual road-network data, we can develop a customized application for an actual road-network with GIS assistance. As suggested by DeMers [12], the GIS encourages us to roll our world in much the same way that geographers, naturalists, and explorers have done, but with a much more precise set of tools. This paper successfully integrates the theoretical aspect (multi-objective shortest route problem), with the practical aspect (actual road-network attributes of GIS), to plan a multi-objective route for transporting nuclear wastes using a practical rather than simplified road-network. Our study is organized as follows: Section 2 illustrates the problem characteristics and the real transportation network for nuclear waste transport in Taiwan. In Section 3, the shortest route model with multiple objectives is established and the concept of multi-objective GIS for selecting such a route for transporting nuclear wastes is introduced. In Section 4, an actual case of Taiwan is used as a numerical example for resolution and discussion. Finally, conclusions and recommendations are presented in Section 5.

2. Problem characteristics

In this section, we focus on the problem characteristics for transporting nuclear wastes and illustrate the transportation network. These efforts are used to formulate our multi-objective shortest route model in Section 3.

2.1. Transportation stages

The Institute of Nuclear Energy Research (INER) of Taiwan was established early in 1968, specializing in nuclear technology R&D programs. INER is under the administration of the Atomic Energy Council of Taiwan (AECT), and is located in scenic Lungtan, Taoyuan, 45 km from Taipei, and occupies 120 acres of land. INER's primary R&D objectives are maintaining nuclear safety, innovating environment and energy technology, as well as promoting nuclear technologies in a civilian application.

The transportation program development strategy for radioactive waste management is to collaborate with the involved parties. Specifically, the transportation plan should present the INER's strategy and describe the management process used to work cooperatively with local governments, police, utilities, transportation carriers, and other public interests to refine the transportation planning as it is developed. The mission of INER is to manage and dispose of nuclear wastes in an open manner that protects public health, safety, and the environment, enhances national and energy security, and merits public confidence. INER is responsible for designing and developing a safe and efficient transportation plan with the capability to support waste acceptance.

The Taiwan Nuclear Waste Policy Act (TNWPA) established a stepwise approach, i.e., three stages for making decisions related to approval, licensing, operation, and eventual closure of the repository. These nuclear waste transportation stages can be summarized as: (a) application for transport; (b) in-plant operation and examination; and (c) road transport. These stages are strictly followed by Solid Waste Association of North America (SWANA) standards [13]. We use the third stage, road transport, to build our multi-objective GIS model.

When all transportation paperwork is approved, the Taiwan INER decides the date and timing of shipment. Nuclear wastes are often transported at midnight in order not to affect prevailing traffic or increase road transportation risk. INER sends personnel to inspect radiation dosage from each container, relevant staff, and equipment, prior to road transport [14]. Nuclear wastes must meet regulations before being released for total safety transport. Once INER personnel inspect and record a 2-m area depth for hourly waste dosage stipulated between 10 and 200 mR [14], these wastes are then permitted for road transport. When the container carrier from each branch waste producer passes inspection and undergoes application procedures, they are given a police escort to avoid unexpected accidents and ensure minimal radiation exposure risk to the population.

Based on operational practices cited earlier, nuclear waste transportation differs widely from general transportation issues: i.e., only minimizing travel time. On the contrary, conflicting objectives, e.g., avoiding accidents, minimizing travel distance, reducing exposure risk to population, etc., should be simultaneously considered to meet INER's mission goals. Thus, our problem is defined to finding an appropriate route with multiple objectives using an actual road-network. This route selection model formulated in Section 3 is eventually a multi-objective shortest route problem.

2.2. Network analysis

The detailed transportation network of nuclear wastes is very complicated, as shown in Fig. 1 by the GIS digital map. The nuclear power plant site is at the exact INER location, in an urban area within the mountains, while the storage site is located at a harbor near the sea,

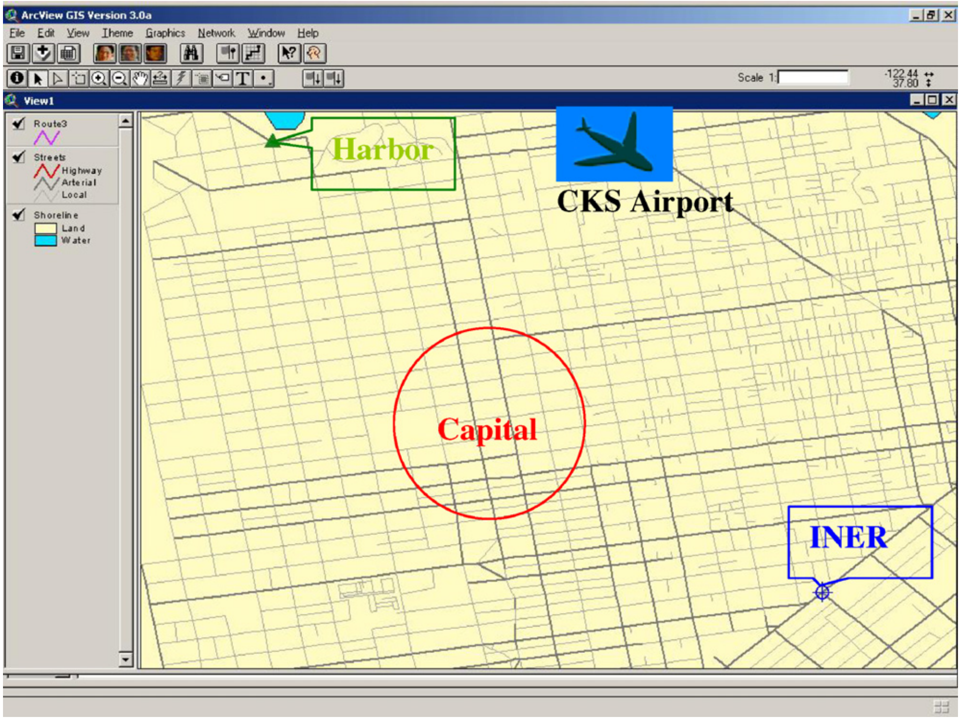

Fig. 1. The transportation network from INER to the harbor.

far from the INER. The big circle denotes the capital of Taoyuan County, the number of residents is estimated over than 100,000 people here. The main international airport of Taiwan: CKS airport is also located near the sea. The area beyond the capital is the low-developed area, most of which are occupied by scattered small villages/towns and light population. Possible transportation routes between INER and the harbor are numerous. The carrier has to pass through several villages/towns by local roads, expressways, or freeways before reaching the storage destination (harbor).

The practical network provided by INER is shown in Fig. 1. We omit the names of villages/towns so as to simplify the digital map and avoid public controversy: the nuclear issue is not so open and transparent in Taiwan till today. The origin point (o) is the INER site and the destination point (d) and final storage site is the harbor. The problem is then defined as finding an appropriate route with multiple-objectives from the node o (origin) to the node d (destination) in Fig. 1.

2.3. *Interested parties*

The INER is responsible for Taiwan's nuclear legacy cleanup, involving complex decisions about how and where to dispose of nuclear waste and how to transport it to its ultimate disposal site (Harbor). A good decision for the transportation of nuclear waste should be recognized that a wide range of interested parties should be involved. However, according to the operation process in Section 2.1, we learn that most interested parties are not included in these stages because Taiwan nuclear power plants are all officially operated nowadays, and reveal little operational information to the public. Thus, the multiple criteria decision making with interested parties seems to be a good solution to reduce the public controversy.

The following experiences from the Consortium for Risk Evaluation with Stakeholder Participation (CRESP) and the Department of Energy (DOE) in America are referred in order to select our interested parties for multi-objective decision. CRESP is a national consortium of university-based researchers operating under a grant from the DOE [15–17]. An important goal for CRESP is to continuously improve the dialogue among decision makers, technicians, medical members and other affected parties so as to create more acceptable decisions of nuclear waste transportation. The DOE of America has also established the Transportation Resource Exchange Service (T-REX) to provide a virtual library of relevant documents. Using T-REX, one can learn many nuclear issues about shippers, packaging, routes, tribal issues, regulations, and more [18].

Since Taiwan government reveals little operational information to the public, opposition to nuclear waste transport is obvious, inevitable and intense. Researchers have found that the public has a higher fear of radiation risk than other type of risk for many years [19]. According to several surveys, the specific problem of waste transportation is also problematic today, and no researcher can claim that he can adequately include all interested parties for such a transportation decision. A survey of neighborhoods adjacent to a radioactive contaminated site [20] found that more respondents favored off-site than on-site waste management; however, no residents would like to approve the transportation of nuclear waste just around them.

Involving the public in waste transportation decisions seems to be a good idea; however, the technical complexities of the material may be a barrier to meaningful and public participation [20]. Today, Taiwan authorities have recognized the same problem: should the nuclear waste transportation issue be professional or public? This is a dilemma because two main political parties have contrary attitudes towards the nuclear power; thus, the decision situation is more complicated when congress and the administrative department belong to two separate political parties in Taiwan today. Kaplan [21] recounted the early history of citizen participation activities at the DOE Hanford site and strongly disputed the notion that citizens lack the ability of handling complexity. Common to these examples is a concerted effort to provide participants with at least some degree of specialized knowledge, information, or training. For example, how can scientists present information in ways that foster participation? We believe that we face a major challenge in getting people to engage in iterative dialogue about defining and addressing nuclear waste transportation issues. How can we develop accessible resources for interested parties so that their inputs are valuable so as to contribute useful outcomes? These questions may be not completely resolved in this study, but according to the aforementioned literatures, full and effective participation in nuclear decision-making by interested parties is critical for improving decision transparency and quality, and seems to be a good solution for such a route selection problem: this validates the use of multiple criteria decision making (MCDM) here [22]. Including all interested parties is a tough task; especially, this study is the first MCDM attempt of INER. We did our best to select five professional parties in this study: they are the INER, the police, the medical technician, the carrier, and a nuclear professor. The residents in the planned area are not fully involved because: (a) the administrative department subjectively opposes nuclear energy and has informed civilians that nuclear power has been unsafe since 2000; and (b) residents are so numerous that the transportation decision may be delayed for a very long time.

3. Multi-objective route selection by GIS

We illustrate our multi-objective model and the multi-objective GIS for selecting the nuclear waste transport route in this section.

3.1. Model construction and resolution

First, all variable notations used for formulation in this study are shown as follows:

z_k the objective value of the kth objective, $k = 1, 2, 3$;
x_{ij} the decision variable, if the link from node i to j is used, then $x_{ij} = 1$; otherwise $x_{ij} = 0$;
t_{ij} the travel time along the link from node i to j; i, $j \in$ network nodes in Fig. 1;
r_{ij} the risk along the link from node i to j; i, $j \in$ network nodes in Fig. 1;
p_{ij} the population along the link from node i to j, i, $j \in$ network nodes in Fig. 1;
o the origin point;
d the destination point.

Model objectives and constraints are summarized as follows:

(a) *Minimizing travel time*: The transportation time of each link (t_{ij}) is directly computed by the length of each link divided by its traveling speed. This objective function is shown in Eq. (1).

$$\text{Min } z_1 = \sum_i \sum_j t_{ij} x_{ij}. \quad (1)$$

(b) *Minimizing transportation risk*: Computing transportation risk is a tough task. Formally speaking, it should be calculated by taking the probability of accident occurrence and consequence into account from the time and spatial aspect. Following application requirements for consolidation containers of radioactive wastes, INER [14,23] researched regulatory criteria and inspection standards since 1999, its transportation risk calculation is just simply employing prevailing traffic volume per hour as an index. We follow INER's consideration and assume that a route risk is summed by the traffic volume of each link, as shown in Eq. (2).

$$\text{Min } z_2 = \sum_i \sum_j r_{ij} x_{ij}. \tag{2}$$

(c) *Minimizing the exposed population*: Transporting nuclear wastes is essentially detested by the general public: as we can see, the greater the population exposed to nuclear wastes along a specified route, the greater the civil resistance to INER vehicles traveling by this route. This objective is shown in Eq. (3).

$$\text{Min } z_3 = \sum_i \sum_j p_{ij} x_{ij}. \tag{3}$$

In addition to the above objectives, constraints considered in this model are:

(d) The first constraint—any node not belonging to the origin or destination point, will have a corresponding pair of links for vehicles traveling in and out, as shown in Eq. (4).

$$\sum_i x_{ij} - \sum_u x_{ju} = 0 \quad \text{if } j \neq o, d; \;\; \forall i \neq j, \;\; u \neq j. \tag{4}$$

(e) The second constraint—any link connected to the origin point, will have only one link with the value of 1 (one way out), as shown in Eq. (5):

$$\sum_j x_{oj} = 1 \quad \forall j. \tag{5}$$

(f) The third constraint—any link connected to the destination point, will have only one link with the value of 1 (one way in), as shown in Eq. (6):

$$\sum_i x_{id} = 1 \quad \forall i. \tag{6}$$

Eqs. (1)–(3) indicate minimization of the total transportation cost, the risk cost, and the public resistance along the route, while Eqs. (4)–(5) are the constant flow constraints. Eqs. (1)–(5) can help resolve a feasible transportation route for nuclear wastes. This multi-objective problem is simply resolved by the weighting method [22,24]. The weighting method is applied for its simplicity in encoding the GIS language: Avenue script.

3.2. Multi-objective decision with the GIS interface

Our multi-objective shortest route problem is resolved by the weighting method in MCDM. The global weight for each objective is determined by the Analytical Hierarchy Process (AHP) procedure [25] from five experts, with the first expert being the officer of INER. The second expert comes from the police department, and is familiar with the prevailing traffic situation and traffic control. The third expert, a doctor from the Taoyuan emergency medical center (EMC), is responsible for nuclear disaster rescue. The fourth expert comes from the transportation carrier, who is experienced to transport INER's wastes so as to meet INER's long term goals. The fifth expert comes from the public, a professor with a major in nuclear energy and also a member of NoNuke Taiwan Union. This Union is designed to establish a non-nuclear living environment for the Taiwan people. The weighting method is applied because of its compatibility to encode computer language: Avenue script in ArcView 3.x. Avenue script is a kind of object-oriented language, not as friendly as Visual Basic or C language [26]. It also does not provide adequate and complicated formulas for mathematics. Since most of our required road-network attributes have been set up on ArcView 3.x by INER for many years, we had no choice but to accommodate to the currently employed ArcView 3.x. It took considerable time to integrate the linear programming model into the ArcView 3.x interface by the Avenue script. The decision steps of constructing such a multi-objective GIS is shown as follows:

(a) *Data collection*: First, our required data for modeling are practically surveyed and updated for GIS database.

(b) *Data normalization*: Since only four basic mathematical functions: plus, minus, multiplication and division are available by the Avenue script of ArcView 3.x (if a complicated formula is desired, you must call it from the external environment), and these attributes are measured with different scales, we use the simple linear scale transformation [24] to normalize our collected data:

$$nv_{ab} = \frac{v_{ab}}{\max_a v_{ab}}, \tag{7}$$

where nv_{ab} is the normalized value, $0 \leqslant nv_{ab} \leqslant 1$; v_{ab} the bth attribute value of the ath record in the GIS database.

(c) *Determine the weight of each objective*: Five experts are invited to give their subjective pair-wise comparison matrices among three objectives: minimizing the total transportation cost, minimizing the risk cost, and minimizing the public resistance. After that, all computed weights from experts are averaged to form the global weight of each objective.

(d) *Model resolution on GIS*: The available data are retrieved into our model for resolving the multi-objective linear model of Eqs. (1)–(5) by Avenue of ArcView 3.x. Dijkstra's algorithm [27] is applied for resolving this shortest route problem. This general algorithm is shown as follows: let e_l be the shortest distance from source node 1 to node l, and define $f_{lm} \geqslant 0$ to be the length (travel cost) of arc (l, m). Then the algorithm defines the label for $[e_m, l] = [e_l + f_{lm}, l]$, $f_{lm} \geqslant 0$. The label for the starting node is [0, −], indicating this node has no predecessor. Node labels in Dijkstra's algorithm are two types: temporary and permanent [27].

Finally, the shortest route is determined by Avenue of ArcView 3.x on GIS. These illustrations are available in Section 4.

4. Actual transportation decision of Taiwan

As a national laboratory, the INER mission is to enhance its current R&D capabilities of nuclear technology, and to further assist local industries in utilizing this technology to benefit the lives of Taiwan citizens. In addition, INER is conscious of the responsibility to help the public understand nuclear science and how radioactive wastes are properly transported and well managed. As a result, INER has opened its transportation planning process in Section 3.2 to the interested parties by the MCDM approach. Currently, there are three nuclear power plants in Taiwan, and the radioactive nuclear wastes are estimated at about 13,500 cans per year [23]. The largest power plant and its corresponding transportation network for radioactive nuclear wastes are exactly located in Lungtan, Taoyuan, as shown in Fig. 1. We apply the decision steps (a)–(d) in Section 3.2 and resolve the shortest route model by the following AHP weights: 0.32 for z_1, 0.37 for z_2 and 0.31 for z_3, respectively. Furthermore, the computed results for each objective and the compromised solution are summarized in Table 1.

Each objective attainment defined in Table 1 is computed by Eq. (8):

$$\text{Attainment}_k = 1 - \frac{z_k - z_k^{\min}}{z_k^{\max} - z_k^{\min}}. \tag{8}$$

Fig. 2 is seeking for the minimal travel time; thus, we found that this single objective optimum of 106.44 min is mainly using the freeway and the expressway for transportation rather than local roads. Fig. 3 is achieved for traveling by the lowest-volume links—the link of high traffic volume leads to the high accident risk; thus, we found this single objective optimum of 720 vehicles per hour is interestingly taking multiple turns so as to be evacuated from the congested traffic area as soon as possible. Fig. 4 is desired for passing through the minimal population area; thus, this single objective optimum of 12819 residents is designing a route very far away the heavily populated area, i.e., the capital area. Each individual single objective optimum reflects the characteristics of actual geography data.

Figs. 2–4 demonstrate finding the best route solely for z_1, z_2 and z_3, respectively. And the most important result: Fig. 5 is the compromised result for weighing z_1, z_2 and z_3. The compromised planning result of Fig. 5 shows that using the expressway when traveling near (into) the capital area, and take more turns to avoid the congested traffic when traveling beyond the capital area, i.e., using the substitutive road system in the urban area. The substitutive road system is the road-network that leads to the same destination, but it is not so familiar by most of the normal drivers. Therefore, the finally programming result of $z_1 = 326.55$ min, $z_2 = 875.98$ vehicles per hour and $z_3 = 16124$ residents, it did help the decision makers for the tradeoff among the minimal travel time, minimal traveling risk and minimal exposed population. We believed, in Fig. 1, the multi-objective route is successfully planned from the INER to the Harbor: this interesting result is shown in Fig. 5 so as to be compared with the individually optimized route from Figs. 2–4. Since three weights are subjectively given by various decision makers, our multi-objective GIS is interactive with decision makers.

The main advantage of GIS differing from other database systems is its ability of showing maps: visualizing the planned results and make them simple and clearer to the decision maker. These graphical solutions of Figs. 2–5 not only visualize the planned results with different weight settings and help the INER distinguish the difference from various optimizations, but also provide the carrier a routing guide (report) through the complicated road-network by ArcView 3.x. The visualized report instantly helps practitioners realize the value

Table 1
Computed results

Objective\value	Compromised	Maximum	Minimum	Attainment
Travel time (z_1)	326.55 (min)	789.93 (min)	106.44 (min)	0.68
Transportation risk (z_2)	875.98 (veh/h)	1421.05 (veh/h)	720.00 (veh/h)	0.77
Exposed population (z_3)	16124 (people)	24036 (people)	12819 (people)	0.53

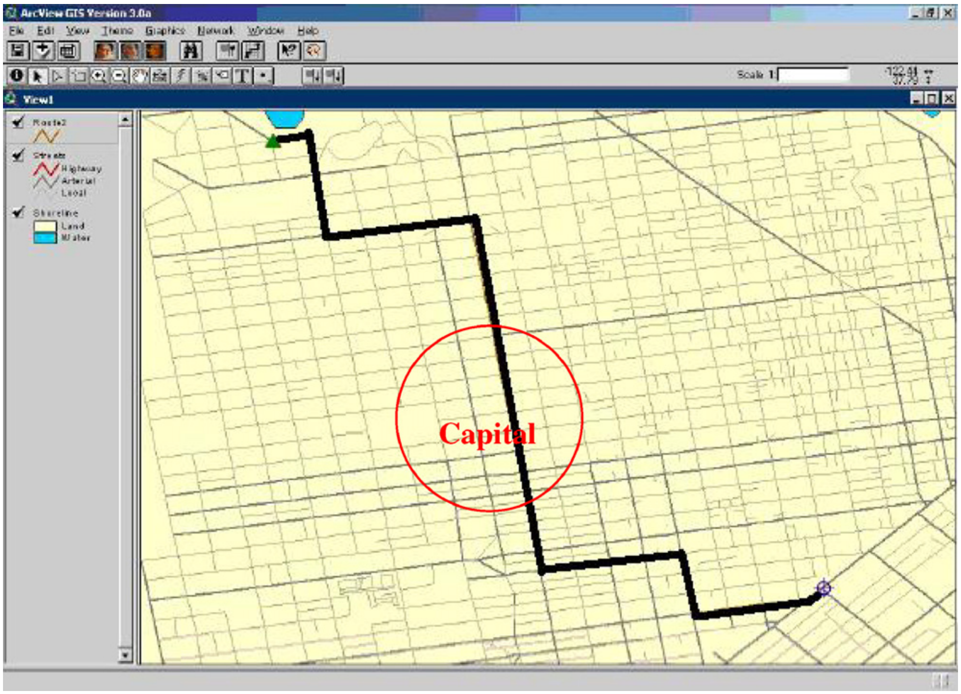

Fig. 2. Optimal route with minimal travel time. $z_1 = 106.44$ (min).

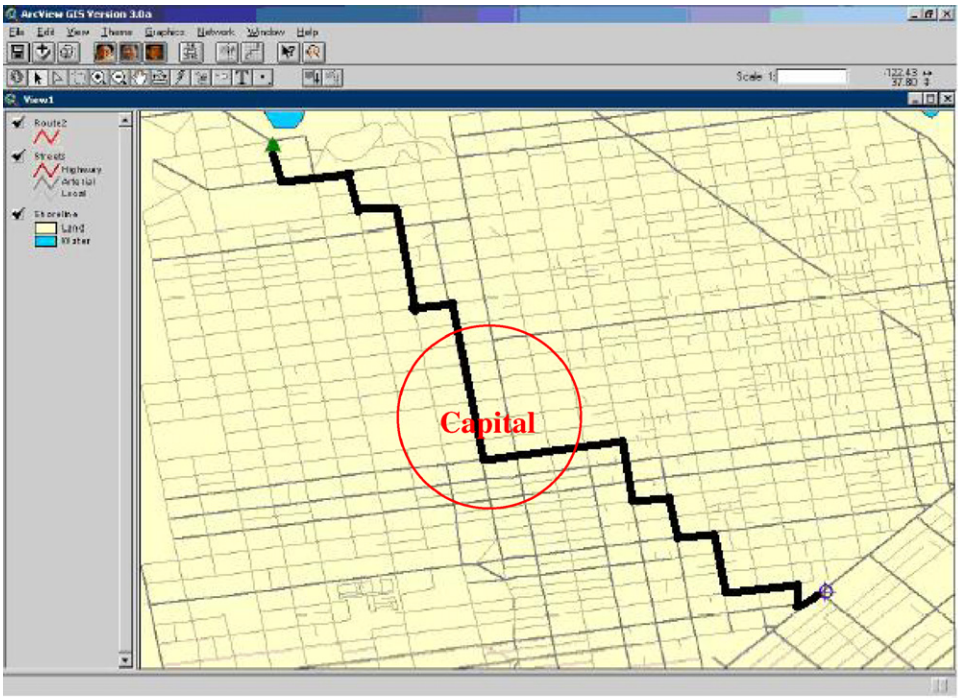

Fig. 3. Optimal route with minimal transportation risk. $z_2 = 720.00$(veh/h).

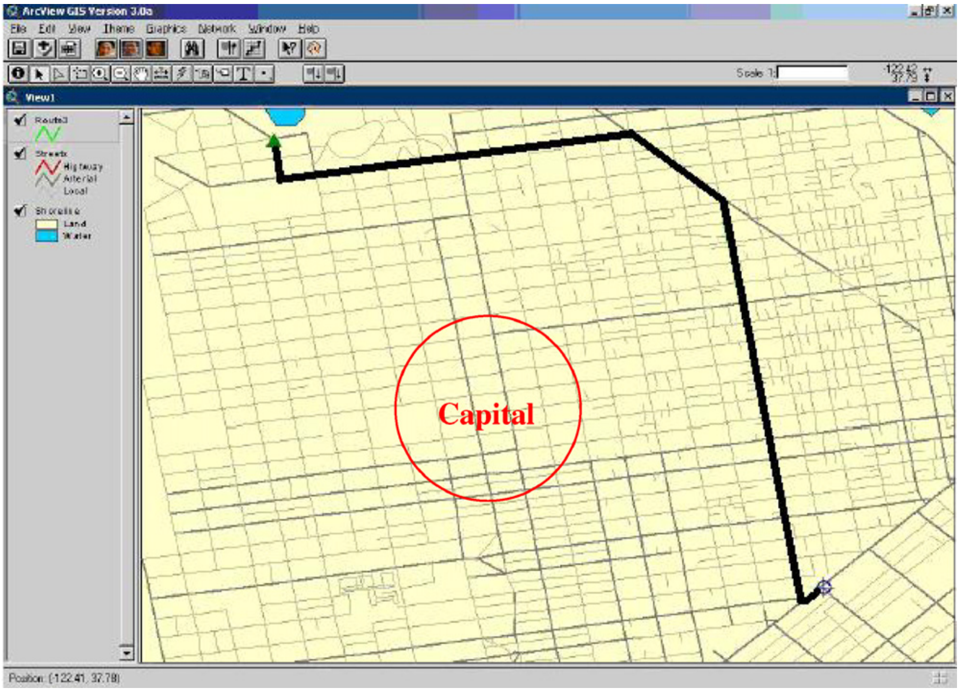

Fig. 4. Optimal route with minimal exposed population. $z_3 = 12819$ (people).

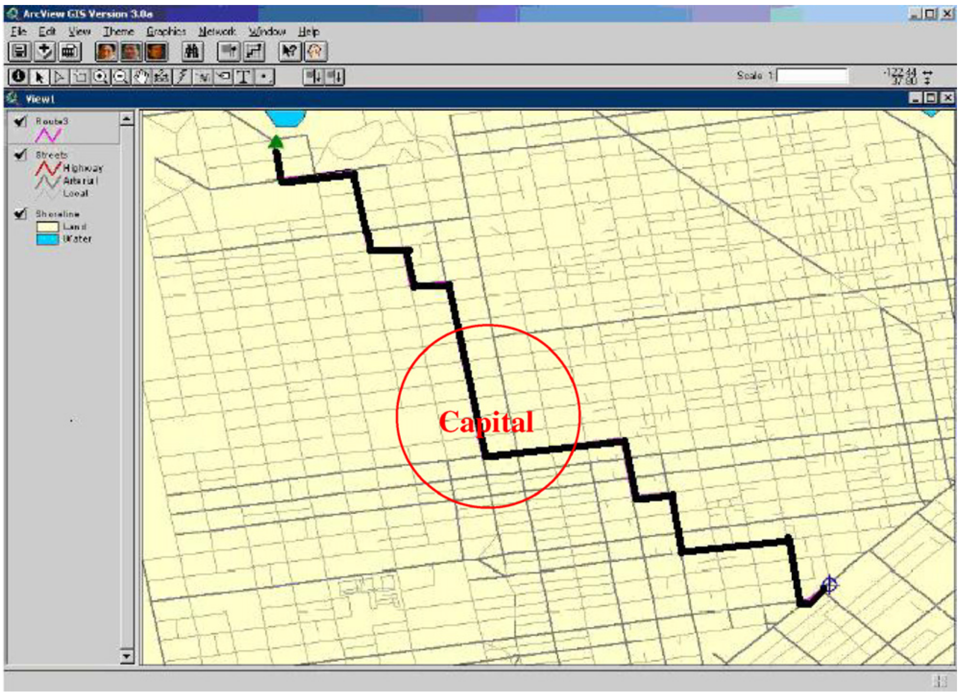

Fig. 5. Compromised route with multi-objective optimization. $z_1 = 326.55$ (min), $z_2 = 875.98$ (veh/h), $z_3 = 16124$ (people).

of multi-objective programming; furthermore, drivers can directly apply the routing guide generated by GIS to decide where to take turns, and driving how long until the next turn. This report is represented by the actual road-name of each passed link to the drivers. The carrier driver can also accomplish his mission through the visualized results, just like finding an optimal route on a map. Decision makers can make better choices if they set various weights with more interested parties for these objectives in the future. Such a multi-objective route analysis is validated for its value in this study.

5. Conclusions and recommendations

The main contribution of this paper is focused on "actual application" for testing the technical feasibility of multi-objective GIS, rather than "theoretical originality" for proposing new multi-objective models for resolution. We successfully developed the multi-objective GIS for route selection of nuclear waste transport, and this system is practically approved by the INER in Taiwan. As the public becomes increasingly concerned about environmental conscience and transportation safety, our efforts are beneficial to the public and the Taiwan government.

However, technical success does not necessarily guarantee successful execution of our multi-objective GIS in practices. This means, the planned result of Fig. 5 is not the finally determined route so far. Why? The difficulty is resulting from the political scope rather than the technical scope: the multi-objective GIS is really brilliant to the INER, but the INER will conditionally apply our approach on the nuclear waste transport in the very near future if we can continuously release our model assumptions and resolve the following questions as soon as possible: for example, what information do participants need to engage in the process? Who should be participating currently in waste cleanup dialogues? Perhaps more important, who is missing from the discussion? Are the current interested parties adequate and sufficient to present the public so as to make a good transportation decision? Is the congress really favored of such a MCDM process that makes each route of nuclear waste transport transparent? Although the concept of multi-objective GIS is approved by the INER, the questions just raised relate to qualitative rather than quantitative issues discussed here—any final decision, i.e., any finally determined route of nuclear waste transport in Taiwan is very sensitive in politics to the public. Therefore, the INER continuously pushes us resolving the proposed difficulties above in the coming project before such a system could be actually launched to the public. We believe our proposed model is a simple interface to integrate the public, the scholars (researchers): who are major in multi-objective modeling and the practitioners: who are major in the administrative affairs. We still negotiate with the INER for the coming research project in order to actually implement our idea by conquering the aforementioned difficulties.

Since calculating the transportation risk is a tough task, the second and the third objective of our study could be better modified to our current ideas. ArcView 3.x is promoted to ArcView 9.x so far as we know, and ArcView 9.x can directly communicate with Visual Basic and C; therefore, some evolutionary algorithms or fuzzy concepts of MCDM might be included.

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