

Research Article

GIS and genetic algorithms for HAZMAT route planning with security considerations

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Abstract. Singapore is the third largest oil-refining centre in the world, with a large petrochemical hub located at Jurong Island. In view of the increasing concern for transportation security, there is an urgent need to improve the way trucks carrying hazardous materials (HAZMATs) are being routed on urban and suburban road networks. Routing of such vehicles should not only ensure the safety of travelers in the network but also consider the risk of the HAZMAT being used as weapon of mass destruction. This paper explores a novel approach to evaluating the risk of HAZMAT transportation by integrating Geographic Information Systems (GISs) and Genetic Algorithms (GAs). A set of evaluation criteria that are used to route the HAZMAT vehicles was identified and assessed. The criteria considered are related to safety, costs and, more importantly, security. A GIS was employed to quantify the factors on each link in the network that contribute to the evaluation criteria for a possible route, while a GA was applied to efficiently determine the weights of the different factors in the hierarchical form, allowing for the computation of the relative total costs of the alternate routes. Therefore, each route can be quantified by a generalized cost function from which the suitability of the routes for HAZMAT transportation can be compared. The proposed route evaluation method was demonstrated on a typical portion of the road network in Singapore.

1. Introduction

Security issues have received increased attention after the terrorist attacks in New York and Washington, DC on September 11, 2001. With this heightened awareness, policy-makers are taking steps to improve the security of transportation systems. Trucks transporting hazardous materials (HAZMATs) may be a form of weapon of mass destruction if abused by terrorists (TRB 2002); hence, a more comprehensive evaluation of their route planning is required to reflect the current shift in the emphasis towards transportation security.

Route planning for trucks carrying HAZMATs has been in practice for decades.

Traditionally, the main considerations include cost, safety in terms of risk of vehicle collision and potential exposure of the public to the HAZMAT substances (Lepofsky and Abkowitz 1993, Turnquist and List 1993). Singapore is a small nation with a high population density and is the world's third largest oil-refining centre, behind Rotterdam and Houston. Owing to land constraints, petrochemical vehicles are bound to pass through highly populated areas from Jurong Island, the petrochemical hub, to the rest of the country. The destinations include not only petrochemical-specific industries and airports but also the various petrol or gasoline stations spread across the island, usually within or in close proximity to populated areas.

Transportation of HAZMATs in Singapore is regulated by the National Environment Agency's (NEA) Pollution Control Department and the Singapore Civil Defence Force (SCDF). The control is effected through the Environmental Pollution Control (Hazardous Substances) Regulations under the Environmental Pollution Control Act (GoS 2002), as well as the Fire Safety Act (GoS 2000). The use of certain types of heavy vehicle (measured by the maximum laden weight) and the goods being transported in public roads is also subject to additional regulations set forth by the Land Transport Authority (LTA), according to the Road Traffic Act (GoS 1997). This Act requires the owners to indemnify the LTA in respect of any damages that may be caused to any road or bridge by the movement of such vehicles.

The existing regulations specify the allowable spots or links to be exact, rather than the approved routes. Given a set of alternate routes between an origin and a destination, the quantitative means of evaluating the possible routes remains unknown. The rationale for deeming a link prohibited is also not made known to the public. This research attempts to identify a set of evaluation criteria that can be used to route trucks carrying HAZMATs, incorporating factors addressing the security aspect, in addition to cost, safety and exposure. A Geographical Information System (GIS) is used as a tool to quantify the identified routing criteria, and a Genetic Algorithm (GA) is applied to efficiently determine the weights of two levels of factors involved in each of the criteria. Eventually, the main objective is to quantify each alternate route by a unique generalized cost to determine its suitability for HAZMAT transportation, based on current conditions.

The remainder of this paper is organized as follows. Section 2 reviews the relevant literature involving HAZMAT transportation. Section 3 introduces our proposed methodology. Then, Section 4 describes in more detail the GIS analysis, the determination of weights using the GA and the results. Finally, Section 5 provides our concluding remarks.

2. Route planning of hazardous material transportation

HAZMAT route planning has been a popular area of research in the United States. The Office of Highway Safety under Federal Highway Administration (FHWA) is responsible for regulating routing procedures for HAZMAT transportation. Its publication (FHWA 1994) outlines the routing process involving HAZMATs. In addition to the exposed population, this guide also identifies factors such as the existence of facilities such as schools, hospitals, fire stations and reservoirs, which may influence a decision among alternative routes that may otherwise present a similar risk. Emergency response capabilities can be a critical

consideration in evaluating the consequences of an accident resulting in a release of HAZMATs. The guide also states that the evaluation of the likelihood of burden on commerce is an intrinsic part of the selection process. In addition, the Level of Service (LOS) of the highway collectively affects travel time, travel speed, safety and also increases the probability of release accidents.

The above factors were evidently used by Turnquist and List (1993). They concurred that multiple objectives must be incorporated in the analysis. They argued that the existence of multiple criteria meant that it was usually not possible to identify a single most preferred route between a given origin and destination. Therefore, the focus should be on finding a set of non-dominated routes which represents the trade-offs explicitly. In their analysis, they focused on the following measures, namely operating cost, accident rate, population exposed and the number of schools in the exposure area.

Abkowitz and Cheng (1988) proposed a risk/cost framework for optimizing HAZMAT routing. In assessing the risks involved, they included the effects of human exposure to a dose of chemicals, to yield human health risk. List and Mirchandani (1991) introduced an integrated multi-objective model for routing and storing HAZMAT wastes. In addition to risk and cost, they also considered risk equity, which is measured as the maximum risk per unit population. Total risk, however, is the sum of all zonal risks from transportation or treatment.

Erhan and Verter (1998) explored the different models of risk. The traditional definition of risk is the product of both the probability and the consequence of the undesirable event. They cited unit road segment risk, edge risk and path risk as models of risk using the traditional definition. They also cited alternative risk models involving perceived risk, the disutility of risk and conditional risk. They suggested that the risk-minimization problem is a bicriterion optimization problem: one of minimizing incident probability and population exposure. The consideration of other criteria is also possible. As long as each criterion is additive to its edge attributes, the weighting method can be used to generate a subset of efficient points.

Goh *et al.* (1995) introduced a methodology for the risk analysis of hazardous chemical transportation in Singapore. A case study involving the transportation of Liquefied Petroleum Gas (LPG) in Singapore was reported, which addressed the modelling of three hazard scenarios: instantaneous release, medium spill and small spill. Risk assessment was also done for the off-road population and the road users.

Existing literature shows that the use of GISs to aid HAZMAT route planning is not new. Lepofsky and Abkowitz (1993) demonstrated that GISs can be used to integrate plume representation with population data and transport maps to estimate consequences more effectively. They cited a case study of rocket-fuel transportation in California. Using combinations of routing criteria (e.g. population exposure, accident likelihood and environmentally sensitive areas) in a single analysis with varying weights on their importance, one can examine the trade-offs between various alternatives. The GIS system allowed for the computation of the average emergency response time to any segment in the state highway network. The GIS could also determine the most efficient method for evacuation and determining the most efficient way to reroute traffic.

Souletrette and Sathisan (1994) applied GISs in the transportation of radioactive materials. Like HAZMAT routing, key inputs include demographics, environmental features and transportation system characteristics. They identified

three methodologies, namely, comparative studies, worst-case assessment and probabilistic risk assessment. Brainard *et al.* (1996) demonstrated the use of GIS to route aqueous waste cargoes using four methods, namely: (1) routing by shortest time only; (2) routing by motorway and dual-carriageway encouragement; (3) routing to avoid population; and (4) routing to avoid accidents. The first two methods were used to identify the most probable routes used by tanker drivers to deliver their consignments. The next two methods were risk-reducing scenarios. Groundwater vulnerability was also considered in their study.

The vast collection of literature involving HAZMAT transportation reveals that the main considerations are exposure and accident likelihood. This is also consistent with the current SCDF practice of avoiding densely populated areas in Singapore. Brainard *et al.*'s consideration of groundwater vulnerability is also taken by the SCDF. The need to include security considerations has only recently gained greater attention. Abkowitz (2002) points out that transportation risk assessment must accommodate terrorism scenarios that have previously been considered so unlikely to warrant risk-management assessment. Likewise, emergency response capabilities must be sufficient to handle impacts beyond what was previously imaginable in terms of number of casualties and the required resources.

Recently, Srinivasan (2002) suggests a framework for network-wide security and vulnerability assessment. He identifies the factors that affect link-level vulnerability which include network attributes, threat attributes, flow attributes and neighbourhood attributes. A thorough vulnerability assessment is described in AASHTO (2002). It describes six steps for conducting a vulnerability assessment. They are (1) identify critical assets; (2) assess vulnerabilities; (3) assess consequences; (4) identify countermeasures; (5) estimate countermeasures cost; and (6) review operational security planning. Therefore, it is apparent that there has been a shift in paradigm towards concerns in security threat and vulnerability, and integrating security considerations into the overall framework of HAZMATs transportation.

GA is a form of randomized-search optimization method mimicking the natural evolutionary process of natural selection, or the 'survival of the fittest' (Goldberg 1989). A more detailed description of GAs can be found in a later section. While Xiao *et al.* (2002) employed GAs to generate alternatives for multi-objective site search problems, the combined use of a GIS and a GA is not widespread, especially in transportation and environmental studies. Two studies were found in the review of the use of such hybrid technique. Matthews *et al.* (2000) applied GAs in rural land-use optimization. The GIS provided spatial data and spatial analysis. The GA was the core of an iterative system, generating alternative land-use plans in a context set by the land manager. Vink and Schot (2000) developed a computer-based procedure for multiple-objective optimization of drinking-water production by combining a transport optimization procedure with a GA. The approach was implemented in a GIS-based decision support system to handle all spatial relations efficiently and to offer decision-makers access to the developed method. To the best of our knowledge, no comprehensive studies involving the use of a GIS and a GA have been attempted before in the field of HAZMAT route planning.

3. Methodology

A number of the evaluation factors have been modified from those recommended by FHWA (1994) and GoS (2002). Factors were added or adapted

to account for security. A scoring system was devised by classifying the identified factors, each being given a score ranging from 1 to 5. Relevant data were gathered and input into the GIS database. The scores can be considered as substitutes to actual population counts or accident probabilities required in the traditional risk analysis. Scores are a better surrogate to actual accident probabilities, which require accident-rate data that are often insufficient or unavailable. Generally, at least three years of truck accident data are preferable to determine accident rates (FHWA 1994).

The relative importance of the respective criteria, together with their factors, was then determined using a GA. The output of the GA is a set of weights representing their relative importance. The cumulative weights and scores that represent a generalized cost of each route are given by:

$$\text{Generalized cost of route } R = \left(\sum_{c=1}^{n_c} \left(w_c \sum_{cf=1}^{n_{cf}} w_{cf} s_{cf} \right) \right) \quad (1)$$

where c = criteria; n_c = number of criteria; w_c = weight of criteria c ; cf = factor under criteria c ; n_{cf} = number of factors under criteria c ; w_{cf} = weight of factor f under criteria c ; s_{cf} = score of factor f under criteria c . The aim of our approach is to ensure that the recommended route has the lowest (or one of the lowest) generalized cost.

To test the feasibility of the proposed evaluation method and criteria used, an area of approximately 3 km by 3 km in Singapore was chosen. This encompasses Clementi Road, West Coast Road and the National University of Singapore (NUS) campus as illustrated in figure 1. In order to compare with the SCDF's approved routes comprehensively, three origin–destination (O–D) pairs were chosen, namely, Routes 1, 8 and 15. In addition, a set of six alternative routes that deviate from each of the three approved routes, respectively, were chosen for comparison.

By taking cost, safety and security into consideration, five criteria have been identified:

1. *Exposure*. The population that is exposed, in the event of a chemical release or explosion, is represented by the population density of the surrounding land use. Exposed population is a key factor in determining the consequences of a chemical release in risk analysis.
2. *Socio-economic impact*. This factor accounts for the direct and indirect costs incurred from damages resulting from a HAZMAT accident, including a terrorist attack.
3. *Risks of hijack*. The population density of the surrounding areas indicates the ease which a hijack can take place. It is assumed that a hijack is more likely to occur along a deserted stretch of road.
4. *Traffic conditions*. The conditions of traffic such as speed and flow affect travel time, road safety and operating costs. Congestion may also lead to a higher risk of accidents.
5. *Emergency response*. Emergency response capabilities can be a critical consideration in evaluating the consequences of an incident leading to a chemical release or explosion. The locations of the SCDF emergency response teams as well as proximity to hospitals contribute to rescue efficiency.

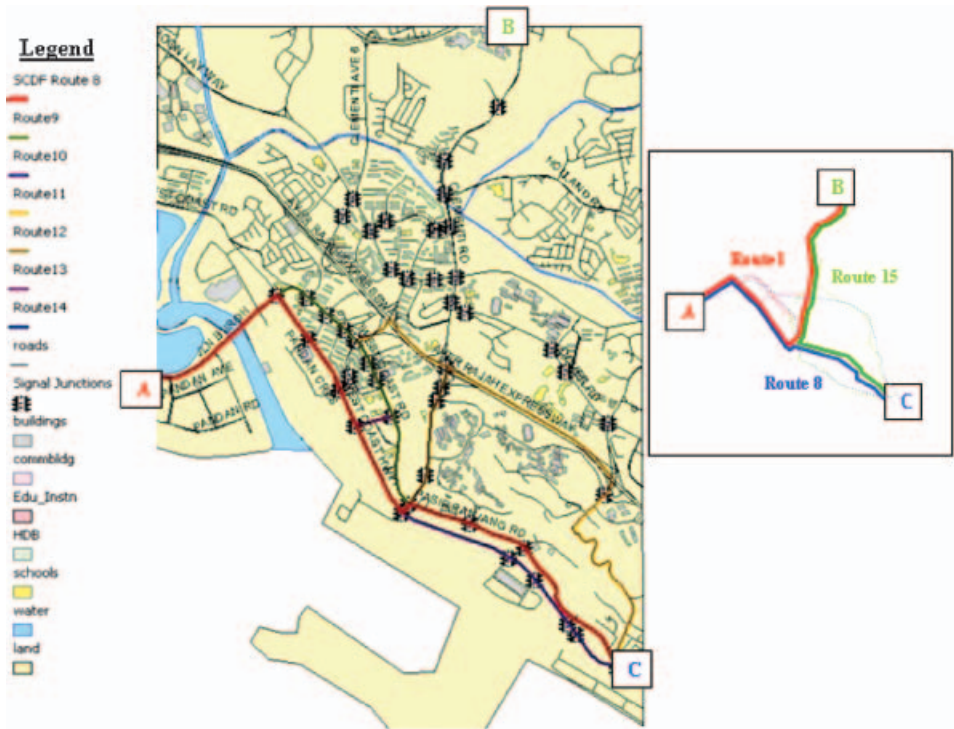


Figure 1. Area of study and SCDF Route 8 and its six alternative routes.

4. Analysis using GIS

The use of GISs in vehicle route planning offers a number of advantages over traditional methods. Using maps alone to determine impact area and to find features are tedious and time-consuming. GIS allows the addition of relevant layers that can be used for such spatial analyses. GISs offer database capabilities that can handle attribute data. Attribute queries are easy and relatively accurate. This project uses ArcGIS (ESRI 1996) as the GIS platform to perform route analysis.

After the identification of the criteria, a number of factors that are subsets of each criterion were identified. These factors are quantifiable and each factor was assigned a numerical score ranging from 1 to 5, depending on the attribute value. Table 1 shows a fragment of the scoring system for the attributes.

Table 1. Scoring system for factors.

Emergency response	1	2	3	4	5
Nearby fire station	0–0.5 km	0.5–1 km	1–1.5 km	1.5–2 km	>2 km
Nearby police	0–0.5 km	0.5–1 km	1–1.5 km	1.5–2 km	>2 km
Nearby hospitals	0–1 km	1–2 km	2–3 km	3–4 km	>4 km
Nearby army camps	0–0.5 km	0.5–1 km	1–1.5 km	1.5–2 km	>2 km
Network redundancy	–	–	3 or more lanes	2 lanes	1 lane

4.1. Exposure

In ArcGIS, a buffer zone is created to simulate the potential impact area. The potential impact zone for flammable or combustible hazardous materials was taken as 0.8 km in all directions (FHWA 1994). Therefore, a buffer of 0.8 km width was generated for each of the 21 routes (including the recommended route). Figure 2 shows the buffer zone of 0.8 km on both sides of the West Coast Highway. As the exposed population was the main concern, the features taken include the type of residential land use, commercial and government buildings, industrial areas, number of school buildings and Mass Rapid Transit (MRT) stations. Through ArcGIS, the appropriate attributes were queried and the respective scores calculated.

4.2. Socio-economic impact

Based on the same buffer zones or impact area, the potential damage of a HAZMAT incident may be estimated based on the physical damage to the

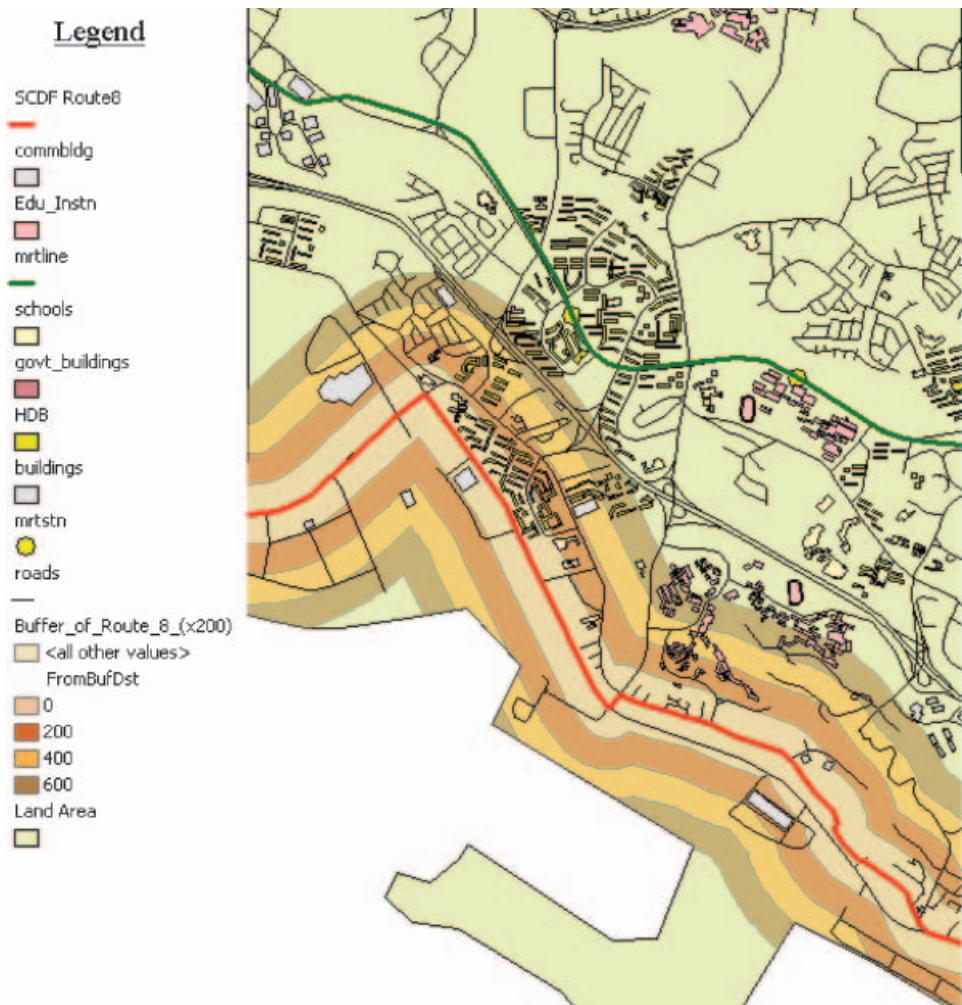


Figure 2. ArcGIS generating buffer zones.

surrounding infrastructure. This may lead to negative socio-economic consequences. The infrastructure under this consideration included the residential housing, commercial and industrial buildings, waterbodies, petrol/gasoline stations, bridges and major transportation terminals (e.g. mass rapid transit stations).

Routes involving tunnels were avoided. This is because tunnels are confined spaces, and any release or explosions within a tunnel will lead to great complications in the rescue effort. Since tunnels are often critical transportation links, they are best avoided during the routing process (Polzin 2002).

4.3. *Risks of hijack*

Trucks may potentially be hijacked in sparsely populated areas. Areas with thick foliage provide good cover and may be used as hiding places for terrorists to ambush the trucks. Therefore, these two attributes were given higher scores that deem them undesirable.

4.4. *Traffic conditions*

Traffic density, flow or volume, average speed, number of signalized intersections and the accident frequency are important considerations for cost, safety and security. A high traffic density implies that a higher population of road users will be exposed to released chemicals or an explosion.

A high average speed leads to a shorter travel time. However, it also leads to a higher possibility of accidents and makes it more difficult for police interdiction (Luedtke and White 2002).

The number of signalized intersections may also aid in police interdiction, since the traffic flow may impede a rogue driver at a rate light. However, a higher number of signalized intersections translates to a longer time taken for the trip and, hence, higher costs.

4.5. *Emergency response*

The proximity of the routes from a particular location or link to a fire station and/or hospital improves the incident response time in rescue operations. Nearby police stations and military bases may also respond to any request for interdiction of rogue driver or road blockage. Their presence in the vicinity may also serve as a deterrent to possible terrorist activity. Figure 3 shows the locational influence of a hospital.

5. **Determination of weights using genetic algorithms**

The generalized cost is a weighted sum of the scores of the criteria and factors under each criterion (equation (1)). However, as mentioned before, to what extent and the relative importance the approving agency takes each criterion and factor into consideration are unknown. Therefore, a method of determining the weights for the five main criteria under consideration, and their respective factors, has to be developed.

The use of GAs proves suitable in this case. GAs are directed random search techniques used to look for parameters that provide a good solution to a problem. GAs are a form of natural optimization method. Optimization is the process of adjusting the inputs to, or the characteristics of, a device, mathematical process or

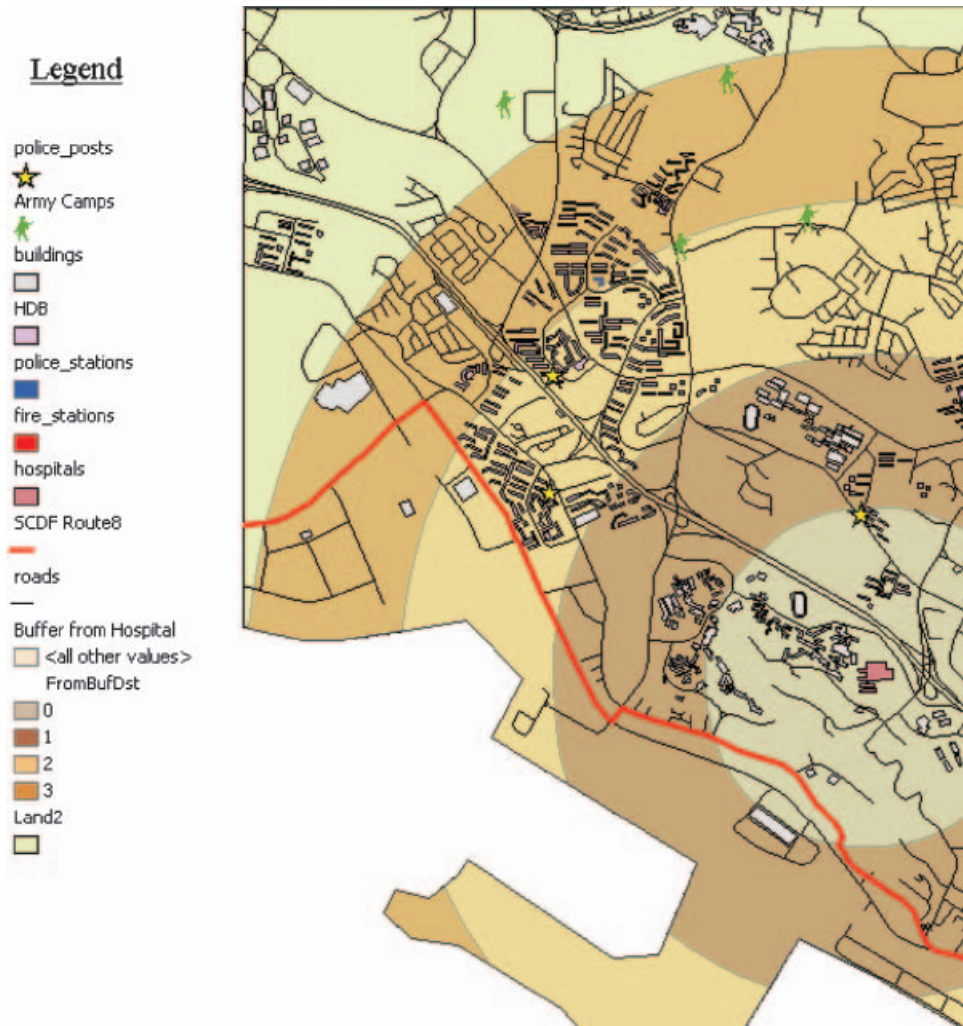


Figure 3. Buffer radiating from a hospital.

experiment to find the minimum or maximum output or result (Goldberg 1989). In this problem, the weights used in equation (1) were optimized. The inputs are scores of the factors that made up the cost function, and the objective is to minimize the generalized cost.

A population of strings, representing solutions to a specified problem, is maintained by the GA. In GA terms, a candidate solution is often referred to as a chromosome or string, which is a sequence of encoded numbers. This is commonly referred to as a bit string if the numbers are binary encoded.

The GA then iteratively creates new populations from the old by ranking the strings and interbreeding the fittest to create new strings, which are ideally closer to the optimum solution to the problem. In each generation, the GA creates a set of strings from the bits and pieces of the previous strings, occasionally adding random new data (mutation) to keep the population from stagnating. The end result is a search strategy that is tailored for vast, complex, multimodal search spaces.

The idea of ‘survival of the fittest’ is of great importance to genetic algorithms. GAs use what is termed as a ‘fitness function’ in order to select the fittest string that will be used to create a new, and conceivably better, population of strings. The fitness function takes a string and assigns a relative fitness value to the string. The method by which it does this and the nature of the fitness value do not matter. The only thing that the fitness function must do is to rank the strings in some way by producing the fitness value. These values are then used to select the fittest strings. The concept of a fitness function is, in fact, a particular instance of a more general Artificial Intelligence concept, the objective function.

The implementation stages of GAs in general are summarized in figure 4. Two optimization methods were used to determine the weights:

Method 1:

$$[\text{Minimum}] = \sum_{cd=1}^3 \left(\sum_{c=1}^{n_c} \left(w_c \sum_{cf=1}^{n_{cf}} w_{cf} S_{cf_r} \right) \right) \tag{2}$$

where $\sum_{c=1}^{n_c} W_c = 1$; $\sum_{cf=1}^{n_{cf}} w_{cf} = 1$

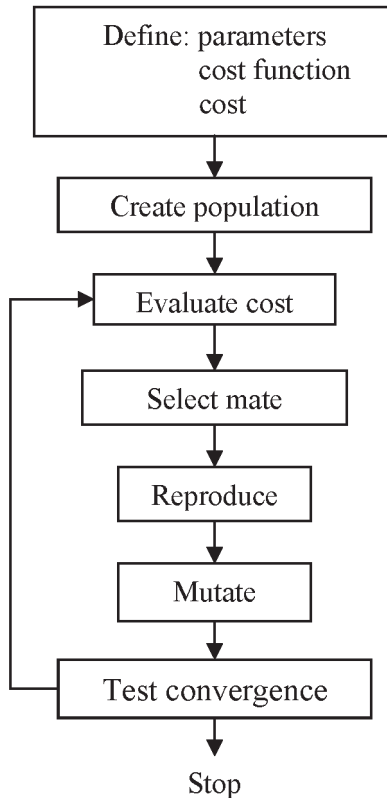


Figure 4. General scheme of a genetic algorithm.

Method 2:

$$[\text{Maximum}] = \sum_{cd=1}^3 \left(\sum_{c=1}^{n_c} \left(w_c \sum_{cf=1}^{n_{cf}} w_{cf} (s_{cf_a} - s_{cf_r}) \right) \right) \tag{3}$$

where $\sum_{c=1}^{n_c} W_c = 1$; $\sum_{cf=1}^{n_{cf}} w_{cf} = 1$

where c = criteria; n_c = number of criteria; w_c = weight of criteria c ; cf = factor under criteria c ; n_{cf} = number of factors under criteria c ; w_{cf} = weight of factor f under criteria c ; s_{cf} = score of factor f under criteria c (subscripts a and r depict alternative routes and their corresponding approved routes, respectively); cd = approved route.

The minimization process in equation(2) is based on the assumption that the three approved routes would incur the least costs. Therefore, just by minimizing the three costs, the most optimum set of weights may be derived. Equation(3) optimizes the differences between the costs of other routes compared with the approved routes. By maximizing the difference, this should ultimately cause the approved routes to incur the least costs. The GA programs used in this study were coded in Visual C++ and run on a Pentium IV PC.

The nature of the problem can be represented by a hierarchical tree. Table 2 is a detailed list of the criteria and factors, and figure 5 shows a hierarchical representation of the problem. In our problem, the first level of consideration is the five criteria. The weights determined for each criterion, w_c , represent both the global and local weights. The next level of the hierarchy consists of the factors. The GA determined the local weights of all the factors, i.e. w_{cf} . The global weight of

Table 2. Detailed list of criteria and factors.

Criteria	Factors
1. Exposure	<ul style="list-style-type: none"> ● Type of residence (A1) ● Commercial and government buildings (A2) ● Industrial buildings (A3) ● Schools and tertiary institutions (A4) ● Mass Rapid Transit stations (A5)
2. Socio-Economic Impact	<ul style="list-style-type: none"> ● Type of residence (B1) ● Commercial and government buildings (B2) ● Industrial buildings (B3) ● Waterbodies (B4) ● Petrol/gas stations (B5) ● Bridges (B6) ● Mass Rapid Transit stations (B7)
3. Risks of Hijack	<ul style="list-style-type: none"> ● Population density (C1) ● Vegetation/foilage cover (C2)
4. Traffic Conditions	<ul style="list-style-type: none"> ● Traffic density (D1) ● Traffic speed (D2) ● Number of signalized junctions (D3) ● Accident frequency (D4)
5. Emergency Response	<ul style="list-style-type: none"> ● Proximity to fire stations (E1) ● Proximity to police stations (E2) ● Proximity to army camps (E3) ● Proximity to hospitals (E4) ● Network redundancy (E5)

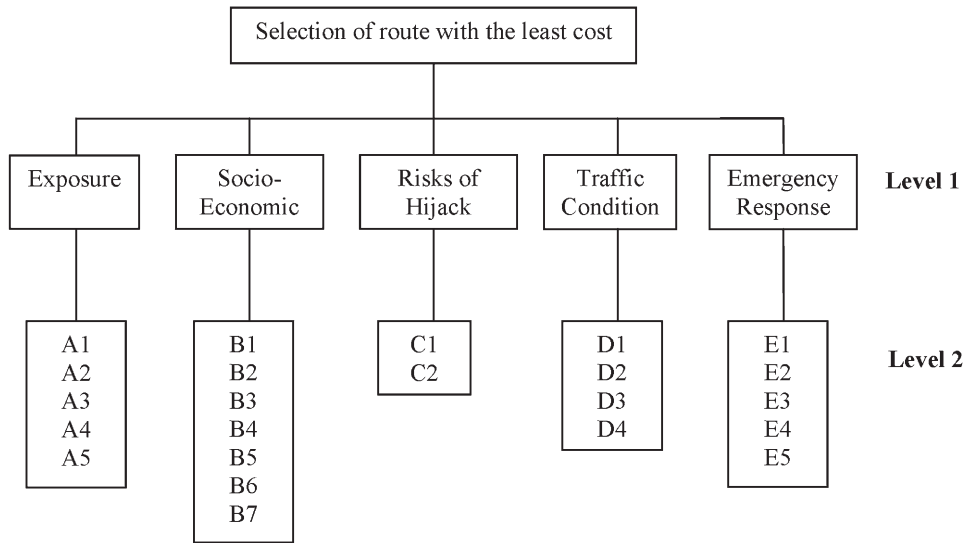


Figure 5. Simplified hierarchical representation of problem.

each factor, W_{cf}' , is defined by equation (4). Therefore, the weight of a criterion is essentially the sum of the global weights of the factors under it, as shown in equation (5):

$$W_{cf}' = w_c \times w_{cf} \tag{4}$$

$$w_c = \sum_{cf=1}^{n_{cf}} w_{cf} \tag{5}$$

It is clear that the objective functions of the two methods are modifications of the cost functions as stated earlier. Owing to the large number of unknown parameters, i.e. the 31 weights to be determined, each optimization was done in two stages. The first stage was the unconstrained stage. Optimization was done only with the upper and lower bounds allowable for the weight of each factor. The weights obtained for the factors were then normalized to fulfil the second constraint, before the second stage was carried out. Only the weights of the five criteria were left to be determined in the second stage (known as the constrained stage).

In both cases, the chromosome string encoding was done using real numbers. Figure 6 illustrates a simple GA using real number encoding. For the unconstrained stage, a population size of 1200 was chosen, for a total of 8000 generations. As for the constrained stage, the population size was set as 500, and a total of 8000 generations were executed.

Tournament selection was used to select parents for breeding, with a two-point crossover of 0.8 probability applied to each pair of selected parents. This means that there was an 80% chance of a crossover at the randomly chosen point. At each generation, each bit of the genotype of every solution can be mutated (i.e. the NOT operator is applied to that bit), with a 0.02 probability of mutation. The role of mutation is to provide genetic diversity. However, the mutation probability was kept small so as not to cause a big disruption in the evolution of solutions by reproduction. Elitism was chosen at 10, meaning that at the end of every

1. Generate population

Chromosomes
0.4 0.6 0.8 0.3 0.1 0.9
0.2 0.4 0.7 0.8 0.1 0.3
0.4 0.7 0.5 0.3 0.9 0.1
0.3 0.8 0.9 0.1 0.2 0.5
0.1 0.3 0.4 0.6 0.9 0.7

2. Evaluate costs

Chromosomes	Cost
0.4 0.6 0.8 0.3 0.1 0.9	3.1
0.2 0.4 0.7 0.8 0.1 0.3	2.5
0.4 0.7 0.5 0.3 0.9 0.1	2.9
0.3 0.8 0.9 0.1 0.2 0.5	2.8
0.1 0.3 0.4 0.6 0.9 0.7	3.0

3. Select mate

Chromosomes	Cost
0.2 0.4 0.7 0.8 0.1 0.3	2.5
0.3 0.8 0.9 0.1 0.2 0.5	2.8

4. Reproduce

Chromosomes	Cost
0.2 0.4 0.9 0.1 0.1 0.3	2.0
0.3 0.8 0.7 0.8 0.2 0.5	3.3

5. Mutation

Chromosomes	Cost
0.2 0.4 0.9 0.1 0.6 0.3	2.5
0.3 0.8 0.7 0.3 0.2 0.5	2.8

Figure 6. Simple example of a real number GA.

generation, the top 10 solutions are stored and used in the next generation without modifications. Elitism can greatly enhance the performance of the algorithm, because it ensures that the best solutions found are not lost. The maximization process is represented graphically in figure 7 and the minimization process by figure 8.

Maximization of Objective Function

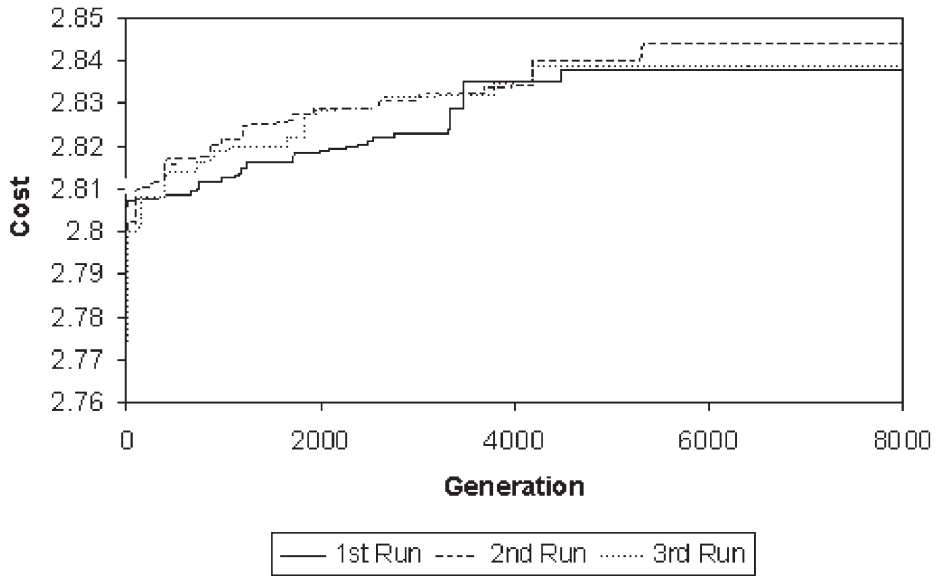


Figure 7. Graphical representation of the maximization process.

Minimization of Objective Function

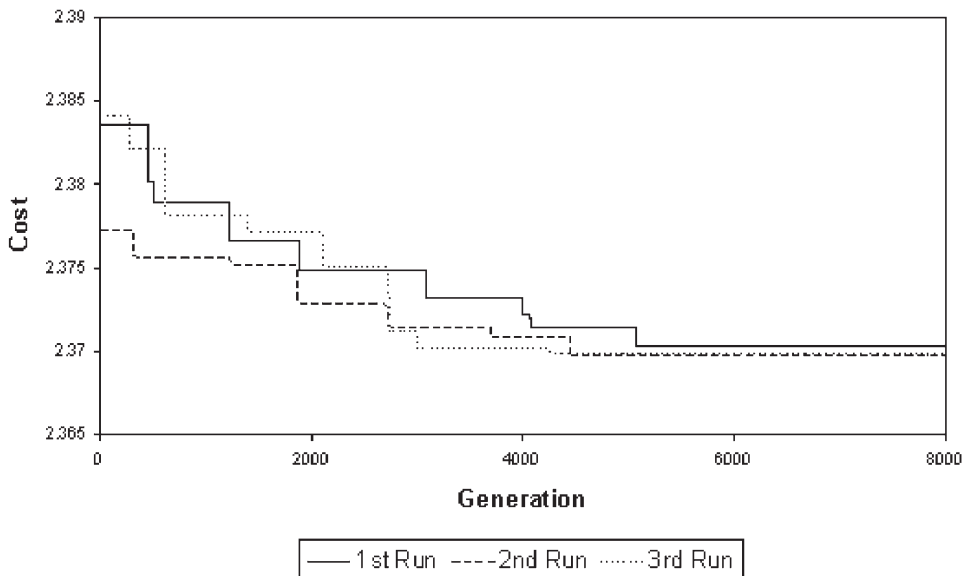


Figure 8. Graphical representation of the minimization process.

However, given nine choices for each factor’s weight (i.e. 0.1, 0.2, 0.3, ..., 0.9), five factors on the upper level and 19 sub-factors on the lower level, the permutations in the enumeration method could be 9^{24} . In this sense, the GA is much more efficient.

6. Results

Based on the derived weights, the costs of the alternative routes can then be evaluated, using equation(1) to determine their relative competitiveness. We will first compare the costs considering each of the five criteria first, before comparing the overall costs as determined by equation(1).

6.1. Exposure

In considering exposure alone, the approved Route 8 has the lowest cost regardless of whether the weights obtained from maximization or minimization processes were used. As shown in figure9, it has a cost of 2.20 using the minimization and 2.24 using maximization. Likewise, the other two approved routes, Routes 1 and 15, incur relatively low costs. It can be concluded that the approved routes are consistent in minimizing the exposure or the consequences as a result of a HAZMAT release.

6.2. Socio-economic impact

Route 8 also has the least cost considering socio-economic impact alone for both optimization processes. It has a cost of 2.31 after minimization and 2.63 after

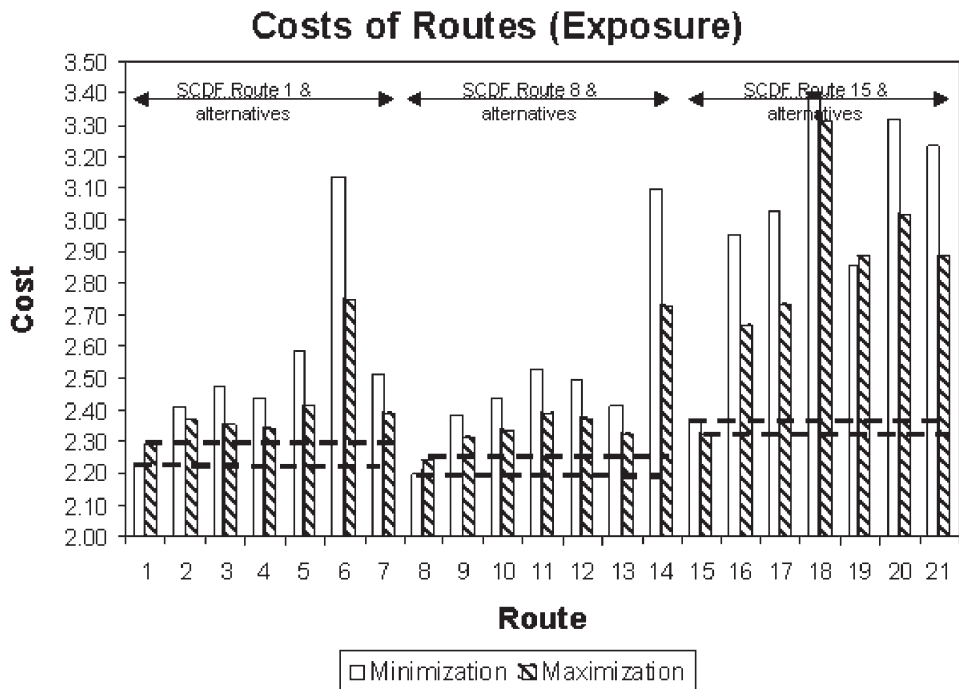


Figure 9. Costs of routes considering exposure only.

maximization. Routes 1 and 15 also have low costs in comparison with their corresponding alternatives. In summary, the three approved routes do well to reduce the socio-economic impact that may potentially arise due to an accident.

6.3. *Risks of hijack*

Among all the routes, Route 21 has the least cost of hijack (1.61) based on minimization of the overall generalized cost. Approved Routes 1, 8 and 15 have relatively high costs of hijack. It can be deduced that as the current practice does not take the risk of hijack into much consideration, alternative routes may be more suitable in reducing the risk of hijack.

6.4. *Traffic conditions*

When considering traffic conditions alone, the least-cost route is alternative Route 21. Routes 6 and 14 are the least-cost alternatives to approved Routes 1 and 8, respectively. The approved routes are ranked in the middle among all alternatives. This may imply that traffic conditions are currently not a main consideration in the selection of the approved routes.

6.5. *Emergency*

Based on emergency response alone, Route 18 has the least costs at 3.00 and 3.65, respectively. It has the least cost because it passes by the vicinity of the only hospital, fire station and police station in the area. The corresponding approved Route 15 has a relatively higher cost. The other two approved routes are found to have rather high costs, although they have comparable costs to their corresponding alternatives. It can be concluded that emergency was not a main priority in designating the recommended route.

6.6. *Overall cost*

The overall costs are summarized in figure 10. The recommended routes have the least costs due to both optimization methods. Based on the weights determined for the five criteria, this further suggests that the main considerations are exposure and socio-economic impact. The relatively low weights obtained for the security considerations, i.e. risk of hijack and emergency response, suggest that if they were to be given more substantial attention, the current approved routes may no longer be optimal. In such a situation, a review of the recommended routes may be warranted.

7. **Conclusions**

The use of GIS allowed for the factors to be quantified so that the right score could be given efficiently. However, the drawbacks include the high dependency of the results upon the quality and consistency of the input data in the GIS database. This can be minimized by using the most reliable data sources available and minimizing arbitrary assumptions. Highly accurate traffic data obtained from surveys would be time-consuming and expensive and potentially become out of date quickly (Brainard *et al.* 1996). Although the study site is relatively small, the criteria, factors and attributes used in this study are deemed representative, and the objective is met with reasonable results.

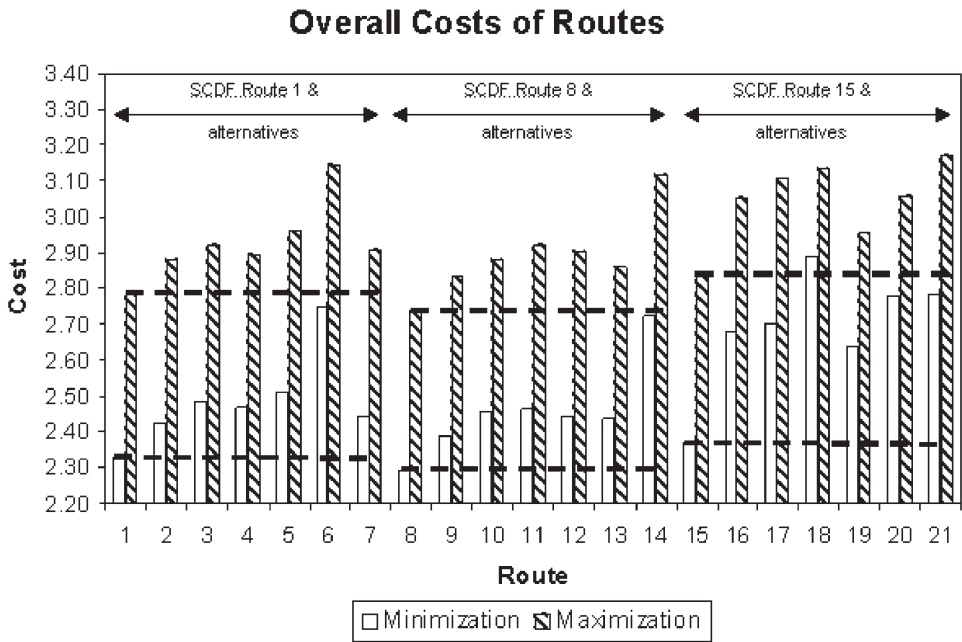


Figure 10. Overall costs of routes considering all the factors.

A GA was applied successfully to determine the weights of the criteria and factors in the complex hierarchical form. This gives an insight to the extent of the considerations that had been used by the government agency in approving routes that are suitable for transporting HAZMATs.

The results show that the current recommended routes are most effective if the main considerations are exposure and socio-economic impact, which is believed to be common practice before September 11, 2001. However, with the raging war against terrorism and the need to step up security measures, these routes may no longer be the best routes available. Based on the same cost functions and changing the weights to give more emphasis on the security aspects, viz. risk of hijack and emergency response, the more optimal routes that are relevant today can then be determined. Therefore, a possible area of future research is to determine the best routes that are not only safe to use, but also secure. New constraints can be added to the weight search process by the GA to input the order of preference for the various criteria. This could be done by the policy-makers, and they can decide on whether emergency response is more important than socio-economic impact, for example.

In addition, the methodology used can be extended to cover a much wider extent of the road network in Singapore. This will require more extensive data collection to ensure that the GIS database is accurate and up to date. Reclassification of the scoring system is necessary to ensure that the appropriate score will be given corresponding to the extent of study. The underlying methodology, however, remains unchanged. Hence, the methodology offers flexibility regardless of the extent of study.

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