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Research Article

Sustainable hazardous materials route planning with environmental consideration

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Abstract

Our society benefits from the chemical, nuclear, electrical and petroleum industries, which require hazardous materials in their production and also produce hazardous wastes as well. There are certain risks associated with a truck being involved in an accident during shipment of Hazardous Materials (HAZMAT). The severity of impact posed to surroundings depends on many factors such as population density, number of sensitive locations, ability to provide rescue operation (such as proximity to rescue units such as fire stations and hospitals) and security issues, not only based on distance and/or time alone. It is essential that all of the related factors and criteria, especially environmental concerns, should be considered prior to making route planning decisions. A lack of a comprehensive framework for the selection of HAZMAT route planning that the transporter can use for aiding their decisions is a current major concern in developing countries.

The main purpose of this paper is to develop a framework based on the integrated Multi Criteria Decision Analysis (MCDA) and Geographic Information System (GIS) approaches for making optimum hazardous waste route planning choices by including environmental consideration. A number of factors and criteria are grouped into three main categories; economic, environmental and societal (exposure and emergency response) issues followed with the sustainability paradigm. A framework has been tested to a regional hazardous waste transport from Map Ta Phut Industrial Estate, Rayong province,

eastern Thailand, to an incinerator plant located in Saraburi province, central Thailand. A framework is based on the simple cost model that calculates the value (Ri) dependent upon each objective. The proposed framework can contribute to the planning processes of governmental policy-makers and HAZMAT carriers when they plan and evaluate possible routes and are making their decision in order to minimize damage from transporting hazardous materials.

Keywords: Hazardous materials transport (HAZMAT)**,** multi criteria decision analysis, geographic information system, risk analysis, route planning framework

Introduction

Our society benefits from the chemical, nuclear, electrical and petroleum industries. These industries require hazardous materials (HAZMAT) in their production process and also produce waste residues as by products. The increase in industrial growth accelerates a demand for hazardous materials to be served as the raw materials for the production of various commercial goods. It can result in the increase of hazardous waste quantities which is a major concern, particularly how to properly and safely manage this waste. Both HAZMAT and hazardous wastes need to be transported from suppliers to manufacturers for production and landfill purposes. Although the probability of an accidental release while transporting these materials is very low, there is certainly concern that HAZMAT be transported in the safest manner as possible, since a release can be catastrophic for a community and the environment.

Hazardous materials include explosives, gases, flammable, liquids and solids, oxidizing substances, poisonous and infectious substances, corrosive substances and hazardous wastes. Accidental releases of HAZMAT do occur during transportation and these events often have very damaging consequences, including fatalities. Historical evidence has shown that the risks related to HAZMAT transportation can be of the same magnitude as those due to fixed installations [1]. Glickman *et al.* [2] compares the percentage of accidents caused by the transportation of hazardous material and those at fixed installation on worldwide basis between 1945 and 1986 as illustrated in Figure 1.

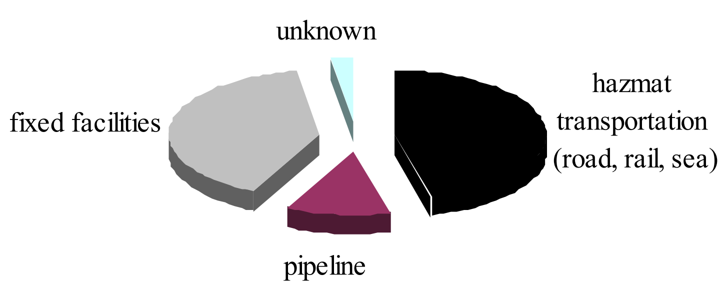

Figure 1. A comparison of types of major technological accidents world wide during 1945 to 1986 [2].

During the early 1990s, it is estimated that there were some 500,000 shipments of HAZMAT every day in the United States [3]. While in the UK, it is currently estimated that each year approximately 80,000 different organizations are involved in carrying around 100,000 tons of dangerous goods by road and rail [4].

Recent evidence has shown an increasing demand for HAZMAT as a result of the industrial growth in Thailand. From statistics of the Pollution Control Department (PCD), the total imports of HAZMAT has increased from 3.11 to 5.22 million tons, while the total amount of HAZMAT production within the country has also increased from 9.80 to 28.81 million tones during the period 1998-2005 [5]. The three highest imported hazardous materials include: flammable liquids (82.08%), flammable gases (15.49%) and corrosive substances (1.28%) respectively. Dangerous goods incidents in Thailand have been increasing during the years 1999-2004. Most incidents have occurred within fixed facilities and during transport of chemical substances. In 2001, 14 HAZMAT incidents, out of a total of 24 incidents, were caused by transportation. A characteristic of these incidents are that they mostly occurred due to a leak of chemical substance and explosion. This can cause a huge impact to people and surrounding environment.

Literature Review

Jenning and Scholars [6] were first to take risk into consideration in HAZMAT transport. They formulated a regional hazardous waste management system (RHWMS) as simply a vehicle routing problem in an attempt to accomplish the goal of achieving either minimum cost and/or minimum risk. Accidents usually result in some form of inconvenience at the very least, or even worse in injury or death of people, and public concern has started to rise about how and when these shipments are planned and routed through specific geographical areas. The size of the population is potentially at risk in the impact area (the routes may cross or pass by towns and villages) rather than from the scale of any accident itself [7].

It is essential to use risk indicators to measure risk in HAZMAT transport. The risk indicator can tell us how much risk there is for a particular element at risk exposed to a given hazard. Bohnenblust and Slovic [8] define individual risk as the annual probability of being harmed by a hazardous situation and societal risk as the probability of a group of individuals, companies or institutions being affected by exposure to a hazardous situation. According to Leonelli *et al.* [1], to quantify the risk indices, it is necessary to access a great amount of data, such as the characteristics of the particular HAZMAT being transported, the meteorological conditions and the properties of the element at risk. A simplified approach has been proposed by Frank, *et al.* [9] to quantify risk. This research focused on the development of a spatial decision support system for the route selection to transport HAZMAT within the United States. The element at risk considered in this research study is the population located in the impact area of the accident. The impact area is located alongside the route and it extends to both sides of the route with a predefined bandwidth.

Karkazis and Boffey [10] also focused on the damage induced to the population in case of an accident. However, this research aimed at studying the dispersion of HAZMAT through air. The impact area, therefore, is not defined by a given bandwidth, but it is a function dependent on the type of material transported and the meteorological conditions at the moment of the accident. Brainard, *et al.* [11] examined the threat to nearby residents and this was assessed by calculating the number of people living within 500m of identified routes. Utilizing a standard distance band was somewhat simplistic, because the zone affected by a spillage will vary according to factors such as wind speed and direction, but these considerations could not be readily incorporated given the regional scale of analysis. He also evaluated the hazard posed to groundwater supplies.

How to develop a method to analyze and quantify a meaningful value from risk framework for HAZMAT transport routing problem is another critical aspect. The typical route finding method applies the shortest path problem or Dijkstra's algorithm that is widely applied in path selection for much transportation research. An optimization technique based on multi objective decision making has been cited for the HAZMAT transport routing in the recent literature for searching the best route by a single objective with a limited set of constraints [12, 13]. List *et al*. [14] 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 from treatment facilities. Erkut & Verter [15] 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. Leonelli, *et al.* [16] used mathematical programming to develop a route optimization model with the purpose of calculating HAZMAT optimal routes. The optimization problem is presented as a single objective minimum cost flow problem, where the overall objective is to minimize the total cost over the route. The total cost over the route is the summation of the cost values assigned to every transport link that is part of the route. The problem of designing a road network for HAZMAT shipments is also proposed by Erkut & Alp [17]. They formulate a tree design problem as an integer programming problem with the objective of minimizing total transport risk. Similarly, the problem of network design for HAZMAT transportation where the government designates a network and the carrier chooses the route on the network is solved by heuristic solution method that always finds a stable solution [18]. Huang *et al.* [19] attempted to identify and evaluate criteria that may be used to route HAZMAT vehicles in Singapore by using Analytical Hierarchy Process (AHP) technique. The criteria considered were related to safety, costs and more importantly, to security based on the finite set of alternative routes that is allowed for HAZMAT transport in Singapore.

With regard to all of the above mentioned literature, the key component of HAZMAT routing is risk factors identification and methodology approach to quantify risk value on the road network. However, it still lacks the environmental factors being taken into consideration in the proposed framework. The major aim of this paper is to consider and to integrate environmental factors into the HAZMAT transport framework with the simplified approach.

Application of Multi Criteria Decision Analysis and GIS in HAZMAT Route Planning

Geographic Information Systems (GIS) are a geo-database system that uses computers to collect, store, manipulate, analyze and display geographic information. GIS technology integrates common database operations by linking spatial and non spatial data in a comprehensive manner. Lepofsky *et al*. [20] demonstrated that GIS can be used to integrate plume representation with population data and dispersion maps to estimate consequences more effectively. GIS has also been applied by routing the transportation of radioactive materials [21]. Key inputs included demographics, environmental features and transportation system characteristics. They identified three methodologies namely; comparative studies, worst-case assessment and probabilistic risk assessment. Lovett *et al.* [22] developed a GIS-based route optimization model for liquid hazardous waste shipment. Four routing scenarios, namely; minimizing travel time, encouraging use of trunk roads, avoiding densely populated areas and minimizing accident rates were used to identify sections of road that consistently saw heavy traffic. Frank *et al.* [9] developed a spatial decision support system for the route selection for HAZMAT transport. A user interface for the model was developed through a GIS environment for the visualization of the optimal routes.

Multi criteria decision analysis (MCDA) aims at supporting decision makers who are faced with making numerous and conflicting evaluations. MCDA aims at highlighting these conflicts and finding a way to come to a compromise in a transparent process. Broadly speaking, Multi-criteria Decision Making (MCDM) problems involve a set of alternatives that are evaluated on the basis of often conflicting and incommensurate criteria. [Note: the term multi criteria decision making (MCDM) and multi criteria decision analysis (MCDA) are used interchangeably] [23]. The integration of MCDA and GIS is capable of being an effective method to manipulate a number of factors and criteria, including both spatial and non-spatial data and display a result in thematic context, which is easy to understand by decision makers and other stakeholders. A relationship amongst sustainability, MCDA and GIS is proposed in Figure 2.

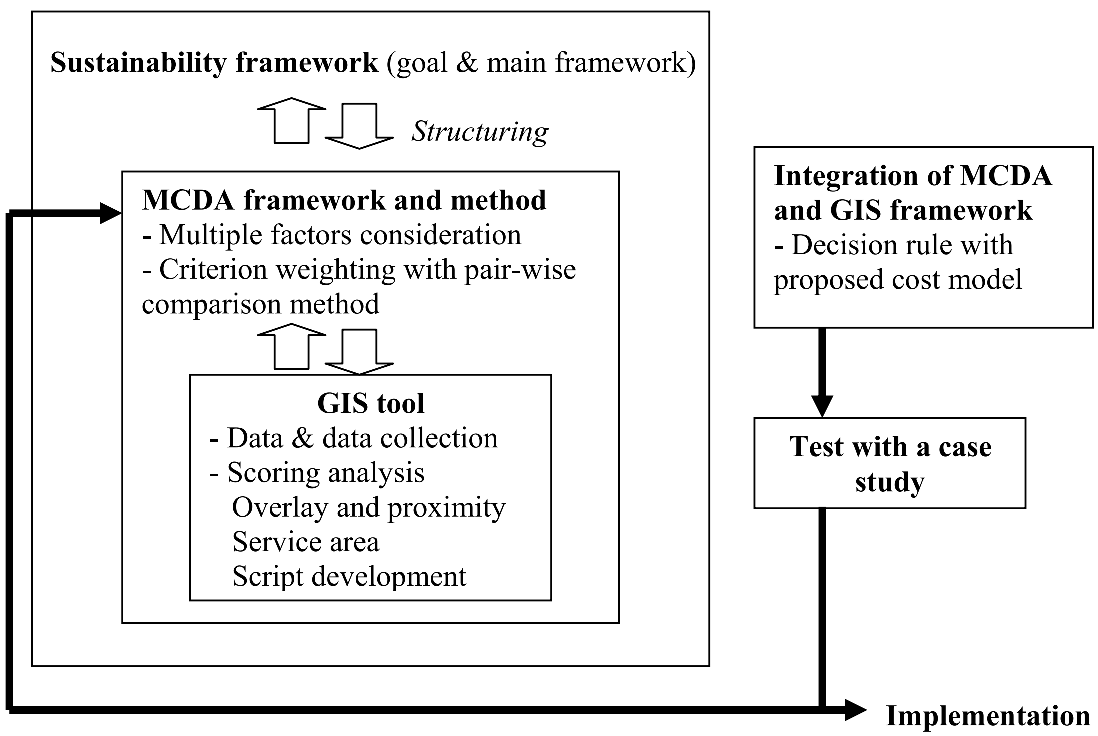

Figure 2. Integration of sustainability, MCDA and GIS in HAZMAT transport.

From Figure 2, the framework aims at generating factors, methods and tool development in an integrative manner. Sustainability thinking has been incorporated into the framework through factors and criteria determination to achieve the goal of sustaining economic, environmental and societal factors at the same time. If multiple factors and criteria consideration are perceived as the important issue to achieve a goal of sustainability, MCDA can serve as the framework and method that can be used to weigh factors and criteria with regard to their relative importance and then combine these with a predefined score generated by GIS. Various cost models can be operated under the integrative framework and provide results in different scenarios varied by different objectives. Integrated multi criteria decision analysis (MCDA) framework with geographic information system tool (GIS) demonstrates a useful approach. It is also flexible for the input of different cost models into the framework. There is currently no common agreement in establishing related factors and criteria when considering HAZMAT transport decision making. A lack of the consideration of environmental and emergency response factors in HAZMAT transport research still exists in much of the literature. Identifying factors and criteria to achieve a sustainability goal in HAZMAT transport framework could add some more strengths and values to HAZMAT transport route planning decision making process.

Case Study

Many industrial estates are located in the eastern part of Thailand. According to statistics of the Department of Industrial Works (DIW), eastern Thailand generates nearly 70% of the country's hazardous waste. Map Ta Phut Industrial Estate (MTPIE) is the biggest industrial estate in eastern Thailand due to its suitable physical geography that connects to both land and sea. The amount of hazardous industrial wastes in 2006 that were permitted to transport from MTPIE for disposal at an incinerator plant in Saraburi Province, located in Central Thailand, was 96,806.20 tons. However, they only categorized the amount of hazardous waste into 43 groups, but did not go into specific detail regarding each waste. Information related to which type and amount of hazardous waste that is sent to each incinerator plant is also not made public, due to the release and enforcement of information law and regulation in Thailand since 2007. Liquid hazardous waste transport from MTPIE to incinerator plants has been chosen because these wastes can potentially have greater adverse affects than solid hazardous waste. Hence, Map Ta Phut Industrial Estate and incinerator plants have been selected as the origin and destinations.

The scoring system for factors and criteria was adopted from Federal Highway Administration (FHWA) [24] and Huang *et al.* [19]. Environment factors have been further established as one of the key factors in addition to economic, safety and emergency response factors in the framework as shown in Table 1. In order to combine a score into a meaningful entity, weight must be assigned to the factors and criteria.

Analytical Hierarchy Process (AHP) was used to assign their weight based on pair-wise comparison method to develop the priority. Pair wise comparison is conducted by 12 people from 6 related government agencies. The results for the criteria level indicate that proximity to fire stations, population density, proximity to ponds and lakes and traffic density were perceived as having the highest priority in societal (emergency response), societal (exposure), environment and economic categories. With regard to the factors level, society (exposure) received the highest weight followed by society (emergency response), environment and economic respectively.

The cumulative weights and scores that represent a final value of each route are given by the following simple cost model;

$$R_i = \sum_{c=1}^{nc} [Wc \sum_{cf=1}^{ncf} WcfScfLi] \qquad (1)$$

Where R_i = the overall final value of link ith
c = criteria
n_c = number of criteria c
W_c = weight of criteria c
n_{cf} = number of factors under criteria c
W_{cf} = weight of factors
S_{cf} = score of factors
Li = the length of each link i

Table 1. Factors and criteria considered in hazardous waste transport.

	Score				
	1	**2**	**3**	**4**	**5**
Economic					
Traffic density	0-200 Veh/hr	201-1000 veh/hr	1001-3000 Veh/hr	3001-5000 Veh/hr	> 5000 Veh/hr
Slope	0-5 %	5-15 %	15-25 %	25-35 %	>35 %
Environment					
Distance to water bodies (km)	>2	1.5-2	1-1.5	0.5-1	0-0.5
Distance to conservation area (km)	>2	1.5-2	1-1.5	0.5-1	0-0.5
Number of streams crossed	0-3	4-6	7-9	10-12	>12
Society (exposure)					
Population density	0-500 ppl/km^2	501-3000 ppl/km^2	3001-10000 ppl/km^2	10001-20000 ppl/km^2	> 20000 ppl/km^2
No. of schools	0-3	4-6	7-9	10-12	>12
No. of heritage & cultural places	0-3	4-6	7-9	10-12	>12
No. of petrol/gas stations	0-1	2-3	4-5	6-7	>7
No. of hospitals	0-1	2-3	4-5	6-7	>7
Society (safety)					
Proximity to police station (km)	0-0.5	0.5-1	1-1.5	1.5-2	>2
Proximity to fire station (km)	0-0.5	0.5-1	1-1.5	1.5-2	>2
Proximity to hospital (km)	0-1.5	1.5-3	3-4.5	4.5-6	>6

Discussion

A case study has been tested with the five different objectives; distance, environment, exposure, emergency response and other economic factors. The total value in equation (1) is minimized in order to derive the best route in each objective. Each scenario is illustrated in Figure 3. Table 2 summarizes the increase in the percentage of distance traveled when compared with the shortest route.

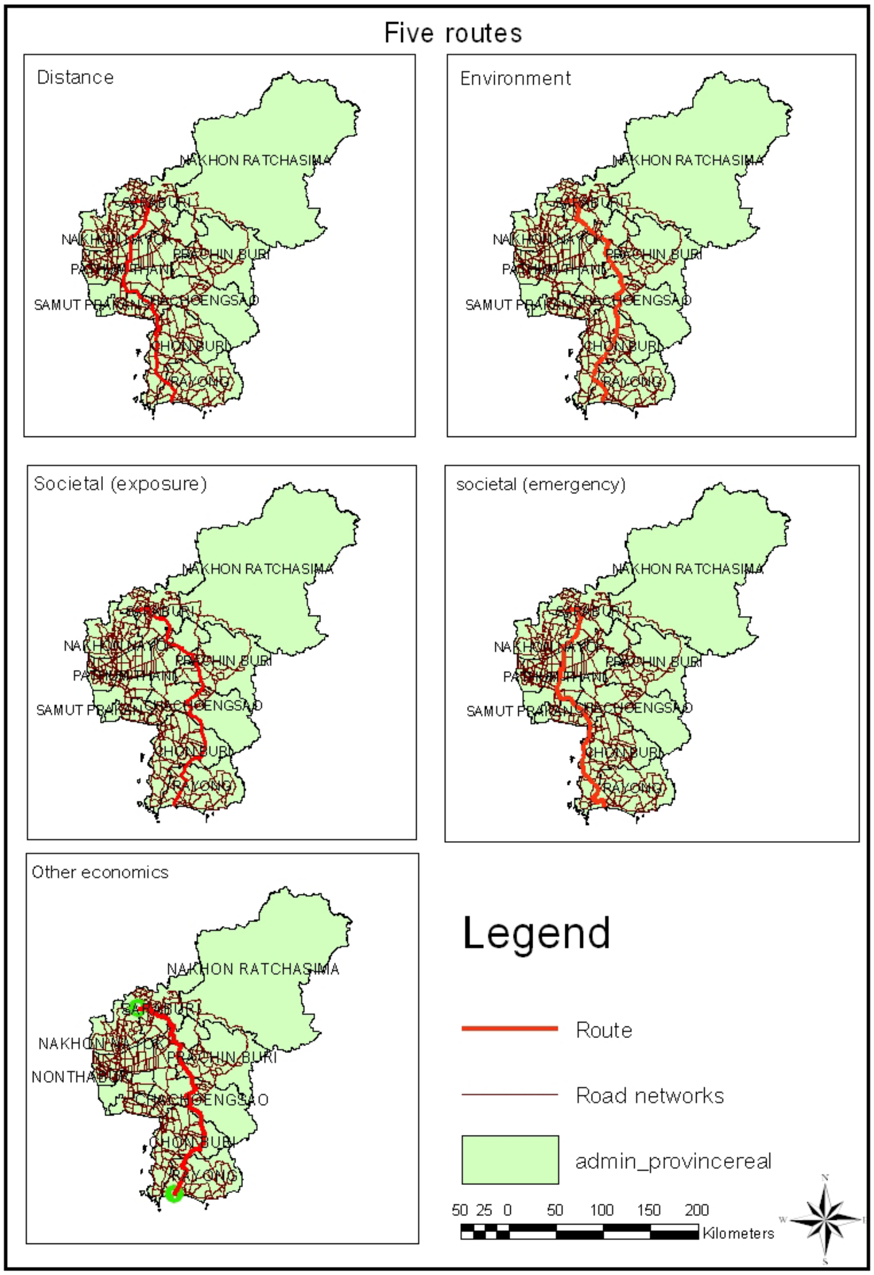

Figure 3. Five route scenarios based on different objectives.

Table 2. Increased % of distance traveled when compared with shortest route.

Objectives	% increase
Environment	1.93
Societal (exposure)	11.43
Societal (emergency response)	1.11
Other economics	1.93

The results reveal the fact that good performance on one factor provides different route scenarios where the minimization of Ri value in one factor was counterbalanced by a less satisfactory outcome in other factors. The results also indicate how hazardous waste transport risk frameworks can be modelled with regard to multiple factors and criteria consideration, including environmental concern. This perspective can be of importance for regulatory agencies in planning effective HAZMAT transport in the future.

Conclusion

Accidents can happen during shipment of HAZMAT and it is possible that the contents of the truck can be leaked in a serious accident and can carry some risks to the public and the environment. Therefore, risk cannot be avoided, but it can in fact be managed. Any risk factor that is managed properly can contribute to the reduction of risk. One of the key goals of this paper was to create a framework for HAZMAT transport to achieve multiple factors and criteria consideration. Environment factors have also been taken into account to the framework because HAZMAT transport incidents can potentially cause adverse effects to the surrounding environment, both in the short term and long term. The integration of Multi Criteria Decision Analysis (MCDA) and a Geographic Information System (GIS) tool can formulate a comprehensive HAZMAT transport framework. Hazardous waste shipment from Map Ta Phut Industrial Estate to an incinerator plant is raised as a case study. The proposed framework allows the application of the simplified cost model to handle complex hazardous waste transport information. There are no fixed answers to what risk factors should be considered when developing the route planning framework. It is dependent on the characteristics of the case study varied by each country and region. Factors and criteria are defined with the focus on sustainability first and are subsequently taken into account through the analysis with the integration of MCDA with GIS framework.

The proposed framework can be customized and applied for other case studies and not just the one presented in this document and should be of great relevance when considering the application of the framework in other regions and/or countries. It is essential to be aware that the realities in developing countries can be so much different and more complex than in the developed countries. The level in which risk factors are perceived by the government in developing countries may be diminished by the need to satisfy the basic services to the population. In cases where there is awareness of the need to manage risk, the access to a framework that can aid the risk management may not be available. Another case could be one where frameworks are available but the lack of information required by the frameworks can represent a drawback in the management process of risk. Consequently, the integrated MCDA framework with GIS tool in order to achieve sustainability goal serves as a framework and tool simultaneously that can be easily adapted and is flexible enough to fit the reality of a given case study. Decision making based on a given comprehensive framework with the effective analysis and synthesizing capability can make a useful contribution in terms of risk prevention. Ultimately, a framework can potentially be applied to any HAZMAT transport case in accordance with a key goal of sustainability, which is aiming at balancing the economic, environment and society conditions for the benefit of our sustainable future.

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