Community Risk Assessment: Spatial Patterns and GIS-Based Model for Fire Risk Assessment - A Case Study of Chiang Mai Municipality
การประเมินความเสี่ยงภัยอัคคีภัยสำหรับชุมชนโดยแบบจำลองระบบสารสนเทศภูมิศาสตร์: กรณีศึกษา เทศบาลนครเชียงใหม่

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Abstract

The main purpose of this study is to develop a GIS-based approach to fire risk assessment to identify sites for disaster mitigation planning and management. Fire risk assessment has two main factors: the vulnerability and capacity for mitigation of the areas, as well as the areas with a fire history. The selection of risk factors is mainly based on stakeholder analysis, involving four groups: urban planners, fire wardens, local residents and local government officials. The above data are integrated into raster-based GIS software and then spatial analysis is performed using an overlay technique to generate the fire risk, ranging from high to low according to its sensitivity to fire or fire-inducing capability. The result is a map of the varying levels of fire risk across the city. The weight to each factor is determined by an Analytical Hierarchy Process (AHP). This model is illustrated with a case study of fire risk of area in the Chiang Mai Municipality (CMM). It is suggested that risk mapping is helpful for fire management to minimize fire hazards.

บทคัดย่อ

บทความนี้มีวัตถุประสงค์เพื่อพัฒนาเทคนิควิธีการประยุกต์ระบบสารสนเทศภูมิศาสตร์ หรือ Geographic Information Systems (GIS) ประเมินความเสี่ยงภัยต่อการเกิดอัคคีภัยโดยระบุพื้นที่เสี่ยงเพื่อนำไปสู่การวางแผนและบริหารจัดการอัคคีภัย โดยการประเมินความเสี่ยงต่อการเกิดอัคคีภัยประกอบด้วยปัจจัยหลักสองปัจจัย คือ ปัจจัยที่จะทำให้พื้นที่มีโอกาสเกิดอัคคีภัย และปัจจัยด้านศักยภาพในการบรรเทาภัยของพื้นที่ รวมถึงประวัติการเกิดอัคคีภัย โดยการกำหนดปัจจัยเสี่ยงมาจากการวิเคราะห์ผู้มีส่วนได้ส่วนเสีย 4 กลุ่ม ได้แก่ นักผังเมือง นักดับเพลิง ประชาชนในพื้นที่ และข้าราชการท้องถิ่น ปัจจัยทั้งหมดจะถูกวิเคราะห์ชั้นข้อมูลแบบราสเตอร์ โดยซอฟต์แวร์ GIS และการวิเคราะห์เชิงพื้นที่จะทำโดยใช้เทคนิคการซ้อนทับข้อมูลเพื่อสร้างแผนที่ความเสี่ยงภัยอัคคีภัยที่แสดงค่าระดับความเสี่ยงต่อการเกิดอัคคีภัยตั้งแต่ค่าสูงไปยังค่าต่ำตามปัจจัยที่ส่งผลต่อความสามารถในการเกิดอัคคีภัย แต่ละปัจจัยจะถูกกำหนดค่าน้ำหนักความสำคัญโดยกระบวนการวิเคราะห์ตามลำดับชั้น หรือ Analytical Hierarchy Process (AHP) โดยเขตเทศบาลนครเชียงใหม่เป็นพื้นที่กรณีศึกษาและชี้ให้เห็นว่าการทำแผนที่ความเสี่ยงจะเป็นประโยชน์สำหรับการจัดการไฟเพื่อลดการเกิดไฟไหม้

Keywords

Fire Risk Assessment (การประเมินความเสี่ยงภัยอัคคีภัย)
Geographic Information System: GIS (ระบบสารสนเทศภูมิศาสตร์)
Raster Analysis (การวิเคราะห์แบบราสเตอร์)
Analytical Hierarchy Process: AHP (กระบวนการวิเคราะห์ตามลำดับชั้น)

1. Introduction

Chiang Mai Municipality (CMM) (Figure 1) has been rapidly increasing in urban population; meanwhile the physical elements of the city face an absence of appropriate urban planning. Many households were built in particular areas of the city, resulting in overly dense building construction and traffic congestion. Moreover, fire-fighting water techniques cannot effectively serve high rise buildings and slum communities (Figures 2). These factors significantly affect the flammability of fire hazards in different geographical areas. The fire hazard phenomena relating to the human activities taking place within the location include electric, heat and flammable material usage. It can be envisaged that areas of dense population contribute to an increasing vulnerability to urban fires (Chainey & Ratcliffe, 2005) which is associated with a lack of good urban planning, inefficient land use policies, and the relevant property and safety regulations. Most buildings such as high-rises, industrial factories, workplaces, residential places and parking areas fail to consider building density, location, and construction materials, as well as the appropriate location of fire stations in areas with wide alleys or streets. Such incidents are major problems and constraints on fire fighting (Nimmanahaeminda, 1967) although the situations did not occur more often. Therefore, a study of urban conditions or an understanding of urban configuration features can help establish scientific procedures of fire risk assessment in the city.

Statistical data on fire hazards during the period 2000-2004 were gathered from Chiang Mai Municipal Fire Station, then analyzed and disaggregated in relation to the building construction and properties of building within the municipal district. The results showed that over five years, there were a total of 247 fire hazards in the city that damaged life and property (Table 1, Figures 3), valued at about 77.91 million baht. The highest number of fire hazards annually during this period was 58 (2002) and the lowest was 45 (2003). It was found that in 2000, the highest loss in life and property of citizens came to a total of 33.66 million baht, while in 2001 the statistical data represented the lowest loss, at about 6.97 million baht. Meanwhile, the number of fire hazards increased up to 53 times (about 20.62 percent of total fire hazard within 5 years). The highest loss from a single fire incident occurred in 2000 and presented a total loss of 15 million baht. It can be summarized that the average loss per incident was highest in 2000 (673,184 baht) and lowest in 2001 (131,449 baht).

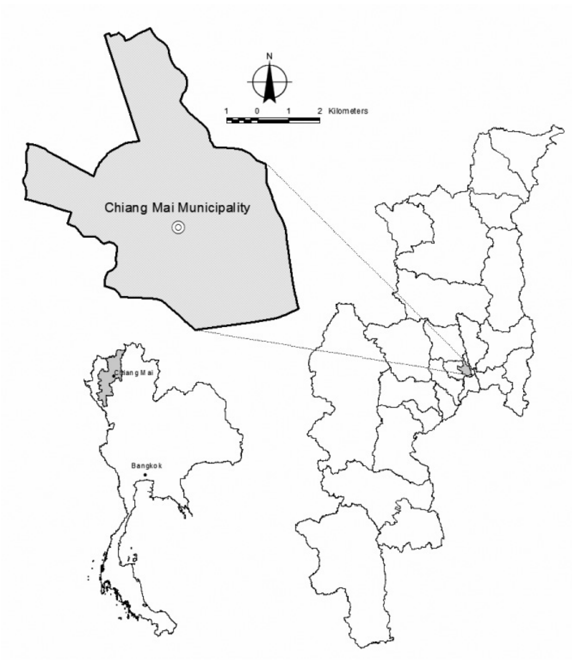


Figure 1. Location of Chiang Mai Municipality (CMM), Chiang Mai Province, Thailand.

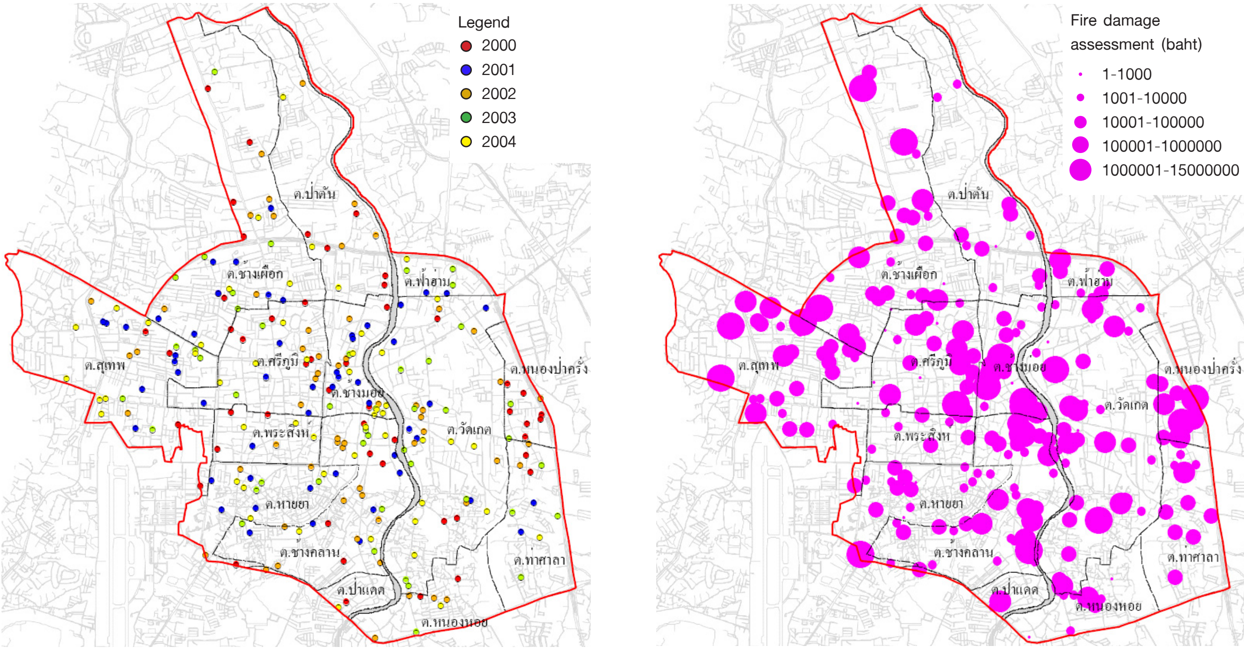
Source: Department of Disaster Prevention and Mitigation, Thailand (www.disaster.go.th)

Figures 2. Fire Incident.

Table 1. Number of fire incidents in Chiang Mai Municipality (2000-2004).

Year	Number of fire incidents	Fire damage assessment (mill. baht)
2000	50	33.66
2001	53	6.97
2002	58	20.53
2003	45	8.24
2004	51	8.52
Total	257	77.91

Source: Department of Disaster Prevention and Mitigation



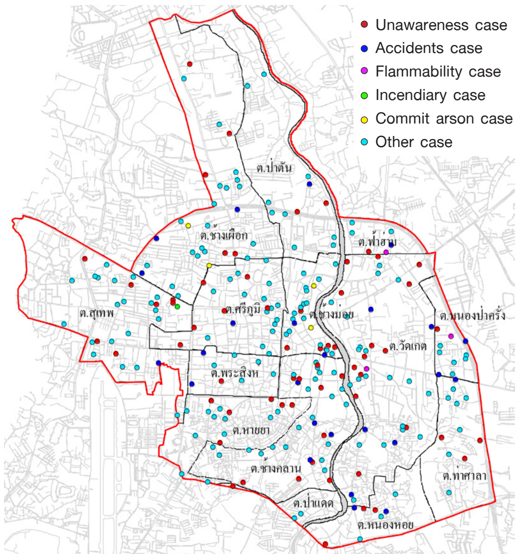
(a) (b)

Figures 3. (a) Location of fire incidents in CMM during 2000-2004, (b) Direct fire property damage during 2000-2004 in CMM.

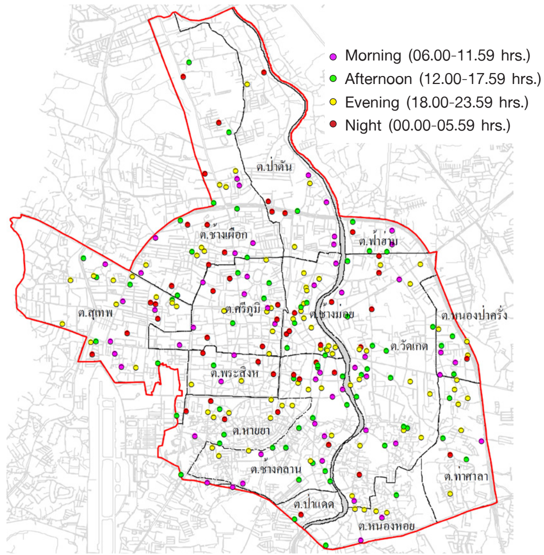
Of the 257 incidents during this period, 61.87 percent of the total (excluding those where the cause was uncertain) resulted from primary cases. Based on this amount, 65 incidents (about 25.29% in total) derived from people's unawareness, and this was in fact the main cause (Figure 4a). Other causes included accidents (25 incidents, or about 9.73%), from flammability with 3 times (about 25.29%), and from incendiary with 4 times (about 1.56%), respectively. Considered annually, unawareness was also the major cause of fire hazards in CMM, with its highest frequency in 2002 when it accounted for around half of all fire hazards that year.

Based on comparisons of the relative proportion of fire frequency in different seasons (Figure 4c), the results found that the dry season appeared to have the highest relative proportion of fire frequency (about 48.87 percent). In 2005, fire hazards occurred mostly in the dry season with a relative proportion of about 9.47 percent, with about 34.01 percent in the winter season. In year 2001 and 2002, fire hazard arose typically in the winter season with a relative proportion of 8.22 percent, while the rainy season presented the lowest proportion (25.12 percent). However, the study also demonstrated that in 2001, fire hazards took place frequently during the rainy season with a relative proportion of about 5.98 percent.

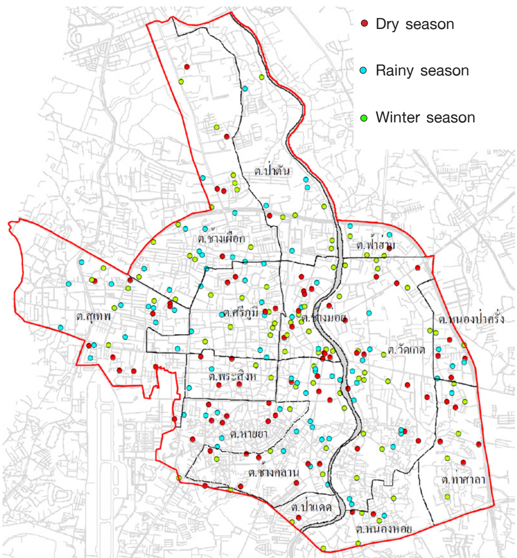
In this study, the researcher aims to find the spatial factors influencing fire hazards and to consider



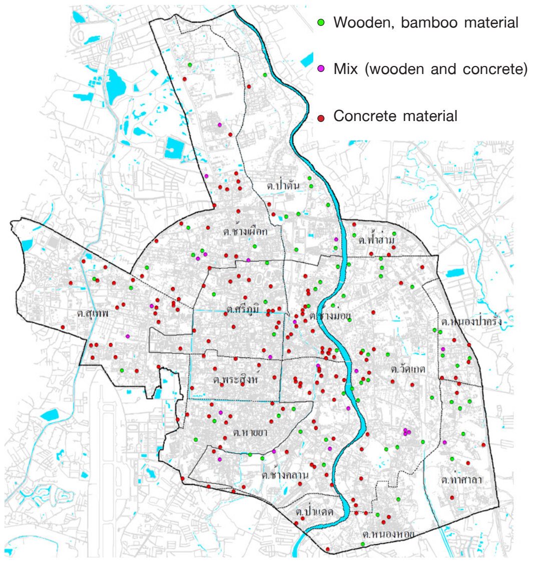
(a) Classified by cause of fire incidents



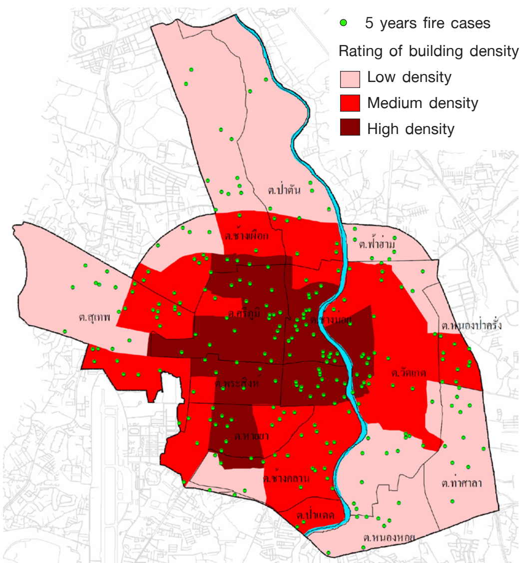
(b) Classified by time period



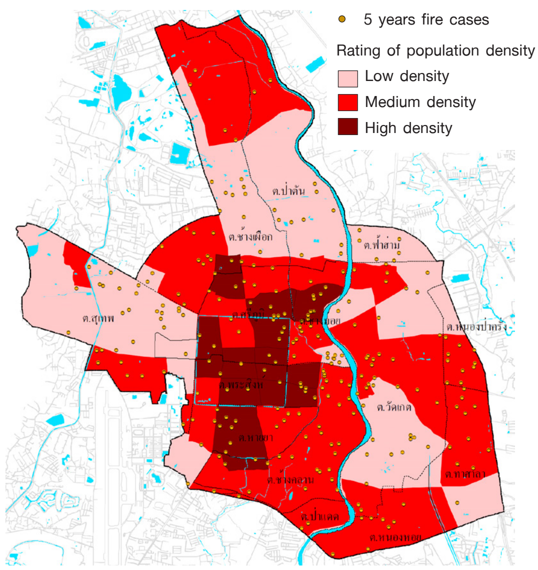
(c) Classified by season



(d) Classified by building material



(e) Building density



(f) Population density

Figures 4. 4 Patterns of fire incidents in Chiang Mai Municipality during 2000-2004.

fire risk in the study area by using geographical information systems (GIS) analysis, combined with other physical data, in order to envisage fire risk areas. Based on background information, the study area illustrates that dense communities including temples, shops and housing present a high risk of fire hazard.

2. Objectives of the Study

2.1 To study the spatial patterns of fire hazard in the areas of Chiang Mai Municipality (CMM), and

2.2 To apply a geographic information system (GIS) grid-based fire hazard model for analysis of damage in risk areas in CMM.

3. Methodology

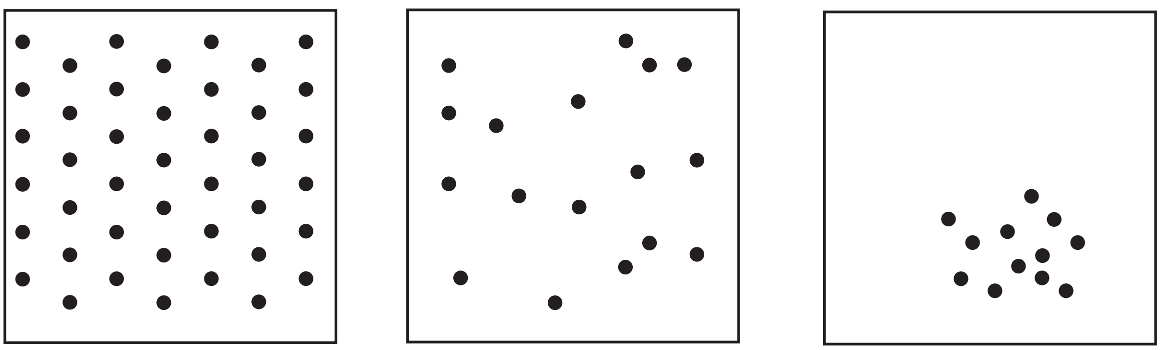
3.1 Spatial Patterns Analysis

The study of spatial patterns of fire hazard in CMM considered areas at two levels - district and sub-district - so as to analyze the relationship between the scattering patterns and physical characteristics in the study area. The investigation applied 'Nearest Neighbor Index Analysis' (O'Sullivan and Unwin, 2003; Suwan, 1998) which is a method of exploring patterns in locational data by comparing graphically the observed distribution functions of event-to-event or random point-to-event nearest neighbor distances. The equation for the nearest neighbor (Equation 1) is computed through the following steps;

$$R = Dob / Dex \qquad \text{(Equation 1)}$$

Where: R is Nearest Neighbor Index (NNI), Dob is the actual average nearest neighbor distance, is the expected average nearest neighbor distance; Dex = 0.5*(n / A)$^{1/2}$; n is number of events in A, A is subset of study area

In general, the values of index R range between two theoretical extremes: 0 and 2.15. When all the points in a pattern fall at the same location, the pattern represents Absolute Aggregated Distribution: in this case, R = 0. The more closely the points are clustered together, the closer to 0 R will be. The closer R gets to 1, the more randomly spaced the points are, representing Random Distribution. On the other hand, if the value of R approaches 2.15, it illustrates perfectly uniformly spaced points or Uniform Distribution. If the value of index R exceeds 2.15, it shows Further Scattered Distribution according to the confidence interval in the statistical analysis of the Nearest Neighbor Index. The illustration of 3 patterns is expressed in Figures 5.



R= 1.31 to 2.15
(Uniform Distribution Pattern)

R= 0.81 to 1.30
(Random Distribution Pattern)

R= 0.00 to 0.80
(Aggregated Distribution Pattern)

Figures 5. Types of point pattern.

3.2 Fire Risk Assessment

In this analysis process, the study provides remediation measures from fire hazard and identifies effective responses to prevent severe consequences. Fortunately a geo-referenced building footprint map was made available in digital format by the Public Works and Town & Country Planning Department, Ministry of Interior, of the Government of Thailand. The footprints of the buildings had been extracted from aerial photographs that were taken in 2004. The GIS layer maps with buildings, roads and drainage information were printed at a scale of 1:4,000 in order to be used as a base map for subsequent field surveys. Each building block on the footprint map was given a unique identification number as a reference number to identify the individual buildings in the field. Hence, fire risk areas could be selected based on the results from spatial patterns analysis before the occurrence of the fire, as well as significant factors influencing inflammability or potential fire vulnerability in cities. There are five significant vulnerabilities related to fire spread in urban areas: building structure, building use, fire-fighting access, locational activities and human vulnerability. However, another factor related to fire hazard, which is included in this study, involves 'fire handling capacity'. This comprises a number of variables such as water sources, fire-fighting equipment and fire stations. Each factor was considered, based on score measurement and weighting, as well as the application of GIS for the fire risk assessment. The approach of the fire risk analysis is illustrated in Figure 6.

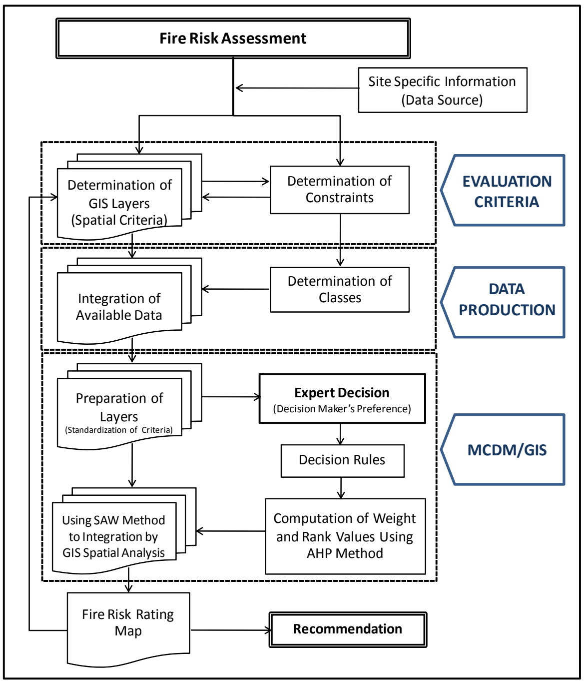


Figure 6. Framework for GIS-based and spatial multi-criteria decision analysis (MCDA) for fire risk assessment.

a. GIS-grid-based Fire Hazard Assessment

A GIS-grid-based fire hazard model was developed to determine the level of severity of fire hazard zones, in terms of mapping fire vulnerability, by assessing the relative importance between fire hazard criteria and the location of fire incidents. A spatially weighted index model was used to develop the fire hazard model. This model was developed based on stakeholder analysis, considering the influence of several factors in fire hazard. There were four groups of stakeholder - urban planners, fire wardens, local residents and local government officials - involved in defining the weight of alternative comparison factors.

For this study, the methodology was modified so that an analytical hierarchy process (AHP) was used to identify the score and weight of each factor. With a weighted linear combination, factors are combined by applying a weight to each, followed by a summation of the results to yield a fire hazard assessment model:

$$S = \sum_{i=1}^{n} W_i X_i \qquad \text{(Equation 2)}$$

Where S is the composite fire hazard value, W_i is the normalized weigh of factor i , and X_i is the vulnerability criterion score of factors i, n is the total number of factor, $i = 1, 2, 3, \ldots, n$

If the scores for the fire hazard criteria are measured on different scales, they must be standardized to a common dimensionless unit before

Table 2. Relative scoring and weighting of 11 factors for fire hazard assessment.

Factors	Fire Risk Rating Score		
	High (3)	**Moderate (2)**	**Low (1)**
1. Vulnerability factor (6 factors)			
1.1 Building material types *(Classified by highly combustible building materials)*	Wood, bamboo, other easily inflammable materials	Mixed-material	Congaed and other noncombustible material
1.2 Building height *(Above the 14th floor is not accessible for fire engines)*	> 14 stories	14-7 stories	< 7 stories
1.3 Building density *(Quartic kernel density estimation surface for building using a bandwidth of 100 m.)*	> 100 units	100-50 units	< 50 units
1.4 Population density *(Estimated population of each building)*	> 50 persons	50-25 persons	< 25 persons
1.5 Building hazard occupancy *(Classification of hazard occupancy of building by available fuel; National Fire Protection Association -NFPA)*	Extra hazard occupancies (gasoline service stations, manufacturing, plastic processing, etc.)	Ordinary hazard occupancies (restaurants, post offices, department stores, etc.)	Light hazard occupancies (dwellings, apartments, colleges and universities, schools, offices, etc.)
1.6 Distance to available fire source *(The quantity of available fuel, which is a major contributory factor, such as gasoline station, liquid gas storage, etc.)*	> 1600 meters	1600-800 meters	< 800 meters
2. Capacity of mitigation factor (5 factors)			
2.1 Accessibility by road *(Roads less than 3 meters wide are not accessible for fire engine)*	> 100 meters	100-50 meters	< 50 meters
2.2 Distance to fire stations *(The effectiveness of the fire fighting service; NFPA, Jaimchaisri, 2006)*	> 2000 meters	2000-1400 meters	< 1400 meters
2.3 Distance to hydrants *(The effectiveness of fire fighting service; NFPA)*	> 100 meters	100-50 meters	< 50 meters
2.4 Fire history *(The history refers to the numerical density of fires initiated within an area in the past, calculated by quartic kernel density estimation)*	> 5 fire incidents	5-3 fire incidents	< 3 fire incidents
2.5 Distance to water supply *(The effectiveness of fire fighting service; NFPA)*	> 200 meters	200-100 meters	< 100 meters

conducting the combination method. The simplest procedure for standardizing the raw data is to divide each raw score by the maximum value for a given criterion (Table 2).

b. Weight of Evaluation Factors

The weight of each factor was determined with AHP, according to the expert advice. This method, developed by Saaty (1980), is based on three principles: decomposition, comparative judgment and synthesis of priorities. AHP is a systematic analyzing evaluation method to treat a complex and multi-index system quantitatively, decomposing the complex problem to a number of layers and factors to then compare and calculate as the result of the weight. In the study, the AHP method was applied to determine the weight of each factor.

In the construction of a pair-wise comparison matrix, each factor is rated against the other by assigning a relative dominant value between 1 and 9 to the intersecting cell (Table 3).

Table 3. Intensity of relative importance scale.

Intensity of Importance	Definition
1	Equal importance
3	Moderate prevalence of one over another
5	Strong or essential prevalence
7	Very strong or demonstrated prevalence
9	Extremely high prevalence
2,4,6,8	Intermediate values
Reciprocals	For inverse comparison

In AHP, an index of consistency, known as the consistency ratio (CR), is used to indicate the probability that the matrix judgments were randomly generated (Equation 3) (Saaty, 1977)

$$CR = CI / RI \qquad \text{(Equation 3)}$$

Where RI is the average of the resulting consistency index depending on the order of the matrix given by Saaty (1977) (Equation 4) and CI is the consistency index and can be expressed as

$$RI = (\lambda_{max} - n) / (n-1) \qquad \text{(Equation 4)}$$

Where λ_{max} is the largest or principal eigen value of the matrix and be easily calculated from the matrix, and n is the order of the matrix.

In this case, the consistency ratio of the matrix of paired comparisons between the two influential factors in the fire hazard assessment is 0.089 and 0.078, and is thus acceptable. Once a satisfactory consistency ratio is obtained, the resultant weights are applied. The weights should add up to a sum of 1.0, as the linear weighted combination calculation requires. A similar process takes place in other factor categories, as shown in Table 4 and Figure 7. Since the matrix is symmetrical, only the lower triangular half needs to be filled. The remaining cells are simply the reciprocals of the lower triangular half.

4. Results of Study

4.1 The Spatial Patterns of Fire Risk Areas

The results illustrated the total number of fire hazards in CMM in the period of 2000-2004 (Figure 8). A visualization of the spatial patterns of fire risk presented a non-uniform distribution pattern, with characteristics mixed between aggregated and random distribution patterns within the municipality area. However, the study area is a large area with the prevalence of a prominent scattering fire that demonstrated in both patterns. Therefore, to clearly identify the distribution of fire risk, the municipality area was sub-divided into a total of 64 zones across CMM.

Table 4. Relative weighting of factors for each fire hazed category.

Factors	1	2	3	4	5	6	Weights
a. Vulnerability factors							
(1) Building material types	1	6	2	6	8	7	0.43
(2) Building height	1/6	1	2	4	2	3	0.17
(3) Building density	1/2	1/2	1	5	7	8	0.24
(4) Population density	1/6	1/4	1/5	1	2	3	0.07
(5) Building hazard occupancy	1/8	1/2	1/7	1/2	1	2	0.05
(6) Availability fire source	1/7	1/3	1/8	1/3	1/2	1	0.03
Consistency ratio (CR): 0.089							
b. Capacity of mitigation factors							
(1) Accessibility by road	1	3	4	5	8		0.47
(2) Distance to fire stations	1/3	1	4	3	6		0.26
(3) Distance to hydrants	1/4	1/4	1	2	5		0.13
(4) Fire history	1/5	1/3	1/2	1	5		0.10
(5) Distance to water supply	1/8	1/6	1/5	1/5	1		0.04
Consistency ratio (CR): 0.078							
c. Main factors of fire hazard							
(1) Vulnerability factor	1	3					0.75
(2) Capacity of mitigation factor	1/3	1					0.25
Consistency ratio (CR): 0.001							

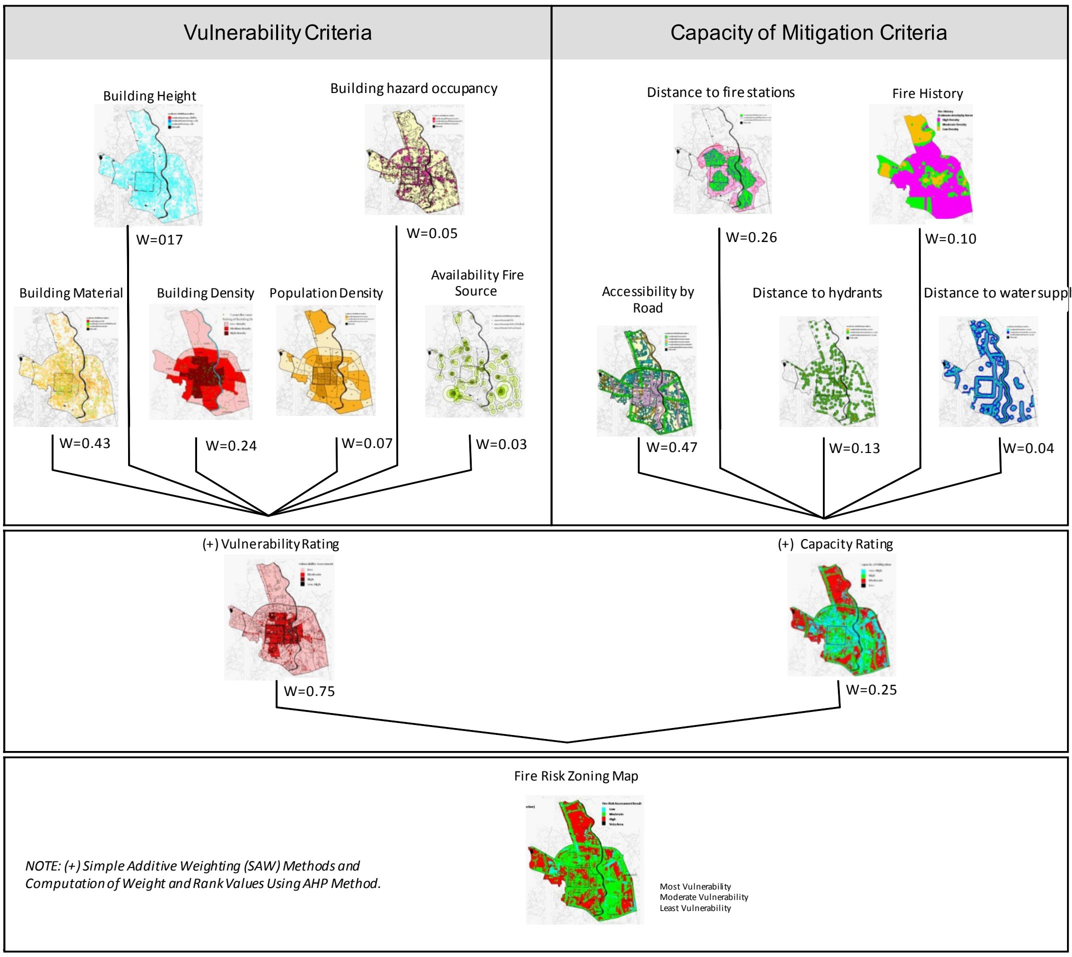


Figure 7. Conceptual diagram (approach) of fire risk analysis.

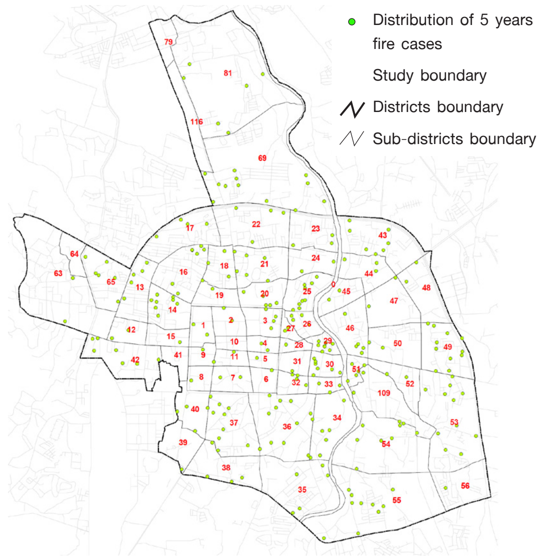


Figure 8. The spatial patterns of fire hazard, by zone.

The results found that there were 9 zones that appeared to be the pattern of aggregated distribution, covering 2.43 square kilometers or about 6.08 percent of the total area. The rationale of this result is that fire hazard occurred only once in such zones that creates NNI (Nearest Neighbor Index) representing Absolute Aggregated Distribution; hence it cannot clearly predict the risk of fire hazard. Another pattern is Aggregate Distribution, which was found in 10 zones covering 5.74 square kilometers or about 14.35 percent of the total area. It also illustrated that NNI of the 25th zone presented a significant pattern of absolute aggregated distribution compared to the other zones (Figure 9).

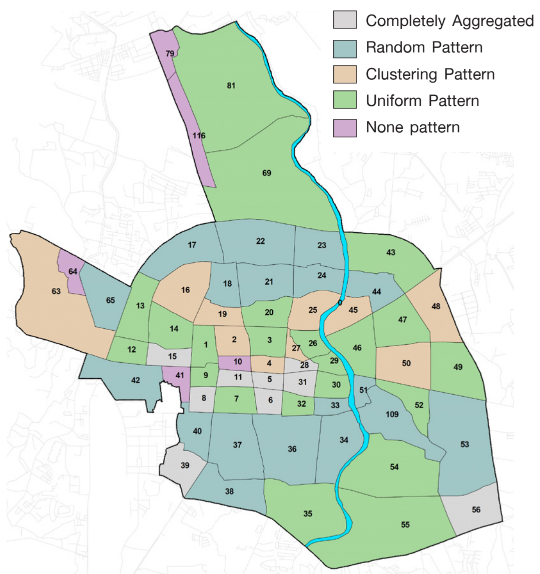


Figure 9. Classification of the spatial patterns of fire hazard, by zone.

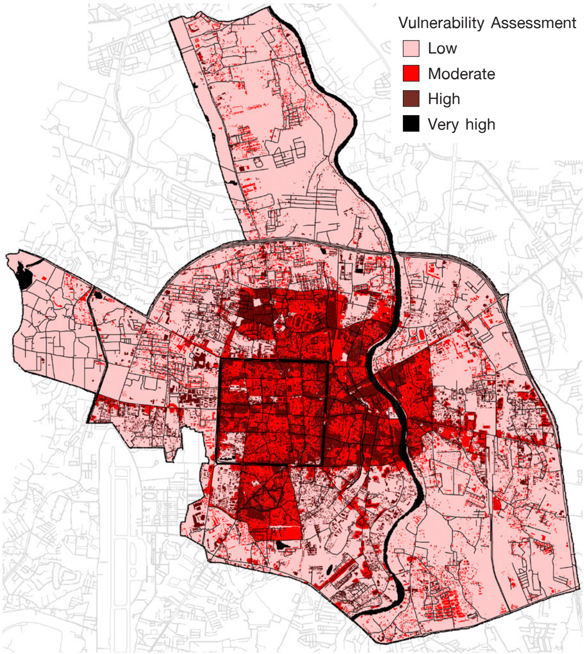
4.2 The Results of Fire Risk Assessment

The overall picture of fire risk areas in CMM illustrated that there was no area that demonstrated non-fire risk (Figures 10), according to its vulnerability to fire or fire-inducing capability (Table 5 and 6). More than half (50.39 percent) of the total study area showed evidence of a high level of fire risk (Table 7). 31.35 percent of the total area, mostly at the edge of the municipality area and main roads, demonstrated a medium level of fire risk.

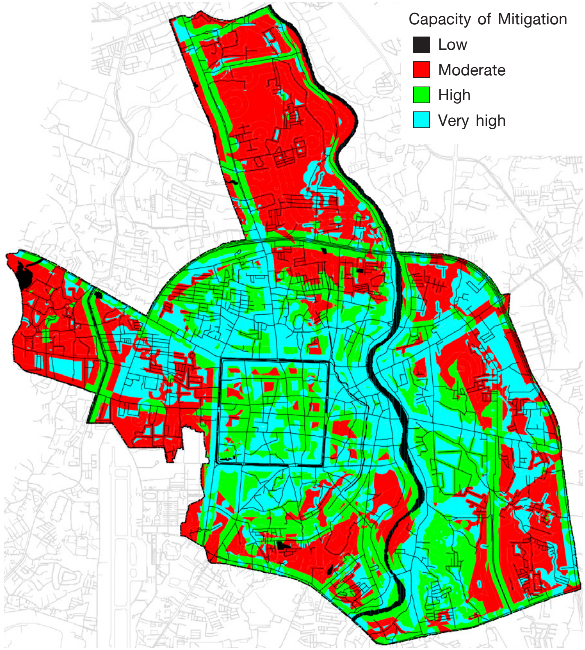
Based on these calculations, it was found that most areas (81.74 percent) within the municipality have a medium-to-high level of fire risk. Less than a fifth (18.26 percent) of the total area, generally in certain areas near main roads and the Ping River, had a low level of fire risk.

5. Conclusions and Discussions

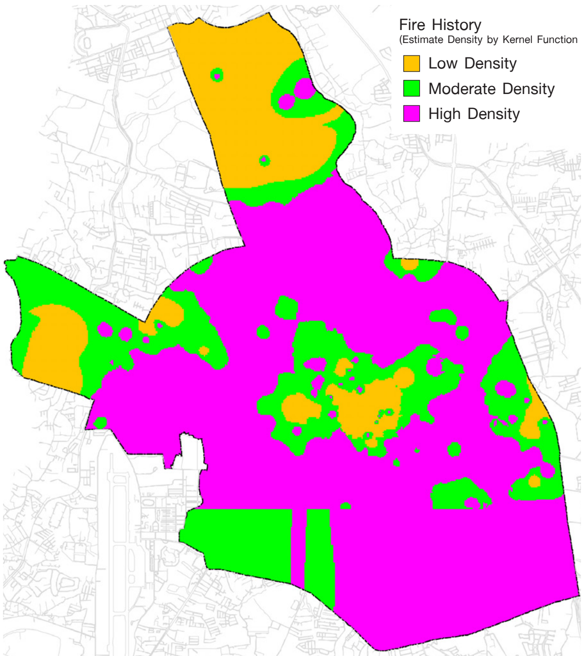
High-fire risk areas are fundamental problems for cities that need effective protection measures to prevent future incidents, as the tragedy of a fire can bring extensive damage to life and properties. The findings illustrated that many areas within the municipality area showed extreme-fire risk characteristics and fire severity conditions. Therefore, it is very important to study the characteristics of high-fire risk areas and the damage caused by fires in order to find appropriate prevention and protective measures and alleviate the damage from these incidents as much as possible. Mitigation supports disaster preparedness by reducing the damage resulting from fire hazard events. It relates to concrete actions which are put into practice to reduce the risk of destruction and causalities. There are two types of mitigation: structural and non-structural. Structural mitigation refers to any physical construction to avoid or reduce possible impacts of the hazard, including hazard-resistant and protective structures and infrastructures. Non-structural mitigation refers to policies, awareness raising, knowledge development, public commitment, and their associated techniques



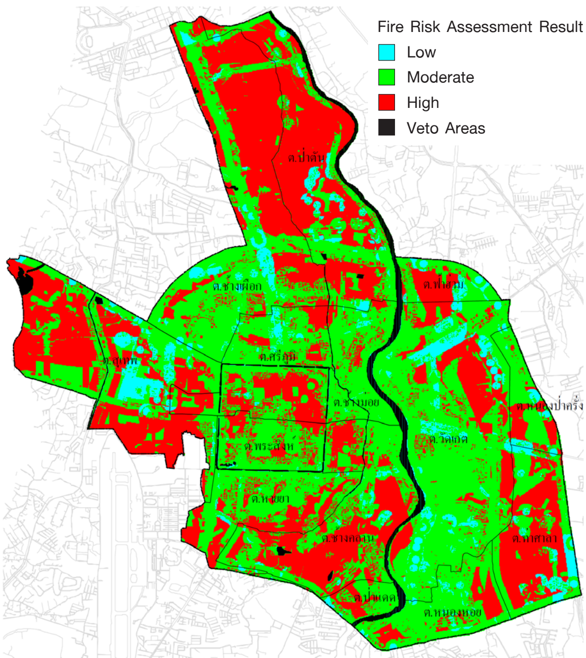
(a) Vulnerability rating



(b) Capacity rating



(c) Areas where fire hazards have happened before



(d) Fire risk areas

Figures 10. An assessment of the risk factors of fire incidents.

Table 5. Summary of capacity area.

Capacity Category/ Capacity Score	Area (sq. km)	Percentage (%)
High (more than 80)	27.99	68.80
Moderate (50-79)	6.94	17.07
Low (less than 49)	5.75	14.13
Total	40.68	100.00

Table 6. Summary of vulnerability area.

Vulnerability Category/ Score	Area (sq. km)	Percentage (%)
High (more than 80)	1.34	3.28
Moderate (50-79)	8.57	21.08
Low (less than 49)	30.77	75.64
Total	40.86	100.00

Table 7. Summary of fire risk area.

Risk Category/ Risk Score	Area (sq. km)	Percentage (%)
High (more than 80)	20.59	50.39
Moderate (50-79)	12.81	31.35
Low (less than 49)	7.46	18.26
Total	40.86	100.00

that contribute directly to reduced loss of life and damage to property. The study has demonstrated the use of AHP and GIS to determine fire hazards in Chiang Mai municipality for various uses, based on geo-environmental criteria.

The advancement of geospatial technologies and capabilities, including the use of GIS data, will allow managers to make decisions based on the most up-to-date information available. The development of Chiang Mai's Fire Risk Assessment System will play a significant role in the way in which fire managers approach urban fire suppression, mitigation planning and public outreach. This valuable tool will provide the CMM with a consistent citywide approach that will be critical for decision-making for fire risk management.

The fire risk assessment can be further improved by using simulation models that include climatic data such as wind speed and direction, atmospheric dryness, rainfall, etc. All in all, we cannot use the same weights and variables in different regions because urban fires in each city have their own specific characteristics. Furthermore, indices should be modified over areas with different environmental conditions. However more modeling results are needed to compare the other methods.

References

Chainey, S., & Ratcliffe, J. (2005). *GIS and crime mapping.* West Sussex, England: John Wiley & Sons.

Jiamchaisri, A. (2006). *ขนาดและขอบเขตพื้นที่รับผิดชอบที่เหมาะสมของสถานีตำรวจนครบาล* [Optimum responsible areas and boundaries for Bangkok metropolitan police station]. Master Thesis, Faculty of Architecture, Chulalongkorn University, Bangkok, Thailand.

Nimmanahaeminda, U. (1967). ปัญหาทางการผังเมืองทางด้านอัคคีภัยในประเทศไทย [The urban planning for fire management in Thailand]. *The conferences proceeding of urban planning and architecture studies*. Bangkok, Thailand: Pranakhorn Publisher.

O'Sullivan, D., & Unwin, D. J. (2003). *Geographic Information Analysis.* USA: John Wiley & Sons.

Saaty, T. L. (1977). A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology, 15*(3), 234-281.

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

Suwan, M. (1998). *ระเบียบวิธีการวิจัยทางภูมิศาสตร์* [The quantitative techniques for geography]. Bangkok, Thailand: Odeon Store.