國立臺灣大學工學院土木工程學系

碩士論文

Department of Civil Engineering
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Master Thesis

考量消防應變效率之狹小巷道改善策略：基於都市路網分析之觀點

Improving narrow alleys for fire response enhancement: the perspective of urban roadway network analysis

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謝誌

小時候總是抱著一本本地圖集，看著圖上的小小山谷、河流、街道，想像著居住於其上的人究竟過著怎樣的日子。這股對地圖的熱愛直到來到交通組才得以重燃。感謝交通組在我的生涯轉捩點時接納了我，而我也順利地以這篇論文作為生涯當中的重要段落。

首先，感謝所有犧牲青春年華，奉獻寶貴生命的消防戰士。浴火鳳凰的守護之下，我們深愛的家園才能夠安和樂利。期望藉由這篇論文的拋磚引玉，讓狹小巷道火災的議題受到更多專注。然而本身並非消防出身，文中淺見若有謬誤或疏漏，則期待各位先進的海涵與指教。

謝謝我的指導教授許聿廷老師，帶領我走進學術的領域。在研究過程中，老師不僅在論文的選題與背景的爬梳上都為我指引了清晰的洞見，也啟發了我災害應變的理論架構。同時，老師也給了我自由發揮的空間，讓這篇探索性的論文成為可能。在交通組的其他課程上，我也收穫甚豐，不論是陳柏華老師在 OR 課程上明朗且條理分明的建立知識基礎，朱致遠老師在最佳化課程中的嚴謹而深入淺出地指導數學方法，或是許添本老師在車流理論的交通方法探索。老師們的專業知識與治學態度引領了我完成論文，也期許這份研究不忝師長的教誨。謝謝口試委員黃俊能、陳柏華、黃尹男老師。在考試的過程中，不論是在背景、方法與實務上，老師們寶貴的建議與回饋，都讓我再一次的學習，使我能將這份研究更加完善。

另外，我要特別感謝國震中心震災模擬組的楊承道博士與黃為學助理。楊博和為學從 TELES 資料庫提供建築物資料，並為我進行了妥善的前處理，以作為本研究之背景數據，同時也給予我許多觀念上的釐清。沒有你們的鼎力協助，本研究是無法順利完成的。

儘管求學生涯當中都在濃厚的理工氛圍下度過，我仍然感覺自己懷著一顆人文學科的心。慶幸在大三的時候修習了人類學系的課程，跨文化的視野開拓了我看待社會時的多元角度。林瑋嬪、王梅霞、呂欣怡老師的課程，是我大學生涯最豐富的時光，妳們的學養與對待學生的溫暖令我印象深刻。黃書緯老師的社會設計帶我們學會去看都市資源與個人和群體間的互動。未來若有機會著力於都市議題，期待自己繼續對周遭的社會充滿好奇。

而我也有幸能與棒球結緣。從怯生生地端著手套和球，到了必須一肩扛起台大王牌，我真的從棒球學到了很多。除了體能、技術、領導之外，最珍貴的就是我們的患難情誼。謦安、俊佑、晉毅帶我成為獨當一面的投手，宇博、鴻揚、厚和、銘哲、干賢，有你們並肩作戰才讓棒球更精采。儘管最後一年的結尾並不完美，或許這才是棒球給我最完美的句點。台大棒球隊是我永遠的家！懷念那段睜開眼睛只

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有棒球，每天與戰友們只想著向前衝的日子。

在碩士班生活的過程中，也感謝小許家的各位。家維帶路讓我們從高中同班再續前緣。柏傑、至佑、譽仁、明儀、薇亘、文宇、智勛，謝謝你們的知識分享和小許家出遊的各種回憶。冠頡、弘亦、秉鈞、張霽，我早一步先畢業啦，希望你們順利跟上！琪雅、美能、揚程，你們真是有趣的學弟妹，祝你們做出厲害的研究。認識英琢之後才知道你的可靠，要是你能考進校棒就太好了，但或許專注學術路線才更適合你呢。

謝謝皓淳陪伴著我完成論文，也跟著我踏遍了台北的每個角落。儘管妳都不認識路，需要我來充當衛星導航，但是妳也是我心裡的指南針，指引著我時時向前走。未來我們要繼續在大街小巷裡一起冒險！

謝謝爸爸媽媽養育我長大成人，也教導了我很多待人處事的道理，你們不辭辛勞，為的就是讓我和妹妹有個自在發展的環境。取得碩士學位之後也將走入社會，我會將你們教給我熱情、堅持、謹慎的態度帶到社會上。也謝謝在路途上給我支持的所有師長，你們的協助以及樹立的典範讓我成為今天的我。

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中文摘要

狹小巷道是造成消防延誤的潛在因素，不論是巷道的寬度不足或是違停車輛的停放都可能阻礙消防車的通行，因而延誤救災時機。由於過往學界均未有發展以網路設計提升消防效率之研究，因此本論文旨在提供一個路網方法，以輔助狹小巷道改善之決策，其中包括（1）劃設消防通道（2）拓寬狹小巷道。

首先，以路網的 Voronoi 圖劃分巷道火災風險負責範圍，再評估建築風險以計算個別巷道的火災風險。考量到消防單位在巷道中的移動限制，本研究建構了雙層隨機阻塞路網來描述消防救災之行動，並藉由分割街廓子路網的方式，將替代路徑的搜索範圍加以限縮。接著，利用蒙地卡羅方法估計出巷道旅行時間之期望值，以此作為消防服務可及性的指標。

在巷道保障通行之關鍵性上，逐一評估巷道通行受到確保之下所增進的消防可及性，再利用關鍵性之排序作為消防通道劃設之參考。而在巷道拓寬的部分，首先分別列舉出個別街廓的巷道拓寬計畫，並計算其效益與成本，再以背包問題決定出限制成本下的巷道拓寬計畫。

在案例分析中，我們將研究方法應用於台北市西區舊市街。結果顯示，本模型能夠辨識保障通行之最關鍵巷道，另外也能求得最有利的巷道拓寬決策，從而促進狹小巷道社區之消防可及性。本研究建議後續研究者進一步探索巷道阻塞之特性，或考慮消防滅火與水源中繼之因素，藉此進一步精進模型的建立。

關鍵字： 狹小巷道、消防可及性、隨機阻塞、巷道改善、關鍵性、蒙地卡羅方法、沃羅諾伊圖

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ABSTRACT

Narrow Alleys are the potential cause of delays in firefighting operations. Once a fire breaks out in an old urban community, fire engines may be blocked in an alley due to insufficient width or illegally parked vehicles, thereby delay firefighting operation. However, few existing studies have assessed the threat of narrow alleys and improvement of firefighting in a systematic manner. Hence, this thesis proposes a network-based method to support decision-making in alley improvement measures, which include (1) marking fire lanes and (2) widening alleys.

First, the Voronoi diagram of the road network is used to divide alley-based zone, and then the fire risk of each alley is estimate by summing up the fire risk of buildings within the alley. Considering the mobility of fire crews in alleys, we construct a two-level road network with stochastic alley blockage to describe pathfinding in firefighting. Also, the division of block subnetworks limits the searching space of alternative paths. Then, the Monte Carlo method is used to estimate the expected travel time over targeted alleys to evaluate fire service accessibility on the network.

To assess the criticality based on passability assurance of alleys, a full-scan approach is conducted to evaluate the improved accessibility index after ensuring their passability. The ranking of the alley criticality provides a reference to the priority of setting fire lanes. To determine the widening alley, this study proposed a block-based widening plan generation process and evaluate the benefit and cost of each widening plan. Then, a knapsack problem is utilized to determine the widening decision over candidate alleys with a budget constraint.

In the case analysis, we apply the solution method to the western of Taipei City. It is

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demonstrated that this model is able to identify the most critical alleys for passability assurance and determines the most cost-effective alley widening decision to enhance the fire service accessibility in the communities. For future research, the nature of alley blockage can be further explored and fire extinguishing or water transport can be further considered to elaborate on the model and analysis.

Keywords: *narrow alley, fire service accessibility, stochastic blockage, alley improvement, criticality, Monte Carlo method, Voronoi diagram*

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Chapter 1 Introduction

1.1 Background and Motivation

Fire emergency response and mitigation are critical issues for urban planning and city governance, especially in old communities with high fire risk. After the rapid industrialization and modernization in Taiwan, the population shifted from rural to urban areas in the mid- and late-20th century. Resulting from the development paradigm of mix land-use and lack of thorough urban planning during the development, cities in Taiwan suffer from high fire risk while densely-populated residential areas and narrow alleys are common in the old and decrepit communities.

Once a fire breaks out in an old community, a narrow alley with insufficient width may block fire engines and thereby delay firefighting operation. Moreover, despite the insufficient width of alleys, lanes in densely-populated residential areas are often filled with illegal parking cars and motorcycles, obstructing the passage of the fire crew, and leading to the delay of rescue and severe casualties.

For instance, the Dasi Community fire in Luzhou District (蘆洲大囍市社區大火), New Taipei City (Taipei County) in 2003 caused the death of 16 and injury of 68. The narrow alleys and the illegal parking along the lane obstructed the path of fire apparatus, which delayed the critical time for extinguishment. This severe accident evoked the attention of society to the issue of fires occurring in narrow alleys and prompted the draft of related legislation.

Although the regulations for fire safety and city environment have been put into practice afterward, the residents still abide the hazard of fire in narrow alleys and the

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associated communities. In 2012, Taipei City Government was denounced by a corrective measure (糾正案) of the Control Yuan, which claimed that the capital did not effectively manage the parking space along the roadway by laws and relevant enforcement. Since the fire lanes were urgently insufficient, and the prohibition of illegal parking on other alley was not effective, the function of firefighting in Taipei was failed to be comprehensively maintained by the government. In 2015, Taipei City Government launched the "Neighborhood Traffic Improvement Plan" (鄰里交通環境改善計畫) to promote traffic safety and fire safety by managing illegal parking and improving the roadway environment. However, there is no quantitative procedure for assessing the criticality or importance of setting up a fire lane, while the current policy of marking fire lanes is only regulated by the principled guidelines.

On the other hand, for those narrow alleys with insufficient width, the problem can be solved by widening them upon the situation that the urban renewal is procrastinated. In recent years, several county and city governments have implemented the roadway bottlenecks breakthrough policy. However, due to the high expense of widening construction for local governments to afford, it is necessary to make better or even optimal decisions that consider the effectiveness of relevant project deployment under the budget limit.

In the past, research on narrow alley fire response and mitigation focused on evacuation preparation, upgrade of firefighting equipment, and mitigation of fire risk in building structure and environment. However, to the best of our knowledge, few studies are applying network-based methods to support the perspective of decision-making. To provide an analytical approach for mitigating fire risk and enhancing fire response, this study considers structural fire risk, road network configuration and characteristics of fire service activities, thereby systematically proposes a strategic approach to assess and

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determine the alley improvement measures including marking fire lane and widening narrow alleys.

1.2 Objective

In the firefighting operation, narrow alleys are not passable by fire vehicles because of their insufficient width. Further, illegal parking in alleys can also block the passage of firefighters. Hence, the firefighting crew has to detour or manually pull the fire hose for a certain distance to attend the fire scene, resulting in the delay of extinguishment and rescue. If the passability of an alley can be ensured, allowing fire engines to pass by, the travel time of fire service can be reduced.

Considering the two alley improvement measures to mitigate urban fire in the different contexts of city governance, the proposed method in this study seeks to support the decision-making of road management and urban planning toward fire service accessibility. To be more specific, the detailed objectives are listed below:

1. Integrate the urban fire risk map and road network configuration.
2. Examine the characteristics of the firefighting operation in an urban road network with narrow alleys and stochastic blockage.
3. Investigate the background of two alley improvement measures, including (1) ensuring passability of alleys by marking them as fire lanes and (2) widening narrow alley.
4. Determine alley criticality based on passability assurance in the road network with stochastic alley blockage.

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5. Propose an optimization model to determine the decision of widening narrow alleys to maximize the overall accessibility of firefighting operation with budget constraints.

1.3 Organization

The remainder of this thesis is organized as follows. Chapter 2 provides the literature review of the background related to fire in narrow alleys and network-based approaches for emergency response. Based on the research gaps specified in Chapter 2, Chapter 3 proposes two network-based approaches to respectively assess two primary alley improvement measures to promote fire service accessibility. In the proposed methods, alley criticality based on passability assurance is evaluated and an optimization model to determine the decision of widening alleys is formulated. Next, a case study using the road network in the old town district of Taipei City is conducted, and the analysis results are visualized and discussed in Chapter 4. Finally, conclusions of research findings and suggestions for future research are summarized in Chapter 5. The flowchart of the thesis organization is illustrated in Figure 1.1.

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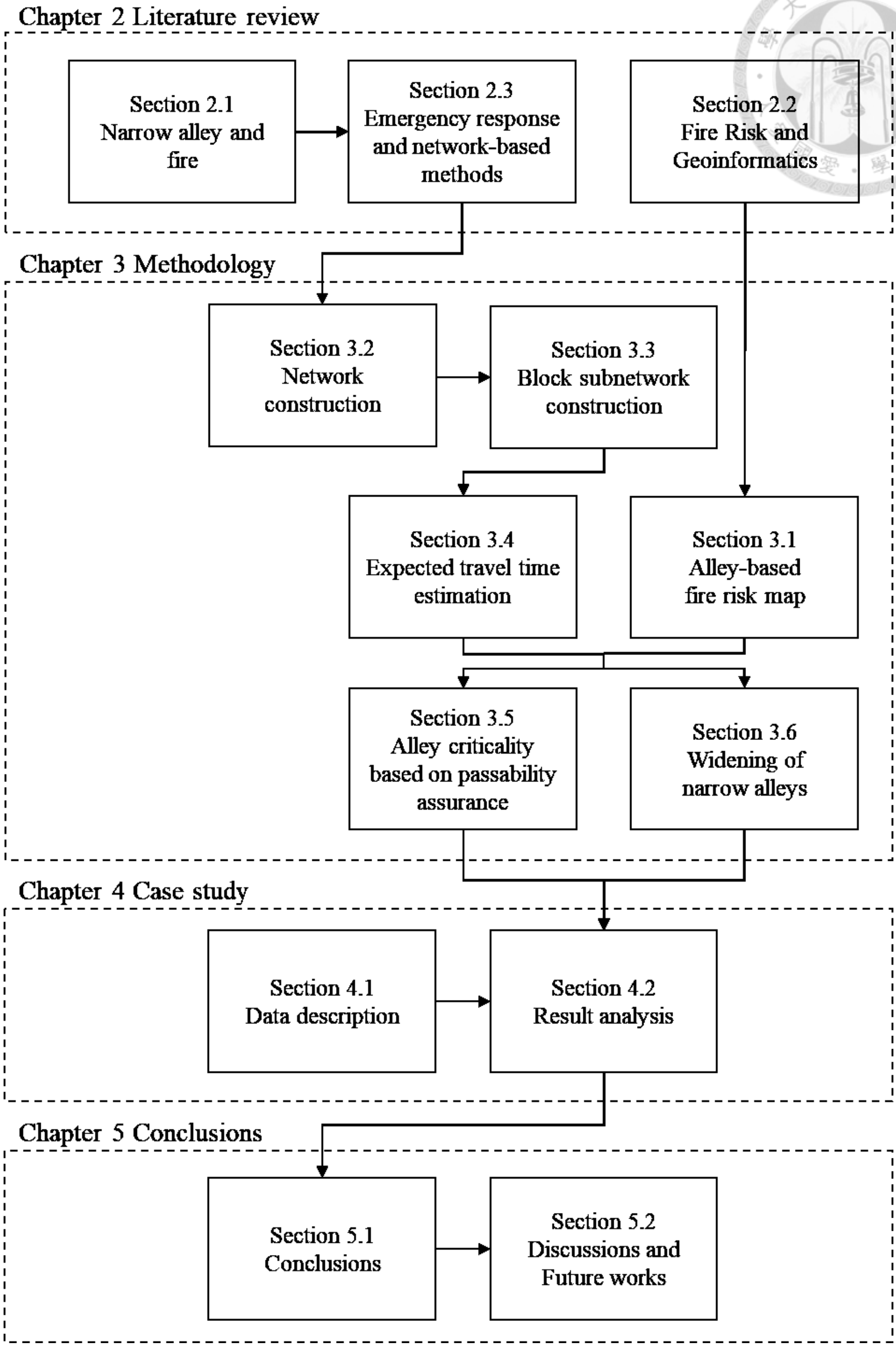

Figure 1.1 Thesis organization.

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Chapter 2 Literature Review

We first collect the background information of fire in narrow alleys in Section 2.1 and examine the fire risk and its spatial characteristics in Section 2.2. In Section 2.3, we discuss the road network analysis and optimization modeling on emergency response. Last, Section 2.4 summarizes the review, clarifies the issue in this research, and points out the gap of previous research.

2.1 Narrow Alleys and Fire

A comprehensive review of emergency response in narrow alley fire is conducted. To begin with, the concept of fire response time is clarified, and the definition of a narrow alley is inspected. Then, the current situation of fires in narrow alleys is introduced. After that, from the perspective of firefighting, the practical difficulties and tactical responses to narrow alley fire are examined. In the last place, we explore the research which takes the road improvement as a mitigation approach and indicate the core concern of this study.

2.1.1 Concepts of fire response

Firefighting is the activity that prevents the spread of unwanted burning and extinguishes significant structure or wildland fire. Casey (1991) in his *The Fire Chief's Handbook* defined the objective of firefighting as (1) identifying the origin of flame, (2) suppressing the expansion of flare, and (3) extinguishing the fire.

As a fire crew receives a fire alarm, firefighters have to arrive at the fire scene in the shortest possible time to suppress the fire with a variety of equipment and tactics. Fire

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suppression is a complex procedure, which involved a number of factors, such as the category of the material, the height of the structure, the utility of the building, the proper rate of the equipment, and the training of firefighters (顏振嘉、葉吉堂, 1993; 熊光華, 1999; 鄧子正, 1999). In addition, the extinguishment of fire is often affected by many uncertain factors, such as the environment, weather, and rescue tactics, which bring uncertainties of firefighting. However, before the fire combat, the primary purpose of fire services is the rapid and timely response to a fire, as the motto says, “every second counts” (Fire Brigade Union, 2010).

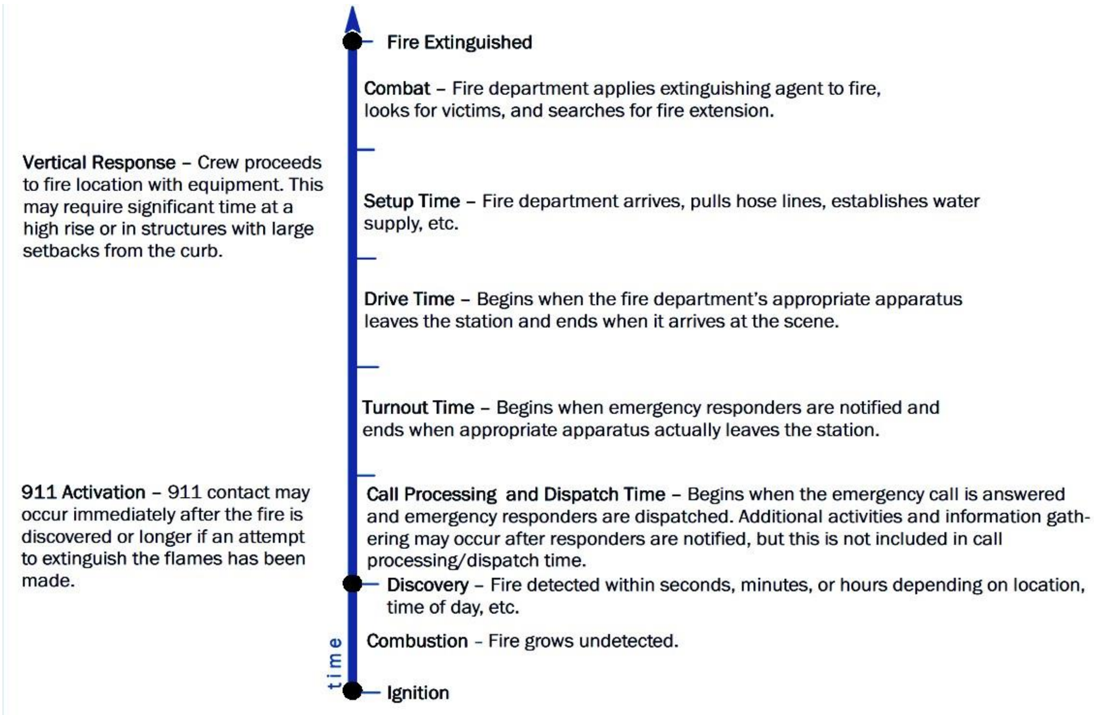

Figure 2.1 Components of total response time. (USFA, 2006)

According to U.S. Fire Administration (USFA), *response time* in the fire service is usually “measured from the time the emergency communications center receives a call to the arrival of the first apparatus at the scene” (2006). The components of fire service, as shown in Figure 2.1, include ignition, combustion, discovery, call processing and dispatch, turnout time, drive time, setup time, combat, and extinguishment. By the definition of

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USFA (2006), the response time of fire service consists of call processing, dispatch, turnout, and drive.

Despite the traffic condition such as congestion, the travel time is also prolonged by blockage of alley due to insufficient width or illegal parking on the path. Therefore, by alley improvement, the reduction of travel time may lead to earlier arrival at the fire and prevent more loss of property and lives. Table 2.1 lists narrow alley fires in recent years, in which firefighting was obstructed because of narrow space for access or combat. The study background of fires in narrow alleys is introduced in Subsection 2.1.4. In this research, the objective is to propose a systematic method to assess the alley improvement with the saving of travel time by preventing obstruction.

Table 2.1 Narrow alley fires in recent years

Date	Location	Description
2003.8.31	Luzhou, New Taipei	Death of 16 and injury of 68. Massive fire in the community. Fire engines blocked by parked scooters along the alleys.
2012.4.28	Datong, Taipei	Death of 3 and injury of 2. The fire spread through awnings and other obstacles in front of buildings. Eight households caught fire.
2013.1.15	Xinpu, Hsinchu	Death of 1. The alley blocked passage of 7 fire apparatus, including a ladder car. Man killed on the 5^{th} floor.
2015.2.26	Sanchong, New Taipei	Death of 4. Nearby Sanhe Night Market. Fire engines blocked by illegal parking along the alleys.
2017.10.29	Shilin, Taipei	Death of 4. Fire engines blocked by illegal parking along the alleys.

Note. Adapted from 李孟原(2018)

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2.1.2 Response time of emergency vehicle

Response time is a research topic of emergency response. Kolesar, Walker, and Hausner (1975) proposed the relationship between distance and travel time of fire engines using historical data. Pietrzak (1979) calculated the difference in velocity by taking the road conditions and power-to-weight ratio (pwr) as variables and found that the lower pwr brings the more extended the travel time under frequent acceleration and deceleration in the journey. Yasukawa and Gagliardi (1988) evaluated the driving speed by linear regression under various conditions, including single-direction or not, residential area or not, and the number of lanes. In recent years, there are fewer studies in the response time of emergency vehicles. Westgate, Woodard, Matteson, and Henderson (2013) evaluate ambulance travel time using GPS data and Bayesian data augmentation. Zhang, He, Gou, and Li (2016) examined travel time reliability of links in emergency vehicle response. Kc and Corcoran (2017) explored the relationship between the travel time of fire trucks with seasons, socioeconomic factors, street density, etc. by employing a spatial analysis method. However, none of the research on emergency vehicle response considers blockage by traffic conditions or improvement by marking fire lanes.

Ideally, in assessing the accessibility of fire service, it can effectively evaluate the improvement if the relationship between response time and fire loss is known. Unfortunately, in the review of Swersey (1994) concluded from previous studies (Hogg, 1973; Corman, Ignall, Rider, and Stevenson, 1976) that the relationship had yet to be demonstrated with substantial evidence. 林元祥(2004) did not find a reliable correlation between response time and property loss when constructing a fire loss model for residential fires. Challands (2010) found a clear correlation between structural damage of fire and response time in New Zealand, but the data also showed a negative correlation

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between response time and casualties.

Although these studies explored the relationship between fire damage and response time, it did not clarify the correlation between fire accessibility and building value, and the spatial distribution of built-up area or population. Accordingly, we argue that there is no appropriate monetized indicator to evaluate the efficiency of the fire response. Thus, in this study, we employ the travel time directly as an indicator of fire accessibility.

2.1.3 Definition of a narrow alley

A *narrow alley*, from the perspective of fire service, refers to the roadway which is too narrow for fire apparatus and ambulance to go through. However, how much space of an alley should be reserved to ensure the passage of emergency vehicles? In practice of emergency response, the criteria for narrow alley should consider the width of the emergency vehicle, the space for a firefighter to get on and off to operate fire equipment, and the tolerance distance between the vehicle and the wall of buildings. According to Article 38 of the Road Traffic Safety Rules (道路交通安全規則, 2003) promulgated by the Ministry of Communications and the Ministry of the Interior, the total length of fire engines must not exceed 15 meters, the total width must not exceed 2.6 meters, and the total height must not exceed 4.2 meters. Thus, the maximum width of a fire vehicle is 2.6 meters, the firefighter's operating space is 0.4 meters, and the space for opening a door is 0.5 meters. To sum up, 3.5 meters is the lower limit of width for fire vehicles (林忠億、陳火炎, 2009).

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Table 2.2 Standards for narrow alleys in Taiwan

Source of the standard	Standard made by	Content of the standard
Guidelines for Improving Fire Service in Narrow Alleys (提昇狹小巷道消防搶救指導計畫)	National Fire Agency, Ministry of the Interior	Narrow Alleys: Alleys less than 4 meters wide, or alleys with a width of more than 4 meters, but often blocked by vehicles or other items, cause the clear width to be less than 4 meters.
Guidelines for Space Planning for Fire Apparatus Operation (劃設消防車輛救災活動空間指導原則)	Construction and Planning Agency, Ministry of the Interior	Roads to buildings below five floors should have a clear width of at least 3.5 meters and a clear height of more than 4.5 meters. Roads to buildings over six floors should maintain a clear width of at least 4 meters and a clear height of at least 4.5 meters.
Improvement Plan for Fire Apparatus Operation Space (臺北市政府消防車輛救災活動空間改善計畫)	Taipei City Government	Red zone: 2.5 to 4 meters wide, 30 meters long cul-de-sacs or 60 meters long alleys. It should maintain a clear width of at least 2.5 meters and a clear height of at least 3.5 meters. Yellow zone: 4 to 5.5 meters wide, 60 meters long cul-de-sacs or 120 meters long alleys. It should maintain a clear width of at least 3.5 meters and a clear height of at least 4.5 meters.
Guidelines for Firefighting Route in Narrow Alleys (新北市政府消防局狹小巷道消防救災動線管理要點)	New Taipei City Fire Department	Narrow Alleys: alleys less than 4.1 meters wide. Firefighting Route: Roadways for passage of emergency response, which should be maintained a clear width of at least 3 meters and a clear height of at least 4.5 meters.

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At present, the central government of Taiwan does not have a unified standard for narrow alleys. The standards for narrow alleys from the different administrative bodies are listed in Table 2.2. For example, the Guidelines for Improving Fire Service in Narrow Alleys (提昇狹小巷道消防搶救指導計畫, National Fire Agency, 2003) sets the standard of narrow alleys at 4 meters, while the Guidelines for Space Planning for Fire Apparatus Operation (劃設消防車輛救災活動空間指導原則, Construction and Planning Agency, 2003) consider the narrow alley as the roadway less than 3.5 meters in width. In consideration of urban planning and parking management, each local government has its own standards. For Instance, the Taipei City Fire Department has classified the narrow alleys into two categories: red zone (紅區) and yellow zone (黃區). The red zone consists of 2.5 to 4 meters wide, 30 meters long cul-de-sacs or 60 meters long alleys; the yellow zone is composed of 4 to 5.5 meters wide, 60 meters long cul-de-sacs or 120 meters long alleys.

2.1.4 Background on fires in narrow alleys

The Dasi Community fire in Luzhou District (蘆洲大囍市社區大火), New Taipei City (Taipei County) in 2003 evoked the attention of society to the issue of fires occurring in narrow alleys. In the conflagration which caused the death of 16 and injury of 68, the narrow alleys and the illegal parking along the lane obstructed the path of fire apparatus and then delayed the critical time for extinguishment.

This severe accident prompted the draft of related legislation. After the fire, the Control Yuan (2003) denounced a corrective measure to the Ministry of the Interior and Taipei County Government. Despite the improper command of fire vehicles and negligence of maintaining fire safety equipment, the Control Yuan (2003) pointed out that

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the government failed to supervise of the community in apartment complex properly and plan the management of vehicle parking in the roadway, which caused the delay of the firefighting operation resulting from parked vehicle along the rescue route. Afterward, the Ministry of the Interior promptly drafted the two following regulations in 2003 to promote the implementation by local governments. Both regulations have their definitions of narrow alleys, which are listed in Table 2.2.

The Guidelines for Improving Fire Service in Narrow Alleys (提昇狹小巷道消防搶救指導計畫, 2003) drafted by the National Fire Agency, Ministry of the Interior are the principles for fire response in narrow alleys. The guidelines suggested checking the narrow alley in the area of every fire department. Also, it recommended to implementing training for narrow alleys and promoting the dispatching capabilities command center. The aspect of strengthening fire response is introduced in Subsection 2.1.6.

The Guidelines and Space Planning for Fire Apparatus Operation (劃設消防車輛救災活動空間指導原則, 2003) formulated by the Construction and Planning Agency, Ministry of the Interior provides guidelines for the space management of urban laneways. The guidelines urged local governments to review parking management in alleys in challenging areas, and strengthen enforcement of the parking ban of police agencies. Subsection 2.1.7 discusses the measures to ensure the passage of emergency vehicles.

However, fire mitigation in communities with narrow alleys is a complex issue involving city governance and urban planning. The Regulations for the Periodical Overall Review of Urban Planning (都市計畫定期通盤檢討實施辦法, 1997) has stipulated that when conducting the review of urban planning, the evacuation sites or facilities, and disaster response routes should be planned and reviewed based on the history, characteristics, and risk of the urban disaster.

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In order to cope with high fire risks and difficulties in disaster relief faced by old urban communities, academia and government have put forward comprehensive studies from the aspects of fire mitigation, emergency response, and regulations. Before the Dasi Community fire, there have been studies about disasters in the old urban communities. 方禎璋(2000) provided mitigating strategies for fires in old buildings, including preventing ignition, fire equipment and monitoring device, space planning of neighborhood, neighborhood association, and fire safety advocacy. 陳建忠、黃志弘(2000) pointed out that a high density of structures and lack of non-combustible construction lead to a high tendency of ignition and expansion of fire in old communities. Therefore, comprehensive disaster prevention measures are a top priority. They emphasized the urgent need of fire prevention measures, including long-term planning (e.g., disaster prevention locations, zones of fire safety, routes for evacuation and fire service, etc.), and short-term preparations (e.g., maintaining evacuation path, preparing equipment, etc.) 丁育群、李威儀(2005) proposed fire risk assessment methods for disaster in urban blue-collar areas. By case studies in Wanhua District, Taipei, 丁育群、李威儀(2005) investigated the physical environment of the residential community, summarized the disaster-prone factors of old communities to assess the fire risk. 陳建忠、張隆盛(2005) suggested the emendation of the Urban Renewal Act to improve the community-based disaster prevention mechanism by updating the standards for designating the renewal unit in order to promote regeneration in the old community at high disaster risk.

However, although the Urban Renewal Act has been implemented since 1998, urban renewal has encountered considerable bottlenecks in the current model of urban renewal with civilians as the main body. 張松源(2005) listed the main difficulties as follows: (1)

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low number of urban renewal applications; (2) dilemmas between involved units in construction projects; and (3) the lengthy process of development review.

Due to the urgency of improving fire safety, the central government has implemented the Statute for Expediting Reconstruction of Urban Unsafe and Old Buildings (都市危險及老舊建築物加速重建條例) in 2017, providing the source of law to urge local governments to promote the regeneration. However, the progress is still procrastinated in the current implementation of urban renewal because the problems mentioned above are still inevitable. Therefore, we argue that it is necessary to improve the fire safety environment of the old community in the medium and short-term measures.

2.1.5 Difficulties in firefighting in narrow alleys

After the conflagration of the Dasi Community in 2003, researchers have investigated the practical situation of fire service in narrow alleys. Through a questionnaire, 洪超倫(2005) found that most firefighters believed that the failure to provide passages of fire vehicle or ladder trucks in surrounding roads and to stack flammable materials beside the building were some of the most essential factors which delay the firefighting operations. Nevertheless, in a comprehensive review and discussion on narrow alley fire, 林忠億、陳火炎(2009) have summarized that the risk factors of narrow alley fire consist of blockage of fire vehicle, lack of water supply, and difficulty of smoke ejection.

When firefighters encounter a narrow alley on their way driving to the fire scene, what should they do? In the interview with senior firefighters about narrow alley issue in the study of 李孟原(2018), a firefighter responded,

"When the vehicle is unable to enter, if you can see the fire scene, you should pull the

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hose lines over the distance. If you cannot see it, you should detour and notify the follow-up vehicle to go other ways, then inform the service center about the situation."

It can be seen that when the path is obstructed, the first choice for firefighters is to get as close to the fire scene as possible, and the second is to lay out hose over a long distance manually.

In general, applying the hose line belongs to the step of setup in the process of fire response. However, in our consideration, the time required for approaching to fire scene, including by pulling hose lines, should be counted as travel time. The longer the distance in the alley, the more time it takes for firefighters to extend the hose, delaying the timing of attendance and fire suppression. A field survey by Yajima (as cited in 陳弘毅, 2003) showed that the time required to applying hose lines was affected by the number of extended hoses required (see Table 2.3), where the hoses are 20 meters long.

According to another field survey by New Taipei City Fire Station in 2011 (as cited in 趙森軒, 2012), the time required for applying the hose line vertically (going up the stair) and horizontally (on the ground) is measured as shown in Table 2.4.

Table 2.3 Elapsed time for extending fire hoses

Number of hoses	1-2	3-6	7-9	10-13	14-16	17-20	21-23	24-27	28-30
Elapsed time (min)	1	2	3	4	5	6	7	8	9

Note. Adapted from 陳弘毅(2003)

Table 2.4 Elapsed time for extending fire hoses vertically and horizontally

Horizontally	Number of hoses	1	2	3	4	5
	Elapsed time (s)	14	30	48	68	90
Vertically	Number of stairs	1	2	3	4	5

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Elapsed time (s)	12	25	40	56	72

Note. Adapted from 趙森軒(2012)

It is clear that if the applying hose line is necessary to approach the fire scene because of the blockage of passage, the number of extended hoses will increase the travel time for arriving at a fire scene. In this study, we adopt the data for assessing travel time in the road network in the case of being blocked by narrow alleys.

2.1.6 Firefighting strategy and technique

Regarding the situation of fire service in narrow alleys, each county and city government has its fire response plan. In this section, we take the example of Fire Response Plan in Challenging Areas in 2019 of Taipei City Fire Department (臺北市政府消防局 108 年度執行火災搶救困難地區暨搶救不易地區火災搶救應變計畫). The objects are the challenging areas, such as communities of flammable building materials, care centers, areas lacking water sources, narrow alleys, etc. In the plan, when a fire occurs, the command system should ensure that map information for challenging areas is displayed on the screen of the intelligent dispatching system. The Disaster & Rescue Division should regularly conduct training such as rescue practice workshop or commanding workshop and set a budget for the purchase of various fire vehicles and equipment for the particular situation. For the training of firefighting capability, each fire station should draw up a rescue plan in advance and submit the information to the intelligent dispatching system, and conduct regular drills (實兵演練). Besides, each HQ and battalion have to conduct training exercise (兵棋推演) in a large site of challenging

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areas. The purpose is to make the firefighters familiar with the internal structure, utility, and characteristics of the building, rescue route, vehicle deployment, locations of water sources, and related firefighting facilities, etc., to enhance the firefighting capability.

In the comprehensive study and review on narrow alley fire, 林忠億、陳火炎(2009) proposed four main improvement approaches for fire rescue along narrow alleys: (1) inspection of narrow alleys in the area; (2) firefighting drills for narrow alleys; (3) improvement of firefighting apparatus and equipment; and (4) assurance of firefighting access routes. 林忠億、陳火炎(2009) summarized the current countermeasures against the difficulty of accessing the fire scene, such as a parking ban in alleys, employment of smaller fire trucks, portable bumps, and extendable hose racks.

Figure 2.2 An extendable hose rack on a fire engine. Reprinted from 趙森軒(2012).

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Small fire trucks have the advantage of entering the narrower space, solving the difficulty of passing through some alleys. However, the ununified widths and less water capacity of small fire trucks are the main drawbacks. Fire motorcycles take advantage of its mobility to reach the fire as soon as possible, without delay by traffic jams or narrow alleys. However, the motorcycle can only play a role in the early stage of a fire due to a minimal capacity for water storage and equipment. The extendable hose racks save the time of pulling hoses for a long distance. As shown in Figure 2.2, it can be deployed on first-response trucks in narrow alley area for timely uses.

The application of small fire vehicles and innovative equipment improves the efficiency of fire service by enhancing mobility in narrow alleys and simplifying the procedure of establishing water supply. However, it is necessary to recruit more personnel and conduct a more specialized training program to implement proper applications.

Besides, fire crew must also strengthen their tactics in narrow alleys. The fire station should list the narrow alleys in their responsible area, and draw up their firefighting strategy based on the spatial and environmental characteristics. Also, training of vertical mobility (ladder rescue technique) and horizontal mobility (hose line establishment) are necessary.

As for studies in firefighting strategy, 黃鼎彥(2012) investigated the road environment in historical streets in Tainan and formulated guidelines for the deployment of firefighting units considering routes of fire vehicles. Then, 黃鼎彥(2012) proposed the general fire preventing plan in historic streets, monuments and buildings. 張書鳴(2014) explored the situation of narrow alley fire based on the present workforce of fire stations in a simulation exercise in Yingge District, New Taipei City. 張書鳴(2014) pointed out the practical difficulties of fire service in narrow alleys and listed the potential risk table of narrow alleys. In Japanese research, Sasaki and Sekizawa (2014) proposed a

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simulation model considering fire risk, firefighting operation, and fire spread prediction to evaluate the efficiency of firefighting in multiple simultaneous conflagrations caused by massive earthquakes in communities with narrow alleys.

After introducing the first three improvements for promoting fire safety, the next subsection discusses the last improvement approaches, which is ensuring firefighting access routes, from background, description, and situation.

2.1.7 Mitigation measures

Last but not least, as 林忠億、陳火炎(2009) have suggested, ensuring firefighting access routes is the primary measure to promote fire safety in narrow alleys. The Dasi Community fire has made central and local governments responded with policies and regulations about fire lanes. In this subsection, the policies and implementation regarding fire lane in Taipei City are taken for example.

In response to public concerns and instructions from the central government, the Taipei City Government executed the Fire Lane Width Project (整頓消防搶救困難地區消防通道淨寬專案計畫) since September 2003 to test the capability of alleys to provide passage of fire vehicles. After the project, the regulation of fire lane is made. According to the Procedures for Marking and Management of Fire Lane (消防通道劃設及管理作業程序, Taipei City Government, 2006), the standards for a fire lane are: (1) the only path to designated challenging area (火災搶救困難地區); (2) a road of less than 7.5 meters wide, while any building in the road is over 140 meters away from area which can be arrived by fire trucks with no obstruction (like intersection on major road). Figure 2.3 shows examples of fire lanes. Apart from the above standards, the road can also be marked as a fire lane if the village chief requests an application after obtaining consent from half

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of the residents on the road.

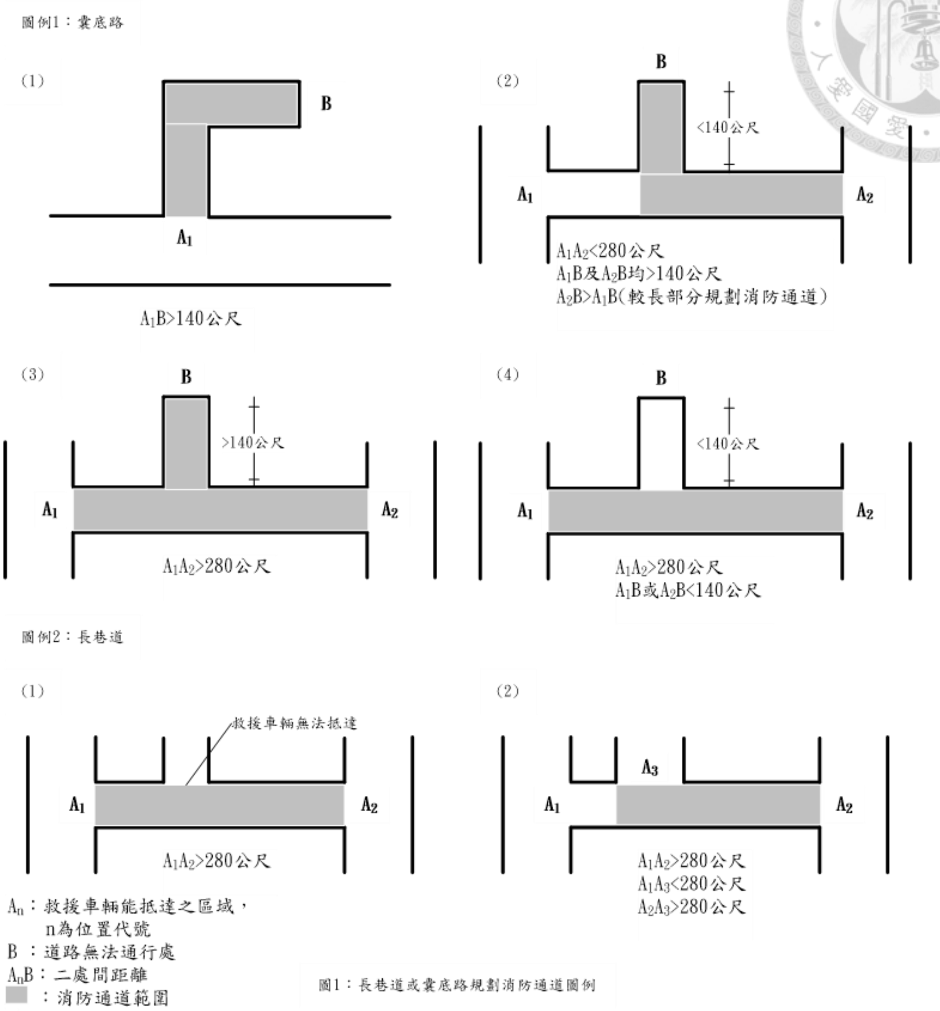

Figure 2.3 Examples of marking fire lanes.
The top four figures are examples of cul-de-sacs. The bottom two figures are examples of long alleys. The gray areas indicate the range of fire lanes. Reprinted from Procedures for Marking and Management of Fire Lane (Taipei City Government, 2006).

After the marking procedure of the fire lane is done, the parking ban and the maintenance will begin. The police stations, the traffic police corps, and the traffic inspectors are given priority to execution of parking ban for 24 hours by notification, towing and custody under the Road Traffic Management and Penalty Act (道路交通管理處罰條例) and Taipei City Police Department Regulations on Towing and Custody of Illegal Parked Vehicles (臺北市政府警察局管理違規停放車輛拖吊及保管作業規定).

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In principle, the fire lane should maintain an available width of 3.5 meters. Therefore, red lines or marking sidewalks are set on both sides of the roads for roads less than 5.5 meters, and one side for roads between 5.5 and 7.5 meters (消防通道劃設及管理作業程序, Taipei City Government, 2006). Accordingly, in the proposed method in Subsection 3.5, the objects of assessing the criticality based on passability assurance are assumed to be the alleys between 3.5 and 7.5 meters wide within the study area.

In previous research, 林忠億、陳火炎(2009) believed that setting fire lanes are an effective method to improve fire service accessibility, and survey from active firefighters supported this concept (趙森軒, 2012). Also, a fire lane satisfactory survey in the study of 曾東和(2009) revealed that fire lanes met the expectations and needs of the residents of the community in Xinyi District, Taipei, yet the enforcement of the parking ban was ineffective. By a firefighting training exercise in Daan District, Taipei, 李孟原(2018) demonstrated the delay in response time caused by illegal parking of narrow alley and suggested more powerful enforcement to ensure the passability of fire lanes.

Furthermore, the number of fire lanes may not be sufficient. According to the List of Fire Lane provided by the Taipei City Fire Department (Retrieved in December 2019), among the total 185 fire lanes in Taipei City, the number of lanes with marking reason “path to challenging area” is the most, with a total of 117, followed by "long alleys" of 25, "requests of community" of 23, and "long cul-de-sacs" of 20. We argue that the local government should promote the requests of the community as a means of marking fire lanes to protect fire safety.

On the other hand, the mean of alley widening has also drawn attention from local governments. Hsinchu City Government has implemented the “Alley Bottleneck Breakthrough Policy” (打通瓶頸巷道政策) in 2001. 葉蓉蓉(2010) conducted a case

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analysis of the alley widening policy in Hsinchu City with the methodology of policy networks analysis and civic engagement, which inspected how the interaction between stakeholders of the policy affects policy implementation. Afterward, New Taipei City Government has also proposed a similar policy since 2013, and so did Taoyuan City Government in 2016.

To investigate the achievement of study in firefighting and emergency response time of narrow alley fire, we review researches on the fire response time under the given road network and the locations of the fire stations. For the densely populated cities in Japanese, Kakuchi (2008) took the corner cut of the roadway as an improvement to ensure the turning radius of fire trucks and assess the reduction of the response time of fire service. 趙森軒(2012) explored the current situation of fire response in Banqiao District, New Taipei City, employed fire operational assessment and Delphi Method to assess the risk of narrow alleys, and suggested the improvement of fire accessibility to local governments.

However, to the best of our knowledge, the previous studies regarding narrow alley fire and network improvement are mostly focusing on case studies, expert interviews, or surveys. There is still a lack of study in network analysis and optimization methods considering spatial characteristics of fire risks, road network configuration, and the planning of emergency routing, especially in the road environment in Taiwan or other East Asian countries.

Therefore, this study seeks to establish an assessment method and optimization model on the issue of improving fire service accessibility to communities with narrow alleys. We focus on (1) marking fire lanes and (2) widening alleys as the solution to reduce the response time for fire service, and evaluate the criticality of alleys and determine the decision of widening narrow alleys.

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2.2 Fire Risk and Geoinformatics

This section explores the fire risks and their assessment methods, especially in spatial analysis. From the perspective of fire risk location, 黃崑鏜(1993) observed that the phenomenon of mix land-use and the densely built-up area in cities has resulted in a highly concentrated and mixed configuration of urban activities, and the fire risk is also concentrated in some regions of the cities. Based on the spatial analysis of historical fire data, 吳榮平(2007) distinguished specific locations with the highest fire risk in Taipei and demonstrated that the characteristics of space syntax also reflected the local fire risk pattern.

Before planning the environment of fire safety in the old urban communities, it is necessary to investigate the fire risks of the buildings within the case area. In related research, there are two types of factors usually considered to evaluate the fire risk/hazard of the area: (1) building characteristics and (2) socioeconomic characteristics.

As for building characteristics, Lo (1999) explored the fire safety environment and fire protection facilities of buildings in Hong Kong, and assess the fire risk of individual buildings using fuzzy logic and analytic hierarchy process. 蔣得心(2004) estimated the fire incidence of the building using historical fire data and building tax statement data, which includes building material, building utility, number of floors, and building age. 謝濠光(2013) estimated the casualties and property loss caused by the fire using demographic characteristics, building structure, and firefighting capabilities.

Socioeconomic characteristics are also essential factors in fire risk assessment. Jennings (1999) reviewed residential fire studies and examined the potential relationship between fire risk and socioeconomic characteristics. Although abandonment of house and urban dereliction considerably increases the fire risk in the context of U.S. cities, Jennings

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concluded with an emphasis on the importance of socioeconomic factors such as building stock, household demographics, and income, etc. As in another study in the United Kingdom, Chandler, Chapman, and Hollington (1984) explored the relationship between fires and socioeconomic factors, including house age, housing holding patterns, social class, ethnicity, and unemployment rate.

For spatial analysis as another approach to explore fire risk, 蕭大山(2003) employed spatial statistical analysis and geographic information systems (GIS) to estimate the damage of fires, then depicted the fire risk map of urban blocks in Kaohsiung City. 陳育瑛(2004) used GIS and multivariate analysis to explore the correlation between the site of the fire and land use and identified the potential threats to urban fires caused by land use and urban activities through discriminant analysis. Corcoran, Higgs, Brunsdon, Ware, and Norman (2007) also applied spatial analysis to examine the relationship between fire incidence and socioeconomic factors. 郭文田、邱榮振(2008) explored how different land use characteristics and related activity, physical spatial structures, and socioeconomic factors affect fire incidence based on the distribution of fire locations. Furthermore, 張學聖、李佳蓁、陳姿伶(2009) adopted a hierarchical linear model to explore the correlation between related factors and fire risks, combined with risk assessment analysis and drawn a fire risk map presented in GIS.

In consideration of the accessibility of the dataset, this study conducts a method proposed by 蔣得心(2004), which employed a dataset of building tax statements and considered building characteristics only. Note that the purpose of fire risk analysis in this study is only to obtain parameters in fire service demand. A more sophisticated model predicting fire risk leads to a more convincing result.

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2.3 Emergency Response and Network-based Methods

This section inspects the situation of network analysis from the perspective of emergency response, and seek to find the missing link between the network-based method and road improvement as a mitigation approach to safety. To explore the research of emergency vehicle response, the network-based methods and optimization models related to emergency vehicles are reviewed. However, to the best of our knowledge, there is no research about network design as a means of promoting emergency service. Then, we review from two research topics: (1) road network performance for disaster or emergency, and (2) network design problems for improving the efficiency in emergency response, to assess the two alley improvements respectively.

2.3.1 Decision-making in emergency vehicle response

The application of mathematical models to solve the decision-making problems in emergency services is widely adopted in previous studies. The review study by Bélanger, Ruiz, and Soriano (2018) investigated optimization models in emergency medical vehicles and classified the models into strategic, tactical, and operational/real-time based on classic decision-making levels. In these optimization models, the objectives are mostly set to maximizing covered demand by emergency service facilities or minimizing the operation cost with all demands satisfied.

The first widely explored problem is the static location problem of emergency vehicles. Toregas, Swain, ReVelle, and Bergman (1971) proposed the location set covering problem, which sought to minimize the number of vehicles such that all zones are reachable within a prescribed time or distance frame by at least one vehicle, that is,

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all locations of demand are adequately covered.

Later studies proposed multiple coverage problem, to minimize the number of vehicles to achieve complete coverage, while maximizing the number of multiple coverage at the demand location (Daskin and Stern, 1981; Eaton, Sanchez, Lantigua, and Morgan, 1986; Hogan and ReVelle, 1986; Gendreau, Laporte, and Semet, 1997; Su, Luo, and Huang, 2015). The stochastic model considered the random availability of the vehicle (Daskin, 1982; Bianchi and Church, 1988) and stochastic travel time (Daskin, 1984; Ingolfsson, Budge, and Erkut, 2008).

Multi-period and dynamic relocation problems consider the assignment of emergency vehicles (Repede and Bernardo,1994; Saydam, Rajagopalan, Sharer, and Lawrimore-Belanger, 2013). There are two kinds of dynamic models. The real-time relocation model is designed to make the best decisions for each online decision phase (Gendreau, Laporte, and Semet, 2001; Andersson and Värbrand, 2007), while the offline relocation model generates a set of relocation plans for all possible states before practicing (Gendreau, Laporte, and Semet, 2006; Maleki, Majlesinasab, and Sepehri, 2014).

In the above problems, the decisions of emergency vehicles focused on the location of facilities and assignment of vehicles, but few studies considered network design as an approach to improve the efficiency of emergency services. In addition, these problems take the coverage of demand as an indicator of accessibility. That is, demand is considered to be covered if its location is reachable within a given time or distance. However, few of the models in previous research seek to reduce response time as much as possible.

2.3.2 Network performance upon emergency response

In recent years, many studies have proposed the methods of assessing vulnerability

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and reliability of road networks in the event of large-scale disasters and disruptions or evaluating the impact of degradable network performance during link blockages.

The first studies on the vulnerability of transmission networks were conducted by Berdica (2002) and D'Este and Taylor (2003). Berdica (2002) defines “vulnerability” as “a susceptibility to incidents that can result in considerable reductions in road network serviceability,” where serviceability of a link/route/road network is interpreted as “the possibility to use that link/route/road network during a given period.”

Most researchers have modeled this type of hazard by removing a single element. Therefore, the criticality of a specific element is determined by the decrease in network functionality, which is due to the expected adverse event leading to the removal of the element. The more considerable criticality index value of an element, the more critical it is to network functionality (Taylor, Sekhar, and D'Este, 2006; Jenelius, Petersen, and Mattsson, 2006).

In previous analyses of network accessibility, the criticality of road sections is evaluated by accessibility indicators (Taylor et al., 2006; Knoop, Snelder, van Zuylen, and Hoogendoorn, 2012). Identifying critical links in the network to mitigate vulnerability (Chen, Yang, Kongsomsaksakul, and Lee, 2007) or prevent outages (Rupi, Bernardi, Rossi, and Danesi, 2015) is crucial in order to prioritize reconstruction of certain links after a catastrophic event (Sohn 2006). For instance, Rodríguez-Nuñez and García-Palomares (2014) systematically analyzed the accessibility impacts of disruption of each element (full scan approach) to obtain the variability of these impacts to determine the most critical element.

The first alley improvement, which is marking fire lane, is assessed by its criticality based on passability assurance. Different from other road network vulnerability studies related to disasters, where the employed indicator is used to evaluate network

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performance loss caused by the closure, this study describes criticality as the network-wide improvement efficiency of the strengthening decision on a single element.

2.3.3 Network design as a mitigation approach

The second improvement approach in this study is the widening of alleys, which is a mitigation measure in the way of network design. The network strengthening problem (NSP), which considers the strengthening decision of a stochastic disruption network, was first proposed by Peeta, Salman, Günneç, and Viswanath (2010). At the pre-disaster stage, a bunch of the road section is strengthened at a fixed expenditure to improves the survival probability after the disaster to minimize the expected shortest path distance of each O-D pair. The author proposed a heuristic method, which uses the knapsack problem to find a local optimal solution, and then applies sample average approximation to obtain the parameters in the objective function. The method was testified with a case study of the highway network in Istanbul.

In the Pre-disaster Transportation Network Preparation (PTNP) problem, Schichl and Sellmann (2015) conducted Constraint programming to generate scenarios of strengthening decisions, which can significantly limit the number of scenarios. Other than Peeta et al. (2010), Schichl and Sellmann (2015) did not consider scenarios and compute the shortest paths for each scenario, but directly calculated the corresponding survival probability of the shortest path, and bundled the scenario that leads to the same shortest paths. Wu, Sheldon, and Zilberstein (2016) defined the effect of road improvement as the random reduction of travel cost and transformed the problem into a network design problem. The problem was demonstrated the ability to solve large-scale instances with over 50 thousand links.

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There are many variations of the NSP. Miller-Hooks, Zhang, and Faturechi (2012) considered service-levels constraints in their model. Du and Peeta (2014) proposed a bi-level stochastic optimization model, in which link investment variables are continuous rather than binary to describe the different levels of strengthening. Chu and Chen (2016) modeled the problem to maximize the expected number of O-D pairs that would survive in all link failure scenarios. Yücel, Salman, and Arsik (2018) considered correlated link failure caused by the earthquake with a Bayesian network, while other studies assumed failure to be independent.

The alley widening problem, in this study, is one of the variations of NSP. In our model, the blockage of alleys is assumed to be independent between each other, and the operational state is defined as operational (passable) or nonoperational (blocked). For the solving algorithm, we refer to the method of Yücel et al. (2018), and generate all possible travel time scenarios from the fire station to the targeted alleys, then use the Monte Carlo method to evaluate the expected reduction of travel time based on alley widening plans. In the final stage, the knapsack problem is employed to solve the widening decision in the network.

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2.4 Summary

In Section 2.1, we review the definition of narrow alleys on fire service and inspect the practical difficulties encountered in narrow alley fire and examine its properties. We also discussed the alley improvement as a means to enhance fire safety but found the lack of quantitative and systematic assessment methods in previous research. Section 2.2 summarizes the method of spatial analysis of fire risks to implement the following background setting. Section 2.3 explores the issue of emergency vehicles, classifies existing models, and finds that no research has been done by network design at this stage. Then, the studies about the network performance evaluation method of the stochastic road network and the network design method for network strengthening are reviewed. Through the review of literature, we investigate the background, characteristic, and methods of narrow alleys fire, and used the obtained results as the prerequisite knowledge of methodology in Chapter 3.

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Chapter 3 Methodology

In this chapter, the methodology of determining and assessing of alley improvements is explained. For those alleys with sufficient width, we inspect their criticality based on passability assurance. Otherwise, for the narrow alleys which do not allow vehicles to pass through, an optimization model is proposed to determine the widening decision. To make it clear, the index employed as fire service accessibility in this study is the travel time from the fire station to the targeted demand unit.

Before the network analysis, there are three steps of data preparation and preprocessing. Firstly, in order to obtain the fire risk of alleys, the method of the fire risk map generated by the alley-based zoning technique using a Voronoi diagram is proposed. Secondly, a two-level network structure with stochastic alley blockage, which is tailored to the firefighting routing procedure in the alley network, is represented. Thirdly, the process of estimating expected travel time on the stochastic network is proposed. After the preprocessing, we provide the methodology of assessing two kinds of alley improvement, including marking fire lanes and widening.

In the part of alley passability assurance, we inspect every alley with sufficient width within the case area. The overall saving of expected travel time is evaluated to be the index of alley criticality under the assumption of probabilistic link blockage. Then, the ranking of every link by its criticality is determined.

As for alley widening, we propose a heuristic algorithm determining narrow alleys to be widened from the candidate set of impassable narrow alleys in order to maximize the saving of overall travel time, with a predefined budget of total widening cost.

The flow chart indicating the involving sections of the method (Figure 3.1) and the notation table (Table 3.1) are shown below.

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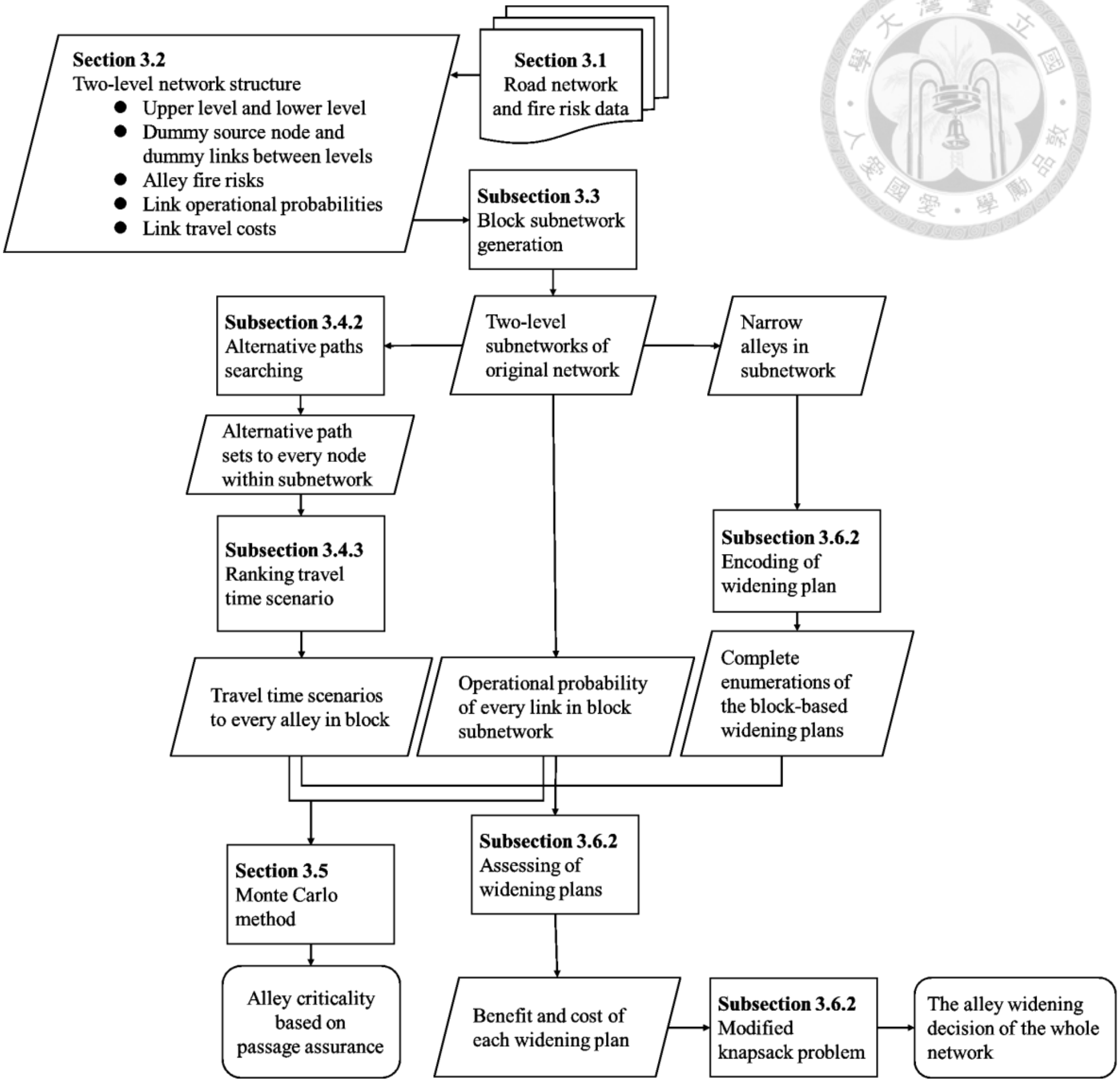

Figure 3.1 Flow chart of the methodology

Table 3.1 Notations.

Notations	**Definitions**
Indices:	
e	Index of links.
i, *j*	Index of nodes.
i'	Index of the counterpart of node *i* from another level.
b	Index of block subnetworks.
a	Index of narrow alleys.
l	Index of narrow alley widening plans.
Parameters:	

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r_e	Fire risk of alley $e \in E^l$.
c_{ij}	Travel cost of link $e_{ij} \in E$.
p_{ij}	Survival probability of link $e_{ij} \in E^u$.
$C_{i,max}$	Travel time of the shortest possible path π_i which only contains the dummy links and links on the lower-level network.
t_i	Travel time from source s to node $i \in N$.
q_a	Cost of widening narrow alley $a \in E^u{}_a$.
$\kappa(\boldsymbol{\omega}^{b,l})$	Cost of widening plan $\boldsymbol{\omega}^{b,l}$.
N	Size of sample set in Monte Carlo method.
Budget	Prescribed budegt of widening alley.

Objects:

s	The dummy source node. $s \in N$
G^{orig}	The original (single-level) network.
G	The two-level network.
G^u	The upper-level network. $G^u = (N^u, E^u)$.
G^l	The lower-level network. $G^l = (N^l, E^l)$.
e_{ij}	The link with two end $i, j \in N$. $e_{ij} \in E$.
G^b	The subnetwork of block b.
π_i	The path from source s to node $i \in N$.
$\pi_{i,k}$	The k-th shortest path from source s to node $i \in N$.
$ts_{e,k}$	The travel time scenario of k-th least travel time from source s to alley $e_{ij} \in E^l$.

Sets:

N^{orig}	Set of nodes in network G^{orig}.
E^{orig}	Set of links in network G^{orig}.
N	Set of nodes in network G.
E	Set of links in network G.
E_r	Set of roads in network G. $E_r \subseteq E$.
E_a	Set of wide-enough alleys in network G. $E_a \subseteq E$.
E_n	Set of narrow alleys in network G. $E_n \subseteq E$.
E_{dt}	Set of transition dummy links in network G. $E_{dt} \subseteq E$.
N_f	Set of fire station nodes in network G. $N_f \subseteq N$.
E_{da}	Set of assignment dummy links in network G. $E_{da} \subseteq E$.
P	Set of link survival probability in upper-level network G^u. $P = (p_{ij})$ for $e_{ij} \in E^u$.
B	Set of block subnetworks.

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$P^{imp}(\boldsymbol{\omega})$	Set of link survival probability P after the widening plan $\boldsymbol{\omega}$ is implemented.
Π_i	Set of alternative paths from source s to node $i \in N$. $\Pi_i = (\pi_{i,k})$.
$\mathbf{ts}_{ij}$	Set of travel time scenarios of from source s to alley $e_{ij} \in E^l$. $\mathbf{ts}_{ij} = (ts_{ij,k})$.
$\boldsymbol{\Omega}^b$	Set of widening plans in block b. $\boldsymbol{\Omega}^b=(\boldsymbol{\omega}^{b,i})$.
Variables:	
σ_{ij}	= 1, if the link e_{ij} is passable; = 0, otherwise.
$\boldsymbol{\sigma}$	A network realization of alleys $N^u{}_a$. $\boldsymbol{\sigma} = (\sigma_{ij})$ for $e_{ij} \in N^u{}_a$.
$\mu_i(\sigma)$	= 1, if the arriving mode at node $i \in N^l$ is by driving; = 0, otherwise.
$\tau_e(P)$	Expected travel time to alley $e \in E^l$ under the link survival probability P.
$EWRT(P^b, \mathbf{ts}^b)$	Expected weighted travel time of block b under link survival probability P^b and alley response time scenarios $\mathbf{ts}^b$ to every node in block b.
$IEWRT(P^b, \mathbf{ts}^b, e)$	Expected weighted travel time of block b under link survival probability P^b with passability of alley $e \in E^{b,n}$ assured, where alley response time scenarios $\mathbf{ts}^b$ to every node in block b are known.
ω_a	= 1, if the narrow alley $a \in N^u{}_a$ is widened; = 0, otherwise.
$\boldsymbol{\omega}$	Widening plan of alleys $N^u{}_a$. $\boldsymbol{\omega} = (\omega_{ij})$ for $e_{ij} \in N^u{}_n$.
$\boldsymbol{\omega}^*$	The optimal widening plan in network of alleys $N^u{}_n$.
$IEWRT(P^b, \mathbf{ts}^b, \boldsymbol{\omega}^{b,l})$	Expected weighted travel time of block b under link operational probability P^b with narrow alley widening plan $\boldsymbol{\omega}^{b,l}$ implemented, where alley response time scenarios $\mathbf{ts}^b$ to every node in block b are known.

3.1 Alley-based Fire Risk Map

The alley fire risk map illustrates the fire risk of alleys in the case area. In this study, the fire risk of every alley is considered as the background parameter for alley improvement assessment in Section 3.5, which computes the weighted travel time of a network. That is, the fire risk considered to be the quantified evaluation of urgency to be protected fire safety in the following model. This section describes the steps of evaluating

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the fire risk of an alley by the method of alley-based zoning technique. Note that the vulnerable facilities (like hospitals or care centers) and dangerous sites with flammable materials can be additionally given higher priority by setting a considerable weight or treating them exclusively depending on the context of the policy.

3.1.1 Fire risk for buildings

As we mentioned in Section 2.2, there is a variety of spatial analysis methods of urban fire distribution. In this study, we directly apply a previous study of 蔣得心(2004) about fire risk zoning based on urban blocks and employ the building fire risk chart to estimate the fire risk. In this method, building tax statement data is the basic unit of fire risk rather than the whole buildings. Due to the mixed land-use pattern of urban areas in Taiwan, it is not appropriate to signify the utility of a building with only one of its floors. A unit building tax statement is categorized by their fire risk factors, which include four features: building material, building utility, number of floors, and building age. After the data collection, the fire risk of each unit is determined by its category regarding the building fire risk chart.

a. <u>Establishment of fire risk factors</u>

The details of the four fire risk factors are described below.

i. Building material

In the fire investigation record data provided by the fire departments, the building materials are divided into steel construction (SC), reinforced concrete (RC), reinforced brick, wood, and iron sheet. Besides, in the building tax statement data, the building materials are divided into SC, RC, steel reinforced

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concrete (SRC), precast concrete, reinforced bricks, steel, wood, bricks, and bamboo. According to the literature review of the original research, SC, concrete, and reinforced bricks are non-combustible materials. Otherwise, steel, wood, and bricks are more flammable, so the study classifies them into the same category. Table 3.2 shows the categories of building materials.

Table 3.2 Categories of building materials

Categories defined by fire departments	Categories in this study	Categories in building tax statement data
Steel construction (SC)	*SC*	Steel construction (SC) Steel reinforced concrete (SRC)
Reinforced concrete (RC)	*RC*	Reinforced concrete (RC) Precast concrete
Reinforced brick	*B*	Reinforced brick
Wood Iron sheet	*W*	Wood Steel Bamboo

ii. The utility of the unit

The utility of the unit directly affects the activities and equipment in the building, further affecting the fire risk. This study classifies categories of utility into hotels (*U1*), entertainment venues (*U2*), shopping malls (*U3*), restaurants (*U4*), public places (*U5*), offices (*U6*), shops (*U7*), hospitals and clinics (*U8*), temples (*U9*), dwelling (*U10*), warehouses (*U11*), factories (*U12*), teaching places (*U13*), others (*U14*), and empty houses (*U15*).

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iii. Number of floors

The height of a building usually reflects its type and year of construction. Buildings of 1 to 2 stories are usually constructed by wooden or brick. Most of the buildings of 3 to 5 stories are apartments. For those buildings over six floors are residential buildings, department stores, multifunction building, etc. In addition, according to Article 227 of the Building Technical Code, those with a height of 50 meters or more than 16 floors are called high-rise buildings. This study classifies building floor heights into four categories: 1- or 2-story buildings (*H1*), 3- to 5-story buildings (*H2*), 6- to 15-story buildings (*H3*), buildings over 16 stories (*H4*).

iv. Age of building

The age of a building reflects the aging conditions of the building and its internal pipelines and other equipment. Moreover, the newer the age of a house, the higher the likelihood that it has been invested in fire-resistant design. According to the definition of the Regulations on the Improvement of Fire Evacuation Facilities and Fire Safety Equipment of Old Buildings, buildings constructed before 1984 are classified as old buildings. Following the definition, this study classifies the age of building into three categories: Buildings after 1999 (*A1*), buildings from 1984 to 1999 (*A2*), houses before 1984 (*A3*).

b. <u>Fire risk estimation method</u>

The estimation of the fire risk is based on each unit of building tax statement data. Based on historical fire data, the number of fires under the combination of four risk factors is calculated. Then, the fire incidence is evaluated by the number of fire divide by the

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total number of tax statement data which have an identical combination of risk factors, to estimate the building fire risk of the same type in the future.

$$R_{S,U,H,A} = M_{S,U,H,A} \ / \ N_{S,U,H,A} \tag{1}$$

Where $R_{S,U,H,A}$ is the fire incidence of the unit with the factor of S, U, H, and A, $M_{S,U,H,A}$ is the number of fires which have the factors of S, U, H, and A, and $N_{S,U,H,A}$ is the total number of the units that meet the characteristics of S, U, H, and A.

$S \in \{RC, SC, B, W\}$

$U \in \{U1, U2, \cdots, U14\}$

$H \in \{H1, H2, H3, H4\}$

$A \in \{A1, A2, A3\}$

In the following case analysis, the value of each $R_{S,U,H,A}$ is referred to the fire risk chart listed in the study of 蔣得心(2004).

3.1.2 Alley-based zoning mechanism

After the fire risk assessment of the building, we integrate the fire risk of buildings in the whole case area into their adjacent alleys. In our network, the individual buildings are not constructed because if all the buildings are constructed in the network, the scale of the network will significantly increase. Therefore, for computational convenience, this study integrates buildings fire risk into alleys by a spatial analysis method to be the parameter of fire service demand.

First, we obtain geographic information on the urban road network and the buildings and integrate them into the GIS platform. Next, we aggregate the fire risks of buildings

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with a *Voronoi diagram*, where the details are described below:

i. Generating a Voronoi diagram

Voronoi diagram, also known as Thiessen polygon and Dirichlet tessellation (Aurenhammer and Klein, 2000), is a partition of a plane that divides a plane into several subsets (*Voronoi cells*), which surrounds each of the given set of objects (*site* or *seed*). The Voronoi cell is the space in which any point is closer to its corresponding site than any other site. The site of a cell is not only limited to points but may also be line segments, polygons, or other elements on the plane.

In a Voronoi diagram generated the road network, a cell indicates the covered area of a single road segment. As Figure 3.2, we distinguish the zone of alleys by the Voronoi diagram of the road network, which takes the links as its sites.

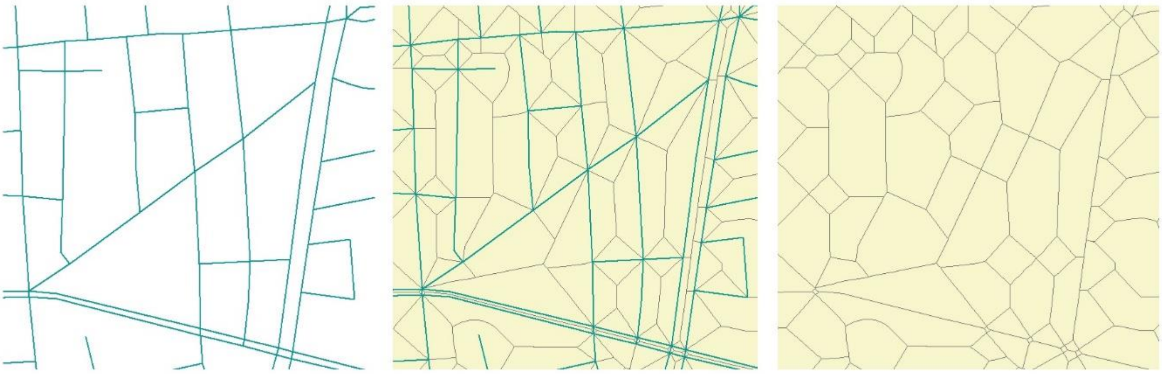

Figure 3.2 Generating a Voronoi diagram.
Left: The road network. Middle: The road network with the Voronoi diagram. Right: The Voronoi diagram.

ii. Summing up risk value for each alley-based zone

With the Voronoi diagram, we directly determine the covered buildings of each alley with its cell (Figure 3.3). After all the covered buildings of the alley have been confirmed, the risks of all buildings can be summed up and eventually become the risk value of a single alley.

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Figure 3.3 The Voronoi cell determines the covering alley of a building.
Line segments represent roads on the network; polygons represent Voronoi cells stemmed from links; points represent buildings.

3.2 Network Construction

In this study, we represent the road network system by a directed network. First, we examine the assumptions and considerations of the fire service in the urban road network, which includes narrow alleys. Then, we proposed a two-level network structure such that every possible path follows the operational constraints. Last, we define the stochasticity of the road network and clarify its characteristics in order to simulate the nature of alley blockage result from illegal parking.

3.2.1 Assumptions and considerations

In the operation of firefighting, firefighters face obstruction if they encounter a narrow alley or be blocked by a car or other obstruction. The assumptions based on the firefighting operation patterns are listed in the subsection.

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When a firefighting crew is blocked by a narrow alley or other obstruction on the route to the fire scene, there are two possible choices. One is to make a detour, and the other is to get off the fire engine and manually pull the hose line by foot to arrive at the fire scene. As mentioned in Subsection 2.1.5, 李孟原(2018) summarized that when the fire truck is blocked, the first choice for the fire crew is to get close to the scene of the fire, and the second is to pull hose over a long distance.

To construct the network structure, we consider the situation above and make the assumptions below:

<u>Assumption 1.</u> Fire service demand is integrated into the unit of alleys

As we mentioned in Subsection 3.1.2, in our network, the individual buildings are not constructed because if all the buildings are constructed in the network, the scale of the network will significantly increase. Therefore, for computational convenience, this study integrates buildings fire risk into alleys by a spatial analysis method to be the parameter of fire service demand.

<u>Assumption 2.</u> There are two modes of passage in a firefighting path.

On the route of firefighting, the priority is to drive the fire engine, and the second is to get off the vehicle and pull the hose line to get close to the fire. The proposed network structure in Subsection 3.2.2 distinguishes two different modes of passage.

<u>Assumption 3.</u> Travel time is considered as the only indicator of fire service accessibility.

The study only considers the travel time to evaluate the efficiency of the fire service. Thus, the combat and reinforcement of firefighting are not under consideration. In terms of reducing response time, the differences in equipment and capabilities between fire stations are ignorable. Also, water supply and transport are not considered in the proposed method.

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Assumption 4. The travel time cost of a roadway is a fixed constant value.

The travel time costs of a road segment by the two modes are predetermined fixed constants, respectively. That is, the cost of travel time is not traffic-dependent nor time-dependent.

Assumption 5. The blockage of the alley is stochastic.

In order to describe the nature of illegal parking on the alley, we define that the *operational state* of an alley can be either *passable* (operational) and *blocked* (non-operational), which implies the *passability* of vehicles. Here, we define that the operational state of an alley only is dependent on any other neighboring alley. The characteristic of stochastic link blockage is detailed in Subsection 3.2.3.

Assumption 6. Routing is based on the full knowledge of alley blockage.

To simplify the computation procedure and to focus on supporting the decision-making in the step of planning, the estimation of travel time in a stochastic network realization is based on the full knowledge of the operational state of every alley. That is, the fire crew always choose the optimal path to avoid blockage if they can get the fire scene faster.

3.2.2 Two-level network structure

Following the assumptions described in Subsection 3.2.1, We apply a two-level network structure, which divides a road network into two levels due to distinguish the two different modes, to follow Assumption 2 and describe the environment of firefighting in a road network with narrow alleys. In the previous studies, the multi-level network structure is effectively employed to improve the efficiency of large-scale shortest path problems (Shapiro Waxman, and Nir, 1992; Fu, Sun, and Rilett, 2006). However, its

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hierarchical topology is also suitable for the framework of the narrow alley firefighting routing in this study. The multi-level network in the routing problem is further discussed in the review by Fu et al. (2006). In the proposed method, the two-level structure is constructed to distinguish the two different methods of passage in firefighting.

The original urban road network is introduced first. The original network is a directed graph $G^{orig} = (N^{orig}, E^{orig})$ with link set E^{orig} and node set N^{orig}. The roadways in link set E^{orig} is composed of wide enough *roads* E_r, *alleys* E_a, and *narrow alleys* E_n, with alley fire risk value r_a for alley $a \in E_a \cup E_n$. The node set N^{orig} consists of all intersections of roadways and fire stations N_f in this area. Stemmed from the original network, in the two-level network structure $G = (N, E)$ consist of two levels, where upper-level network $G^u = (N^u, E^u)$ stands for road network of driving vehicles, and lower-level network $G^l = (N^l, E^l)$ stands for road network of pulling hose by foot.

The two links e_{ij}, $e_{i'j'} \in E$ indicating the geographically identical passage of two different modes, where the i' and j' indicate the counterpart of $i, j \in N$ from another level. Note that we do not use the prime mark (') to identify the lower- or upper-level in the following articles. The two links have different travel time costs c_{ij}, $c_{i'j'}$, while the upper-level one has the lesser travel cost due to the faster travel mode.

To connect two levels, we construct a *transition dummy link* $e_{ii'} \in E_{dt}$ from each node i in the upper-level network to its lower-level counterpart i'. This dummy link $e_{ii'}$ represents the transition of the passage mode. Thus, if a path consists of a transition dummy link, it implies that the fire crew gets off the vehicle in the firefighting route. Here, we set the travel cost of transition dummy links as 0.

The *dummy source node* s connecting all the fire station nodes N^u_f on the upper level is the origin of the fire service. According to Subsection 3.1.1, there is no distinction between fire stations. The dummy source node represents the fire control center, and the

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assignment dummy link E_{da} from the dummy source node to a fire station node represents the assigning process of a fire crew from the neighboring fire station when a fire breaks out. Similarly, we set the cost assignment dummy link to 0. The establishment of the dummy source node makes the routing problem in this network to be a single-source pathfinding problem. Figure 3.4 depicts the elements and configuration of the proposed network structure.

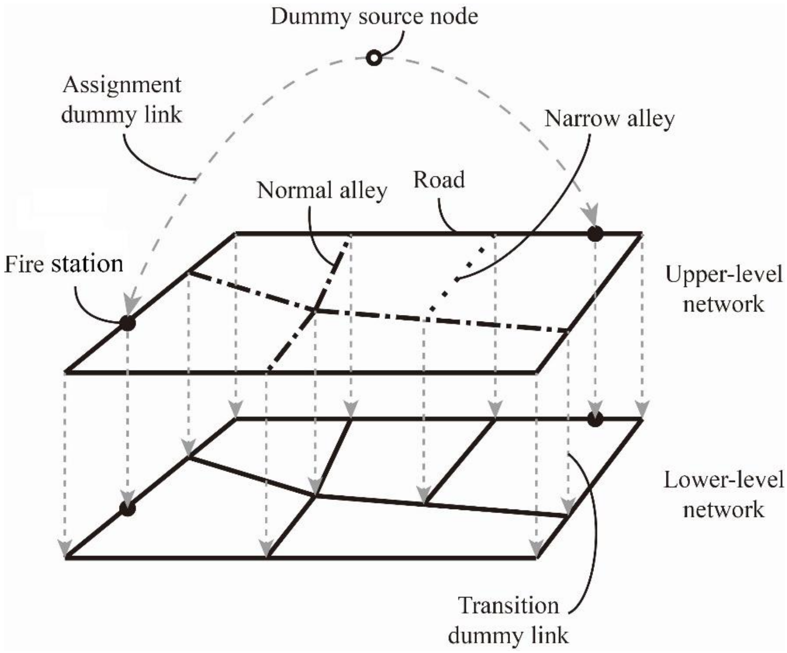

Figure 3.4 The two-level network structure.

It is necessary to clarify that the locations of the building are not constructed as elements in the proposed network. As mentioned in Subsection 3.1.2, the reason is that if all the buildings in the area are included in the network as components, the scale of the network will significantly increase. For the consideration of the network scale and convenience of the analysis, we consider alleys in the lower-level network $E^l_a \cup E^l_n$ as the target of firefighting operations (Figure 3.5). The procedure of estimating travel time to the targeted alley is described later in Section 3.4. To make it practicable, a *firefighting path* is introduced to be the key concept in the procedure. A firefighting path π_i is a journey

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from the fire station toward a node $i \in N$ in a firefighting operation, where a *path*, by the definition of graph theory, is a finite or infinite sequence of links that joins a sequence of nodes in which all links are distinct. With the two firefighting paths π_i, π_j to the two ends of the targeted alley $e_{ij} \in E^l_a \cup E^l_n$, the travel time to the destination, alley e_{ij}, can be determined using the procedure in Section 3.4.

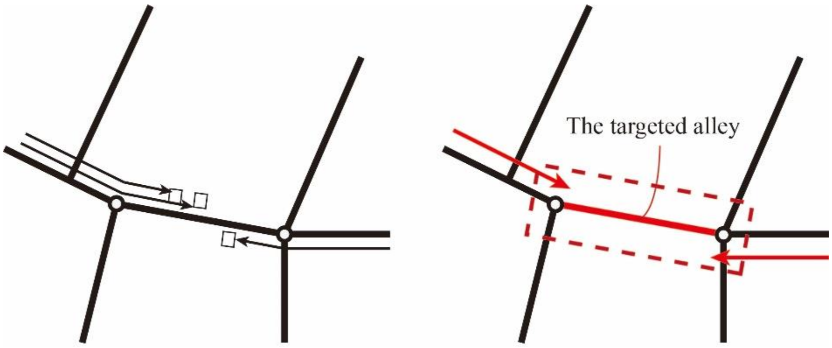

Figure 3.5 Demand for firefighting operation is considered in the unit of the alley.

In the proposed network structure, the firefighting path is always valid, where the impossible paths are prevented that firefighters get off once and get on from another place because there is no link from lower to the upper-level network (see Figure 3.6).

In summary, this two-level network $G = (N, E) = (N^u \cup N^l \cup s, E^u \cup E^l \cup E_{dt} \cup E_{da})$ is composed of an upper-level network $G^u = (N^u, E^u)$, a lower-level network $G^l = (N^l, E^l)$, the dummy source node s, transition dummy links E_{dt}, and assignment dummy links E_{da}. The dummy elements in the network are constructed to implement the function, such that any path on the network follows the assumption of firefighting described in Section 3.2.1. Also, the lower-level alleys $E^l_a \cup E^l_n$ are the basic unit of fire service demand in the model. In the next subsection, the characteristic of link blockage on the upper-level alleys E^u is to be discussed.

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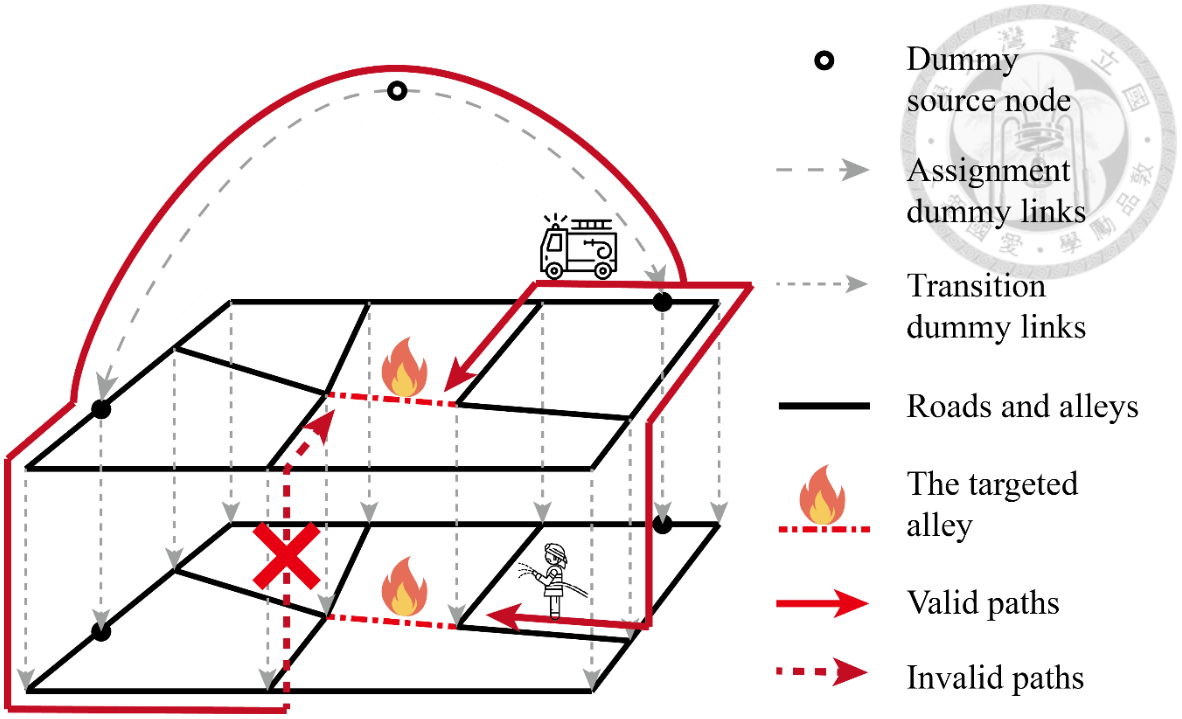

Figure 3.6 Firefighting paths.
The structure prevents the impossible path from the lower-level network to the upper-level one.

3.2.3 link blockage on the stochastic network

The operational state of links in this stochastic network can be either operational (*passable*) and nonoperational (*blocked*), showing its passability by vehicles. For each link on the upper network E^u, we let the operational state of the link follow a Bernoulli distribution, and the operational probability is given to be $P = (p_{ij})$ for any link $e_{ij} \in E^u$. Therefore, a stochastic network consists of the nodes N, the links E, and operational probabilities P of the links. That is, $G = (N, E, P)$. Also, we assume the independence between the states of any two links. That is, the state of a link does not affect the state of any other link.

In the proposed network structure, the links on lower-level network E^l and the dummy links $E_{dt} \cup E_{da}$ are assumed to be always passable. Otherwise, the links on the upper-level E^u are exposed to the incidence of blockage. The wide-enough roads $E^u{}_r$ are

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set to be always passable (p_{ij} = 1), while the narrow alleys $E^u{}_n$ are always blocked (p_{ij} = 0). For the rest of the alleys $E^u{}_a$, their operational probabilities, which vary between 0 to 1. Figure 3.7 is one of the settings of operational probability, which is determined by road width as the only factor. It should be clarified that in Figure 3.7 and the following analysis in Chapter 4, the settings of operational probability are not supported by any previous study and numerical evidence of actual alley blockage states in the study area. The following researchers are suggested to link the missing gap by proposing their models, which reflect the nature of blockage in urban residential areas.

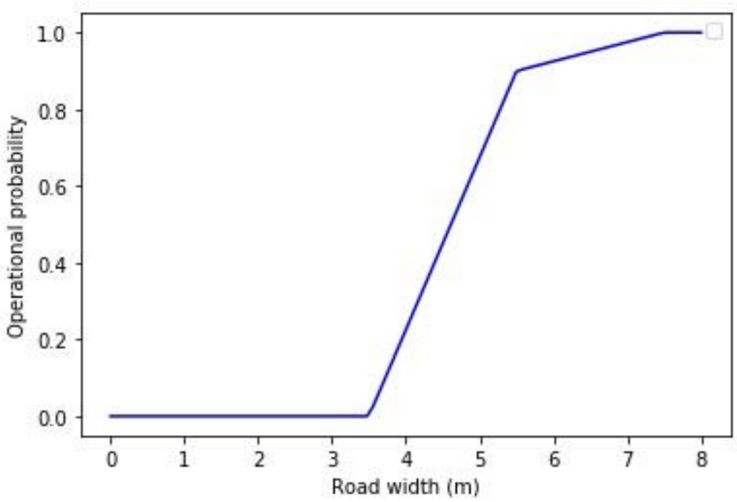

Figure 3.7 One of the setting of alley operational probability.

Here, we define the *network realization* as the operational state of every link in the network. As Figure 3.8 shows, for each observation, there is an independent network realization **σ** of the network G, where **σ** = (σ_{ij}) is a binary vector of size $|E^u|$, and σ_{ij} denotes the operational state of alley $e_{ij} \in E^u$. Following the probability distribution, the operational state of an alley varies in the different network realization. Moreover, the shortest path of an origin/destination pair is not always operational if any of the traveled links in the path fails in the realization. The path π_i *survives* in network realization **σ** if every alley along the path is passable, and *fail* if any one of the alleys along the path is

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blocked.

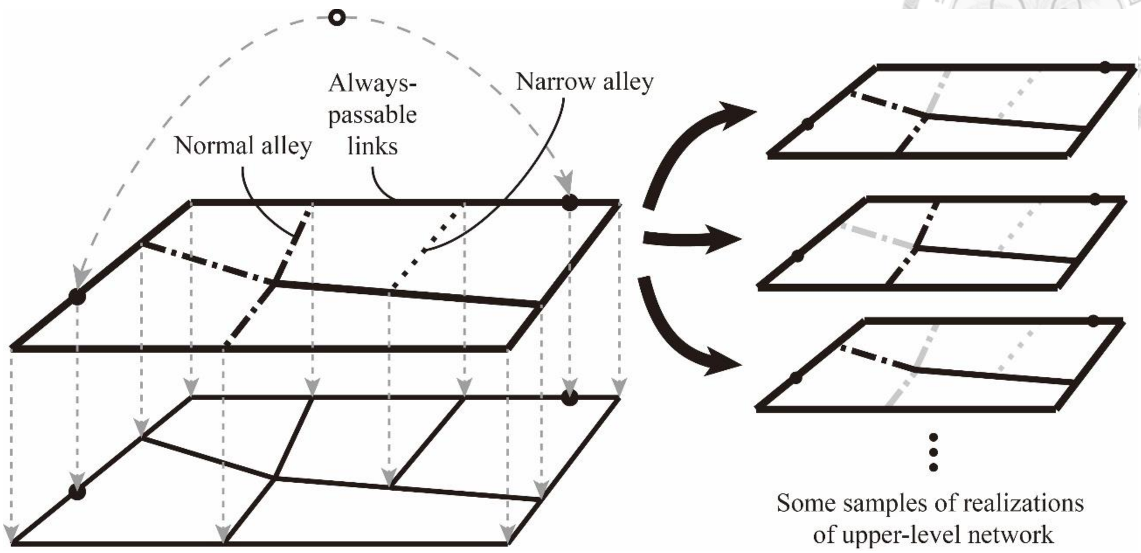

Figure 3.8 The stochastic network and network realizations.
Network realizations determine the operational state of links in the stochastic network with link blockage. In the right of the figure, some examples of realization are illustrated, where the black lines stand for passable links and gray lines represent the blocked links

3.3 Block Subnetwork Construction

In our network, the travel time is considered as an index of fire service accessibility. However, in the stochastic network with link blockage, the shortest path of an origin/destination pair is not always operational. In a real fire service operation, if the original path is blocked, the fire crew may choose another passable route. To estimate the expected travel time to the targeted alley, the alternative paths should be prepared beforehand under the circumstance of a stochastic path failure.

To complement the procedure described in Section 3.4, this section narrates the method of generating block subnetworks, which limit the searching space of finding alternative paths. In the situation of pathfinding on the road network, the searching space

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can be prune according to the road types (Liu, 1997). When firefighters are in the process of route finding, before they enter the block to go deep into alleys, they always go through the wide roads, which are always passable. In the process of finding alternative paths, there is no reason to consider routes detouring into other blocks rather than the shortest path to reach the boundary of the targeted block (Figure 3.9). Using the knowledge of routing, we separate the road network into block subnetworks with the wide roads $E^u{}_r$.

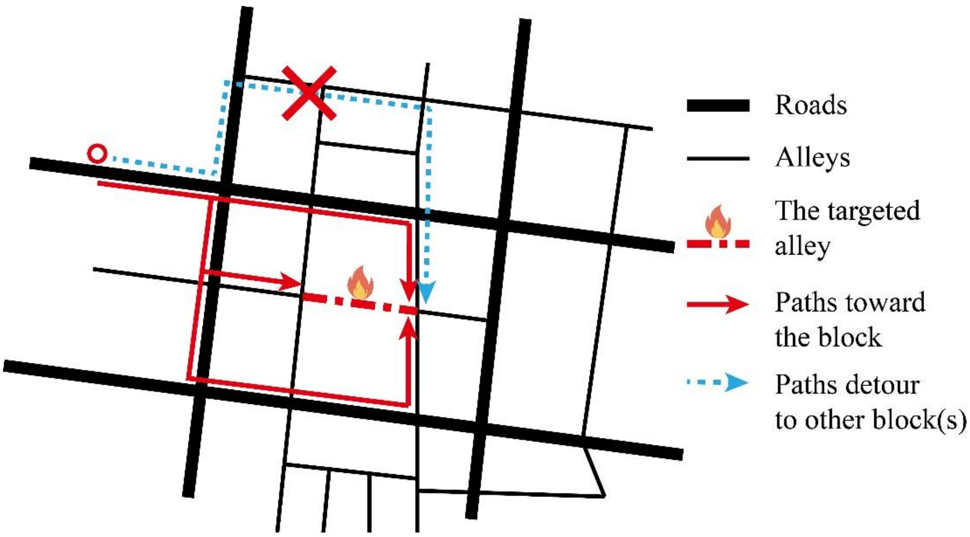

Figure 3.9 Routing on the network.
The searching space for finding alternative firefighting path can be limited to the block. Wide road represented by thick lines is always passable according to the network assumption, so the blue path detouring through another block is not considered in the routing algorithm rather than red paths going directly to the targeted block.

Thus, the block subnetwork limits the searching space of finding firefighting paths, thereby defines the boundary of the impact of an alley improvement approach. That is, the benefit of ensuring the passage of an alley will not improve the accessibility of anywhere from other nearby blocks because the involving paths to an alley from another block entirely lie in that block.

A graph traversal algorithm is employed to construct subnetwork G^b of each block b in the road network. A block in the following article represents a subnetwork consisting

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of connected links of alleys surrounded by roads in $E^u{}_r \cup E^l{}_r$.

Algorithm 1: Block subnetwork construction

Input: *G*, the original network
Output: **G** = (G^1, G^2, ...), all block subnetworks of *G*

```
function identifyBlock(link):
    Construct a subnetwork
    if both ends of link are on wide road then
        Add link, its lowerLink (counterpart of link in lower level)
            and its dummyLink_1, dummyLink_2 of two ends into subnetwork
        // end of subnetwork traversal
    else:
        Initialize queue
        Initialize visitedNodeSet
        Choose a currentNode from two ends of link which is not on wide road
        // a graph traversal algorithm begins
        loop:
            for each adjacentLink of currentNode do
                if adjacentLink is an alley and it is not in subnetwork then
                    Add adjacentLink into queue
                end if
                Add currentNode into visitedNodeSet
            end for
            while queue is not empty do
                Pop currentLink from queue
                Add currentLink, its lowerLink (counterpart of link in lower level)
                    and its dummyLink_1, dummyLink_2 of two ends
                    into subnetwork
                for each intersection of currentLink do
                    if (intersection is not on a wide road
                            and it is not in visitedNodeSet) then
                        newNode <- intersection
                        break while-loop
                    end if
                end for
            end while
            if there is no newNode then:
                // end of subnetwork traversal
                break loop
            end if
    end if
    return subnetwork

// main algorithm begins
E^{u,copy} <- a copy of E^u
b <- 0
while E^{u,copy} is not empty do
```


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Pop a link e from $E^{u,copy}$
if e is in E_a **then**
b += 1
// construct the subnetwork of the link
$G^b = (N^b, E^b, P^b)$ <- *identifyBlock*(e)
N^b_{ent} <- set of block entrance from wide road in the G^i
for each block entrance $j \in N^b_{ent}$ **do**
t_j <- the travel time of the shortest path
from source s to j through wide road only
e'_{sj} <- the link from source s to j with cost of t_j
Add e'_{sj} into G^b
end if
for each $e_l \in E^{b,u}$ **do**
Remove e^b_l from $E^{u,copy}$
end for
end if
end while
return G = (G^1, G^2, ...)

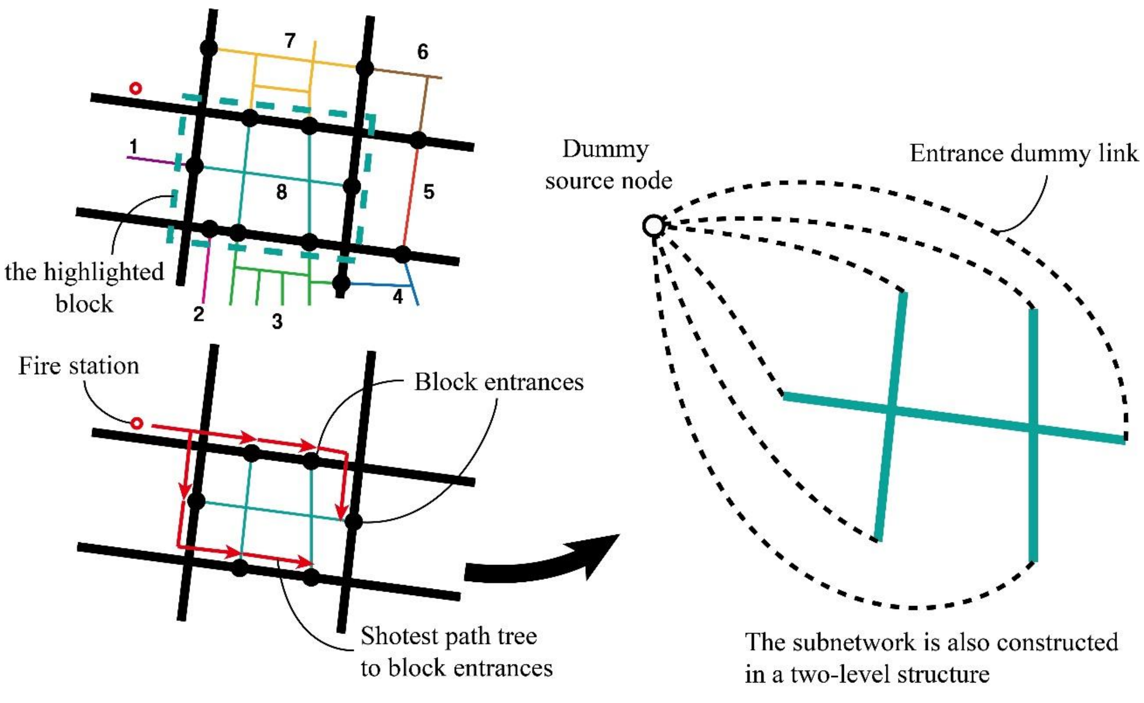

Figure 3.10 Block subnetwork construction.
The left top figure shows the division of blocks on the network, with the central block highlighted. The left bottom figure depicts the shortest path tree through a wide road to every *block entrance*. The right figure displays the subnetwork of the highlighted block, where the costs of entrance dummy links are determined with the shortest path tree in the left bottom figure. Note that the subnetwork is constructed in a two-level structure as Subnetwork 3.2.2 has described.

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The above algorithm searched all of the block subnetworks. Figure 3.10 illustrates a block subnetwork, including a two-level alley network, a dummy source node, and *entrance dummy links* connecting from the dummy source node s to the *block entrances* of the alley network. *Block entrances* stand for the nodes for vehicles to get into blocks. The cost of an entrance dummy link e_{si} of an entrance i is determined as the cost of the shortest path from the source s to the entrance i of along roads. This design ensures that the travel cost of arriving at the entrance is no different from the original shortest path cost. Then, the routing process can be implemented on the subnetwork of each targeted alley. After constructing block subnetwork, we define the set of blocks B where $G^b = (N^b, E^b, P^b)$ is the subnetwork of block $b \in B$.

3.4 Expected Travel Time Estimation

the index of fire service accessibility in this study is the expected value of travel time to the targeted alley on the network with stochastic alley blockage. As for evaluating the travel time on a stochastic network, there are previous studies (Mirchandani, 1976; Jaillet, 1992; Fu and Rilett, 1998; Chen, Lam, Sumalee, and Li, 2012), which inspected a variety of stochastic characteristics in networks and derived computing algorithms of shortest path or least travel time. To estimate the expected travel time, we refer to the path-based approach of Yücel et al. (2018). In our method, for each alley, alternative shortest paths to the two ends of the alley are prepared to cope with every possible network realization. Then, a ranking of the *travel time scenario* of alley based on the alternative paths is generated. Last, the Monte Carlo method of network realization sampling is to evaluate the expected value of travel time. The flow chart of the estimation process is shown in Figure 3.11.

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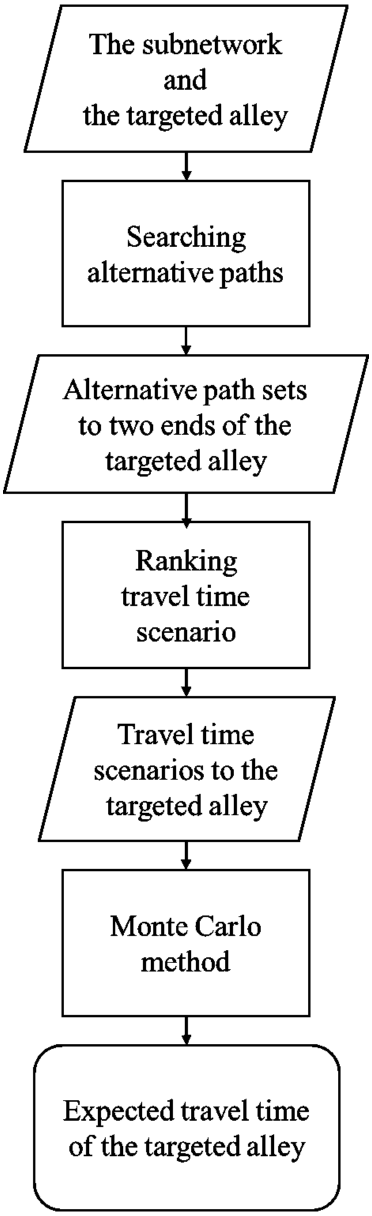

Figure 3.11 Flow chart of the step of estimating expected travel time.

3.4.1 Estimation of average travel time to the targeted alley

According to Assumption 1, the demand for fire service is integrated into the unit of alleys. Thus, the alleys are assumed to be destinations of firefighting routing. This subsection illustrates the method of computing the average travel time from source to the targeted alley using the shortest survived paths and arrival time to the two ends of the

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alley, where the survived paths are predetermined based on a specific network realization.

Under the network realization $\boldsymbol{\sigma}$, assume that we already know the shortest survived paths $\pi_i(\boldsymbol{\sigma})$, $\pi_j(\boldsymbol{\sigma})$, their elapsed time $t_i(\boldsymbol{\sigma})$, $t_j(\boldsymbol{\sigma})$ from fire station to the two end i, j of the lower-level alley $e_{ij} \in E^l$, and the passability σ_{ij} of alley e_{ij}. With the above knowledge, the alley average travel time $t_{ij}(\boldsymbol{\sigma})$ of getting into an alley can be computed.

We notice that there are also two modes of getting into an alley with respective moving velocity. The mode of getting into the alley is determined by the mode of arriving at the end, and the passability of the alley. That is, if firefighters arrive at the alley by foot or the alley is blocked, they have to go into the alley on foot. The arriving mode $\mu_i(\boldsymbol{\sigma})$, $\mu_j(\boldsymbol{\sigma})$ of each end i, j of alley e_{ij} can be determined by paths $\pi_i(\boldsymbol{\sigma})$, $\pi_j(\boldsymbol{\sigma})$.

The mode of arriving at node $i \in N^l$ can be determined by the path to the π_i. If the last link in the path π_i is the dummy link $e_{i'i}$, where i' denotes the upper-level counterpart of i, then the links prior to $e_{i'i}$ in π_i are links from the upper level. That is, the destination is arrived by driving the vehicle.

The concept of computing average travel time along an alley can be explained in Figure 3.12. The paths $\pi_i(\boldsymbol{\sigma})$, $\pi_j(\boldsymbol{\sigma})$ to the two ends a, b and their elapsed time t_a, t_b are known (Figure 3.12.(a)). However, the time to get deep into the alley has not been evaluated. To compute the consuming time in the alley, the time-space diagram is illustrated as Figure 3.12.(b), where the solid arrows stand for the trajectories of vehicle driving and the dashed arrows stand for the trajectories of pulling hose lines, which imply the arrival time at the position by the two modes. Using the gray area surrounded by axes and trajectories in Figure 3.12.(b), as Figure 3.12.(c) shows, the average travel time t_{ab} of the alley e_{ab} can be further computed as the gray area divided by the length of the alley e_{ab}.

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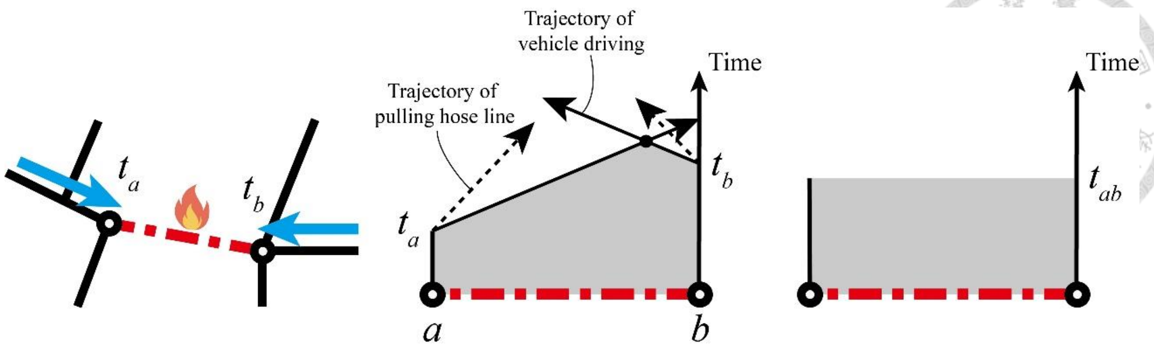

(a) (b) (c)

Figure 3.12 The concept of computing average travel time along an alley.

Then, the three cases of the arrival time of the two ends *a*, *b* are discussed. Let us assume that, based on the subnetwork realization, for an alley e_{ab}, the less arriving time among the two ends is t_n, and the more arriving time among the two ends is t_f, and then the alley becomes e_{nf}. With the mode of passage from node *n* and the operational state σ_{nf}, the time to cross the alley e_{nf} from the nearer end *n* is $t(e_{nf}, \mu_n, \sigma_{nf})$. Figure 3.13 depicts time-space diagrams of some travel time scenarios to support the following discussion. There are three cases of arriving time of two ends:

Case 1 $t_n + t(e_{nf}, \mu_n, \sigma_{nf}) = t_f$

In this case, the reason that the left-hand side equals the right-hand side is that the path to the farther end *f* contains the alley e_{nf} and the nearer end *n*. Hence, the alley average travel time t_{nf} can be computed as $(t_n + t_f)/2$, which is equal to the gray area divided by the length of the alley, as Figure 3.13.(a) shows.

Case 2 $t_n + t(e_{nf}, \mu_n, \sigma_{nf}) > t_f$

In this case, the path of arriving the farther end *f* does not contain the alley

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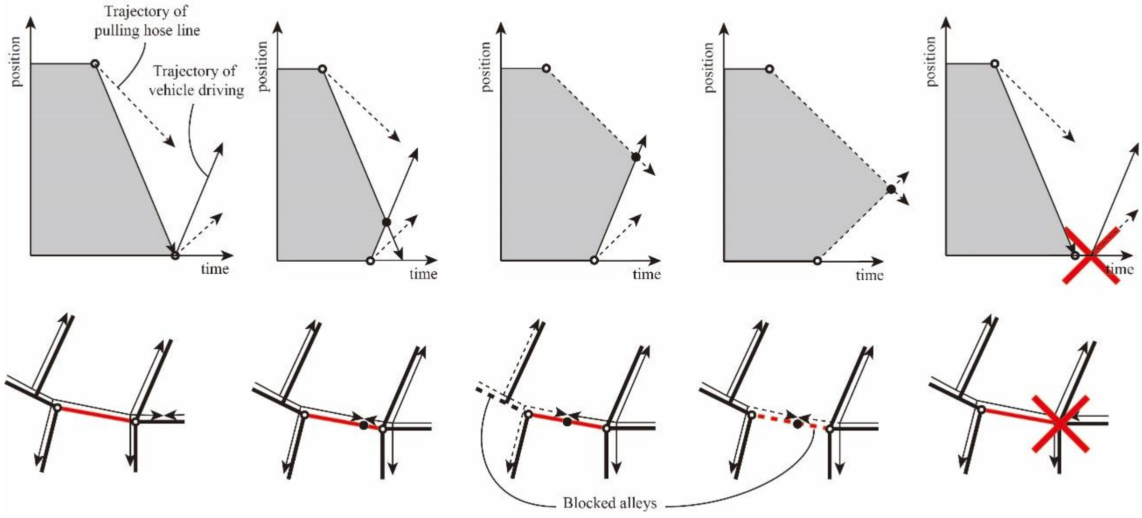
and the nearer end, but from another alley. First, the mode of getting into the alley is determined by the mode of arriving at two intersections and the operational state of the alley. Then, the average travel time t_{nf}, as the time-space diagrams shown in Figure 3.13.(b)-(d), is the gray area A surrounded by the axes and the two trajectories divided by the length of the alley.

Case 3 $t_n + t(e_{nf}, \mu_n, \sigma_{nf}) < t_f$

In this case, as Figure 3.13.(e) illustrates, the statement is impossible.

Proposition Case 3 cannot happen in any situation.

Proof. By definition, t_f is the least required time to arrive at node f. However, one can arrive at node f in $t_n + t(e_{nf}, \mu_n, \sigma_{nf})$ smaller than t_f, which leads to the contradiction. Hence, the proposition is true. ■



(a) (b) (c) (d) (e)

Figure 3.13 Five travel time scenarios and their time-space diagrams.
In these figures, the upper part shows the time-space diagram and the lower part depicts the network and the paths of firefighting, where the red line stands for the targeted alley. Figure (a) shows Case 1 and Figure (b), (c) and (d) narrate Case 2 under different block realizations. Figure (e) stands for Case 3, which is an impossible situation.

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Here, we define the *travel time scenario* to refer to the state of travel time derived from (1) the paths and travel time to the two ends of the targeted alley and (2) the passability of the targeted alley itself. The travel time scenario $ts_{ij,k}$ to the targeted alley e_{ij} survives if every alley involved in the scenario is passable under the network realization, implying the travel time to the alley e_{ij} is no more than $t_{ij,k}$, the k-th least travel time among all scenarios. The ranking of travel time scenarios is generated in Subsection 3.4.3.

The reason we generate the travel time scenario is that, with all scenarios enumerated, the travel time in a network realization can be determined by only using operational states of alleys rather than doing a complete routing. It is valid for saving computation effort in the Monte Carlo method in Subsection 3.4.4.

3.4.2 Algorithm for searching alternative paths

In the last subsection, the time travel scenario of a targeted alley is defined to describe the situation deriving a specific value of travel time based on the paths and travel time to the two ends of the alley. In this subsection, before the ranking of all possible scenarios in Subsection 3.4.3, the preparation of alternative paths to the two ends of the alley is implemented to enumerated all possible scenarios.

This study applies the k shortest path problem to the alternative path searching method. The k shortest path problem is a widely explored problem of pathfinding where the two main variations include loopy (Eppstein, 1998) and loopless (Yen, 1971; Hershberger, Maxel, and Suri, 2007). A loopy path indicates that the path may go through a node twice or more. To compute the travel time in this study, it is meaningless to find a path with a loop. Therefore, we consider the problem as a k shortest loopless path problem. In this study, we implement Yen's algorithm (1971), which is the most competitive

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algorithm in k shortest loopless path problem (Hershberger et al., 2007).

After the construction of subnetwork by Algorithm 1, the Yen's algorithm is employed to generate the set of alternative paths within the subnetwork. The only thing we have modified from the original Yen's algorithm is the stopping criteria that the algorithm stops when the total number of shortest paths found has reached the given value *K*. On the contrary, in our alternative shortest pathfinding process, the constraint is constructed rather than a stopping criterion, which is set to be an upper limit of cost $T_{i,max}$ of finding alternative paths to the destination node *i*. The upper limit value $T_{i,max}$ is determined as the travel time of the shortest path among all of the paths to *i* which only traverse the dummy links and lower-level network. That is, $T_{i,max}$ is the least possible travel time if the fire crew does not drive the fire engine after entering the block.
In other words, the path found in the algorithm will be abandoned if its travel time cost is more than any full walking path of the block. This approach implies that, in the proposed algorithm, the last found path is ensured to be always operational under any possible network realization because the full walking path is assumed to be always passable.

The alternative path set from source *s* to a node *i* is obtained by Algorithm 2. The set of alternative paths to node *i* is denoted by $\Pi_i = (\pi_{i,k})$, where $\pi_{i,k}$ represents the *k*-th shortest path of Π_i.

Algorithm 2: Alternative paths searching

Input: $G^b = (N^b, E^b, P^b)$, the block subnetworks;
Output: Π_i for $i \in N^{b,l}$, the set of alternative paths to every node

for $i \in N^{b,l}$ **do**
    $C_{i,max}$ <- the travel time of the shortest path which only contains
        the dummy links and links on the lower-level network
    Π_i < - set of alternative paths by Yen's algorithm with the cost limit $C_{i,max}$
end for
return Π_i for $i \in N^{b,l}$

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3.4.3 Ranking of travel time scenarios

As Subsection 3.3.1 has mentioned, the travel time to the targeted alley is determined with firefighting paths toward both two ends, rather than one of them. Then, we define the survival of the travel time scenario, which implies the lower limit of passable travel time. By obtaining the set of alternative paths Π_i, Π_j for the arriving the two intersections i, j of alley $e_{ij} \in E^l$ (Subsection 3.4.2) and computing method of the average alley travel time $t_{ij}(\boldsymbol{\sigma})$ (Subsection 3.4.1), we can sort all possible travel time scenarios $\mathbf{ts}_{ij}$. With a ranking of the travel time scenarios $\mathbf{ts}_{ij}$, the least travel time under the subnetwork realization can be obtained by eliminating the failed scenarios to find the best one.

Using the network realization, which shows the operational states of all links in the road network, the best travel time scenario can be determined with the travel time scenario ranking by eliminating failed scenario.

Algorithm 3: Travel time scenario ranking

input: $e_{ij} \in E^l$; Π_i; Π_j
output: $\mathbf{ts}_{ij}$, travel time scenarios to the targeted alley e_{ij},

$e_{i'j'}$ <- counterpart of alley e_{ij} from upper-level network
Initialize *scenarioRanking*
for each $\pi_{i,p}$ in Π_i **do**
    for each $\pi_{j,q}$ in Π_j **do**
        if $\pi_{i,p}$ and $\pi_{j,q}$ do not violate Case 3 **then**
            // two possible situations of the alley: passable or blocked
            for each e in ($e_{i'j'}$, e_{ij}) **do**
                t_{ij} <- travel time using $\pi_{i,p}$, $\pi_{j,q}$, and e
                A <- all of the alleys used (including e)
                Add (t_{ij}, A) into *scenarioRanking*
            end for
        end if
    end for
end for
$\mathbf{ts}_{ij}$ <- sort *scenarioRanking* by each t_{ij}
return $\mathbf{ts}_{ij}$

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3.4.4 Estimation of expected travel time

The expected value of the travel time to the targeted alley should be obtained because, on a stochastic road network, the shortest path cannot be determined in every network realization, such that the least travel time is not a fixed value accordingly. The analytical algorithm of expected travel time on the network with stochastic link blockage is proposed by Mirchandani (1976). However, the massive scale of the road network makes the problem intractable. Therefore, the Monte Carlo method is applied in this study to estimate the expected travel time.

Monte Carlo method is an algorithm based on a random sampling of huge sample space to estimate a numerical result for which the analytical expression is not available (Kalos and Whitlock, 2009). As we mentioned in Subsection 3.1.3, the prior operational probability $P = (p_{ij})$ for every link $e_{ij} \in E^u$ of is set to be given values. Hence, for the stochastic network, the estimation $\hat{\tau}_{ij}(P)$ of expected travel time $\tau_{ij}(P)$ to link e_{ij} can be obtained by computing the average travel time $\overline{t_{ij}}$ with a sufficient amount of sample set of network realizations and travel time scenarios $\mathbf{ts}_e$. The method of estimating expected travel time to the targeted alley is detailed in Algorithm 4.

Algorithm 4: Monte Carlo method

input: P; $\mathbf{ts}_{ij}$, the ranking of travel time scenarios to alley $e_{ij} \in E^l{}_a$
output: $\hat{\tau}_{ij}(P)$

function *sample*(*operationalProbability*):
    for each *linkProb* in *operationalProbability* **do**
        randomNumber <- a random number between 0 and 1
        if *randomNumber* is greater than *linkProb* **then**
            Mark *link* as failed
        else
            Mark *link* as survived
        end if

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end for
return marks of every *link* in *linkProb*

// main algorithm begins
$\overline{t_{ij}}$ <- 0
N <- number of iteration
for n = 1 to N **do**
$\boldsymbol{\sigma}^n$ <- *sample*(P)
for ($t_{ij,k}$, A_k) in $\mathbf{ts}_{ij}$ **do**
// there will be at least one scenario survived
if $\sigma^n_{ij} = 1$ for every $(i, j) \in A_k$ **then**
// the k-th scenario survives
$\overline{t_{ij}}$ += $t_{ij,k}$ / N
break for
end if
end for
end for
$\hat{\tau}_{ij}(P)$ <- $\overline{t_{ij}}$
return $\hat{\tau}_{ij}(P)$

3.5 Alley Criticality Based on Passability Assurance

In this section, a full network scan approach is used to evaluate the influence of passability assurance as a roadway improvement in each alley. In dense residential areas, the lanes and alleys beside the house are often parked by the car or motorcycle of residents. As described in Subsection 2.1.7, although the city government has already prohibited parking in the crucial alleys for fire service, it is still failed to prevent illegal parking completely. If the authority strengthens the enforcement of the parking ban and guarantees its passability, it improves the fire service accessibility of the alley and its adjacent area. Therefore, assessing the priority of alley passability assurance (1) helps policy units to manage policy and personnel for law enforcement, and (2) provides a suggestion for firefighting units to promote marking of fire lanes.

In this study, we consider the criticality based on alley passability assurance by the induced improvement in fire service accessibility for those alleys which have enough

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width for vehicles but are prone to be blocked by illegal parking. Other than the study of transportation network vulnerability focusing on degraded network performance, this study employs the concept of criticality to evaluate the improvement by upgrading network elements. Hence, the index of the criticality is evaluated as benefit from alley improvement.

Before evaluating the benefits of alley passability assurance, we first clarify the influence area of this improvement measure. As mentioned in the previous section, the searching range of any firefighting path can be limited to the block subnetwork of the targeted alley. Therefore, the benefits of improving an alley will only occur in the subnetwork. That is to say, the guaranteed passage of a certain alley will only benefit the area of the block without affecting the neighboring block.

Secondly, the benefit from ensuring the passability of an alley is estimated by improved network performance of its block subnetwork. In the firefighting issue, travel time can be considered as an indicator of fire accessibility. Accordingly, for a subnetwork $G^b = (N^b, E^b, P^b)$ of block $b \in B$, we define the network performance as $EWTT$ by evaluating the expected weighted sum of travel time τ_{ij} of link $e_{ij} \in E^{b,l}$ under operational probability $P^b = (p_{ij})$ for any link $e_{ij} \in E^{b,u}$, where the travel time τ_{ij} is estimated using Algorithm 4 with travel time scenarios $\mathbf{ts}^b{}_{ij}$ to every link in $e_{ij} \in E^{b,l}$. The weight r_{ij} is the alley fire risk value of alley $e_{ij} \in E^{b,l}$ to represent the urgency to be enhanced its fire safety.

$$EWTT\,(P^b, \mathbf{ts}^b) = \Sigma_{eij \in E^{b,l}}\, \tau_{ij}(P^b) r_{ij} \tag{2}$$

Lastly, the criticality of alley $e_{ij} \in E^u{}_a$ can be obtained by comparing the performance before and after the alley passability assurance using the network performance indicator $EWTT$. For an alley $e_{ij} \in E^{b,u}$ of a subnetwork G^b, the operational probabilities with passability assurance of alley e_{ij} is denoted by $P^{b,ij}$, where the operational probability p_{ij} = 1 of alley e_{ij}. Then, the improvement of network performance $IEWTT$ is calculated as

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Formula (3). After the full scan of the network, the priority of alley passability assurance can be determined by ranking the *IEWTT* of each alley within the whole study area.

$$IEWTT(P^b, \mathbf{ts}^b, e_{ij}) = EWTT(P^b, \mathbf{ts}^b) - EWTT(P^{b,ij}, \mathbf{ts}^b) \quad (3)$$

3.6 Widening of Narrow Alleys

In this section, an optimization model is employed to determine the alleys to be widened in the network to reduced overall travel time. In the dense residential area, the narrow alleys with insufficient width obstruct fire engines and endanger the fire safety. If a narrow alley can be widened so that a fire vehicle can pass through, the firefighting accessibility to the alley and the area will improve. However, for the high expense of road widening, the resource should be invested in the most critical place to achieve the most cost-effective results. The model provides a framework for alley widening to support decision-making in urban planning. First, the alley widening problem (AWP) is constructed. Then, a heuristic algorithm based on the knapsack problem is proposed to solve the AWP.

3.6.1 Problem formulation

For a narrow alley $a \in E^u_n$, the *widening* of narrow alley a produces its passability through increasing its operational probability p_a to 1 from the original value of zero. In the alley widening problem (AWP) formulated in Problem 1, the objective in (4) is to minimize the *EWTT* with the budget constraint of widening cost. The *widening plan vector* $\boldsymbol{\omega} = (\omega_a)$ indicates the widening decision of each narrow alley a, where the constraint in (6) defines that ω_a can only be 1 if a is widened, or 0 otherwise. As (5)

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formulates, the cost of widening alley a is q_a. A widening plan vector is *feasible* if $\Sigma_{a\in E^u{}_n} q_a\omega_a \leq Budget$ and *infeasible* otherwise, where the total widening budget B is prescribed for limiting investing alley improvement. $P^{imp}(\boldsymbol{\omega})$ denotes the improved operational probability of P after the widening plan $\boldsymbol{\omega}$, which implies the increased operational probability $p_a = 1$ for every narrow alley a whose $\omega_a = 1$. The expected travel time $\tau_{ij}(P^{imp}(\boldsymbol{\omega}))$ to alley $e_{ij} \in E^l$ is derived by Algorithm 4 with the improved operational probability $P^{imp}(\boldsymbol{\omega})$.

The decision variable for this problem is the widening plan vector with a size of $|E_n|$, which is the total number of narrow alleys to be widened. Thus, if we enumerate all possible widening plan realizations, there will be a total of $2^{|En|}$ realizations. However, it is intractable to solving the problem by enumerating a large number of solutions.

Moreover, the complicated derivation of expected travel time τ_{ij} in (4), which is concerning the pathfinding in the network with its alley operational probability P, makes the problem not available to be solved by commercial optimization solver. In the next subsection, the heuristic algorithm is proposed to solve the AWP.

Problem 1: Alley widening problem (AWP)

Min $\Sigma_{eij\in E^l} \tau_{ij}(P^{imp}(\boldsymbol{\omega}))r_{ij}$ (4)

s.t. $\Sigma_{a\in E^u{}_n} q_a\omega_a \leq Budget$ (5)

$\omega_a \in \{0, 1\}, \quad \forall\, a \in E^u{}_n$ (6)

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3.6.2 Heuristic algorithm

In this subsection, we propose a heuristic algorithm based on the knapsack problem to solve the AWP. The number of possible solutions in Problem 1, which grows exponentially as the variables increase, makes the brute-force method prohibitive. However, if the number of the narrow alleys to be widened is limited to a smaller scale, the outcomes of the widening plans can be tractably enumerated. Following this concept, we divide the network into block subnetworks using Algorithm 1 in Section 3.3, and next enumerates the widening plan in each subnetwork, then compute their widening costs and improved network performance. Finally, a modified 0-1 knapsack problem is used to obtain the final widening decision of the whole network.

<u>Step 1: Block-based widening plan generation process</u>

First, we use Algorithm 1 to divide the network into block subnetworks. After construction of subnetwork, narrow alleys are now scattered into subnetworks, so that the number of narrow alleys in each subnetwork is small enough in terms of the tractability of enumerating every possible widening plan.

Then, in the block-based widening plan generation process, 2^m possible widening plan realizations are enumerated in each block subnetwork G^b, where $m_b = |E^{b,u}{}_n|$ is the number of narrow alleys in the block $b \in B$. For a widening plan $\boldsymbol{\omega}^{b,l}$, the improved network performance $IEWTT(P^b, \mathbf{ts}^b, \boldsymbol{\omega}^{b,l})$ and the cost of widening plan $\kappa(\boldsymbol{\omega}^{b,l})$ are estimated using Formula (7). Note that $EWTT$ can be computed using Formula (2) in Section 3.5.

$$IEWTT(P^b, \mathbf{ts}^b, \boldsymbol{\omega}^{\mathbf{b},l}) = EWRT(P^b, \mathbf{ts}^b) - EWRT(P^{b,imp}(\boldsymbol{\omega}^{\mathbf{b},i}), \mathbf{ts}^b) \quad (7)$$

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Algorithm 5.1: Encoding of widening plan

input: P^b; $m_b = |E^{b,u}{}_n|$, the number of narrow alleys
output: $\mathbf{\Omega}^b = \boldsymbol{\omega}^{b,1}, \boldsymbol{\omega}^{b,2}, ..., \boldsymbol{\omega}^{b,m}$, for i = 1 to 2^m

$\mathbf{\Omega}^b$ <- the complete enumeration of the binary vectors
of widening plans of block b
return $\mathbf{\Omega}^b$

Algorithm 5.2: Assessing of widening plan

input: $\mathbf{\Omega}^b = \boldsymbol{\omega}^{b,1}, \boldsymbol{\omega}^{b,2}, ..., \boldsymbol{\omega}^{b,mb}$, for i = 1 to 2^m; P^b; $\mathbf{ts}^b$; $q_a \in E^{b,u}{}_n$
output: $IEWRT(P^b, \mathbf{ts}^b, \boldsymbol{\omega}^{b,i})$, $\kappa(\boldsymbol{\omega}^{b,i})$, for i = 1 to 2^m

for each $\boldsymbol{\omega}^{b,i}$ in $\mathbf{\Omega}^b$ **do**
Compute $IEWRT(P^b, \mathbf{ts}^b, \boldsymbol{\omega}^{b,i})$ using (3)
$\kappa(\boldsymbol{\omega}^{b,i})$ <- $\Sigma_{a\in E^{b,u}{}_n} q_a \omega^{b,i}{}_a$
end for
return $IEWRT(P^b, \boldsymbol{\omega}^{b,i})$, $\kappa(\boldsymbol{\omega}^{b,i})$, for i = 1 to 2^m

Step 2: Modified 0-1 knapsack problem

In this step, after obtaining the benefits and costs of all widening plans, we formulate a modified 0-1 knapsack problem in Problem 2 to determine the widening plan $\boldsymbol{\omega}^{b,l}$ to implement in each block $b \in B$. The objective in (8) is to maximize the improved accessibility *IEWTT* after widening the alleys. The widening plan $\boldsymbol{\omega}^{b,l}$, as (11) formulates, is a binary variable which can only be 0 (not to implement the plan) or 1 (to implement the plan). Different from the original 0-1 knapsack problem, there is one more constraint in the modified 0-1 knapsack problem. The first constraint in (9) is the budget *Budget* which limits the total cost of block widening plans. The second in (10) is that only one widening plan can be taken in each block. With this modified 0-1 knapsack problem, the narrow alley widening decision $\boldsymbol{\omega}^* = (\boldsymbol{\omega}^{1*}, \boldsymbol{\omega}^{2*}, ..., \boldsymbol{\omega}^{b*}, ...)$ of the whole network G is determined.

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Problem 2: Modified 0-1 knapsack problem for AWP

Max $\Sigma_{b\in B}\,\Sigma_{i=1}^{\,2^{\wedge}mb}\;\; IEWTT(P^b, \boldsymbol{\omega}^{b,i})x^{b,i}$ (8)

s.t. $\Sigma_{b\in B}\Sigma_{i=1}^{\,2^{\wedge}mb}\;\; \kappa(\boldsymbol{\omega}^{b,i})x^{b,i} \leq Budget$ (9)

$\Sigma_{i=1}^{\,2^{\wedge}mb}\;\; x^{b,i} = 1, \forall b \in B$ (10)

$\boldsymbol{\omega}^{b,i} \in \{0, 1\}, \quad \forall\, b \in B, i \in \{1, 2, \ldots, m_b\}$ (11)

3.7 Overall Procedure

This chapter details the assessment approach for the urban alley improvement to enhance firefighting accessibility.

Before the network analysis, the background data are prepared. In Section 3.1, the risk of alleys is obtained by historical data and spatial approach. The road network for firefighting is constructed by the method of Section 3.2, which is a two-level network with stochastic link blockage. Section 3.3 narrates Algorithm 1, which divides the network into block subnetwork, thereby the searching space of the alternative paths on the stochastic network can be limited. Also, the impact zone of any alley improvement approach is delineated by the boundary of its block subnetwork. Therefore, the process of estimating travel time on the stochastic network lies within the subnetwork.

In Section 3.4, the computing method of travel time to a targeted alley is firstly depicted, and the definition of the travel time scenario is described. Next, Algorithm 2 searches alternative paths in order to generate all possible travel time scenarios. Then, Algorithm 3 ranks all scenarios by their travel time. Last, the Monte Carlo method in Algorithm 4 estimates the expected travel time using a large number of network realizations. With the above procedure, the accessibility of fire service is possible to be evaluated.

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To obtain the value of criticality based on passability assurance, Section 3.5 proposed the index *IEWTT* to estimate the improved expected weighted sum of travel time within the block after ensuring the passability of an alley. The full network scan is conducted to evaluate the criticality of every alley.

In Section 3.5, in order to tractably solve Problem 1 to determine the widening alleys, a heuristic algorithm is proposed, which is composed of a block-based widening decision process (Algorithm 5.1 and 5.2) and a modified knapsack problem (Problem 2).

The flowchart of the whole method is shown in Figure 3.14, which indicates the involved parameters, variables, problems, and algorithms.

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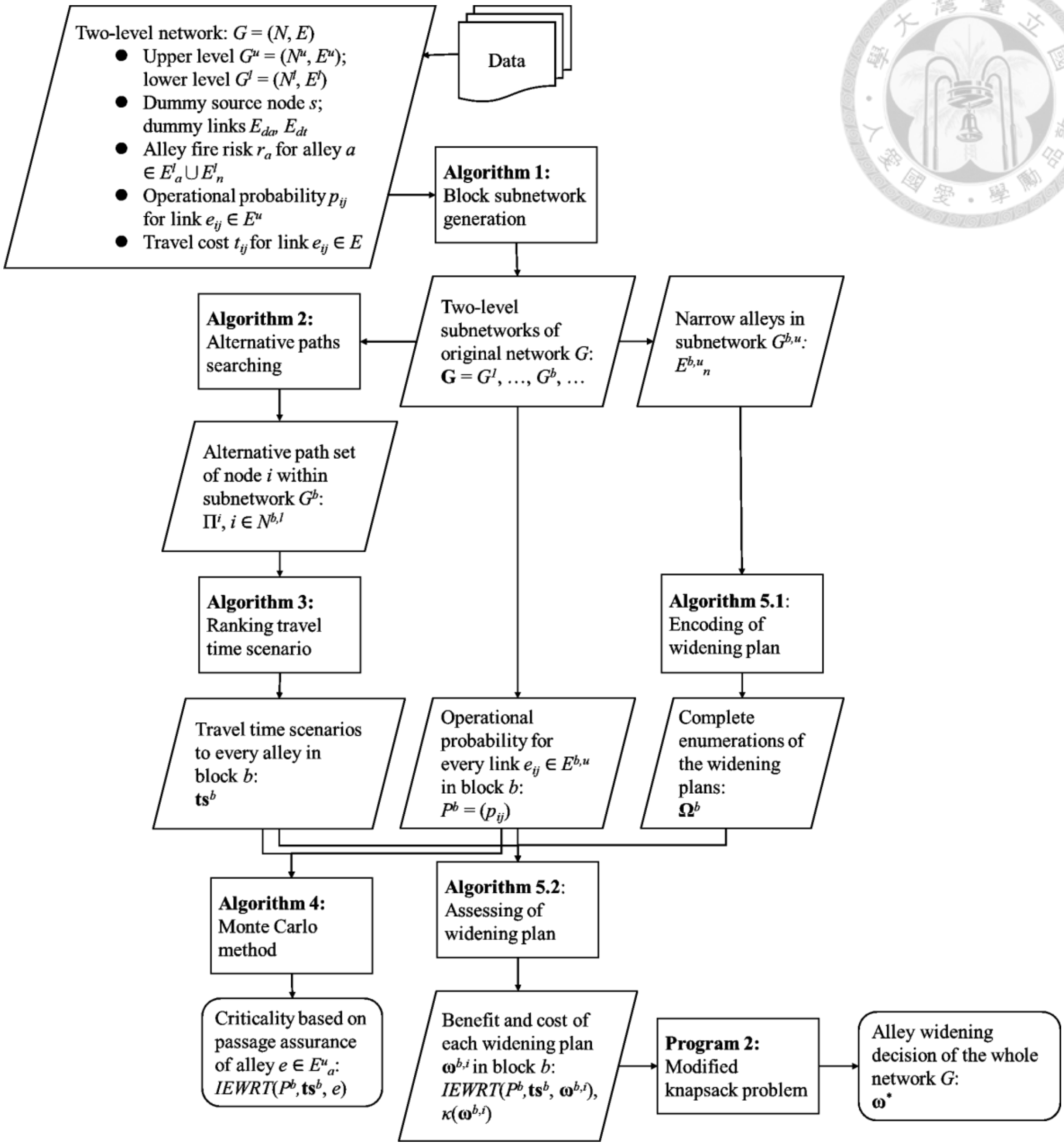

Figure 3.14 Flow chart of the methodology.
The network elements, objects, and derived variables are shown for every step or algorithm.

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Chapter 4 Case Study

In this chapter, a case study is performed to test the applicability of the proposed method. The old town of Taipei, which is known as the Three Settlements (三市街), is selected as the study area. The Three Settlements, which were developed in the 18th and 19th centuries, is the origin and historical district of Taipei. With the development of commerce and the growth of migration, streets in Taipei have gradually paved as well as the formation of built-up areas. In the early era, based on the lifestyle of residents, the width of the street was only suitable for pedestrians and rickshaws to pass. Although in the early 20th century, Japanese-ruled Taipei City Government implemented a large-scale road construction plan (台北市區改正), in which the roads were paved and widened for vehicles, the narrow streets have not disappeared in this area. Afterward, the newly migrated residents entered the neighboring area before the thorough planning, resulting in the expansion of the densely-populated area. Consequently, the narrow alleys remain in the landscape of Taipei, hindering the access of firefighting operation and expose the fire risk to its residents.

This chapter first describes the scope, overview, and characteristics of the study area. Next, the data collection, pre-processing, and model parameter settings are detailed. Finally, we apply the proposed method of assessing alley improvement to the study area and discuss the results.

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4.1 Data Description

As Figure 4.1, the study area lies in the region north of Heping West Road, Nanning Road, and Aiguo West Road (和平西路, 南寧路, 愛國西路), west of Zhongshan South and North Road (中山南北路), south of Minquan West Road (民權西路), and east of Huanhe South and North Road (環河南北路).

First, we inspect the fire lane and narrow alleys managed by Taipei City Fire Department in the study area. According to the List of Fire Lanes (劃設消防通道清冊) provided by the Taipei City Fire Department, fire lanes in the study area are shown in Figure 4.2, where the requirements for marking fire lanes are described in Subsection 2.1.7. Figure 4.3 illustrates the map of the narrow alleys according to the List of Challenging Narrow Alleys (搶救不易狹小巷道清冊) provided by the Taipei City Fire Department. The regulations for *red zone* and *yellow zone* alleys have been listed in Subsection 2.1.3. By definitions of the two kinds of roads, there is no contradiction between narrow alleys and fire lanes so that a roadway may be both a fire lane and a narrow alley.

It is noteworthy that, in the model of this analysis, the *de jure* fire lanes will not be considered passage-ensured because the actual impact of the alley width and passability assurance is to be explored. Also, the terms (like narrow alleys) may not be exactly the same as the definition by Taipei City Fire Department. Road levels are distinguished using the width of the roadway. The settings of the road level in this analysis will be described in the following article.

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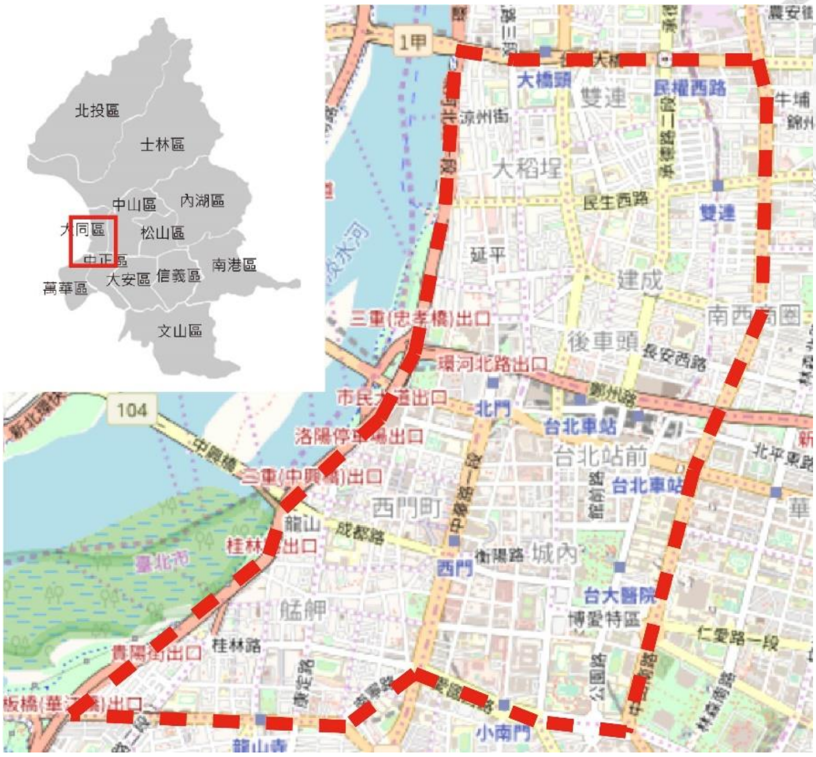

Figure 4.1 Study area.

Figure 4.2 Map of fire lanes in the study area.

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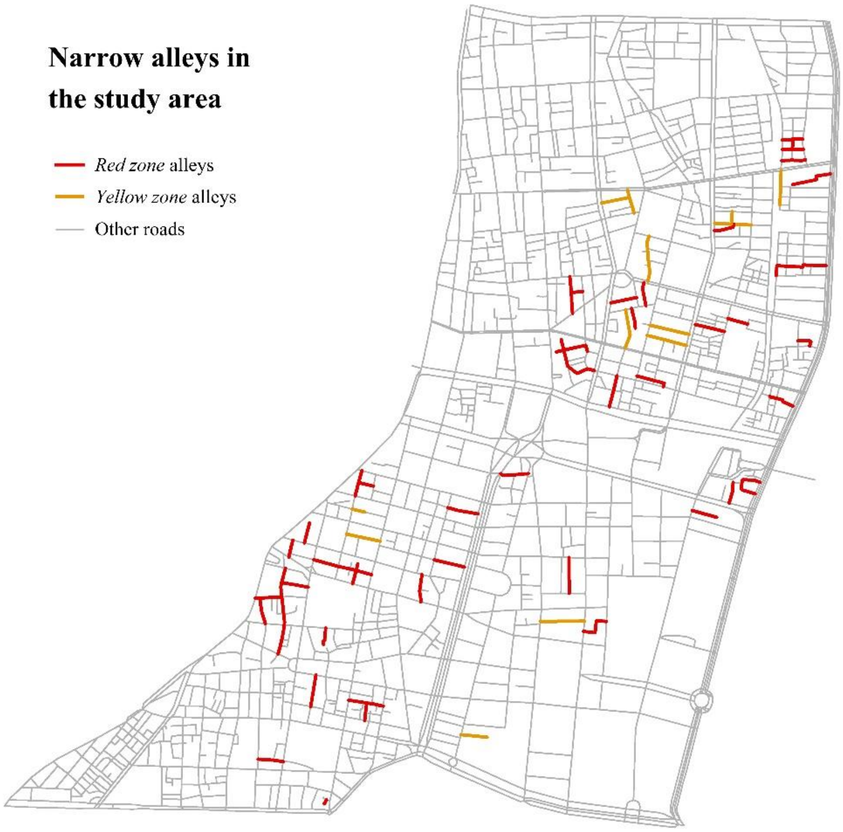

Figure 4.3 Map of the narrow alleys in the study area.

We employ ArcGIS as the platform of the geographic information system (GIS) and obtain the ESRI Shapefile of the Transportation Road Network Digital Atlas of the Ministry of Transportation and Communications as background data within the study area. Aside from the geometric formation of the road network in Taipei, the Atlas also provides information on road segment codes, road names, road widths, codes of the start node, codes of the end node, and direction. Using the "Calculate geometry" function of ArcGIS, the length of road segments can also be calculated.

There are six fire stations located within the study area, including Huashan, Chengzhong, Longshan, Jiancheng, Yanping, and Datong Station (華山, 城中, 龍山, 建成, 延平, 大同分隊). The locations of the fire stations are also considered as nodes in the network, so we use the "Split line at point" function of ArcGIS to cut the road segment

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into two segments at the exit point of the fire engine. After the above procedures, there are a total of 2923 links in the study area. With this dataset, the configuration of the two-level network structure can be constructed according to Section 3.2.

Road width is the core concern of this study. As the road width provided by Transportation Road Network Digital Atlas is not accurate, we refer to the Topographic Map of Taipei City 2017 Version and measure the road widths to obtain accurate width values. In a single road segment, if the road width is not uniform, the width value of the road segment is determined at the narrowest point (Figure 4.4).

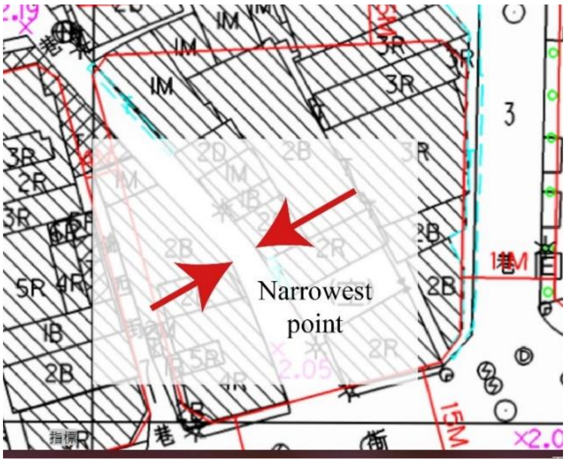

Figure 4.4 The narrowest point determines the width of an alley.

After inspecting the width of the road segment, the links can be divided into roads, alleys, and narrow alleys according to the width. As mentioned above, the definition of narrow alleys by the Taipei City Fire Department is not directly employed. The purpose is to analyze the actual impact of alley width and the criticality based on the passage in this model. Therefore, the following definitions are only applicable to this analysis.

According to Procedures for Marking and Management of Fire Lane (消防通道劃設及管理作業程序), to ensure the passage of fire vehicle, an alley should maintain an

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available width of 3.5 meters. Also, the parking ban is implemented in the alleys with a width of fewer than 7.5 meters. Therefore, the two values in the standard are employed to define the road width in the analysis.

Links with a width of more than 7.5 meters are defined as *roads*, whose passability are assumed to be ensured. We also assumed that the links between 6 and 7.5 meters and with the "road" or "street" in its name (like Chifeng St., or 赤峰街) are *roads*. *Alleys* between 3.5 and 7.5 meters are the potential fire lanes and objects of assessing the criticality based on passability assurance in Subsection 4.2.3. *Narrow alleys* between 2 and 3.5 meters, which are impassable by fire engines, are the targets of alley widening in Subsection 4.2.4. On those *unwidenable alleys* less than 2 meters, the buildings on the two sides are too close to each other, making them no possibility of widening.

According to these settings, there are 1841 roads, 739 alleys, 131 narrow alleys, and 212 unwidenable alleys in the network. Figure 4.5 illustrates the map of the road level. The travel time cost of a link is estimated by dividing the length by the moving velocity. The setting of the moving velocity at each road level is shown in Table 4.1.

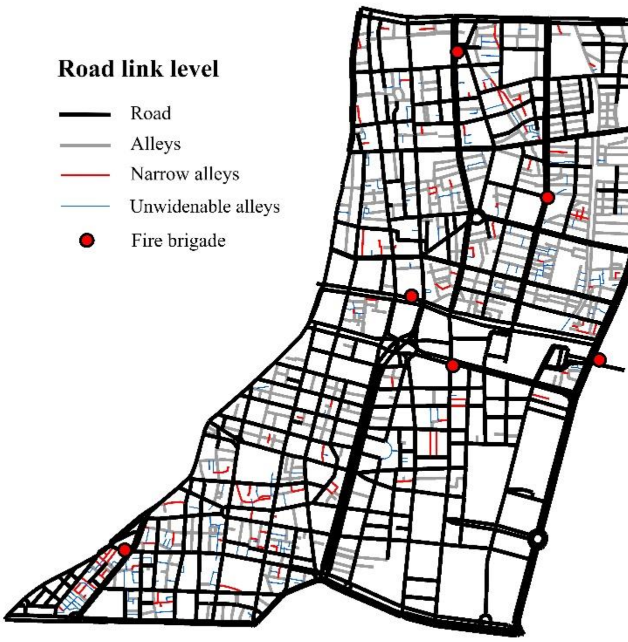

Figure 4.5 Road level map.

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Table 4.1 The moving velocity (in km/hr) for each road level and network level.

	Road	Alley	Narrow alley
Upper-level network	30	10	10 (if widened)
Lower-level network	3.6	3.6	3.6

As for the probability of blockage in the alley, this study assumes that the operational probability of alley is determined by road width as the only factor, where the setting of operational probability is shown in Figure 4.6. In the following analysis, the default setting is assumed as Setting A in Figure 4.6, but different settings of operational probability function will also be discussed. Note that all links follow the operational probability, including the *de jure* fire lanes, in the following analysis.

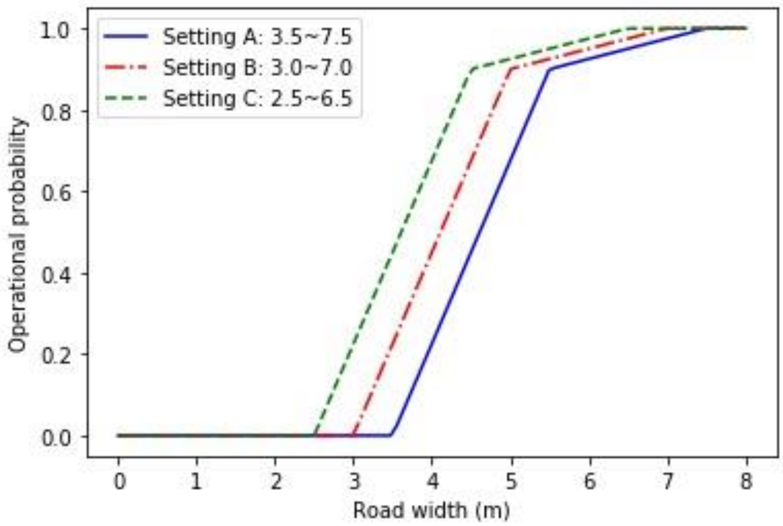

Figure 4.6 The curve of link operational probability.

The fire risk of alleys is generated as follows. First, we obtain the building data in the study area from the database of Taiwan Earthquake Loss Estimation System (TELES) of National Center for Research on Earthquake Engineering, which consist of building

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locations and fire factors, such as building material, building utility, number of floors, and building age. Using the fire risk chart summarized by 蔣得心(2004), the fire risk of the building can be evaluated.

Then, the Voronoi diagram is generated by the spatial analysis method in the GIS platform to determine the alley to which the building belongs, and the fire risk of the building is integrated into the alley fire risk. Figure 4.7 shows the map of alley fire risk.

Figure 4.7 Map of alley fire risk.

In the proposed method in Chapter 3, the identification of block is a crucial step for limiting the searching space of alternative paths and demonstrating the impact of alley improvement. Using Algorithm 1, we divide the road network into block subnetworks by wide roads and obtain 270 block subnetworks from the original network, as shown in Figure 4.8.

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Figure 4.8 Map of block subnetworks.

4.2 Result Analysis

We apply the proposed model to the study area to (1) obtain the ranking of alley criticality based on passability assurance, and (2) determine the decision of narrow alley widening. In Subsection 4.2.1, we analyze the sample size used in the Monte Carlo method and determine the sample size to be adopted in the analysis. Then, in Subsection 4.2.2, we compute the travel time and the accessibility performance of the road network in the base case. Also, we evaluate the differences in travel time under various alley operational probability functions. Subsection 4.2.3 discusses the result and analysis of alley criticality. Section 4.2.4 describes the widening decision of narrow alleys and analyzes the budget size to show the tradeoff between accessibility performance and the budget.

The solution approach was implemented in Python, and all computational experiments were conducted on a workstation with Intel® Core™ i7-6500U processor running at 2.50 Gigahertz and 8 Gigabytes of memory.

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4.2.1 Sample size analysis

Before the analysis, the sample size suitable for producing a reasonable result with an acceptable computation cost in the Monte Carlo method of Section 3.4 is determined in this subsection. By the method in Subsection 3.4.4, to estimate the travel time $\tau_{ij}(P^b)$ to alley $e_{ij} \in E^{b,u}{}_a$ in block b, a set of network realization with sufficient amount N is generated based on operational probability P^b of the block b. According to the law of large numbers, if an experiment is performed repeatedly for a large number of times, the average of the observation will tend to get close to the expected value. Therefore, if the sample size approaches infinity, the average of observed travel time will approach the exact $\tau_{ij}(P^b)$. However, a huge sample set is a burden of computation; that is, the higher cost of computation time may not bring a more meaningful result. Thus, we analyze to determine a sufficient sample size to produce reasonable results in the following analysis.

First, we test the computation time required for various sizes of N. Here, we arbitrarily selected Block 21, a block with 50 links in a single level, to calculate its $EWTT$ (P^b, $\mathbf{ts}^b$) and illustrate the result in Figure 4.9. From the result, it can be seen that when N is large, the computation time grows linearly. The result is expectable because the computational cost is proportional to the number of iterations.

Then, we observe the variability of $EWTT$ under various sizes of N to determine how large of N can provide a reasonable value sufficiently close to the expected value. In Figure 4.10, the box-and-whisker plot is illustrating $EWTT$ values of 20 samples for each value of N. When $N > 20{,}000$, the output values are close enough between each other. Considering the computation effort and quality of the result, we set $N = 20{,}000$ as the sample size for the following analysis.

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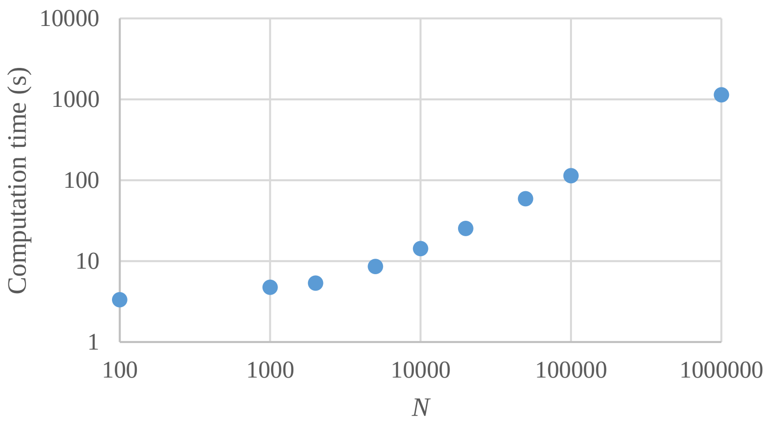

Figure 4.9 Computation time for varying size of sample set *N*.

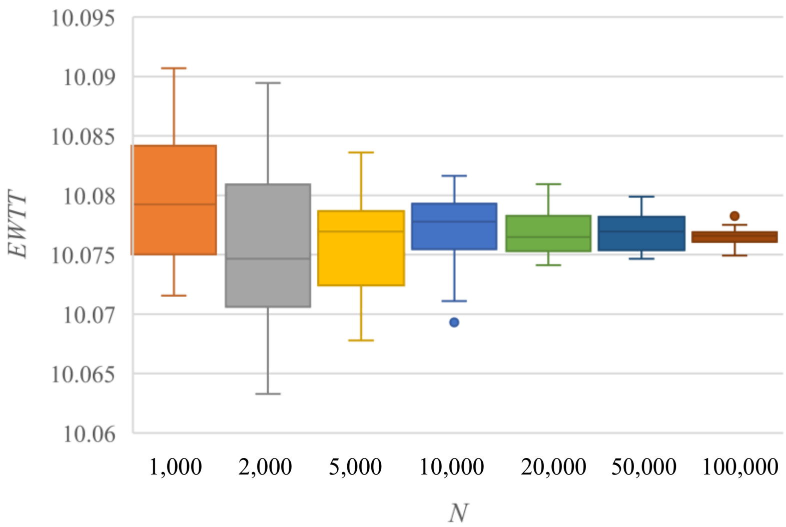

Figure 4.10 Estimated *EWTT* of Block 21 for varying sizes of sample set *N*.

4.2.2 Base case

After the construction of the block subnetwork, and set of parameters, the costs of all links in each subnetwork are known, including alley on upper- and lower-level, and entrance dummy links to every block entrance. Then, we apply the method in Section 3.4 to calculate the expected travel time of all alleys in the network as a benchmark for comparison in the following alley improvement analysis. The result is shown in Figure 4.11 below.

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Figure 4.11 Expected travel time to intersections and alleys.

To employ various considerations, if the setting of the operational probability function is changed, it will also reflect the performance of the road network under the network configuration. To put it concretely, if the fire stations employ a smaller fire engine, allowing them to drive into the narrower alleys, fire service accessibility will increase. As Figure 4.6 has shown, there are three settings of operational probability functions. For example, under the default setting of Setting A, blockage of an alley with a width of 3.5 to 7.5 meters occurs stochastically. According to new operational probability functions, Table 4.2 shows the accessibility indices *EWTT* of the whole network under different settings. Then, the results of expected reduced travel time due to

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the higher operational probability than the original value are illustrated in Figure 4.12 and Figure 4.13. From the results in Table 4.2, Figure 4.12, and Figure 4.13, it can be summarized that enhancing the mobility of fire vehicles actually reduces travel time in communities with narrow alleys.

Table 4.2 Accessibility under different settings of the operational probability.

Function settings	*EWTT* of the whole network
Setting A (3.5-7.5)	686.5533
Setting B (3.0-7.0)	669.1676
Setting C (2.5-6.5)	653.7605

Figure 4.12 Reduced travel time from Setting A to Setting B.

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Figure 4.13 Reduced travel time from Setting A to Setting C.

4.2.3 Alley criticality based on passability assurance

In the subsection, the alley criticality based on passability assurance, which is the first alley improvement, is to be explored. On this stochastic alley, the fire service accessibility can be improved by ensuring the passability of an alley whose width ranges from 3.5 to 7.5 meters. The criticality of the approach can be interpreted as the increase of accessibility before and after the implementation. According to Section 3.5, the improvement by ensuring the passability of an alley can be expressed as *IEWTT*, the *EWTT* before implementation minus the *EWTT* after implementation. After the computation time of 2.8525 hours, the *IEWTT* of all alleys in the network is evaluated, where the result is shown in Figure 4.14.

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Figure 4.14 Alley criticality based on passability assurance (Setting A).

After the ranking of criticality, the priority order of assuring the passability of alleys can be determined. In order to investigate the effect of fire risk to the priority of criticality, we compare the two criticality rankings, in which the *IEWTT* are weighted by fire risk as default and by length, respectively. It is assumed that the *IEWTT* weighted by length implies that the fire service demand of an alley is proportional to its length. Figure 4.15 depicts the analysis of the two rankings, which shows the percentage of the same alleys among the most *N* critical alleys. In Figure 4.15, it can be seen that in the top 20 critical alleys, there are only 40% of identical alleys, and the ratio rises as *N* increases and gradually goes steady at 80%. The little significant difference in a bigger *N* shows that the set of the more critical alleys are likely to be distinguished despite the setting of weights. However, a different setting leads to a distinctive suggestion of the most crucial

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alleys. Accordingly, we argue that employing fire risk in evaluation the criticality helps to identify the most critical alleys by reflecting higher demands for fire service accessibility.

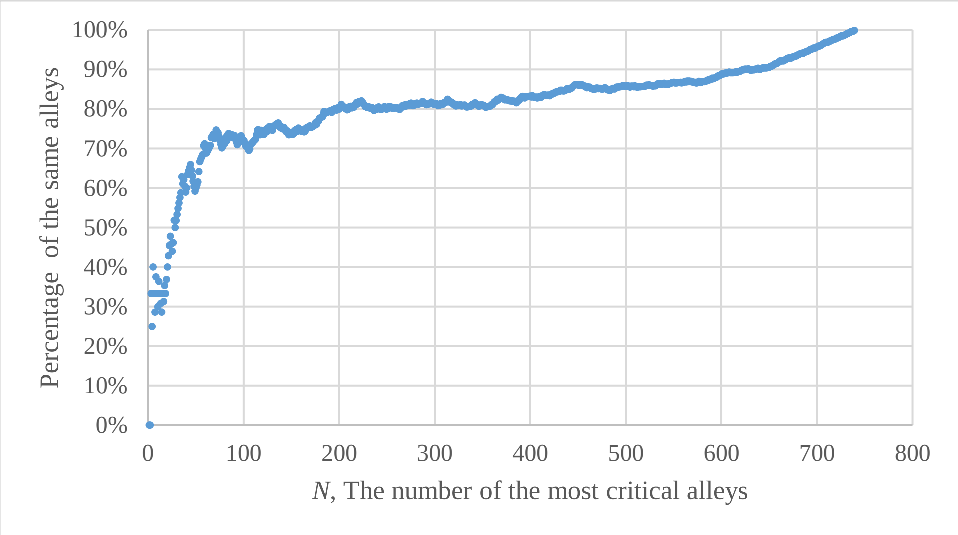

Figure 4.15 Analysis of fire risk and priority order.
Ratio of the same alleys among the most *N* critical alleys with two modes of weighting parameters, including fire risk and length of alleys.

In the following discussion, we select the most critical alleys and their blocks for examples. Figure 4.16-18 illustrate the network of the example areas, where black stripes stand for roads, gray lines represent for alleys (width signifies the real alley width), red lines denote critical alleys and dashed arrows indicate the coming routes from fire stations.

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Example area 1

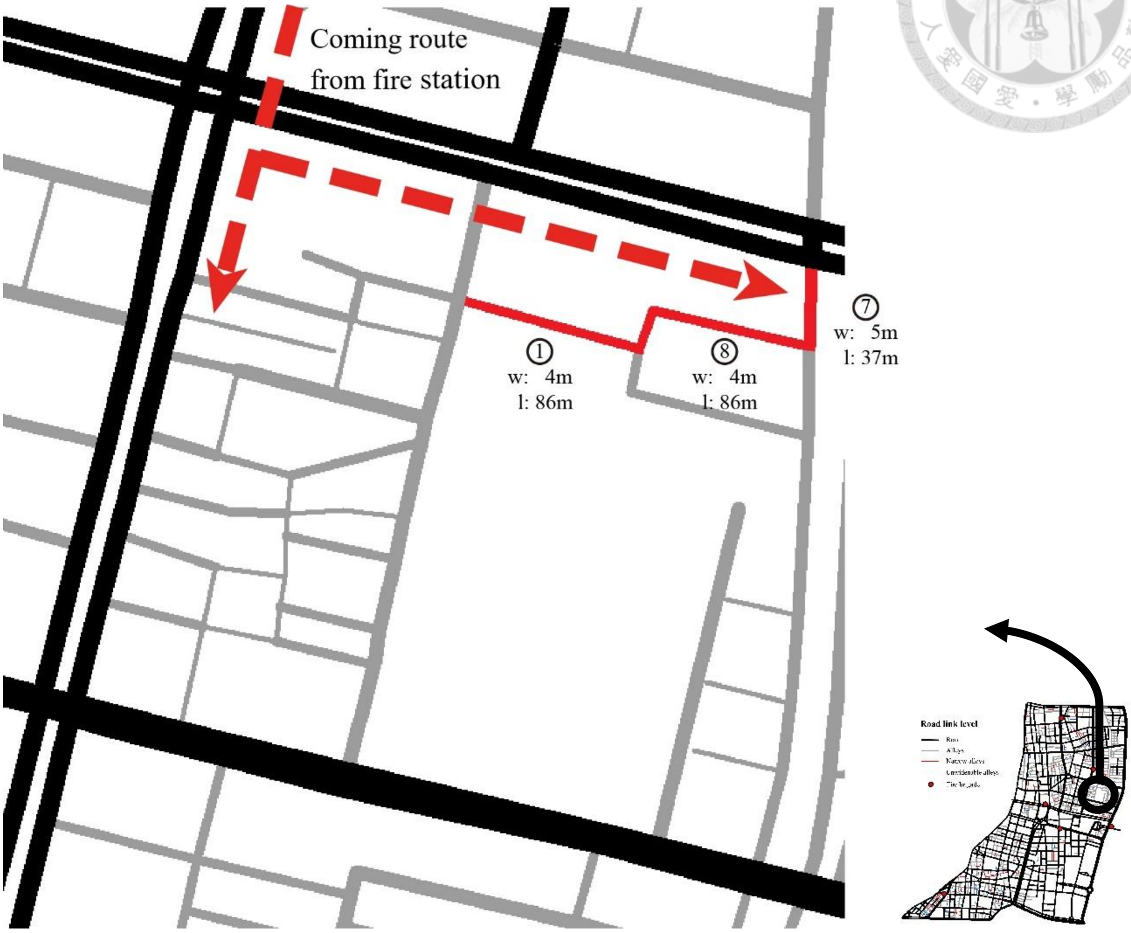

Figure 4.16 Example area 1.

In this example area, there are three alleys in the top ten of the most critical alleys. These three alleys serve as a necessary route from block entrances to the southeast area in the block. Therefore, they also carry the fire risk of the communities facing the south. The key factor of the three alleys is the narrow width, which is prone to delay fire service due to blockage. Even if a detour is taken in advance, the travel time is increased to a certain degree. Moreover, these three alleys lie in alternative roads to each other. If over one of three alleys are blocked at the same time, it is difficult for the fire crew to attend the fire scene in time.

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Example area 2

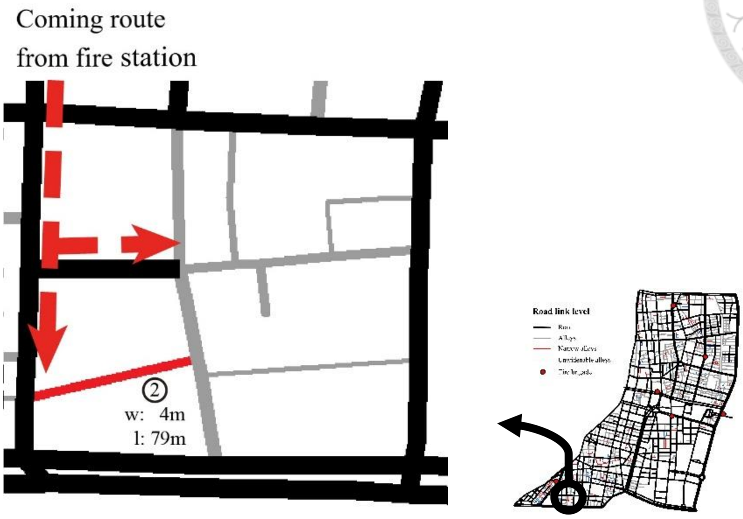

Figure 4.17 Example area 2.

This alley is ranked at the second critical alley in the study area. The alley is also narrow and long. However, the most crucial factor is the high fire risk in the alleys. The alley is known as the street of traditional night clubs, so that full of night clubs and restaurants in the narrow street bring a high fire risk. Therefore, ensuring that the alley is passable helps maintain fire accessibility.

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Example area 3

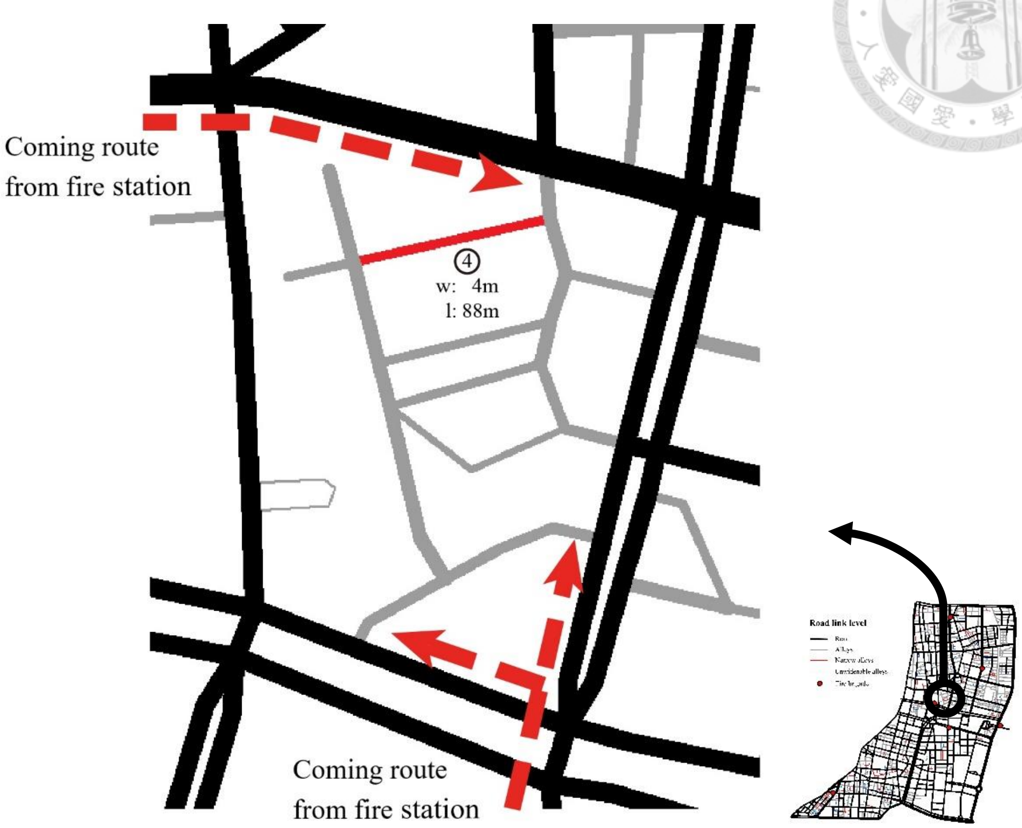

Figure 4.18 Example area 3.

Within this block, there are two wider longitudinal alleys and four narrower transverse alleys, among which three transverse alleys on the north side can marginally allow fire engines to pass. If all of the three transverse alleys carry the function from east to west, why is the northernmost one the most critical? It can be seen that the northernmost alley fully bears the fire risk in the northwest corner of the block. If firefighters entering from the north entrance of the block are obstructed, the travel time will be seriously delayed.

In summary, these most critical alleys have the following characteristics: (1) narrow width, (2) high risk of fire, (3) in a necessary path to somewhere in the block while few reliable alternative paths available.

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The reason that the narrowness of the alley becomes a necessary factor of criticality is that, when the alleys have a high probability of blockage, it naturally increases the expected travel time of the neighboring area. However, some important alleys are possible to be ignored if they are wider but have little tolerance for blockage. To cover this problem, the importance of passability assurance can be evaluated as the *EWTT* under blockage of the alley minus the *EWTT* under the full passability of the alley. (Figure 4.19)

Figure 4.19 Importance of alleys based on passability assurance from full blockage.

The alley criticality under different settings of the operational probability function can be evaluated by the same method to reflect the result in another situation. Figure 4.20 and Figure 4.21 depict the maps of the alley criticality under Setting B and Setting C, respectively.

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Figure 4.20 Alley criticality based on passability assurance (Setting B).

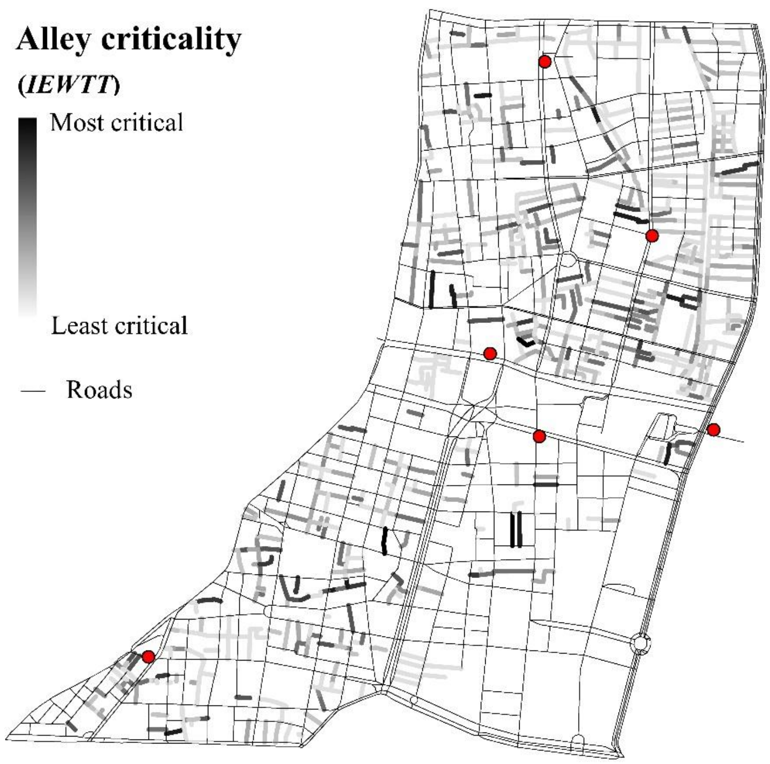

Figure 4.21 Alley criticality based on passability assurance (Setting C).

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4.2.4 Widening narrow alleys

In the subsection, the widening narrow alleys, which is the second alley improvement, is to be examined. The alley widening problem (AWP) is solved to determine the set of narrow alleys to be widened from all narrow alleys of 2 to 3.5 meters wide (as shown in Figure 4.22) under a prescribed budget B such that the $EWTT$ of the overall road network after the implementation of widening is minimized. Here, we do not consider unwidenable alleys with a width of fewer than 2 meters, because for those alleys, the buildings on the two sides are too close to each other, making them no possibility of widening.

Figure 4.22 The Objects of alley widening in the study area.

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We apply the heuristic algorithm proposed in Section 3.6 to the road network. After 1.8728 hours of CPU time computing the widening plan generation process, the knapsack problem is easily solved in 0.007 seconds, which is powered by Gurobi Optimizer 8.1.0. The result of widening decision on the road network is obtained and shown in Figure 4.23, with the total widening length B of 500 meters long. The expected reduced travel time due to alley widening is illustrated in Figure 4.24. It can be seen that the widening decision does not only benefit improved alleys. As for the alleys nearby those improved alleys, the travel time has decreased at 0~30 seconds of reduction.

Figure 4.23 Widening decision with the total widening length B = 500 meters long.

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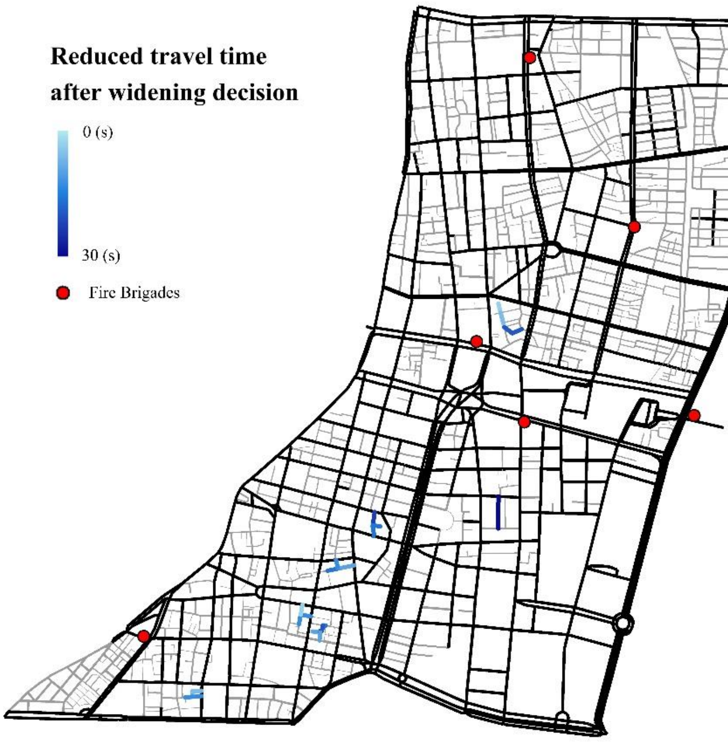

Figure 4.24 Reduced travel time after widening decision.

Also, an analysis is performed for the budget size (total widening length) B in order to assess the tradeoff between the budget and objective by describing how the accessibility improves as the budget increases. The result is shown in Figure 4.24. It can be observed from Figure 4.25 that the proposed model effectively picks out critical alleys, and then the growth of the objective value gradually slows down and declines on a steady path. As Figure 4.26 shows, nearly 50 percent of the improved accessibility can be accomplished by widening ten percent in length of the all narrow alleys, and there is no significant change as the budget is over 50 percent.

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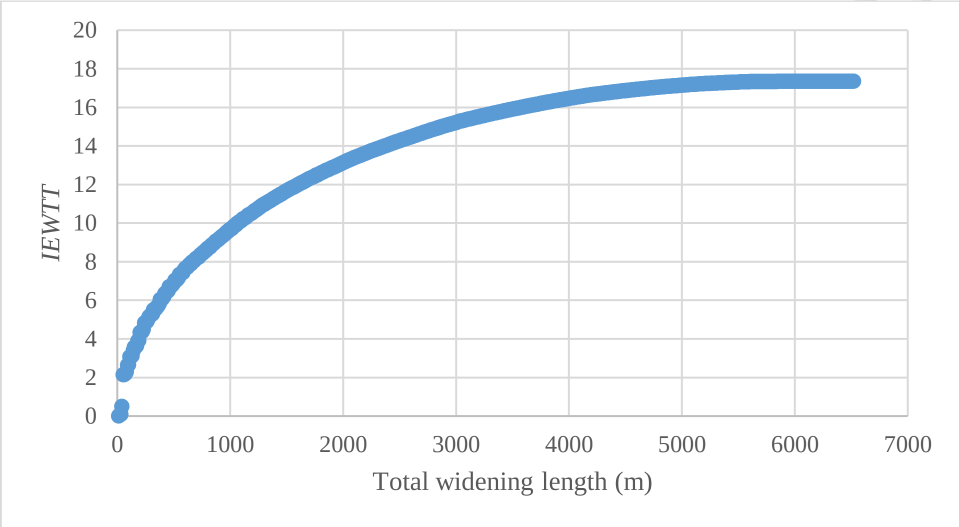

Figure 4.25 Analysis of the budget size (exact value).

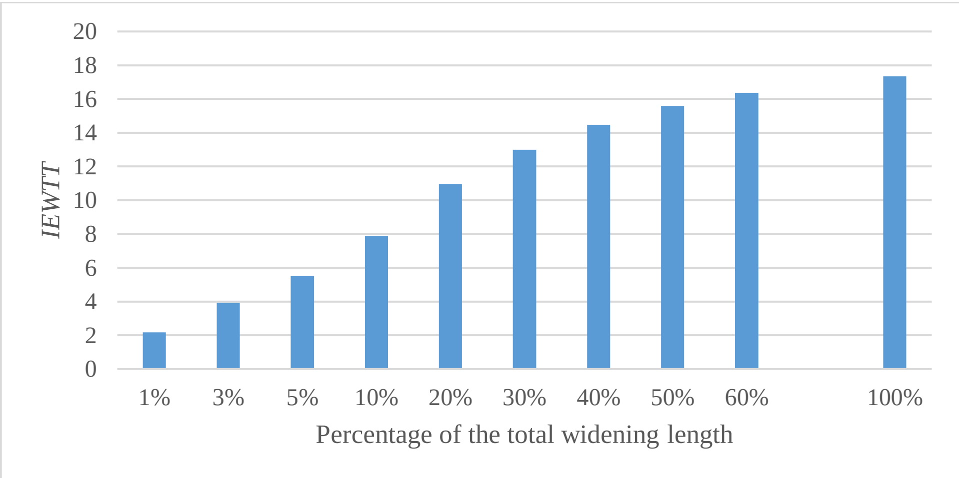

Figure 4.26 Analysis of the budget size (ratio).

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Chapter 5 Conclusions

5.1 Conclusions

Narrow width and blockage of alleys are the potential cause of delays in firefighting operations. However, few existing studies assess the threat of narrow alleys or improve the efficiency of firefighting thereupon in a systematic manner. Hence, this study seeks to link the gap by proposing a network-based method which focuses on enhancing the accessibility of fire service from the perspective of network design. In the proposed method, fire risk and stochastic blockage of alleys are considered.

First, we create a fire risk map and integrate the risk into each alley using the Voronoi diagram of the network, and the obtained alley fire risk is used as a parameter in the following model. The two-level road network is proposed for the firefighting operation. The upper- and lower-level represent the vehicle-driving and pulling-hose-line network, respectively, where dummy variables are used to denote the linkage between two levels from the intact network.

Then, we divide the road network into block subnetworks enclosed by the major roads such that the impact area of alley improvement can be delineated at the boundary of the block and evaluated based on the firefighting paths searching within the block (with limited path searching space).

Next, we propose a method to estimate the expected travel time over targeted alleys in the context of a network with stochastic alley blockage. Since the analytical expected travel time is intractable to be computed, a Monte Carlo method is applied to estimate the expected value by producing a sufficient number of network realizations.

After the construction of the aforementioned methods, it is possible to evaluate the

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two alley improvement measures. As for ensuring the passability of a single alley, a full-scan approach is conducted to obtain the criticality of every alley by evaluating the improved accessibility index after ensuring its passability. The ranking of the alley criticality provides a reference to the priority of setting fire lanes or protecting the passage for police and firefighting units.

To determine the alley widening plan for an urban network, this study proposes a block-based widening plan generation process and evaluate the benefit and cost of each widening decision over candidate alley(s). Then, the knapsack problem is formulated to determine the widening decisions over the entire network in a prescribed expenditure of widening cost. The problem and its solving algorithm help the decision-maker in urban planning by suggesting the most cost-effective widening decision.

In the case analysis, we apply the proposed model to the old town district of Taipei as the study area. It is demonstrated that the model is able to identify the critical alleys for passability assurance and determine the most cost-effective alley widening plan to enhance the fire service accessibility in the communities with narrow alleys.

5.2 Discussions and Future Work

This research hopes to primarily propose a network-based method to complement the lack of attention in academia on the issue of emergency response in narrow alleys. However, there are many aspects to the research background that have not been adequately supported by previous research, so there are expedient considerations assumed in the proposed method. Nevertheless, many assumptions are set to maintain the justifiability of the methodology. Based on the methodologies and case studies provided in this thesis, the discussions concerning assumptions, limitations, and results are stated

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as follows to suggest considerations for practical management and directions for future work.

(1) This study primarily focuses on the travel time to assess firefighting efficiency and does not consider the spread of fire and the difficulties encountered in reinforcement and water transport. To complement the incomplete consideration, the other parts of firefighting activities can be considered in the following studies to more comprehensively evaluate fire service efficiency. Furthermore, fire hydrants and water resources can be constructed in model formulation. For example, the following researchers can also refer to the simulation-based model by Sasaki and Sekizawa (2014). It is expedient to take travel time as the index of fire service accessibility. If an effective assessment model for fire response time can be established to predict property or life losses, it may be more appropriate for evaluating the benefits of improved accessibility.

(2) In the model of assessing the alley criticality and determining alley widening decision, the weight of fire service demand is presented with the fire risk, which reflects the degree of urgency to enhance the accessibility to the alley, or potential property loss and casualty of a fire. A model based on historical data, spatial analysis method, and socioeconomic background is recommended to determine the weight of fire service demand.

(3) In the fire response, it is necessary to exclusively consider the critical facilities such as hospitals, care centers, and kindergartens, etc., and hazardous locations like chemical stores, laboratories, etc. The following researchers can further employ fire risk parameters for critical facilities based on knowledge about firefighting practices and disaster management.

(4) The model to determine alley operational states employed in the proposed method

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may not fully reflect the actual parking behavior in densely populated residential areas. The spatial distribution of parking in alleys and the characteristics of parking demand can be further analyzed to build a more sophisticated model to estimate the operational state of an alley.

(5) In this study, the estimation of travel time through stochastic network realization is based on the assumption of full knowledge regarding the operational state of every alley. However, in actual firefighting, the routing of a fire crew is conducted based on partial knowledge or experience. The pathfinding process or travel time estimation model considering route choice can be further established in the following research to reflect the realism of practical operation better.

(6) In the proposed method, the criticality of every single alley is estimated based on improved accessibility with passability assurance. However, the full-scan method cannot directly estimate the benefit of improvement with the passability assurance of multiple alleys. Future research may adopt more sophisticated analysis methods or network design models to support the problem context of decision-making for real-life city management.

(7) For solving the alley widening problem (AWP), the division of block subnetwork delineate the scope of alley improvement, and lowers the number of narrow alleys in each subnetwork, allowing enumeration of every widening plan. However, if the number of narrow alleys cannot be lowered to a small enough number, the enumerating process may still be prohibitive. In future research, exploring more effective methods of generating widening plans may be a further direction. For example, the procedure which only generates competitive plans and abandons uncompetitive plans (e.g. searching plans on the Pareto front) can prevent the intractable size of plans while providing reasonable results.

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(8) In the case study, we select the old town district of Taipei as the study area for the analysis and apply the model to examine the applicability of the method. However, there is a lack of rigorous evidence to support validation. Moreover, in contrast to abundant firefighting capacity and high density of fire hydrants in Taipei City, other cities and counties face a more difficult situation. Besides, the grid pattern of the road network in Taipei City is different from the network configuration of a residential area in other cities. Therefore, the applicability of this method to any other urban communities should be further verified.

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