**UNIVERSITI PUTRA MALAYSIA**

# *DEVELOPMENT OF A COMPLEX NETWORK-BASED INTEGRATED MULTI-LAYER URBAN GROWTH AND OPTIMISATION MODEL FOR EFFICIENT URBAN TRAFFIC NETWORK*

**DING RUI**

**FRSB 2018 17**

# DEVELOPMENT OF A COMPLEX NETWORK-BASED INTEGRATED MULTI-LAYER URBAN GROWTH AND OPTIMISATION MODEL FOR EFFICIENT URBAN TRAFFIC NETWORK

**By**

**DING RUI**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy**

**August 2018**

**DEDICATION**

**TO**

my dear parents Kelong Ding and Ping He,

my lovely wife Xiaohui Guo and my cute daughter Xiluo Ding,

my respectful uncle Xiaoyong Ding and auntie Lufang Zheng

my big family and my dear friends

for their unwavering love and strong supports

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

**DEVELOPMENT OF A COMPLEX NETWORK-BASED INTEGRATED MULTI-LAYER URBAN GROWTH AND OPTIMISATION MODEL FOR EFFICIENT URBAN TRAFFIC NETWORK**

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**Chair: Assoc. Prof. Norsidah Ujang, PhD**
**Faculty: Design and Architecture**

Nowadays, most cities and urban areas increasingly pay attention to issues relating to urban growth, while studies on the urban traffic network structure is important to increase the efficiency of urban traffic networks. Analysis of the basic properties of the current urban transportation network can be used to optimise the urban design process. However, the analyses that integrate traffic network and land-use in light of their co-evolution process are still very limited, and there is a need to link the rail and the street network analysis and to examine the influence of multi-layer networks on the structures. This study can give a clear indication for the urban traffic network design and growth. The goal of this study is to apply the network analysis through simulation and optimisation methods to obtain a more efficient urban traffic network.

The study adopts single-layer and multi-layer network representation methods to capture traffic networks' basic characteristics, properties and the growth trends. The complexity and impacts of evolving multi-layer network and the co-evolution model are discussed, to address the multi-layer network and land-use based co-evolution process. Network growth methods, robustness methods and some multi-objective methods are used to optimise both the single-layer and multi-layer urban traffic networks. This study proposed the complex network based integrated multi-layer urban growth and optimisation model (CNIMUGOM) to explain the co-evolution process of the land-use, urban traffic network and population, and to obtain an efficient network structures.

The complexity of Kuala Lumpur street networks and worldwide rail networks (sampled from 45 cities) are presented to show their basic structural properties to guide the future traffic network design. The Public Urban Rail Transit Networks of Kuala Lumpur (PURTNoKL) is taken as a sample case to capture the network growth process and the change trends of a single-layer network more clearly.

The relationships between traffic multi-layer networks and land-uses were discussed, and their co-evolution model is established. The study found that the rail network growth triggers the variation of urban traffic network structure and community partition; the network diameter and the average shortest path length are decreasing dramatically, while the highest decreasing rate of accessibility is around 12%. The Relative Neighbourhood Graph (RNG) and Gabriel Graph (GG) are introduced to represent the multi-layer traffic network. Considering the cooperation strength and average operation speed ratio in different layers, the impacts of these variable parameters to the network structures are analysed.

The optimisation methods are proposed based on the maximisation of network performance from the growth and robustness. These nodes with the biggest shortest path lengths can be treated as the important and potential nodes for the future development of the single-layer network. Then these methods are expanded to multi-layer networks, and are tested using their coupling networks. For those nodes with biggest cluster centrality and closeness centrality can be treated as important and potential nodes. Then the multi-objective methods based analysis indicated that for a single-layer urban traffic network, the scale-free based networks could support more traffic flow than other coupling networks. When considering the multi-layer urban traffic networks, small-world based networks can support more traffic flow than other forms of network. After considering the traffic network structure and traffic flow constraints, the small-world based multi-layer network co-evolution model is proposed.

The findings of the study afford to improve the current land-use and traffic integrated models. Based on the traffic network and urban land-use co-evolution process, the proposed CNIMUGOM model can save the traffic network construction investment, reduce the travel cost and make the urban traffic network more efficient. Based on the simulation, the proposed network can increase the network efficiency around 30%, and the total traffic flow amount is decreased around 30%.

This study contributes to the current literature of complex network theory by gaining additional insights on multi-layer networks related studies and the modelling applications. With the use of the network growth measurement method, the multi-layer network co-evolution model, the network optimisation method and CNIMUGOM, urban planners and designers can provide a better design network structures and optimise the urban traffic networks for rail and road networks efficiency.

**Keywords:** Urban Traffic Networks, Complex Network Theory, Multi-layer Networks, Urban Growth, Traffic Network Design, Network Optimisation

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**PEMBANGUNAN BERASASKAN RANGKAIAN KOMPLEKS PERTUMBUHAN BANDAR MULTI-LAPISAN BERSEPADU DAN MODEL PENGOPTIMUMAN UNTUK RANGKAIAN TRAFIK BANDAR EFISEN**

Oleh

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**Ogos 2018**

**Pengerusi: Professor Madya Norsidah Ujang, PhD**
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Di masakini, kebanyakan bandar raya dan kawasan bandar semakin menumpukan perhatian kepada isu-isu berkaitan pertumbuhan bandar. Oleh itu, kajian struktur rangkaian lalu lintas bandar adalah penting untuk meningkatkan kecekapan jaringan trafik bandar. Analisis sifat asas rangkaian pengangkutan bandar sediada boleh digunakan untuk mengoptimumkan proses reka bentuk bandar. Bagaimanapun, analisis yang menyepadukan rangkaian lalu lintas dan guna tanah berdasarkan proses *co-evolution* masih amat terhad. Terdapat keperluan untuk menghubungkan analisis rangkaian rel dan jalan raya dan meneliti pengaruh jaringan berbilang lapisan terhadap struktur-strukturnya. Kajian ini boleh memberikan petunjuk jelas mengenai reka bentuk dan pertumbuhan rangkaian trafik bandar. Matlamat kajian ini ialah untuk menggunakan analisis rangkaian menerusi simulasi dan kaedah optimum bagi menghasilkam rangkaian trafik bandar yang lebih cekap.

Kajian mengguna pakai kaedah representasi satu lapisan dan berbilang lapisan untuk mendapatkan ciri-ciri asas rangkaian lalu lintas, sifat dan corak pertumbuhannya. Kompleksiti dan impak perkembangan rangkaian berbilang lapis dan model *co-evolution* diperbincangkan, untuk menangani rangkaian berbilang lapis dan guna tanah berdasarkan proses *co-evolution*. Kaedah-kaedah pertumbuhan rangkaian, *robustness* dan beberapa kaedah multi-objektif digunakan untuk mengoptimumkan satu dan berbilang lapisan jaringan trafik bandar. Kajian ini mencadangkan rangkaian komplek

berdasarkan integrasi bersepadu pertumbuhan bandar dan model *optimisation* (CNIMUGOM) untuk menjelaskan proses *co-evolution* guna tanah, rangkaian trafik bandar dan populasi, dan menghasilkan struktur-struktur rangkaian yang cekap.

Kompleksiti jaringan jalan raya di Kuala Lumpur dan rangkaian rel seluruh dunia (sampel diambil dari 45 buah bandar) dibentangkan untuk menunjukkan sifat struktur asas mereka mensimulasi reka bentuk rangkaian lalu lintas di masa akan datang. *Public Urban Rail Transit Networks of Kuala Lumpur* (PURTNoKL) dipilih sebagai kes sampel untuk memahami proses pertumbuhan rangkaian dan corak perubahan rangkaian satu lapisan dengan lebih jelas.

Hubungan antara trafik jaringan berbilang lapisan dan guna tanah telah dibincangkan, dan model *co-evolution* telah dibentuk. Kajian mendapati pertumbuhan rangkaian rel menyebabkan variasi struktur rangkaian lalu lintas bandar dan sekatan komuniti; diameter jaringan dan purata panjang laluan terdekat menurun secara mendadak, manakala penyusutan kadar tertinggi kebolehcapaian ialah sekitar 12%. *Relative Neighbourhood Graph* (RNG) dan *Gabriel Graph* (GG) diperkenalkan untuk mewakili rangkaian lalu lintas berbilang lapisan. Dengan mempertimbangkan kekuatan kerjasama dan purata nisbah kelajuan pengendalian dalam lapisan berbeza, impak parameter boleh ubah terhadap struktur rangkaian telah di analisis.

Kaedah-kaedah pengoptimuman telah dicadangkan berdasarkan pemaksimuman prestasi rangkaian dari pertumbuhan dan *robustness*. Nodus ini dengan panjang laluan terdekat terbesar boleh di kira sebagai nodus penting dan berpotensi untuk pembangunan masa depan rangkaian satu lapisan. Kemudian kaedah-kaedah ini diperluaskan kepada jaringan berbilang lapis, dan diuji menggunakan gandingan jaringan mereka. Untuk nodus dengan *cluster centrality* yang terbesar dan *closeness centrality* boleh di kira sebagai nodus penting dan berpotensi. Kemudian, pelbagai kaedah objektif berdasarkan analisis menunjukkan bahawa bagi rangkaian trafik bandar satu lapisan, jaringan bebas skala boleh menampung lebih banyak aliran trafik daripada jaringan gandingan lain. Dengan mempertimbangkan jaringan trafik bandar yang berbilang lapisan, jaringan berasaskan *small world* boleh menyokong lebih banyak aliran trafik daripada corak rangkaian lain. Setelah mengambil kira struktur rangkaian lalu lintas dan kekangan aliran trafik, rangkaian berbilang lapisan berasaskan *small-world co-evolution* model telah dicadangkan.

Penemuan kajian ini mampu memperbaiki guna tanah sediada dan model trafik bersepadu. Berdasarkan rangkaian lalu lintas dan proses *co-evolution* guna tanah bandar, cadangan model CNIMUGOM boleh menjimatkan pelaburan pembinaan rangkaian lalu lintas, mengurangkan kos perjalanan dan menjadikan rangkaian trafik bandar lebih efisien. Berdasarkan simulasi, rangkaian yang dicadangkan boleh meningkatkan kecekapan jaringan sekitar 30%, dan keseluruhan aliran trafik menurun kepada sekitar 30%.

Kajian ini menyumbang kepada literatur semasa berkaitan teori rangkaian kompleks dengan memperoleh perspektif tambahan mengenai kajian berkaitan jaringan berbilang lapisan dan aplikasi model. Dengan penggunaan kaedah pengukuran pertumbuhan rangkaian, rangkaian berbilang lapisan model *co-evolution*, kaedah pengoptimuman rangkaian dan CNIMUGOM, perancang dan pereka bentuk bandar boleh menyediakan reka bentuk struktur jaringan yang lebih baik dan mengoptimumkan jaringan trafik bandar untuk kecekapan jaringan rel dan lalu lintas bandar.

**Kata Kunci:** Jaringan Trafik Bandar, Teori Rangkaian Kompleks, Jaringan Berbilang Lapisan, Pertumbuhan Bandar, Reka Bentuk Rangkaian Trafik, Pengoptimum Rangkaian

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I certify that a Thesis Examination Committee has met on 16 August 2018 to conduct the final examination of Ding Rui on his thesis entitled "Development of a Complex Network-Based Integrated Multi-Layer Urban Growth and Optimisation Model for Efficient Urban Traffic Network" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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| | |
|---|---|
| MMST | Minimal Spanning Tree |
| RNG | Relative Neighbour Graph |
| GG | Gabriel Graph |
| OSM | Open Street Map |
| VGI | Volunteered Geographic Information |
| LRT | The light rail transport |
| PURTNoKL | Public Urban Rail Transit Networks of Kuala Lumpur |
| CNIMUGOM | The complex network based integrated multi-layer urban growth and optimisation Model |
| URDP | The urban rail development plan |
| UE | User Equilibrium |
| SUE | Stochastic User Equilibrium |
| FW | Frank-Wolfe algorithm |

## NOTATIONS OF TERMS

| | |
|---|---|
| G | The network |
| V | The set of nodes |
| N | The total number of nodes (network size) |
| $N^L$ | The network size of lower-layer network |
| $N^U$ | The network size of upper -layer network |
| E | The set of edges |
| M | The total number of edges |
| W | The weight of each edge |
| $C$ | The network community |
| $k_i$ | The degree of node i |
| $A_{ij}$ | The adjacency matrix |
| $adj^{multi}$ | The adjacency matrix of multi-layer network |
| $M_{loops}$ | The number of loops |
| $a_{loops}$ | The potential number of loops |
| $\tau$ | The potential number of edges (connectivity) |
| $\beta$ | The ratio of edges versus vertices (complexity) |
| TD | The total degree |
| $< k >$ | The average degree |
| r | The Pearson coefficient (assortativity coefficient) |
| $APL$ | The average path length |
| $SPL$ | The shortest path length |
| $Cc(v_i)$ | The clustering coefficient |
| $Cc(G)$ | The global clustering coefficient |
| $DC(v_i)$ | The degree centrality |
| $C_{closeness}$ | The closeness centrality |
| $C_{betweenness}$ | The betweenness centrality |
| $\gamma$ | The degree exponent of scale-free network |
| $E(G)$ | The network efficiency |
| $IC$ | The information centrality |

| | |
|---|---|
| $\theta$ | The average passenger flow |
| $\eta$ | The average edge length |
| $\pi$ | The network extension |
| $\iota$ | The average weight of nodes |
| $n_{add}$ | The number of nodes added in |
| $\Theta$ | The average operation speed ratio |
| $\Lambda$ | The cooperation strength |
| $\Psi$ | The ratio of the total travel cost |
| $\Psi'$ | The ratio between the sum of the SPL of the new and old network |
| $Coverage$ | The urban street coverage |
| $Gini$ | The Gini coefficient of betweenness centrality |
| $S^L$ | The average speeds of the lower-layer |
| $S^U$ | The average speeds of the upper-layer |
| $w_s\tau_s$ | The travel cost of the lower-layer network's shortest weighted path |
| $w_r\tau_r$ | The travel expenses of the shortest weighted path of the rail network |
| $w_c\tau_c$ | The travel costs on the shortest weighted path of crossing links |
| $w_s$ | The weights of the related links on street network |
| $w_r$ | The weights of the related links on rail network |
| $w_c$ | The weights of the related links of crossing links |
| $U_{ij}$, $C_{ij}$, $L_{ij}$ | The total shortest weighted path distance of trips passing upper-layer links, crossing links and lower-layer links connecting zone i and j |
| Å | The network expansion ability |
| Q | The network modularity |
| $rp$ | The population growth rate |
| A | The accessibility |
| $A_i$ or $A_{node}$ | The accessibility of node i |
| r′ | The radius of the rail station service area |
| $R_{change}$ | The accessibility change rate |
| L | The total length of a network |

| | |
|---|---|
| $C_{system}$ | The total travel cost of whole system |
| $t_{coop}$ | The time cost determined by the cooperation strength |
| $f_a$ | The ratio of the total number of links are added |
| $E'$ | The total construction cost of the network |
| $D_t$ | The total Euclidean distance between every vertex ($d_{ij}^E$) |
| $L_{sg}$ | The length of the shortest geometrical path of every vertices ($l_{ij}^S$) |
| $p$ | The connect probability of random graph |
| J | The congestion factor |
| $E_i$ | The amount of the employment of traffic zone i |
| $P_i$ | The amount of the population of traffic zone i |
| $\mathrm{A}_i^E$ | The change of accessibility of employment of node i |
| $\mathrm{A}_i^P$ | The change of accessibility of population of node i |
| $\mathrm{O}_i$ | The number of trip generation |
| $\mathrm{D}_i$ | The number of trip attraction |
| $T_{ij}$ | The number of trips from node i to j |
| $t_{ij}$ | The generalized travel cost from node i to j |
| $l_a$ | The length of link a |
| $v_a$ | The speed limit on link a |
| $v_a^c$ | The congested speed |
| $C_a$ | Link capacity |
| $t_a$ | The travel time on the link a |
| $f_a$ | The traffic flow on the link a |
| $f_r$ | The traffic flow on the rail network |
| $c_A$ | The travel cost when using street transit mode |
| $c_R$ | The travel cost when using rail transit mode |
| $t_A$ | The travel time when using street transit mode |
| $t_R$ | The travel time when using rail transit mode |
| $I_c$ | Income |
| $N_t$ | The number of travelers |

| | |
|---|---|
| $q_{ij}$ | The trips between i and j |
| $x_a$ | The equilibrium traffic flows on link a |
| $R_a$ | The collected revenue |
| $P^k$ | The profit of iteration $k$ |
| $NS_i$ | The measurement of multi-layer network structure status |
| $S_a$ | The overall spending |
| $I^{k+1}$ | The general investment of iteration $k+1$ |
| $\Delta E$ | The increase in employment |
| $\Delta P$ | The increase in population |

# CHAPTER 1

# INTRODUCTION

## 1.1 Background of the Study

Nowadays, most of cities and urban areas pay progressively more attentions to the urban growth related issues. They widely and continually increase the investments in transport infrastructures, use those strategies such as building new streets, new lines, rebuild and broaden the old paths, build some overpasses or flyovers to improve traffic conditions and make the urban transport network more efficient. On the other hand, the urban population, car ownership, the streets lengths and land-use have increased dramatically. However, after decades of enhancement, the traffic situations have improved distinctly but still limited in terms of traffic network efficiency. To some extent the traffic network structure is still unreasonable, and the urban planning is lacking advanced traffic planning theory as their guidance. As stated by the relevant information (Lu, Liu *et al.*, 2012), in Beijing, commuters spend an average of two hours in commuting for every day. Traffic problems have brought a great inconvenience and damage to our work and life, also has restricted the sustainable development of urban form and national economy. At the beginning of the research of Texas Transportation Institute, Schrank and Lomax (2007) state that "Congestion caused urban Americans to travel 4.2 billion hours more and to purchase an extra 2.9 billion gallons of fuel for a congestion cost of $78 billion… This was an increase of 220 million man-hours, 140 million gallons and $5 billion from 2004" (p.1). Based on the World Bank's 2015 Malaysia's Economic Monitor report, it shows that "Jams in Greater Kuala Lumpur may be getting bigger; Commuters wasted between 270 and 500 million man-hours in the Greater KL jams last year. Cars used a possible 1.2 billion litres of fuel idling in traffic; Lost hours and fuel for each person in Greater KL came to at least RM3,100 each year, more than the monthly local average salary (RM2,795); and Total cost of traffic in Greater KL is estimated at 1.1% to 2.2% of GDP in 2014."

From another angle, more people are clustering closer together in the restricted large metropolitan areas. The United Nations predicts that the world's 3.2 billion urban population will increase to 5 billion in 2030. By 2030, there will be 60% even more of the world's population lives in urban areas (Lewis, 2007), as **Figure 1** shows the urban growth and rural population distribution. With the improvement of the social economy and the deeper process of urbanization, where the growth of population always company with the dramatic increase in traffic demand. The **Figure 2a** shows the dramatic increasing trend of streets length, railways and highways length, and **Figure 2b** shows the changing trend of vehicle numbers in China since 1995 to 2015. For Malaysia, the average growth rate of the number of car was over 9% during the period of 1986-2003 (Hossain, 2006).

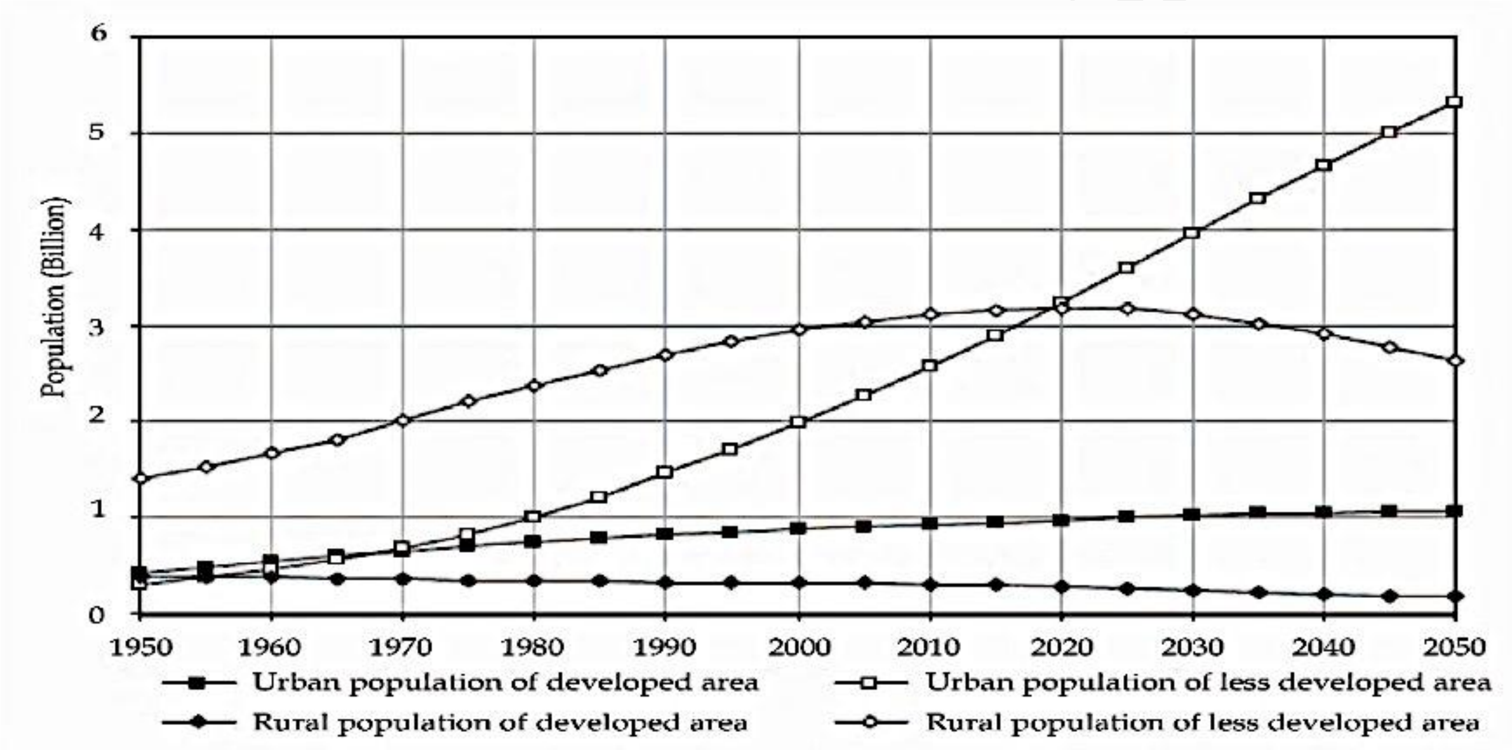


**Figure 1: The urban and rural population distribution since 1950 to 2050.**
[Source: DESA, Economic *et al.* (2012)]

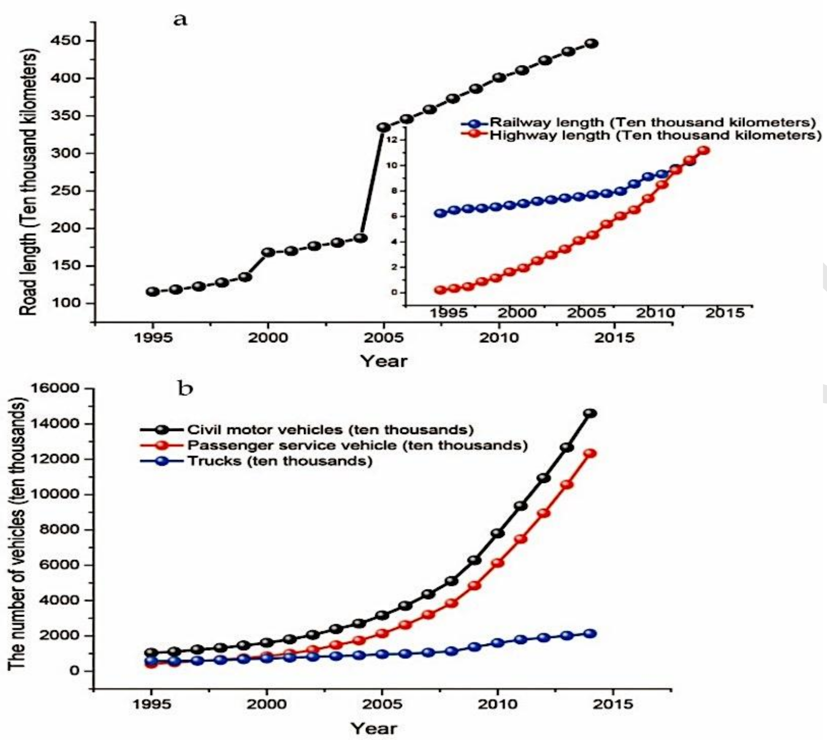


**Figure 2: The changing trends of road length and vehicle numbers.**
a. The changing trend of streets length, railways and highways of China since 1995 to 2015. b. The changing trend of vehicle numbers in China since 1995 to 2015. Data from the National Bureau of Statistics of China.

Hence the urban growth studies mainly focused on the next three parts: the urban traffic network growth, the urban land-use growth, and the urban population growth (Rui, 2013). Further focusing on their feed backs on each other, the co-evolution were studied (D. Levinson, F. Xie *et al.*, 2007; Raimbault, 2016; Schweitzer & Nanumyan, 2016; Wegener, 2004; Zhang, Xu *et al.*, 2009). The contradiction between the supply and demand is manifested in snowballing increase, and the traffic congestion problems become much serious, eventually result in urban traffic development bottlenecks.

The urban form, urban population, and the street networks have increased intensely, but these conditions and complications have not solved these problems fundamentally. For example the distribution of transportation resources and land-use of most cities are not reasonably enough, can hardly be fully and more efficiently utilised (Magnanti & Wong, 1984; McFadden, 1978); normally the traffic flows are concentrated by a few arterial streets in an areas (Lammer, Gehlsen *et al.*, 2006); this cause the impacts of traffic congestion, traffic delay and roundabout transport can be serious (Noland & Quddus, 2005; Retting, Luttrell *et al.*, 2002; Yang, Li *et al.*, 2004); the function, connections, and hierarchies of urban street networks also not that clear (Marshall, 2004). From **Figure 3**, it shows that both cities have some unreasonable parts in urban traffic network and land-use distribution, which triggered this kind of one-sided traffic congestion in a normal day, and make the urban life less efficient. Also, this situation can be seen easily in many other cities. For example in Beijing, central urban functions of excessive accumulation and intensive land development lead to a large concentration of population and employment. With highly concentrated transportation, the 3rd ring road centralizes approximately 50% of the total amount of traffic flow (Yang, Shao *et al.*, 2006). In the meantime, owing to the fact that downtown traffic infrastructure construction of surrounding areas and satellite cities lag behind the urban development, it was problematic to meet the needs of urban spatial structure and function layout of optimisation and adjustment. Moreover, it objectively worsens the circle of excessive development trends and accelerates the spread of chaotic extension. If the problems are not mitigated, it could be damage to the city livability and function efficiency, as the decrease of the future urban traffic network efficiency can increase the total travel costs and travel time.


**Figure 3: Traffic jams in different places with the same performance – one-sided traffic congestion.**
For the left image: England, Parramatta road, source from Www.abc.net (2016); For the right image: Malaysia, source from Ramanujam (April 2017).

The importance of urban traffic network studies to the urban economic and social development is self-evident, the development of traffic network perfectly provide a guarantee for the steady increase of the urban economy, and rational distribution of traffic network can effectively promote the movement of urban economic activities (Rodrigue, Comtois *et al.*, 2013). In urban planning specifically traffic planning process, normally following this basic process: traffic survey, background prediction, traffic forecasting, layout scheme design, and project evaluation. Moreover, the urban traffic network design is the most crucial point of layout scheme design (Liu, 2001), which fundamentally decide the basis of the future urban planning, economic development direction, and the operational efficiency. Finally, this function layout affects the urban form conspicuously.

According to the irreversibility of urban development and hard to change the land-use pattern, the research and prove of how the traffic network topology structure to affect urban traffic distribution earned much attention, can say very detailed (De Montis, Barthelemy *et al.*, 2007; Lammer, Gehlsen *et al.*, 2006; Wu, Gao *et al.*, 2006). Hence the designation and choose of networks layout need concern particularly, especially during the assessment of land-use distribution, traffic situation improvement, functional zoning, population distribution, and the construction process of new areas. Later, many studies have been conducted to examine the structure and function with respect to different forms of the traffic network, such as public transit network (Chen, Huang *et al.*, 2014), marine networks (Kaluza, Kolzsch *et al.*, 2010), railway networks (Latora & Marchiori, 2002), airport networks (Barrat, Barthelemy *et al.*, 2004), and street networks (Lammer, Gehlsen *et al.*, 2006). With the analysis of urban traffic networks, the urban growth process can be better discussed and then the potential parts of the future development can be figured out. With known of its structural characteristics, can provide relevant references to the urban planning, design, optimisation, the sustainable development and maintenance.

The complex network theory is a multidisciplinary research direction of complexity science, which has been widely exposed with a rapid surge of interest since Watts and Strogatz (1998b) and Barabasi and Albert (1999) described the collective dynamics of small-world networks, and the emergence of scaling in random scale-free networks. The small-world network is a kind of network structured with high clustering coefficient and small average shortest distance, while a scale-free network is a type of network in which the degree distribution of nodes obeys the power-law distribution. The complex networks theory has been widely used and made astonishing achievement in Empirical Science and Basic Science, being regarded as a paradigm representative of complexity system science. It mainly concentrates on the following aspects: the empirical research of the networks characteristics; network hub nodes detection; dynamical changing and spreading processes; the seeking and detection of communities and groups; robustness and vulnerability; and multi-layer network method and applications.

The research of complex network provides a new method and novel insight into analyzing the complex urban traffic networks. The paradigms of the small-world and scale-free networks changed the stereotyped thinking of traffic networks. Before these two model were proposed, traffic networks were normally tackled as either regular networks or ER random networks (Erdos & Renyi, 1960), as inherited from the definitions of graph theory. Moreover, more and more scholars have recognized the importance of complex network science, including Masud, Ravindran *et al.* (2008), who treated this theory as an independent and key chapter in their book "Operations Research and Management Science Handbook". In urban studies, Neal (2012) described in "The Connected City: How Networks are Shaping the Modern Metropolis" the application of network science related indices in this specific direction. Additionally, Batty (2013) published his book "The New Science of Cities" concerning his vast experience in urban models and complexity research. These works made significant contributions to the art of the complex network research related to modern urban studies. Hence, the complex network theory has huge potential in the urban study.

## 1.2 Problem Statement

The propose of problem statement is based on three parts, from the urban growth, the traffic network design and the complex network theory point of view, in which the lack points of existing studies are shown. Here we discuss them respectively.

### 1.2.1 From the urban growth point of view

Ioannides and Rossi-Hansberg (2010) defined the urban growth is "the growth and decline of urban areas, as an economic phenomenon is inextricably linked with the process of urbanization" (p.264). An urban system is a complex system comprised of many subsystems (Bretagnolle, Daude *et al.*, 2006). Land-use, transportation and population are the most important subsystems when considering the urban growth process, as they develop, prosper, and influence each other (Levinson, 2007).

To understand and measure the urban growth phenomena, linear, nonlinear and mathematical models which include more complex, dynamic, and intelligent elements were proposed in modelling approaches since the mid-1950s. Although scholars gradually realise the important relationships between land-use planning and transport planning in the urban growth process, unfortunately in practice, the connections between urban land-use and urban traffic network are separated and not clear enough (Li, Wu *et al.*, 2015; Waddell, 2011). This make the transport planning important to strengthen the develop trend of the past, such as satisfying the need of private automobile travel habits; or induce the urban land-use development to those regions without regional development plans; by contrast, in land-use planning process scholars normally ignore the influence of traffic infrastructure investment to the regional land-use (Parker, 2013; Wu & Li, 2010). For example in China, urban traffic and land-use stay in disconnect status, their co-evolution process is poorly considered and their inharmonious interactions are mainly embodied in the following aspects (Chen, Xia *et al.*, 2010; Hao & Zhang, 2014; Wu & Yeh, 1999; Yang, Shao *et al.*, 2006): discordance between the high density of urban land development and urban traffic system structure; unreasonable situation between the city traffic distribution and the process of urban expansion; disequilibrium between the large-scale construction of new districts and inefficient transportation facilities; disharmonious gap between the highly traffic demands of urban centre and the simple street facilities and stereotyped planning supply; dissonance between the advanced traffic facility supplies and the inefficient land utilization. While Kuala Lumpur have same problems as Hossain (2006) and DBKL (2004) have illustrated that "uneven distribution of utilities and facilities; and development has favoured new areas at the expense of upgrading older established residential areas".

Hence, the real need of the connection of land-use and transport together based on the network structural analysis and the lack of quantitative analyse methods lead us to develop a more effective method to address this gap.

### 1.2.2 From the traffic network design point of view

Most of the cities still using old transit network design models and methods were basically generated during the quantitative revolution. In fact, the traffic data investigation, creation of relevant models, travel forecasts and much more traffic planning process are based on the quantitative scientific methods, which make the results reliable. However, the using of the traditional transportation planning theories in many countries, are lacking the sense of quantitative studies of network structures at the key process of planning, and just put forward some qualitative principles to guide the design (Wu & Li, 2010). Traditional urban traffic network planning partly focused on the integration of urban transport and land-use system, such as location theory proposed by Isard (1956), which originally shown the fundamental understanding of geographical systems of human is that networks consist of interrelating nodes and interactions between geographical locations (Andersson, Frenken *et al.*, 2006), but the importance of network still not exposed enough. With the improvement of urban form and transportation network due to the influence of Transit Oriented Development (TOD) (Boarnet & Compin, 1999; Cervero, 2004; Cervero & Day, 2008; Cervero, Ferrell *et al.*, 2002; Dittmar & Ohland, 2012; Messenger & Ewing, 1996) and Smart City concepts (Bowerman, Braverman *et al.*, 2000; Hollands, 2008; Nam & Pardo, 2011; Neirotti, De Marco *et al.*, 2014), more researchers realised the importance of network structures (Crucitti, Latora *et al.*, 2006a, 2006b; Latora & Marchiori, 2002; Porta, Strano *et al.*, 2009), but still lack structural analysis methods to analyse the dynamics and structure changing trends of urban traffic networks.

The study of the urban traffic network structure is good for us to understand the important role of the traffic network played in urban complex systems; analyse the basic properties of the current urban transportation network can guide, promote and optimise the urban design process. While the design of urban traffic network in Kuala Lumpur is related poor which have caused traffic congestion and bottleneck in some area like Sungai Besi, Jalan Tun Razak, MRR2 and Jalan Kuching (Thestar.com, 2018). The network optimization is widely studied by many researchers (Bertsekas, 1998; Li, Liu *et al.*, 2011), as Li, Wang *et al.* (2017) said "…It can reasonably adjust the relationship between traffic demand and traffic supply so as to make better use of road resources...Further the traffic flow can be smooth and safety. The traffic congestion can be reduced to a certain degree."(p.1).

Regarding traffic network design and its optimisation, the study need quantitative methods to illustrate their network characteristics, and much further, to figure out their inner relationships and mechanisms for the base of future growth trends, optimisation and co-evolution process (Achibet, Balev *et al.*, 2014; Wu, Li *et al.*, 2017).

### 1.2.3 From the complex network theory point of view

The complex network theory is within the context of network theory with the widely study of real-world networks since the paper "Collective dynamics of 'small-world' networks" of Watts and Strogatz (1998b) and the paper "Emergence of scaling in random networks" of Barabasi and Albert (1999) were published. It defined as Papo, Buldu *et al.* (2014) stated "a subfield of statistical physics for structurally disordered, dynamically heterogeneous systems with non-trivial topology" (p.2). From the Cambridge Dictionary, the definition of "network" is "A large system consisting of many similar parts that are connected together to allow movement or communication between or along the parts, or between the parts and a control centre." Further Newman (2010) defined " a network is, in its simplest form, a collection of points joined together in pairs by lines" while "Many objects of interest in the physical, biological, and social sciences can be thought of as networks…" (p.1). Further Aparicio, Ribeiro *et al.* (2015) defined the complex networks as "If a network has topological features that are not expected to occur in neither purely random nor purely regular graphs it is considered to be a complex network" (p.1). The basic elements of a complex network system are multiple nodes and edges. The research about traffic intersections, lines is the basis of studying the urban traffic networks, its function is not only the simple superposition of these subsystems, but the relationships between them.

With many traffic network related researches (Crucitti, Latora *et al.*, 2006a; Latora & Marchiori, 2003; Porta, Crucitti *et al.*, 2006a, 2006b, 2008; Porta & Latora, 2007; Porta, Latora *et al.*, 2012; Porta, Strano *et al.*, 2009), the advantages and disadvantages of the complex network theory are shown very clearly. As a favorable practice to help urban and transportation planners, the utilizations of the complex network theory are mainly focused on the following: By using the definitions of complex network theory, the complex connections of street networks can be easily represented as directed or undirected graph, their weights of nodes and edges can also be effortlessly represented, and some new statistical characteristics could be uncovered. Secondly, the change trends of the street network can be shown by the research of complex networks, the characteristics of network evolution process can be demonstrated clearly and comprehensively. Thirdly, by the definitions of the urban street network and public rail network characteristics, the real complex systems macro and microscopes properties which have not been fully discovered can be explored. The next is that the dynamics characteristics can be measured, such as the spreading of traffic jams and the robustness of networks. Fifth, it can be used to predict and optimise the street network. The disadvantages of the complex network theory are with different representation methods, the performances and discussions of the same network are different, and some indicators are not suitable with the aspect of urban traffic network. Moreover, the analysis of network structure are hard to connect with real situations, it need extra abilities to explain the results.

Although these traffic network related researches are important and necessary, the rail network and street network integrated researches are less considered with the lack of quantitative research methods as the layered analysis approach is proposed to urban studies very recently (Strano, Shai *et al.*, 2015b). As Kuala Lumpur have similar problems as DBKL (2004) have shown in the master plan that "the primary objective of achieving a significant modal shift from private to public transportation has not been achieved mainly because of the lack of integration between the various modes of public transportation and between land use planning and the rail-based public transport network" (p. 157) and "low public transport modal share resulting in high demand on road infrastructure and traffic congestion" (p.385), which shown the close relationships between the rail network and road network were less considered. Especially researchers short of studies on the influence of multi-layer networks (Aleta, Meloni *et al.*, 2016; Boccaletti, Bianconi *et al.*, 2014; Ducruet, 2017), which illustrate and represent different appropriate urban traffic modes and their relationships in different layers, with the development of rail and road networks is inseparable in urban growth process.

## 1.3 The Research Gaps

Therefore, this study was triggered by these recent thinkings of urban traffic network design and the advantages and disadvantages of the complex network theory. This is because with the study of the traffic network structures, understand the performances of these networks and optimise them based on different purposes can increase the efficiency of urban transportation network.

The research gaps of this study can be obtained. From the urban growth models point of view, these researches lack the consideration of traffic network and land-use integrated models. From the traffic network design point of view, the study need to understand the network structure characteristics, to illustrate the inner relationships between urban land-use and urban traffic network, to figure out their changing trends and co-evolution process. From the complex network theory point of view, these researches short of considering the integrated research of the rail network and street network, the influence of multi-layer networks. Hence, the research gaps clearly as shown in **Figure 4**:

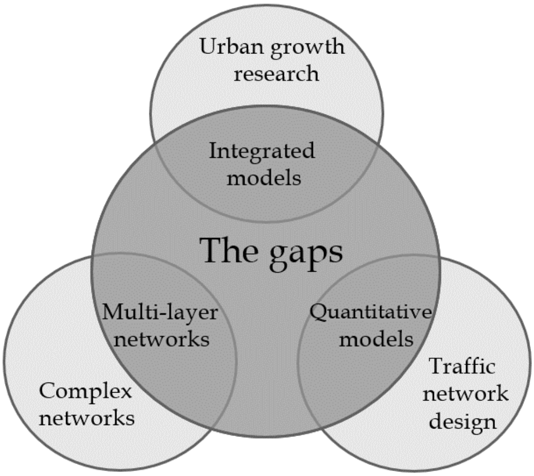


**Figure 4: The research gaps.**

## 1.4 Research Questions

To fulfill those research gaps proposed above, with the advantages of complex network theory, the aim of this research is to develop an integrated and optimisation model of complex network for a more efficient urban traffic network. Hence, this study aims to answer the following questions:

- RQ1: How to capture the urban traffic network's characteristics, properties and their growth trends based on the complex network theory?
- RQ2: How to determine the co-evolution relationships between urban traffic network and urban land-use?
- RQ3: How to optimise the urban traffic network structure based on the urban growth process?

- RQ4: How to improve the efficiency of urban traffic network with the aspect of complex network theory?

## 1.5 Research Aim and Objectives

The main objective of this study is to analyse the single-layer and multi-layer network urban traffic network structure characteristics and growth process from different aspects, to optimise the urban traffic network structures. To answer these research questions, the research objectives are proposed respectively:

- RO1: To capture traffic network's characteristics, properties and the growth trends.

- RO2: To analyse the multi-layer network and land-use (accessibility) based co-evolution process.

- RO3: To determine the local or global best traffic network structures based on the network growth process by comparing different optimisation and simulation scenarios.

- RO4: To explain the co-evolution process of the land-use, urban traffic network and population, and obtain a much efficient network, the complex network based integrated multi-layer urban growth and optimisation model (CNIMUGOM) is proposed.

## 1.6 Research Scopes and Limitations

This study is based on the urban traffic networks, which is only focusing on the intra-city rail and street networks from the view of network structure, other types of networks are not considered here. Here this study only consider the network structure topological and geographical characteristics, other indicators of traffic system like parking area, road space, car ownership and buffer space are not considered. Based on our case study, the rail network includes the light rail transport (LRT) system, monorail system, commuter rail system and Airport rail link system. In this study the node and vertex, and link and edge are respectively synonymous in this context.

This research tested the rail network and street network data of Kuala Lumpur, but the data of network growth and network optimisation process are based on models and simulations. For the simulation of the co-evolution of networks, limited by the computation time, this study suppose that a square urban area has an initial number of nodes, with an initial population and an increasing rate per iteration (include migration), this kind of simulation were used in many recent researches. The analysis of urban land-use is mainly based on the analysis of accessibility, the patterns and the price are not considered. This study consider the traffic network structure and the accessibility together in the land-use model, however, the related policies are not included, which may have a huge influence on the population distribution. This study also does not consider the effect of population movements on multi-layer networks with GPS data and another big datasets, which can make the communities partition different. However, with certain simplifications, the main change trends can be figured out very efficiently with affordable calculations.

This research also has some obvious limitations, as it does not consider the hierarchy of streets, which might make the results of accessibility change trends different. Although it used a co-evolution relationship to discuss the relationship between multi-layer networks, but this relationship is highly simplified, which might hardly describe the real relationships between rail networks and street networks. Although the simulation of the multi-layer network may include every situation of worldwide cities, this study still need more data to apply the heuristic method to real projects, and further the network optimisation.

## 1.7 Significance of the Study

This study provides a unique sight to discover and analyse the urban rail and street traffic multi-layer networks growth process based on the complex network theory. With the analysis of traffic network growth process, it is more clear of the urban growth process and can make related optimisation and prediction. As the existing research limited analysised the great function of multi-layer traffic networks, and this research fill the gaps. This study is novel in the field of urban planning and transport planning, as the connections between Physics and Urban Studies can be partly discovered, and it is helpful for the improvement of traffic network accessibility. This study do support the application of TOD and Smart city concepts from the aspect of traffic network structures, which was partly ignored in previous studies.

This study contribute to the current literature of complex network theory by gaining additional insights into these modelling applications. The relationships between traffic multi-layer networks and land-uses, and their co-evolution process are also discussed. This study also affords valuable information and contribution on the improvement and development of current integrated modelling approaches, it combined the accessibility and traffic network growth together.

## 1.8 Study Organisation

Based on the objectives and research questions, this study is organised as:

In Chapter 1, this study introduced the backgrounds of this research and its importance of further this research direction. Focused on those research problems, these research questions, research objectives, research significance of this study are offered, and illustrated the organisation of this study.

In Chapter 2, a review of the existing literature that their basic concepts, the applications of complex network theory to urban traffic network design are given, further, it reviewed the urban growth theory, the land-use and transportation integrated models and traffic network design models.

In Chapter 3, this study offered the preparation of relevant data and related research methods, such as the network representation methods, their indicators used both in single-layer network and multi-layer network, and some typical analysis process.

In Chapter 4, this study first examined the street networks and rail networks, some basic network properties are given. From the discussion of the worldwide public urban rail transit networks, with the understanding of their performances and properties, strong guidance can be given to our study. The example of the Public Urban Rail Transit Networks of Kuala Lumpur (PURTNoKL) can clearly show the network growth process and the change trends of the complexity of a single-layer network.

Then multi-layer network co-evolution approach for urban traffic network design is proposed. The network structure complexity of evolving multi-layer network is obtained, the impacts of multi-layer network growth to the change of street network accessibility, to the network expansion ability, and to the evolution of detected network communities are discussed. A multi-layer network based co-evolution and optimisation model is given, which shown the co-evolution approach, with considering different land-use scenarios. The importance of the operation speeds and the cooperation strength are discussed.

After that, the optimisation methods are proposed based on the maximisation of network performance. Some network growth and network robustness based optimisation methods are given. Further, with consider these multi-objectives such as construction costs, transportation costs, traffic flow and congestion, the better multi-layer network structures are suggested for different aims.

The propose of CNIMUGOM make us clearly understand the structural relations and co-evolution properties of traffic network and urban land-use. From the traffic network and urban land-use co-evolution process, this research provided a new vision to design and optimise the urban traffic networks.

Chapter 5 is the conclusion and future outlooks of the application of complex network theory in urban studies.

These chapters mainly based on these already published, accepted and submitted papers:

1. **Ding, R.**, Ujang, N., Bin Hamid, H., & Wu, J. (2015). Complex Network Theory Applied to the Growth of Kuala Lumpur's Public Urban Rail Transit Network. PLoS One, 10(10), e0139961. **(SCI, IF= 3.057)**

2. **Ding, R.**, Ujang, N., Bin Hamid, H., Mohd Shahrudin Abd, M., Li, R., Safwan Subhi Mousa, A., . . . Wu, J. (2018). Application of Complex Networks Theory in Urban Traffic Network Researches. (Under review).

3. **Ding, R.**, Ujang, N., bin Hamid, H., Manan, M. S. A., Li, R., & Wu, J. (2017). Heuristic urban transportation network design method, a multilayer coevolution approach. Physica A: Statistical Mechanics and its Applications, 479, 71-83. **(SCI, IF= 2.243)**

4. **Ding, R.**, Ujang, N., bin Hamid, H., Manan, M. S. A., Li, R., & Wu, J. (2017). The complex network theory based urban land-use and transport interaction (LUTI) studies, review and research perspectives. (Under review).

5. **Ding, R.**, Ujang, N., bin Hamid, H., Manan, M. S. A., He, Y., Li, R., & Wu, J. (2018). Detecting the urban traffic network structure dynamics through the growth and analysis of multi-layer networks. Physica A: Statistical Mechanics and its Applications, 503, 800-817. **(SCI, IF= 2.243)**

6. **Ding, R.**, Ujang, N., bin Hamid, H., Manan, M. S. A., He, Y., Li, R., & Wu, J. (2018). A simple and effective computational technique for detecting the urban traffic network structure dynamics through the growth and analysis of multi-layer networks. (Under review).

## 1.9 Summary

This chapter highlights the background of this study, underlines its problem statement and provides its research gaps, research questions, as well as its research aims and objectives. This chapter also includes the research scopes, significance and the structure of this study.

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