

Measuring Transit-Oriented Development Network Synergy Based on Node Typology

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ABSTRACT:

Recent research has focused on assessing the Transit-Oriented Development (TOD) level of individual transit nodes within a TOD network. However, this thesis argues that having such a TOD level value is not sufficient for understanding the role each particular transit node plays within a TOD network. In other words, a transit node may have a low performance when evaluating its individual TOD level, but it may serve an important role within the TOD network as a whole, for example as a feeder node.

In this thesis, a TOD typology is developed based on five built-form indicators to identify their roles in the transit network, and to discuss how their effects contribute to the large-scale TOD. Based on the TOD typology, a correspondence analysis is conducted to measure the potential synergy effect of the TOD network system in the Arnhem-Nijmegen city region, in the Netherlands.

In the results, the urban core central nodes reach high TOD scores in the 5D built-form aspects as well as the aspect of ridership, whereas, in the aspect of ridership, some low TOD level suburban stations outperform some urban stations with higher TOD level values. This outperformance indicates the importance of these low TOD-ness suburban stations. A correspondence analysis is conducted based on the developed typology. The results suggest that there are differentiations among the TOD nodes, in terms of residential housing price and building use. Based on thesis result, this thesis argues that these differentiations would lead to the complementarity among the stations. Thus, a station should not be seen as an isolated node. In other word, TOD should be assessed and planned in a network system view.

Keywords:

Transit-oriented development, TOD Typology, TOD Network, Network Synergy, Complementarity

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1. INTRODUCTION

1.1. Background and Justification

With increasing urbanization rates worldwide, cities are being challenged by urban problems such as traffic congestion, sprawl, environmental degradation and spatial segregation. The automobile-oriented, road-based transport systems are criticized for contributing to these challenges. While the demands on higher mobility and land are still increasing, the resources of land and fuel are limited. Moreover, the overuse of private automobiles is one of the main contributors to greenhouse gas emissions (U.N. Habitat, 2009). Thus, it is an urgent and significant issue to develop a sustainable transport system that can improve efficient use of the scarce resources.

Seen as a planning tool that integrates transport and land use, transit-oriented development (TOD) is a promising approach to promote transit patronage and dissuade citizens from the usage of the private automobile. It is typically understood as the development of transit stations around high-density (density), land use mixed (diversity) and, walkable and cycling-friendly environments (design). Density, diversity and design are disseminated as the three of the most important dimensions of TOD (Cervero & Kockelman, 1997). It is such a development located at a rapid transit system that can compete with automobiles in long trips and attract more people to walk or cycle in short trips. This can lead to lower usage of the automobile and a denser urban fabric, consequently, less consumption of fossil fuel and concentrated opportunities and services (Calthorpe, 1993; Cervero and Kockelman, 1997; Cervero, Murphy, Feerell, Goguts & Tsai, 2004).

‘TOD-ness’, a term first developed by Evans, Stryker, Kuzmyak & Pratt, (2007) was defined as “potential device for considering the degree to which a particular project is intrinsically oriented towards transit”. TOD has been championed as one of the most effective solutions for maximizing the potential return on investment for transit projects (Higgins & Kanaroglou, 2016), but due to the starting conditions of different stations, the actual implementation may be different. Assessing the existing TOD conditions and understanding the heterogeneity of the built environment before implementing a TOD project become vital to enhance the success rate of the project.

1.2. Research Problem

Recent research has been focusing on assessing the performance of individual transit nodes within a TOD network, using methods such as Spatial Multiple Criteria Analysis (SMCA) (Singh, 2015), in order to arrive at a TOD-ness value for different transit nodes. Such measurement is important to evaluate the extent to which an area is oriented towards transit, but usually insufficient for the understanding of the heterogeneous built environment characteristics of area around train stations. This is because the TOD characteristics at the node level (in this thesis, defined as TOD nodes) tend to be lost in the process of indicator aggregation. Studies have suggested that the heterogeneous built environments critically affect the implementation of TOD, which means TOD might have different typologies according to its built environment. This implies that general TOD-ness values might not be able to **reflect the performance** across different types of nodes in the transit network because the nodes might play different roles in the network, and as a network system, there might be synergy effects between nodes of the TOD network.

1.3. Research Objectives and Questions

1.3.1. General Objective

This thesis aims to develop a TOD typology, which will serve to identify the characteristics of different nodes in the transit network. Based on this typology, to further analyse synergy effects between TOD nodes of the TOD network, understanding how the individual nodes interact and contribute to the large-scale TOD network, potentially to network synergy.

1.3.2. Sub-objectives

In order to achieve the research objective, several sub-objectives are derived:

- i. To identify the reasons of the variation of TOD at node scale
- ii. To identify the dimensions, and the indicators to enable the TOD typology development
- iii. To develop the TOD typology
- iv. To identify the roles of the TOD nodes in a TOD network
- v. To measure the synergy in a TOD network

1.4. Research Questions

The research questions related to the sub-objectives are:

(i.) To identify the factors causing the variation of TOD at node scale

(1) What are the factors that causes the difference in TOD implementation?

(ii.) To identify the dimensions, and the indicators to enable the TOD typology development

(2) What are the main dimensions of TOD?

(3) What indicators of the dimensions should be used to develop a TOD typology.

(iii.) To develop the TOD typology

(4) What methods can be used to develop a TOD typology?

(iv.) To identify the roles of the TOD nodes in the TOD network

(5) What kind of interaction might exist between the nodes?

(v.) To measure the synergy in a TOD network

(6) What is synergy effect?

(7) What method should be used to measure the network synergy?

(8) In which of the 5D dimension of a TOD are network synergy likely to play a role?

1.5. Thesis Structure and the Conceptual Framework

The thesis is structured as follows: in chapter 1, the background, research problem, research objectives and problem, and the conceptual framework of the thesis are presented; chapter 2 contains the discussions of the literatures about the concept of TOD, its measurement, existing studies which have also developed

TOD typologies, the general economic theory of network synergy and the transferring of network synergy theory to the urban issue; chapter 3 explains the methodology, presenting the study area, illustration of the unit of analysis, the geo-processing of 5D indicators, the development of TOD typology and the network synergy measurement; chapter 4 discusses the results of the two main analyses: latent class analysis and correspondence analysis; finally, conclusions are drawn and plans for future research are discussed in chapter.

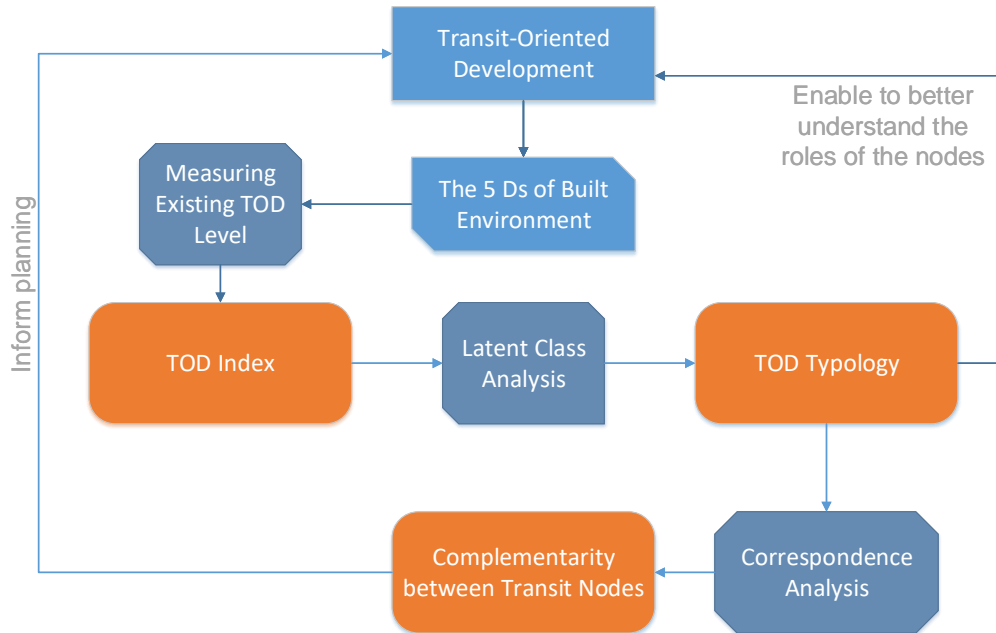


Figure 1 Conceptual Framework of the thesis

Figure 1 illustrates the conceptual framework of this thesis. As the essence of TOD, the 5Ds dimension (*density, diversity, design, distance to transit* and *destination accessibility*) are adopted to first measure the existing TOD level (which is referred as TOD-ness in this thesis), and based on the measurement, the TOD node typology will be developed with the latent class cluster method. Later on, based on the developed TOD node typology, correspondence analysis will be conducted to explore the complementarity between the transit nodes.

2. LITERATURE REVIEW

2.1. Concept of TOD

Concisely, the main characteristics of a TOD development are commonly referred to as the 3D's of the built environment: *density*, *diversity* and *design* (Cervero & Kockelman, 1997). Later on, these were expanded into 5Ds, adding another two criteria of the built environment: *destination accessibility* and *distance to transit* (Ewing & Cervero, 2001). Cervero and Kockelman (1997) argue that compact neighbourhoods (*density*) can dissuade vehicle trips and encourage non-motorized travel by bringing origins and destinations closer together to create an opportunities-concentrated (*diversity*) zone within walking or cycling distance (*design*). While *destination accessibility* refers to the ease of access to trip attractions, *distance to transit* is the factor measured as an average of the shortest street routes from the residences or workplaces to the nearest transit node. Therefore, *distance to transit* delineates the impedance to take transit. These criteria are interrelated (e.g. Ewing (2008) argues that since density and diversity co-exist, many of their benefits are inextricable) and even overlap (e.g., to some extent, diversity and destination accessibility are related to trip attraction (Ewing & Cervero, 2010). Yet, the interrelation shows that the criteria of TOD are not isolated, which also indicates that the implementation of TOD is **multi-dimensional**.

When implemented correctly, the potential benefits of TOD are abundant. Cervero and Murakami (2009) found that TOD is well suited for financing railway infrastructures, especially in the cases characterized by high densities. They take Hong Kong as example, and demonstrate how the investment in TOD might be paid off with the increase in transit patronage and the gaining from higher real estate prices. In the cases of suburbanization, TOD can also be adopted to address the problem of declining accessibility. Cervero and Day (2008) found that relocation to the suburban areas near a transit station could moderate the decline in job accessibility, encouraging more people to take transit. Studies also find that TOD has positive effects in creating vibrant, rich and liveable urban places, increasing physical activities and thus enhancing the public health and quality of life (Frank, 2000; Dittmar & Poticha, 2004). From these points of views, it can be concluded that TOD is **multi-functional**, as its core assumptions are manifold, such as to reduce sprawl, increase transit ridership, reduce car use, etc.

2.2. TOD Measurement

Depending on the conditions around the different stations, the implementation of a TOD may be different. Assessing the existing TOD conditions and understanding the heterogeneity of the built environment before implementing a TOD project become vital to enhance the success rate of the project. A thoughtful analysis of the existing built environment can ease facilitation of a future TOD (Kamruzzaman, Bakker, Washington and Turrell, 2014). (Singh, 2015) shares a similar opinion and she argues that a scientific analysis on measuring existing TOD levels is a prerequisite that can help to uncover to what extent an area is transit-oriented, and because of what reasons. Therefore, she carried out her research in the TOD network of the city region of Arnhem and Nijmegen, in the Netherlands, by aggregating multiple spatial indicators under a SMCA framework to arrive at a general TOD level value.

However, for measuring the existing levels of TOD, having such a general value is essential but it is insufficient for the understanding of the heterogeneous built environment because the TOD characteristics are lost in the process of indicator aggregation. Understanding the heterogeneous built environment of TOD is important since it help to understand why TOD unfolds differently across the system (Atkinson-

palombo & Kuby, 2011). Given the fact that TOD is multi-dimensional and multi-functional, with different purposes and different aims, TOD implementation can take a variety of forms and the individual node can have different roles within the network system, complementing each other (Atkinson-Palombo & Kuby, 2011). Furthermore, there is no “one-size-fits-all” TOD mode (Austin et al., 2010). Based on these arguments, it can be indicated that a well-performing TOD transit node does not necessarily have to be ideal in all dimensions of the conventional TOD criteria and that TOD planning rarely starts from zero. Therefore, the various characteristics of the existing built environment could be the determinant factors forming the heterogeneous typologies of TOD. Studying the typology of TOD is, therefore, in a prominent position to address the problem.

2.3. TOD Typology

Interest in developing a TOD typology is emerging which regards TOD typology as a tool for informing policy prescription and evaluation (Higgins & Kanaroglou, 2016). According to (Kamruzzaman al., 2014), “developing a typology is a way to group together areas that have a common set of characteristics”. The authors also indicate the benefit of developing a TOD typology which are as following: (1) bring convenience to urban planning, design, and operation since within the same TOD typology they can share a same set of strategies; (2) identify the general development potentials so that once a TOD is classified, the optimal figuration can be deducted (e.g. the desirable density, mixed use); (3) reduce the complexity of managing the infrastructure by enabling a common standard within the same TOD typology (e.g. operations); (4) enable comparison within the same typology, identifying the benchmark station of a certain type which can help to assess the other stations of the same type.

Research regarding the definition of TOD typologies has been carried out since the birth of TOD. Calthorpe (1993) made a dichotomy between residential TOD and job-generating TOD. Dittmar and Poticha (2004) expanded these dichotomous typologies with the distinction between urban and suburban areas. In addition, Hancock et al., (2014) identified 5 types of TOD for strategic planning. These typologies are regarded by Higgins and Kanaroglou (2016) as the “normative TOD typologies” since it only generally “outlines the characteristics of what different TOD contexts should look like in terms of factors such as densities, housing types, and transit service”. Aside from these normative typologies, research has been conducted to achieve a more rigorous assessment by using the “positive approaches”, which aims to reduce the complexity created by the heterogeneity in node context. Table 1 to 3 are the gist of relevant researches conducted with the “positive approaches” and figure 2 is the typologies of unsupervised cluster analysis methods used by different literatures.

Table 1, Method adopted by Higgins & Kanaroglou (2016)

Method	Latent Class Analysis
Objectives	To develop a TOD typology with latent class analysis to reduce the complexity creating by the heterogeneity in node contexts.
Conclusion	Latent Class Analysis is a good method for deriving TOD typologies that are statistically rigorous, geographically rich, easily interpretable, and readily transferable.

Table 2, Method adopted by Atkinson-Palombo & Kuby (2011)

Methods	Hierarchical Cluster Analysis, Factor Analysis, ANOVA Tests
Objectives	To evaluate the relationship between geography and the amount and type of advance TOD that takes place across a light-rail transit system, and to provide a baseline for future studies that will investigate how TOD unfolds over time.
Conclusion	Overlay zoning was used most in areas of urban poverty and least in node types with the most single-family housing. Advance TOD coincided strongly with overlay zoning in areas of urban poverty and least in employment and amenity centres.

Table 3, Method adopted by Key literature 3: Kamruzzaman et al. (2014)

Methods	Two-step Cluster Analysis, Multinomial Logistic Regression Model
Objectives	<ul style="list-style-type: none"> To develop a typology for existing neighbourhoods in order to understand the potential for different types of TODs in Brisbane, Australia; To validate the typologies with performance indicators; To support the planning of advanced TOD typologies based on readily available policy indicators.
Conclusion	<ul style="list-style-type: none"> Two types of TODs may be suitable for classification and effect mode choice in Brisbane; TOD typology should be developed based on their TOD profile and performance matrices; Both bus stop and train station based TODs are suitable for development in Brisbane.

There is a variety of methods to develop a TOD typology, through the comparison, LCCM has more advantages as: (1) it uses a probabilistic approach (in case of categorical variables) or means/rates (in case of continuous or count variables) to clustering methods, (2) accommodates unscaled/unstandardized variables, allowing the model outputs to be analysed in their own units, (3) accommodates different data formats (nominal, ordinal, continuous) (Higgins and Kanaroglou, 2016).

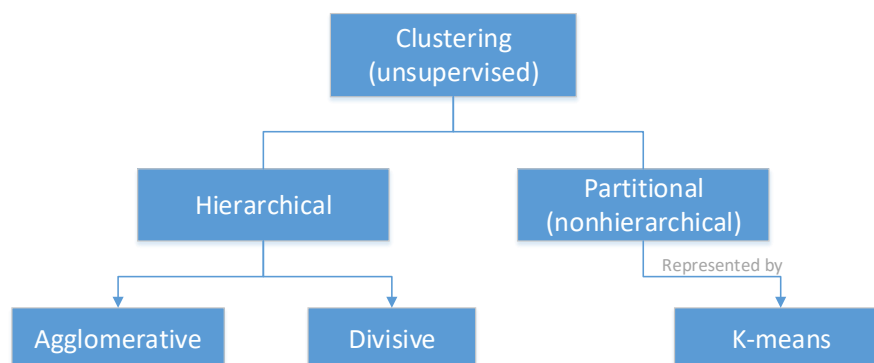


Figure 2, typologies of unsupervised cluster analysis methods

2.4. Synergy Effect of Network

As one of the objectives of this research is to understand the synergy effects among different TOD nodes within a TOD network system, a discussion of the literatures about synergy effects and network system are undoubtedly important.

Described by Meijers (2005), linguistically, the word synergy refers to “a situation in which the effect of two or more co-operating or combined bodies or functions is larger than the sum of the effects each body or function alone can achieve”. The concept of network system is highly associated with synergy effects. A network is basically consisted of the four elements: nodes, linkages between the nodes, flows and meshes (Meijers, 2005). In the sense of urban transport and land use, nodes can be understood as cities, stations etc. and while linkages can be seen as the roads or railways that connect the nodes, flows can be referred to people with travel demands or the goods to be transferred, and meshes, the undeveloped or preserved land (or hinterland) compassed by the nodes and linkages. When these elements function as a network, the nodes cease to be the isolated nodes. With such a network, the interactions between the nodes create synergy effects.

However, the meaning of synergy is too fuzzy to be a concept to understand the mechanism of network synergy (Meijers, 2005). Extensive researches have been done in explaining the concept of synergy and network synergy. Capello & Rietveld (1998) distil the essence of the synergy concept from economic theories, arriving at co-operation, complementarity and externalities, by which they reckon synergy is manifold and it is the expression of beneficial results of co-operation and complementarity.

Linking synergy to network, Capineri & Kamann (1998) categorize networks in two types: ‘club’ type networks and ‘web’ type networks. In the club networks, actors (the nodes, the linkages or the flows) ‘share a common objective, activity or service, while also having parallel interests and transaction chains’. This is also known as ‘horizontal synergy’ that co-operating with each other, actors contribute the common goals, leading to economies of scale, thus an averaging lower fixed cost and positive externalities. Meijers (2005) exemplifies the club networks with the memberships system of a tennis club: individuals cannot afford the facilities but coalesced, they can and the more members the lower membership fees or the longer opening hours. However, if the members all want to play at the same time, it causes negative externalities. In web networks, actors usually have different characteristics (the differentiation). By complementing each other, they reach a positive outcome. This is also known as ‘vertical synergy’ that ‘results from a specialisation process, redistributing resources and activities among the participating actors according to their competence’. The example given by Meijers (2005) is the chain of enterprises. The highly-specialized enterprises focus the effect on a particular stage of the production to achieve elaboration. Together, they form a more exquisite industrial chain. To summarize, table 4 shows the revised types of network and the characteristics.

Table 4, Summary of the club- and web-type network characteristics from Meijers (2005)

Types of Network	Types of Synergy	Types of Interaction	Actor Behaviour	Results
Club network	Horizontal synergy	Co-operation	Common objective or interest among actors	Agglomeration leading to economies of scale
Web network	Vertical synergy	Complementarity	Differentiation in the roles	Actors being specialized in their fields

2.5. Measuring Network Synergy

Transferring the concept of synergy to the urban issues, Meijers (2005) reckon multitude of networks can be found. For example, on a micro level, the urban network nodes can be households, firms, individuals, organisations. On a macro level, it can be the network of cities, in which the nodes are the cities. To build the conceptual framework to measure the network synergy, the urban network synergy needs to be defined.

To structure the framework, Meijers (2005) put up two questions: (1) whether a polycentric urban region is a club- or a web- type; (2) how co-operation and complementarity should be interpreted in the context of polycentric urban regions to provide a meaningful framework for analysis.

For the first question, Capineri & Kamann (1998) reckon (as cited by Meijers (2005)), in real life, networks will have both club-type aspects and web-type dimensions, which means co-operation and complementarity can coexist. This coexistence can be understood as: within a network, nodes can co-operate with certain nodes, at the same time, complement each other with other nodes.

The second question has two pillars: for co-operation and for complementarity. In term of co-operation, Meijers & Romein (2003) argue what is needed is the **regional organising capacity**, which helps to co-ordinate the relationship between the members and generate the network cohesion. Such a regional organising capacity can be achieved through an institutionalised framework of co-operation, debate, negotiation and decision-making. As for complementarity, according to Meijers (2005), in urban regions, complementarity exists between relatively similar ‘activities’ or ‘places’. ‘Activities’ include economic, social and environmental activities, e.g. commercial services, education or medical care. On the other hand, ‘place’ can be referred to business milieus or residential milieus.

Moreover, two important preconditions related to supply and demand must be satisfied: (a) **“there must be differentiation in the supply of activities or places”**, otherwise, the activities or places will be in a relationship of competition (since they are more or less similar and mutually replaceable) instead of complementarity; (b) **“the geographical markets of demand for these activities or places must at least partly overlap”**, which means if they are not in the same markets, the supplies cannot meet the demands even if the supplies can cater the demands. Therefore, no overlapping geographical markets will result in no supply-demand interaction, thus no complementarity occurrence. Example given by Musterd & van Zelm (2001) is that if the provisions of different types of residential milieus matches the need of different preferences of a regional population, these provisions are complementary. Additionally, Meijers (2005) states “complementarity often leads to **spatial interaction**”, however, on the other way around, it can be argued that without spatial interaction, the synergy from complementarity can never be achieved. For example, the economies of two cities are complementary, however, if the infrastructure between the two cities (the network linkage) is inefficient and ineffective to enable the spatial interaction (or most extremely, they are completely separated from each other), there will be no synergy generated from the ‘complementary economies’ of these two cities.

Ullman (1956) (as quoted by Meijers (2005)) points out the importance of **intervening opportunities** and the role of **transferability (the costs of interaction)** in the occurrence of spatial interactions. As for intervening opportunities, the term inventor Stouffer (1940) states “The number of persons going to a given distance is directly proportional to the number of opportunities at that distance and inversely proportional to the number of intervening opportunities”, which can be understand, in the network view, as that the more opportunities provided by one node the stronger linkage can this node build with the others; the intervening opportunities offered by the in-between nodes can weaken the linkage between the two end nodes. On the other hand, transferability (the costs of interact) emphasizes on the capacity of the linkage between the nodes.

Interpretation of how intervening opportunities and transferability can be measured in the TOD context is elaborated further in sections 3.5 and 4.3.

2.6. Conclusion

TOD, in simple terms, aims to encourage people to drive less, walk or cycle more in short distance and take public transit in the long trips. In this sense, whenever the trip-makers feel it is easy, comfortable, efficient or effective to travel or commute by walking, cycling or taking public transit, this type of planning can be regarded as successful TOD planning. Therefore, to understand the current TOD level, which is esteemed to be a prerequisite of successful TOD planning, should not be constrained too much by theories or empirical rules. Thus, this thesis argues individual nodes should not be seen in an isolated way but in a systematic view that nodes may play different roles in the system. Based on what has been done by researchers, developing a typology for the transit nodes can facilitate the understanding of the system. Moreover, as a network system, a TOD network in nature may generate network synergy which is usually associated with network systems. Based on existing studies that measure network synergy in the polycentric urban region, this thesis will explore synergy effects in the TOD network. Further explanation and analysis of the TOD network synergy are in section 4.3.

The bundled concepts: places and activities, supplies and demands can help to understand why there are complementarity in the network. As places make up cities, and most activities take place within cities (Meijers, 2005), the concepts of 'places' and 'activities' explain where do people stay/depart to, and why do they stay/depart to. With the rules of 'overlapped market for demands and supplies' and 'differentiation in places and activities', complementarity can be stimulated. In this sense, the supplies and demands of places and activities offer a way to understand the interaction between land use and transport: activities stimulate travel demands, related to transport; places offer the site to hold the activities, related to land use. Transferring this thinking to a TOD network, the TOD nodes are the places, whilst activities around the nodes characterize the nodes (e.g. different land uses invite different activities) and become the reason why people travel to these nodes (because activities have attractiveness). Based on this conceptual transformation, the complementarity within a TOD network can be discussed. The further discussion is in section 3.5, and application in section 4.3.

3. METHODOLOGY

In this section, the unit of analysis, the measurement of the indicators and the Latent Class Cluster Method (LCCM) will be described. The TOD typologies will be discussed based on the results of the LCCM and the TOD-ness ranking of the nodes calculated, and validated with passenger-count data at each transit station. To further explore the roles of the nodes, the framework of TOD network synergy is established and followed by the measurement with correspondence analysis.

3.1. Study Area



Figure 3 Arnhem-Nijmegen region is located in the Netherlands.

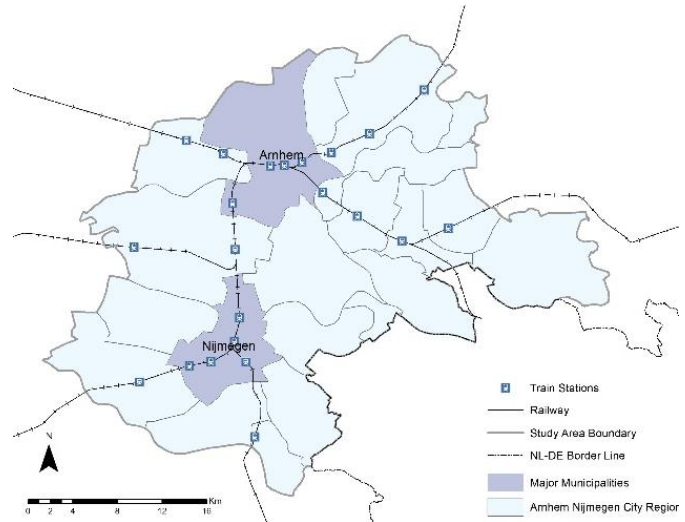


Figure 4 The TOD network of the region, with its 20 train stations.

The Arnhem Nijmegen City Region is located at the heart of a vast metropolitan area in the east of the Netherlands. Consisting of twenty municipalities, the region aims to promote regional cooperation. The region is flanked by the Randstad conglomeration in the west, the Flemish Diamond to the south and the Ruhr to the east. With the ambition to become the second largest economic area in the Netherlands after Randstad by 2020, the city region aims to promote regional co-operation (“Arnhem-Nijmegen Metropolitan area,” 2013). As it is esteemed to be one of the beacons of TOD in the Netherlands (Poiani & Stead, 2014), the city region of Arnhem and Nijmegen was considered a suitable case study for this thesis. Moreover, the city region of Arnhem and Nijmegen is a public body and inter-municipal institution, which accords with the requirement of “regional organizing capacity” as discussed in Section 2.5.

The city region covers more than 1000 km² with a population over 750,000 inhabitants. However, individually, Arnhem and Nijmegen are relatively small-size cities, with the respective population about 154,000 and 170,000, comparing to Amsterdam (845,000) and Rotterdam (620,000). Arnhem-Nijmegen city region can be subdivided into seven regions (Geography of the Arnhem-Nijmegen region, 2015), served by a rail-based national as well as regional transit system composed of 22 train stations, as

shown in figures 3 and figure 4. The railway connection in the region is shown in figure 5. Notably, the rail service shown in figure 5 is the partial railway service of the large railway network in the Netherlands. There are 8 lines serving through the region. The two major stations of the region are Arnhem Centraal Station and Nijmegen Station. Several companies operate the train system in the Netherlands among which NS, ARRIVA and VEOLIA are the three railway companies providing train service in the region. Unlike the usual metro system in other metropolis, only the Sprinter trains (local service) stop at the small stations (such as the stations with relatively low ridership) while the Intercity trains (express service) only stop at the central station of the cities. Nevertheless, the railway service provided in the region is still fast and frequent enough to form the ‘rapid transit corridor’ to enable TOD. According to the time tables published by NS (“Nederlandse Spoorwegen”, the Dutch Railway), in 2016, the daily train frequency in Arnhem Central Station is 597 times which is the highest among the 22 stations in the region.

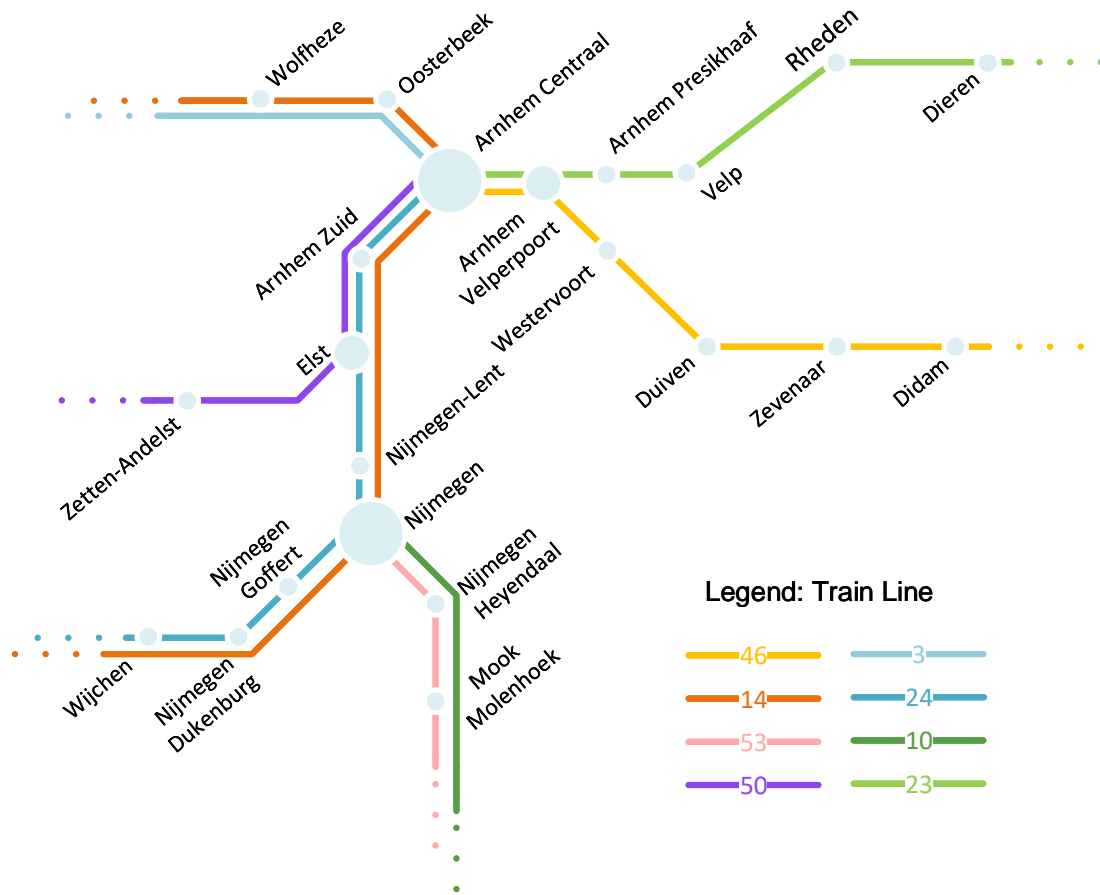


Figure 5 Railway Service in the Region of Arnhem-Nijmegen

3.2. Unit of Analysis

Based on the study of Guerra, Cervero, & Tischler (2013), we take the 800-metre buffer around the transit station as the unit of analysis. The size of the buffer can simulate the catchment of people walking to/from the station along the pedestrian network within 10 minutes, which is a fundamental assumption of this thesis. Figure 6 illustrates the buffers around 3 train stations in Arnhem and the distribution of different uses of buildings. If the Euclidean distance between two station is less than 1600m, the solution in this thesis was to divide the overlapped part into two equal parts and assign them to the each corresponding station, as show in figure 6. Since the value of indicators will be finally be averaged by the buffer size and this is the only case in the region, the overlapping procedure will not cause problems.

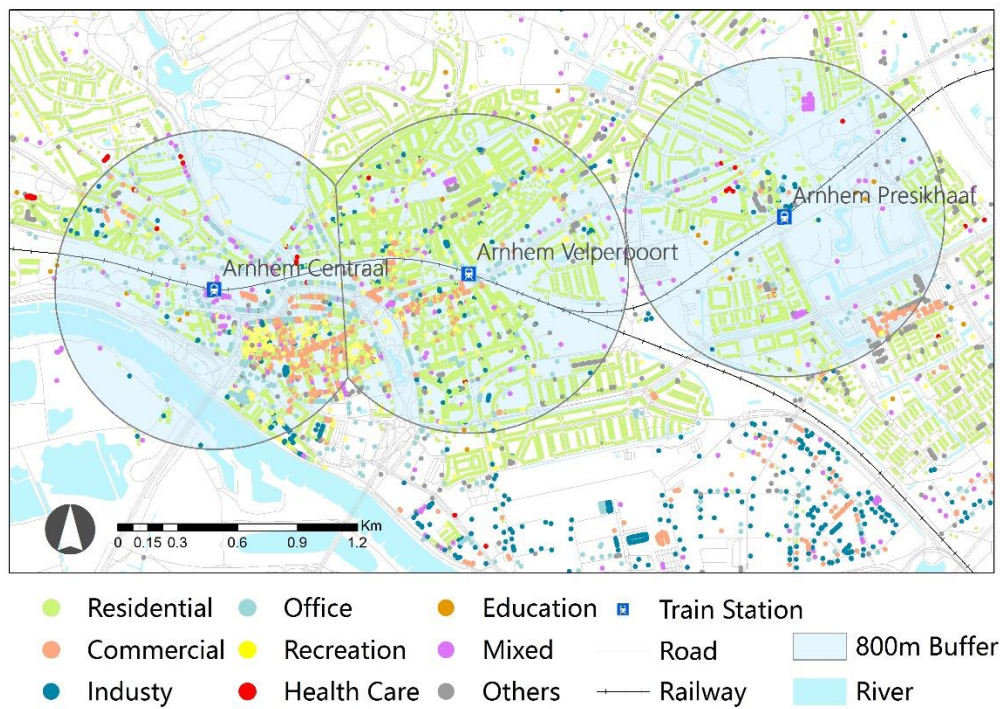


Figure 6 Buffer areas of 800 meters from the three train stations

3.3. Operationalization of the 5D Indicators

The indicators selected for this thesis are quantitative, and derived from the 5D of the built environment indicators (Ewing & Cervero, 2001, 2010). The measurement variables for the indicators and the corresponding data source are presented in Table 5.

Table 5, 5D Indicators and Measurement Variables

Indicator	Measurement variables	Data source
Density	Population Density	Dutch Statistics Office (CBS)
	Job density*	Provincial Employment Survey, 2015 (Province of Gelderland)
	Business Density	Dutch Cadastral Office - <i>Basisregistratie Adressen en Gebouwen</i> (BAG)
Distance to transit	Walking Impedance	Dutch Cadastral Office - <i>Basisregistratie Topografie</i> (TOP10NL)
Diversity	Land Use Diversity	(BAG)
Destination Accessibility	Mixed-ness of Land Uses	(BAG)
Design	Intersection Density	(BAG)
	Length of Bicycle Network	Dutch Cyclist Union (Fietzersbond)
	Length of Pedestrian Network	

*Data not available for stations 5 and 16.

3.3.1. Density

Density was expressed using three measurement variables: population, job and business density, as residential population density is a primary element to promote ridership; job density indicates the attractiveness of a node as trip destination; and business density measures the small business for example the small pedestrian-friendly shop that can maximize the possibility for people to access by walking. All variables were calculated for the buffer area (800 meters), and reflect the density per Km², i.e., population density includes the number of residents living within 800-meter buffer area, around each of the 20 train stations. Job density includes the number of jobs in 21 different sectors, in the buffer area, and was used to reflect the intensity of employment that brings commuters to the buffer area. Business density includes industrial, shops and offices facilities, and it is used to reflect the trip attraction of the buffer area, including the services and the opportunities provided within the buffer.

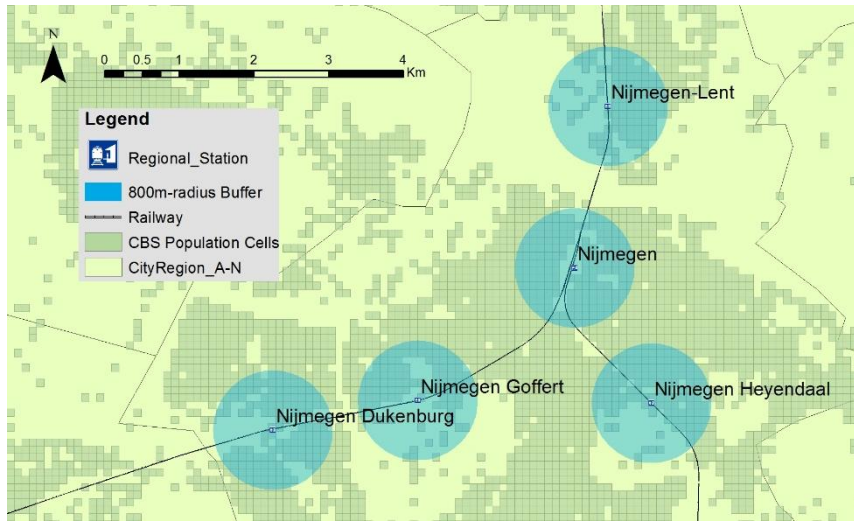


Figure 7 population distribution (source: CBS)

The population data used in this thesis is derived from CBS (Statistics Netherlands) in the form of 100m x 100m grid shape file. Each grid contains the demographic information of corresponding geographic area. Information was extracted by using the 800m buffers of the stations (as shown in figure 7).

3.3.2. Distance to transit

Distance to transit was calculated as the network distance to the transit station within the buffer area. The “closest facility” function of Network Analysis in ArcGIS was used to calculate the distance from the centroid of each cell (CBS data) to the station (illustrated in figure 8), through the pedestrian network. The distances were averaged and calculated for each station. Since the patterns of road network around the stations are different, high values on this variable mean high impedance walking from the resident to the station, i.e., the street is less direct; therefore, it is more detouring to reach the station by walking.

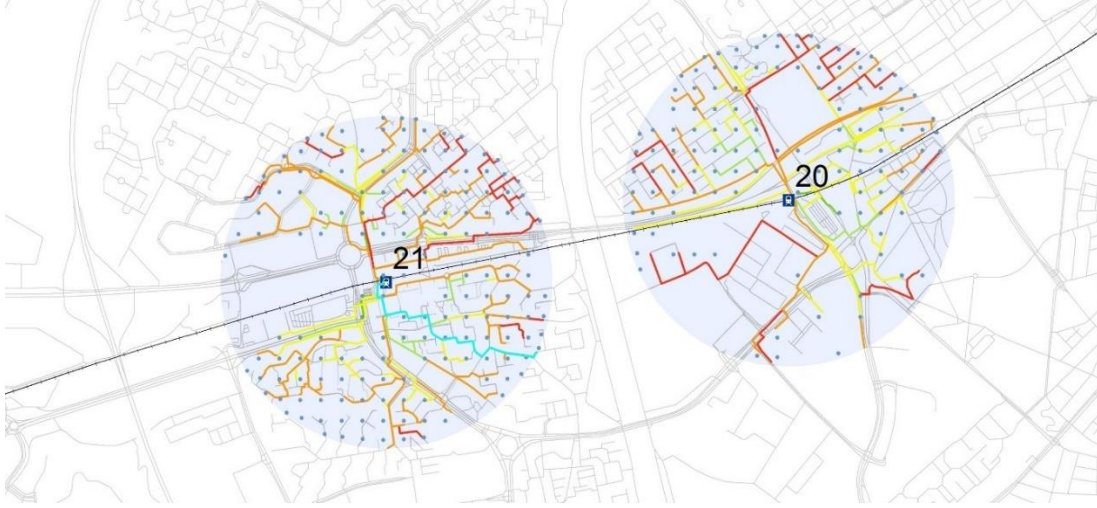


Figure 8 The network distance to transit calculated by Network Analysis in ArcGIS

3.3.3. Destination accessibility

The local *destination accessibility* was measured with the land use mixed-ness index, which indicates the easiness to access resources within short trips. It is calculated with a formula adapted from (Zhang & Guindon, 2006):

$$MI(i) = \frac{\sum_j L_o}{\sum_j (L_r + L_o)}$$

Equation 1, the mixed-ness formula

where $MI(i)$ is the Mixed-ness Index of buffer area i , L_r and L_o are respectively residential land uses and non-residential land uses. The proportion of non-residential land uses within a small calculation area is calculated for each residential point j . The value of $MI(i)$ shows a balanced mixed-ness when it is 0.5. The index is closer to 0 or 1, the more biased to the respective land use.

The geoprocessing was conducted in ArcGIS with the function of ModelBuilder. Since the proportions of residential land uses and non-residential land uses are the key element, their calculation within a certain area is the core. The building use data is derived from BAG. Followed is the procession.



Figure 9 The urban fabric of the area around Station Arnhem Centraal, Arnhem Velperpoort, Arnhem Presikhaaf and Velp.

First, enlarged buffers ($r=1000m$) are created to capture the mixed-ness of margin. The uses of the building were divided into to dichotomy: residential and non-residential, representing by 1 and 0. In figure 9, the blue points are the residential building (marked as 1), the bright orange are the non-residential.

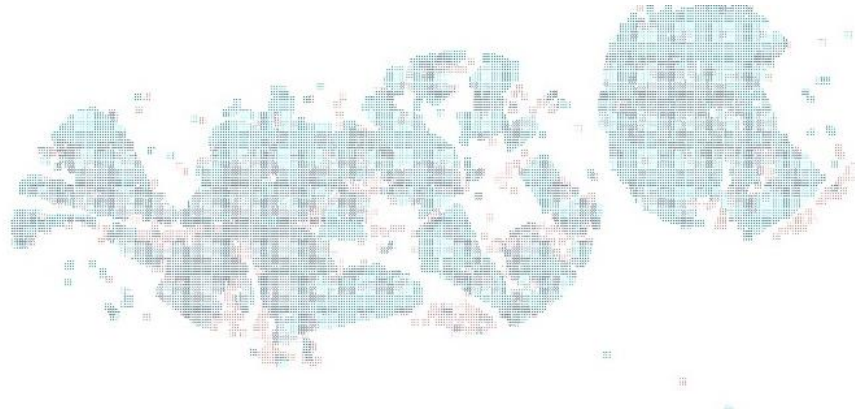


Figure 10 The '1' and '0' points captured by the fishnets

Then, As shown in figure 10, fishnets (the size is 10m x 10m, simulating the average size of the buildings) are created to capture the numbers of '1' and '0' points. They are then translated in two raster images with the cell value representing the number of the respective type of building. (figure 11)

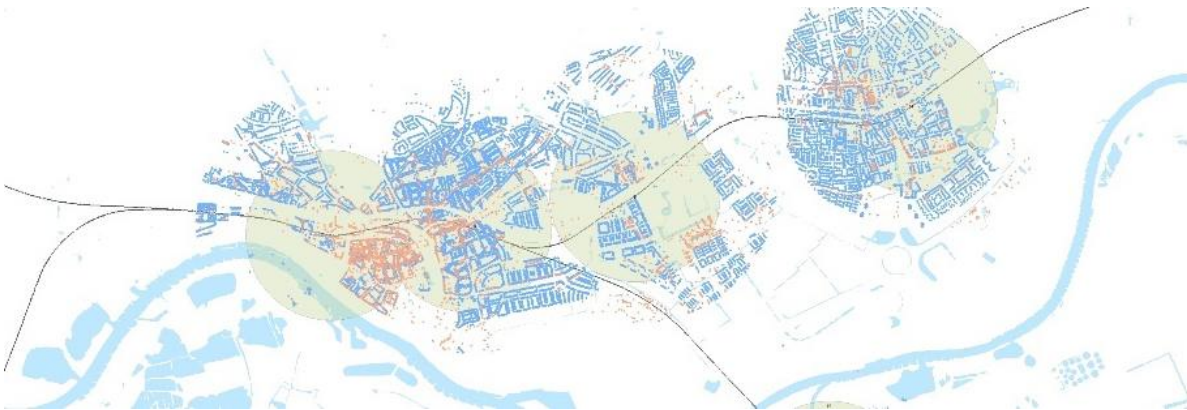


Figure 11 Buildings of residential and non-residential

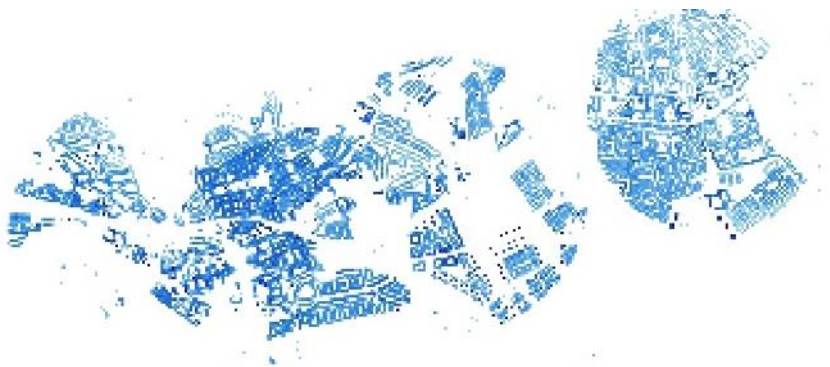


Figure 12The raster image of residential buildings' density



Figure 13, The raster image of non-residential buildings' density

As the next step, the function of “focal statistics” is performed to calculate the number of the building of the same type. The values of the cells within the 100m buffers (simulating the proximity of the buildings) of each cell were summed up, producing a ‘hot spot’ map, with the red spots indicating high residential/none-residential density within the 100m buffers, and low residential/none-residential density in blue (figure 14 show the focal statistics for residential buildings, figure 15 for none-residential)

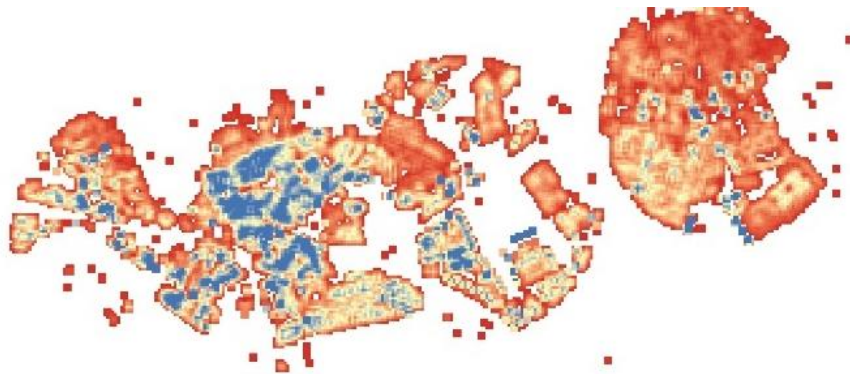


Figure 14, result of the focal statistics for residential buildings

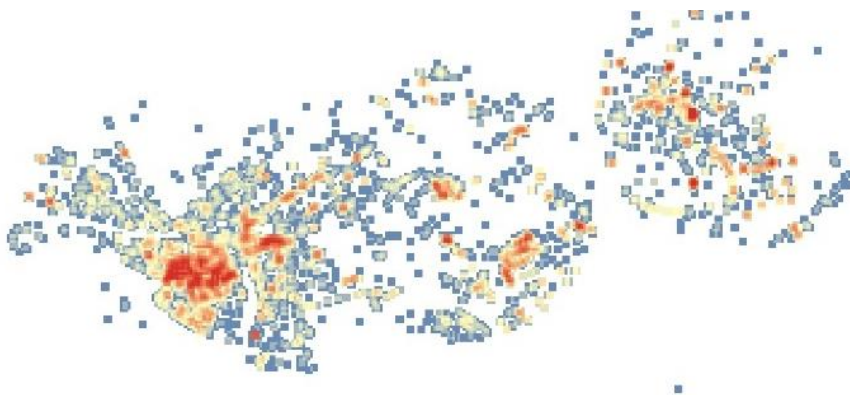


Figure 15, result of the focal statistics for non-residential buildings

Then, the two images are transferred into vector point and aggregated into one layer which contains the focal information of the two types of building use. (figure 16)



Figure 16, the point containing the focal statistics information of the residential and non-residential

3.3.4. Diversity

Land use *Diversity*, referring to the number of different land uses in a given area and the degree to which they are represented in land area, is measured with the widely used ‘entropy’ concept. High land use diversity is indicated by a high value of entropy, thus, higher levels of TOD-ness. This indicator was applied to the Dutch spatial planning context by Ritsema van Eck and Koomen (2008) and adapted by Singh (2015) as follows:

$$LU_d(i) = \frac{-\sum_i Q_{lui} \times \ln(U_{lui})}{\ln(n)}$$

where,

$$Q_{lui} = \frac{S_{lui}}{S_i}$$

LU_i = Land use class within the buffer area i

Q_{lui} = The share of specific land use within the buffer area i

S_{lui} = Total area of the specific land use within the buffer area i

S_i = Total area of buffer i

Equation 2, the entropy formula

Adopted from Cervero and Kockelman (1997), the mean entropy for land use categories is calculated within a half-mile (804.5m) radius which is almost the same as the buffer size of this thesis. To conduct this calculation, information of the different land use points within the 800m-radius buffer around the stations extracted to Excel table, using the above formula.

3.3.5. Design

As for the *Design* aspect, the total length of pedestrian and bicycle lanes was taken as a measure that reflects the length of accessible roads for non-motorized transport, key to the success of a TOD. The total length of pedestrian and bicycle lanes of each node was calculated by summarizing the sub-network clipped with the buffer.

Besides that, intersection density was calculated to measure the street connectivity of the road network of each node. The higher the density, the better for cyclists and pedestrians as the routes may become shorter in terms of travel distance although not necessarily in terms of travel times.

A straight but artful way to calculate this indicator was as follows: (1) to transform the network (which is jointed polylines) into points, since one line segment has two end point, the “intersections” are then the points containing more than two overlapping points which have the same x-y coordinates; (2) to calculate the geometry adding the coordinates to the points, then after giving the point the station ID, extract the data to Excel file; (3) to create an ID for each point attribute using the X-Y coordinates in Excel, then, use the formula “COUNTIF” to count the repeating time of the unique X-Y coordinates, after that use the advance filter to keep one record for one unique X-Y coordinates, finally use pivot table to summarize the numbers of records for each of the stations, which are the numbers of intersections with the buffer. (4) to calculate the density, dividing the numbers of intersections by the buffer area.

3.4. Latent Class Cluster Model (LCCM)

This thesis adopts the positive perspective by applying a Latent Class Cluster Method (LCCM) as a tool for developing a TOD typology for the Arnhem-Nijmegen region. LCCM was chosen for this thesis because (1) it uses a probabilistic approach (in case of categorical variables) or means/rates (in case of continuous or count variables) to clustering methods, (2) accommodates unscaled/unstandardized variables, allowing the model outputs to be analyzed in their own units, (3) accommodates different data formats (nominal, ordinal, continuous) (also illustrated in figure 17) (Higgins and Kanaroglou, 2016).

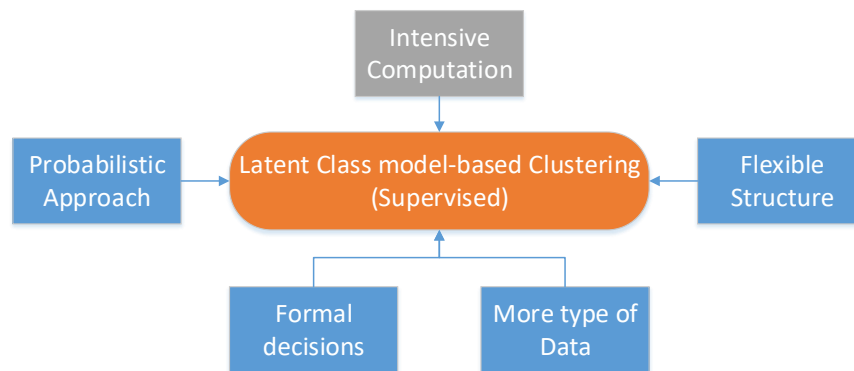


Figure 17 merits and demerits of latent class model-based clustering method

The quantified 5D indicators were input to the software LatentGold (version 5.1) where the LCCM was estimated. The class selection choice was done by analysing two output statistics: the BIC value and entropy value. The BIC statistic is a complement to model fit, and takes into account the parsimony (degrees of freedom or number of parameters) of the model. As for entropy, it indicates how well the model predicts class memberships. The closer these values are to 1 the better the prediction.

In table 6, the model fit statistics of the LCCM are shown. To demonstrate the class selection, the distribution of BIC and Entropy are presented across different classes. The model was estimated from 2 to 7 classes. The selected number of classes was the one with the highest Entropy value, followed by the lowest BIC value. The model with 3 classes was selected as a better solution for the class division.

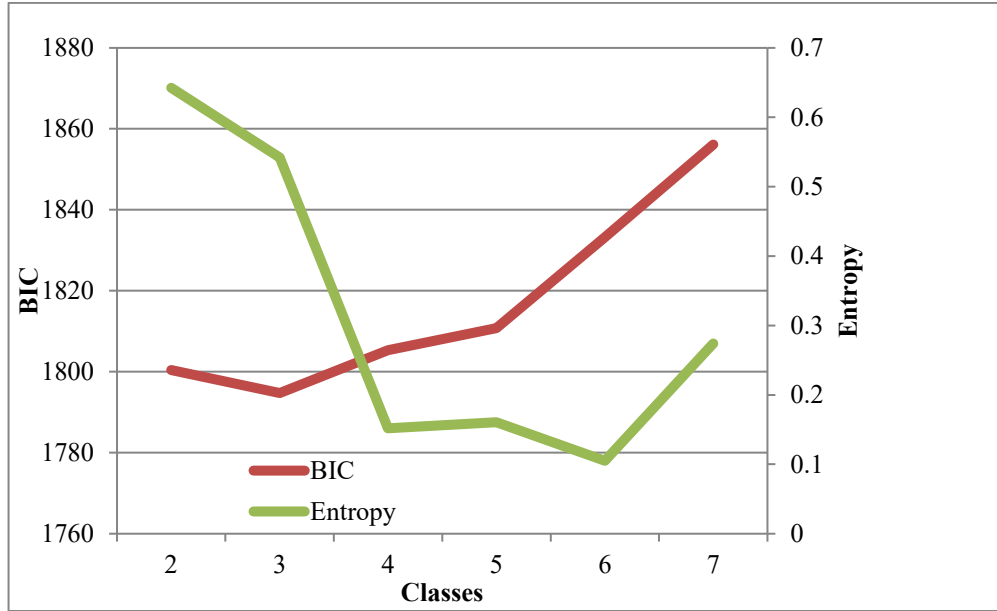


Table 6 Latent Class model fit statistics

3.5. Measuring the synergy in the TOD network

3.5.1 Co-operation and complementarity in TOD network

As a network system, a TOD network also consists of nodes, linkages, flows and meshes, where nodes are the nodes with TOD planning; linkages can mean the pedestrian paths, bicycle lanes and transit services; flows are the trip-makers, and meshes, the none-TOD areas (e.g. farmlands, wetlands, forest). In this sense, a well-coordinated TOD network could also generate network synergy. The TOD network is usually composed by club-type aspects and the web-type dimensions.

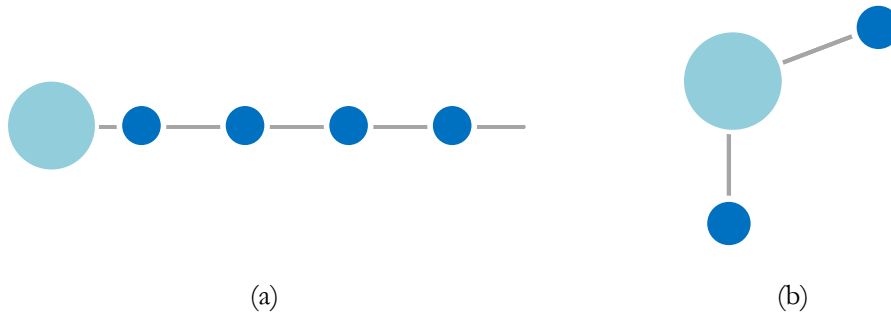


Figure 18 Illustrations of the club type (a) and the web type (b) TOD networks

In terms of club-type network, TOD nodes of the same type may achieve horizontal synergy by jointly contributing to the ridership of the shared transit line. Similar to the tennis club example in section 2.4, it is not economical to build a railway line or a station for just one small, stand-alone municipality, considering the potentially low ridership. But if a railway line will traverse and connect several relatively small municipalities, together, the relatively small nodes of the municipalities can contribute a considerably high level of ridership. As illustrated in figure 18 (a), if all the small nodes on the line are residential nodes (thus, they may have lower land use diversity) and the big one is a node with high attractiveness (e.g. high land use diversity and provide high density of jobs), the small nodes might form a row of feeder nodes with a common objective to access the resources in the big node and together generating stable ridership to the line, which is corresponding to the intervening opportunities theory, as discussed in section 2.6, that the

number of people (in this case, ridership) going to a place (the big node) is in positive correlation to the attractiveness of that place. And since the small nodes in figure 18 (a) are of the same type, the intervening opportunities offered by the in-between nodes will be considerably limited. Thus, in the club type network, the co-operation among the similar nodes can agglomerate the individual demands into a non-negligible one, inviting services. As ridership is a key performance indicator of the railway service, this kind of co-operation among the small nodes could be valuable to railway operation.

As for the web-type network aspects, a TOD network can generate the vertical synergy by the complementation between two different types of TOD nodes in different aspects. For example, the differentiation of different type to the nodes in terms of density can provide different groups of people their preferable choices.

However, in this thesis, the emphasis of measuring the synergy in TOD network will be focus on complementarity, the vertical synergy from web-type network, since (1) the co-operation between the nodes is not the main interaction between the nodes in the network, considering such an interaction requires all the mentioned conditions at the same time to stimulate travel demand; (2) such co-operation is hard to quantify, thus, there is no suitable statistical method to measure and analyse co-operation among these nodes. Nevertheless, measuring only complementarity based on the TOD typologies is still significant to identify the TOD network synergy.

The TOD network in Arnhem and Nijmegen City Region fits well into the requirements of network synergy: (1) for the requirement of '**regional organising capacity**', the city region of Arnhem and Nijmegen is a public body and inter-municipal institution; (2) as for '**the overlapped geographical markets of demand**', the city region has the ambition to become the second largest economic area in the Netherlands, aiming to promote regional co-operation within the region; (3) in term of '**spatial interaction**', the railway services can be assured, as discussed in section 3.1. What remains to be measured and testified is the '**differentiation in the supply of activities or places**'.

To summarize, in this thesis, measuring TOD network synergy will be carried out as measuring the differentiation in the supply of activities or places.

3.5.2 Indicators to measure TOD network complementarity

Ideally, the 5D dimensions, which reflex the TOD characteristics, would structure a coherent framework corresponding to the typology framework. However, not every aspect of TOD can be complementary in terms of demands and supplies of the places or activities. Some of the aspects appear to be unshareable to the other nodes, breaking the rule of 'overlapped geographical markets'. For example, the dimension of '*distance to transit*' measures the catchment area of a station, which cannot fit the rule of complementarity that the demand market should be geographically overlapped. As for the '*design*' dimension, it seems to be of little significance to discuss how the street connectivity or the friendly walking environment of a particular node complement those of the other nodes, because these built-environments tend to be exclusive. Only the dimensions of density and diversity can represent the demands and supplies of activities or places and at the same time meet the two fundamental rules of complementarity, which are 'the overlapped geographical markets of demand' and 'the differentiation in the supply of activities or places'. However, due to the limitation of the data availability, the collected data of density (job density, population density) cannot reflect well the characteristics of TOD network synergy, because these data are just the sum within the buffer.

The **Residential Housing Price (RHP)** is, instead, the selected indicator to measure people's housing choice. The reasons are: (1) RHP is related to several variables, for example land price, the size of the house, convenience degrees to different activities, etc., these variables lead to a variety of RHP, providing different residential choice and catering different residential preference (as discussed in section 2.6, an important aspects of complementarity is to provide different choices to different preference); (2) residential housing fits the 'places' and 'activities' concepts as discuss in section 2.7, since the residential milieus are the 'places' providing residential function (activities) and usually the start point or the end point of a trip, thus RHP, a

reveal of the relationship between supplies and demands, can be considered an indicator to measure complementarity among the nodes in the TOD network.

The data used in the analysis is from *Dutch Statistics Office (CBS)*, it is a geographical dataset providing information at the community level. Since the analysing unit in this thesis is the 800-metre buffer around the station, the communities that are spatially intersected with a station buffer were assigned to the buffer.

The indicator of **Building Use (BU)** of the nodes is also adopted, because the building use distribution indicate the association between node types and activity types. After analysing the correlation between the node typology and the building uses, and the potential differentiation in activities can be identified.

The data source of building use is *Basisregistratie Adressen en Gebouwen (BAG)*. The building within a station buffer is assigned to the buffer. After that, in ArcGIS, the data can be summed up in a table, which is the input in the following analysis.

It should be also indicated that complementarity is multi-dimensional (considering the varieties of ‘places’ and ‘activities’), the two indicators of RHP and BU are just two (albeit important) ones to demonstrate the potential complementarity of a TOD network. Assumed that the ‘null hypothesis’ is ‘there is no complementarity among the nodes in a TOD network’, if only an indicator could prove complementarity, it is good enough to demonstrate the idea. Therefore, the point of the following exploratory analysis is not to be exhaustive, but to test, since not all the dimensions of the nodes can be complementary. The framework in figure 19 illustrates the method to identify and measure the complementarity in TOD network.

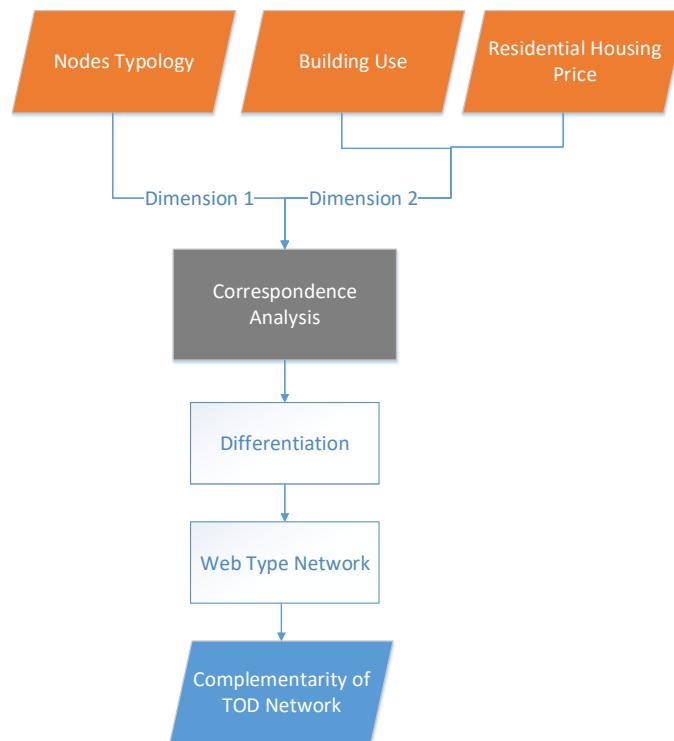


Figure 19 Conceptual framework of identification and measurement of complementarity in TOD network.

3.6. Correspondence Analysis

Correspondence analysis (CA) in this thesis is used as a tool to measure the differentiation among the TOD typology. The analysis was conducted with IBM SPSS Statistics (version 24). It is an analysis that aims to visualize the nature of correlations between the column and the row of the contingency table. The final visualization result of CA is a map with two axes, in which positions of the points (representing the categories) reveal the correlations of the points. Followed are the basic steps to conduct CA, as well as its fundamental formulas and the interpretation. The following kernel of CA is derived from Husson, Lê, & Pagès (2010).

i. Data

The data required is a contingency table where the row and column respectively represent two qualitative variables. Table 7 shows a sample data of CA, where variable 1 is the station types and variable 2, the types of building uses, and value in the table means the number of building. The total sum of the buildings is 3519.

As we want to inspect the correlation between the two qualitative variables (in the case of table 7, how different station type are associated with the building uses), the mathematical language is needed to explore the potential correlation.

If we abstract the contingency table in a mathematical way, it could be shown in the way as figure 20, where x_{ij} is value of row i and column j , with the maximum row/column number as I/J . Therefore, in a table like figure 20, the number of x_{ij} individuals are $I \times J$ (the table cells, in the case of table 7, it is $3 \times 4 = 12$).

		Variable 2				
		Building Use				
Variable 1	Station Type	Social	Health Care	Industrial	Office	Sum
	Suburban Residential Station	141	91	233	231	696
	Urban Residential Station	250	115	149	393	907
	Urban Mixed Core Station	572	42	459	843	1916
	Sum	963	248	841	1467	3519
	Mean	321	83	280	489	\

Table 7, sample data of CA

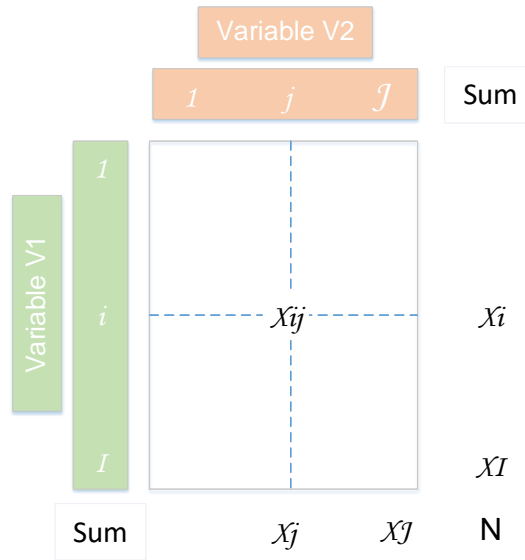


Figure 20 Mathematical abstract of the contingency table

ii. Independence model

Thinking in a probabilistic way, total sum of the building can be seen as the sample size, which is 3519, then in the probability of a building being in social category is the sum of social use buildings divided by the total sum: $963/3519=0.274$. In this way, the probability table can be calculated (see tables 8).

	Variable V2				
	Social	Health Care	Industrial	Office	Sum
Variable V1	Suburban Residential	0.040	0.026	0.066	0.198
	Urban Residential	0.071	0.033	0.042	0.112
	Urban Mixed Core	0.163	0.012	0.130	0.240
	Sum	0.274	0.070	0.239	0.417

Table 8, probability table for the two variables

As a generally acknowledged rule of probability theory, if event A and event B are independent, the probability of ‘A and B happen at the same time’ is equal to the probability of A times the probability of B, which can be formulated as: $P(A|B) = P(A) \times P(B)$. Again, take the social use buildings near the suburban station for example (see tables 8), the probability for a building falling into social use type is 0.274 while the probability for a building being a suburban residential type station is 0.198. According to probability theory, if being a social use building is independent (set as event A) from being a building near suburban residential station (set as event B), the probability of a building being social use building near suburban residential station is $P(A|B) = P(A) \times P(B) = 0.274 \times 0.198 = 0.054$, which however, is not equal to the corresponding value in table 8, which means the category of ‘social’ is not independent from the category of ‘suburban residential’. The difference indicates correlation. To further analyse this indicated correlation, the concept of chi-square distance is introduced.

Before looking into the chi-square distance, some mathematics derivation is needed. Since the probability of an incident can be understood as the proportion of the sample, figure 20 can also be transfer into figure 21, wherein f_i represents the probability of being in variable i, f_j is the probability of falling into variable j, and f_{ij} is the probability of being in row i, at the same time, in column j.

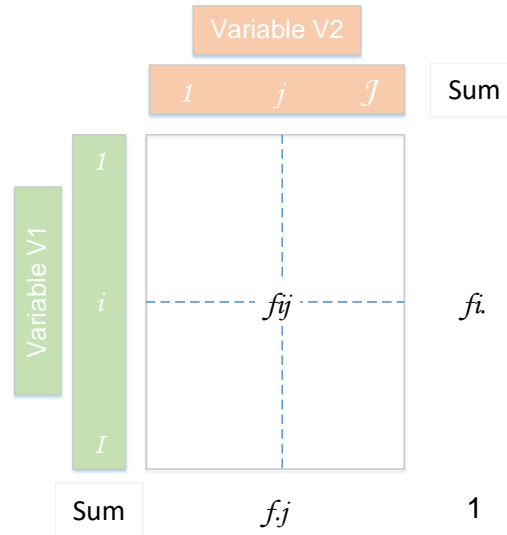


Figure 21, a probability table

iii. Chi-square distance

In the theory of statistics, the general idea of Chi-square test is to determine the difference between the observed number and the theoretical number. In the case of correspondence analysis, this idea of Chi-square is adapted to measure the deviation of the observed probability from the theoretical probability (as shown

in the below formula reasoning). In this light, the chi-square distance can be understood a distance measuring the deviation from independence of the two variables, since the theoretical probabilities is based on the hypothesis that the two variables are independent, so deviating from the theoretical probability means deviating from independence between the two variables. The higher chi-square distance is, the further the observed number is from the theoretical number, thus, the two variables from the corresponding row and column are more independent (less correlated). In a nutshell, CA works with the table of probabilities and aims to visualize the nature of correlation between the two variables.

$$\begin{aligned}
\chi_{obs}^2 &= \sum_{i=1}^I \sum_{j=1}^J \frac{(\text{observed number} - \text{theoretical number})^2}{\text{theoretical number}} \\
&= \sum_{i=1}^I \sum_{j=1}^J \frac{(nf_{ij} - nf_i \cdot f_j)^2}{nf_i \cdot f_j} \\
&= \sum_{i=1}^I \sum_{j=1}^J n \frac{(\text{observed probability} - \text{theoretical probability})^2}{\text{theoretical probability}}
\end{aligned}$$

iv. Inertia

Statistically, inertia can be defined as $\frac{\chi^2}{n}$, a measure without regard to the total number. It describes the independence between the row categories and the column categories. The value of inertia is between 0 and 1, and it is usually far lower than 1. It would have the value of 1 if there would be an utterly exclusive association between the row categories and the column categories. For example, if all the incidents of social building uses belong to the urban mixed core nodes, at the same time the urban mixed core nodes do not have the other building uses, the two categories have the ‘utterly exclusive association’, by which the inertia = 1. In reality, situations are far away from such an extreme hypothesis. The land uses are, to some extent, spread out well (albeit some may lean towards certain types) to the nodes, thus the value of inertia is far lower than 1. On the contrary, the inertia value would be 0, if the observed probability is equal to the theoretical probability, which mean the row categories and the column categories are completely independent. For example, if the proportion of the different building uses are completely the same across the three types of nodes, the inertia value will be 0.

The total inertia of the rows or the columns can be seen as a value measuring the general differentiation among the categories in the rows or the columns. It would be interesting to compare the temporal data to track the path of differentiation changes in time.

v. Graphical interpretation

As described by Meijers (2005): ‘Correspondence analysis is a technique to analyse the association between rows and columns of a table or matrix by representing the rows and columns as points in a low-dimensional Euclidean space (in practice, often a two-dimensional plot). Categories with similar distributions will be represented as points that are close in space and categories that have very dissimilar distributions will be positioned far apart.’

Till here, the introduction of correspondence analysis is enough to understand the result interpretation. For further discussion of correspondence analysis, please see Jolliffe (2002)

4. RESULTS

4.1. Variables Correlation

All the measurement variables are quantified by using ArcGIS. All the indicators are continuous variables. Correlations between the variables were examined (Pearson's correlation coefficient), and results do show high and significant correlation between the variables (Table 9). But according to the fundamental assumption of latent class analysis: the "local independence", input indicators can be highly correlated while output classes are conditionally independent of each other, which means they are not correlated within the class (Masyn, 2013).

Table 9 Correlation matrix of the TOD variables

	Population Density	Job Density	Business Density	Intersection Density	Walking Impedance	Land Use Diversity	Mixed-ness of Land Uses	Length Bicycle + Pedestrian
Population Density	1	.562**	.874**	.748**	-0,126	-0,077	-0,160	.797**
Job Density	.562**	1	.681**	0,436	0,382	0,213	0,147	.518*
Business Density	.874**	.681**	1	.529*	0,073	0,196	0,117	.587**
Intersection Density	.748**	0,436	.529*	1	-0,109	-0,333	-0,403	.876**
Walking Impedance	-0,126	0,382	0,073	-0,109	1	0,220	0,174	0,114
Land Use Diversity	-0,077	0,213	0,196	-0,333	0,220	1	.961**	-0,244
Mixed-ness of Land Uses	-0,160	0,147	0,117	-0,403	0,174	.961**	1	-0,312
Length Bicycle + Pedestrian Network	.797**	.518*	.587**	.876**	0,114	-0,244	-0,312	1

*, ** Correlation is significant at the 0,05; 0,01 level (2-tailed)

4.2. TOD Typology

Table 10 presents the full model results. Model coefficients indicate each class's mean value for each TOD indicator, and associated statistical test. The percentages in parentheses correspond to each cluster's deviation in percentage terms from the sample mean. It is important to say that LCCM's do not require variable transformation, therefore the model outputs are interpreted based on the original units of each variable.

Table 10 Latent Class Cluster Model of TOD nodes

Indicator	Measurement variables	1. Suburban Residential	2. Urban Residential	3. Urban Mixed Core	p-value	R2
Density	Population Density	-2614,01 (-131%)	-582,40 (-14%)	3196,41 (41%)	0,00	0,70
	Job Density	-2466,79 (-248%)	-612,30 (-21%)	3079,09 (47%)	0,00	0,58
	Business Density	-352,28 (-195%)	-238,99 (-81%)	591,27 (53%)	0,00	0,86
Distance to transit	Walking Impedance	-7,20 (-1%)	-15,81 (-2%)	23,01 (3%)	0,79	0,04
Diversity	Land Use Diversity	0,003 (1%)	-0,06 (-28%)	0,05 (17%)	0,06	0,18
Destination accessibility	Mixed-ness of Land Uses	0,005 (3%)	-0,04 (-37%)	0,03 (19%)	0,08	0,16
Design	Intersection Density	-45,96 (-46%)	23,84 (14%)	22,12 (13%)	0,00	0,66
	Length Bicycle + Pedestrian Network	-14853,73 (-42%)	5456,63 (10%)	9397,10 (16%)	0,00	0,71

Percentage between parentheses corresponds to each class deviation from the sample mean.

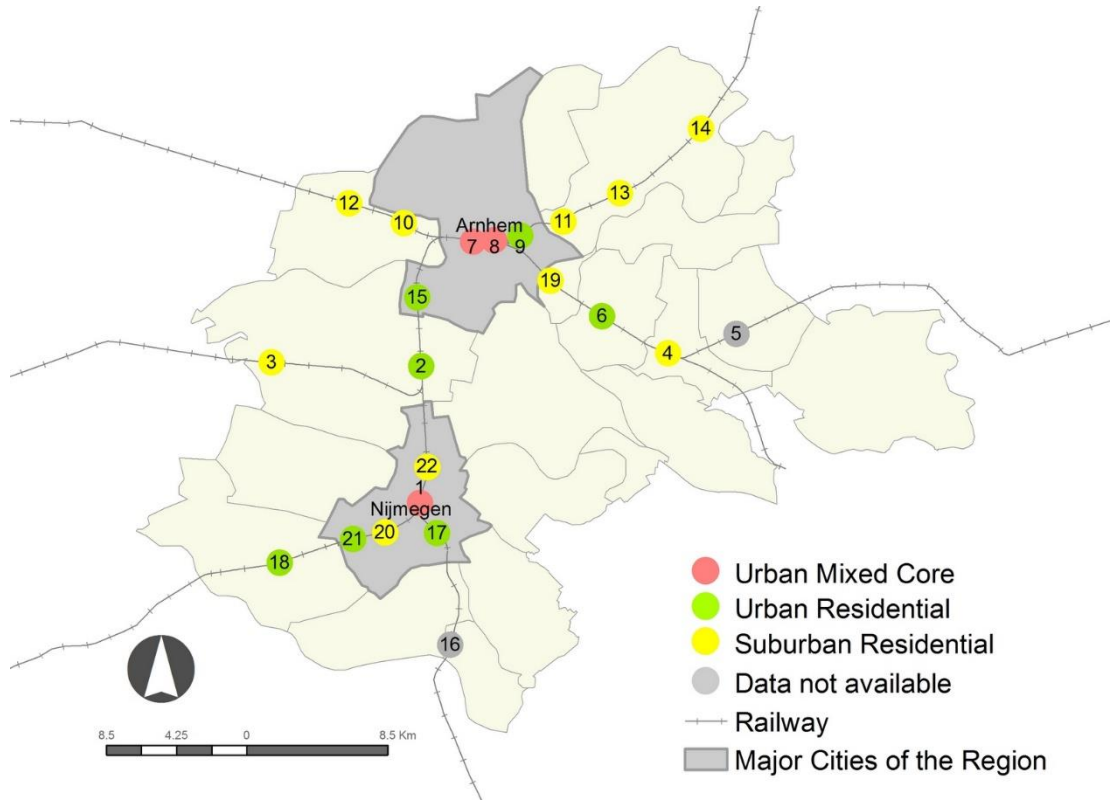


Figure 22, Typology of the TOD network of region Arnhem-Nijmegen

The LCCM clustered 20 train stations of the Arnhem-Nijmegen region into three TOD typologies. Based on the characteristics of the typologies, names are given to enable the recognition and discussion: Suburban Residential Station, Urban Residential Station and Urban Mixed Core Station (figure 22).

The *Suburban Residential* class contains 10 stations, illustrated in yellow in Figure 23. It is characterized by low population density (131% smaller than the sample average) and low job and employment density (respectively 248% and 195% smaller than the sample average). These stations also feature lower-than-average intersection density (a measure for street connectivity), length of bicycle and pedestrian networks. These features are predominantly residential, and located farther away from employment centres. They might be, however, important as trip origins. For instance, station 4 (Zevenaar) ranks low in TOD-ness and the absolute population is relatively low. However, it has a relatively high transit ridership, which accounts for its important role within the TOD network. This means that the TOD-ness value does not necessarily capture the significance of this station for the TOD network.

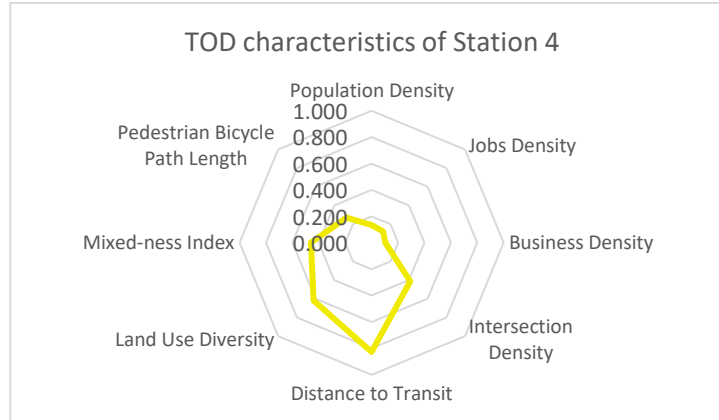


Figure 23, TOD characteristics of Station 4. For illustration, the indicator values were normalized

The second typology was labelled as *Urban Residential* and it is characterized by lower destination accessibility (37% smaller than the average) and lower diversity of land uses (28% smaller than the average) (table 10, figure 24). However, it has more job opportunities when compared to the suburban residential class. The design indicator scores higher for this class, meaning that the street design around the station is suitable for cyclists and pedestrians. Seven stations were classified in this typology and Station 21 is taken as illustration.

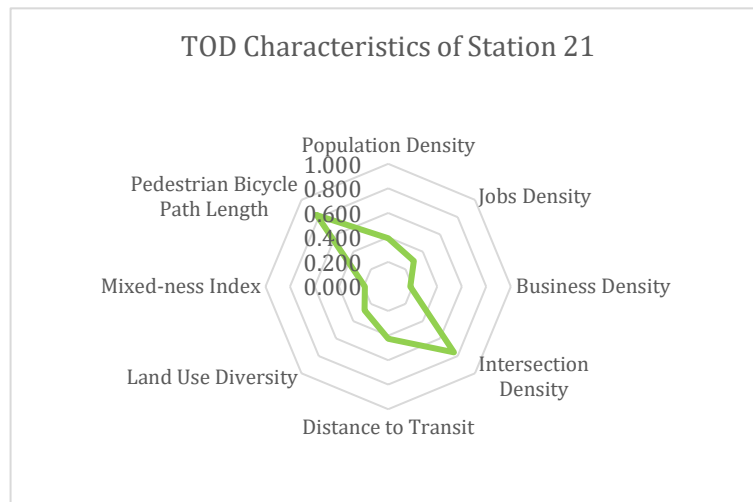


Figure 24, TOD characteristics of Station 21 (indicator values normalized)

The *Urban Mixed Core* class contains the three most urban stations, with all estimated indicators higher than the sample mean (figure 25). These features are characteristic of central business districts and indeed this is where these three stations are located. Station 1 is used to exemplify this station type.

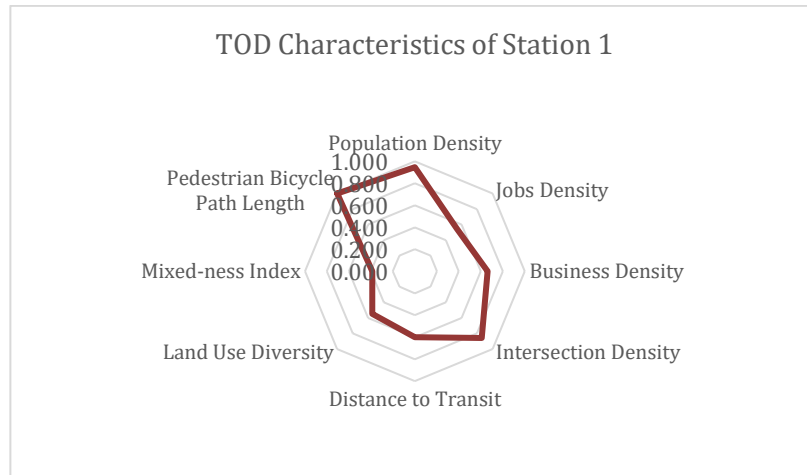


Figure 25, TOD characteristics of Station 1 (indicator values normalized)

Some unexpected classifications were encountered for some stations. For instance, station 6 was hypothesized as a suburban residential instead of urban residential. This can be explained by the location of the station within the urban fabric. Figure 26 shows that station 6 is located right in the middle of the town, while station 19 is located at the edge of the town.



Figure 26, Location of stations 6 and 19 within the urban fabric.

In an attempt to validate the TOD typology, Table 11 discusses the relationship between the ridership of each station (passenger count) with its TOD-ness value (TOD-ness). The assumption is that high ridership would positively correlate with TOD-ness because one of the objectives of TOD is to dissuade travelers from taking the automobile. However, by looking at the difference between passenger count rank and TOD-ness rank, we can explain characteristics of the different stations by highlighting variables other than trip

generators, namely job density, diversity of usage, etc. The passenger count is a good predictor for TOD-ness, but it is not the only, therefore it was used in this analysis as a control variable. For example, station 8 ranks 8th in relation to passenger count, but ranks 2nd in TOD-ness. It is located in the inner city, with the university and the hospital in its surroundings, generating a lot of employment opportunities. The difference in rank may be explained by the power of attraction of this station as an important business center, whereas passenger counts are associated with origins of trips. Also, since this station is near to Arnhem central, which has a higher train frequency, a lot of people cycle directly to this station, thus causing lower passenger counts in station 8. The opposite is observed when analysing the differences in rank of station 4 (3rd in passenger count and 16th in TOD-ness). This station is characterized mainly as a feeder station, performing low within the built-form indicators.

Table 11 Validation of the Typology with Passenger Count Information

Typology	Station	Passenger Count	Passenger count rank	TOD-ness	TOD-ness rank	Difference in rank
3	1	43149	1	0,695	1	0
3	7	38442	2	0,656	3	1
3	8	3672	8	0,668	2	-6
2	2	3863	6	0,375	10	4
2	6	3865	5	0,392	8	3
2	9	3162	10	0,404	7	-3
2	15	2790	11	0,334	11	0
2	17	3287	9	0,426	5	-4
2	18	4214	4	0,458	4	0
2	21	2151	13	0,379	9	-4
1	3	732	18	0,304	14	-4
1	4	4652	3	0,280	16	13
1	10	482	20	0,226	19	-1
1	11	1625	14	0,405	6	-8
1	12	542	19	0,243	17	-2
1	13	907	17	0,228	18	1
1	14	3848	7	0,306	13	6
1	19	2250	12	0,282	15	3
1	20	1000	15	0,319	12	-3
1	22	925	16	0,140	20	4

Passenger count data was supplied from the Dutch train service provider (Nederlandse Spoorwegen – ns.nl).

4.3. Complementarity in TOD Network

The method of correspondence analysis was discussed in section 3.5. In section 4.2, the typology of the nodes in the Arnhem-Nijmegen TOD network is identified. Based on this typology, this section presents the results of the identified complementarities of the TOD network in Arnhem-Nijmegen City Region by using the data of ‘TOD node typologies vs. residential housing price’ and ‘TOD node typologies vs. building uses’ in correspondence analysis, IBM SPSS Statistics (version 24). Many other relations could be explored, for example, job type or house type differentiation among the nodes. However, only *Residential Housing Price* (RHP) and *Building Use* (BU) were selected based on data availability.

4.3.1 TOD node typologies vs. residential housing price

As shown in table 12, the inertia values are far lower than 1, indicated no utterly exclusive association (as discussed in section 3.6) between the TOD node typologies and the RHP. However, the inertia of Urban Mixed Core (0.056) is significantly higher than the other two (0.022 and 0.01), indicating a higher diversity of the residential housing price in the Urban Mixed Core nodes. It means, within the nodes, Urban Mixed Core nodes provide more choices in terms of residential housing price.

Table 12, inertia value for the CA of TOD node typologies vs. residential housing price

Station Type	Inertia
Suburban Residential	0.022
Urban Residential	0.01
Urban Mixed Core	0.056
Total	0.087

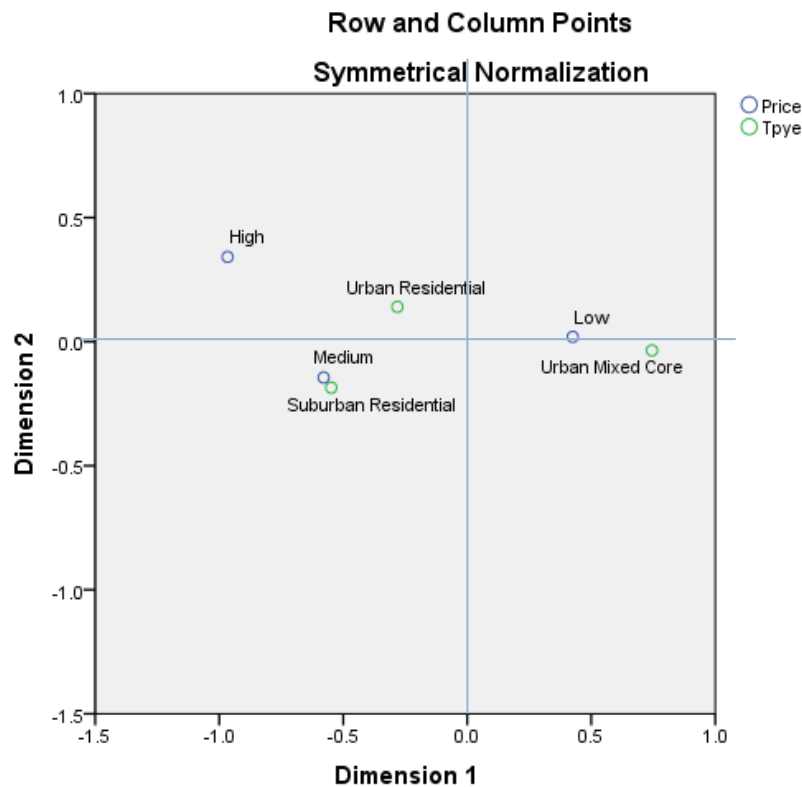


Figure 27, TOD node typologies associated with Residential Housing Price

As an advantage of correspondence analysis, the result of CA is revealed not only in tables but also graphically visualized. Figure 27 suggests the association between different type of TOD nodes and different levels of RHP. In the graph, the origin (0,0) is the mean profile of the three TOD node typologies (as discussed in section 3.6, the origin can also be understood as the theoretical probability wherein the node typologies are independent from levels of RHP). If two node typologies lie close together, then their RHP profile are more homogeneous, whilst the further they stay away, the more heterogeneous. The same condition applies to the RHP: the points of RHP levels lie closer, the more similarly the levels of RHP

distributed between the node typologies. In this light, the point of medium RHP lying very close to the point of the suburban residential node typology indicates the suburban residential nodes is characterized by the medium-priced residential housing. And the urban mixed core typology is more or less closer to the low-price residential housing, whereas, the three node typologies are all not highly associated with high-price residential housing. These can be understood as: (1) since it is the housing price not the land price, the average house size in the urban mixed core nodes might be smaller than the other two typologies, given the prominently higher population density within the urban mixed core nodes (as shown in section 4.2, table 10), an assumption could be that in the urban mixed core nodes, there more multi-story apartments, lowering the average housing price in the communities. With proper data (e.g. the housing type), such an assumption can be tested; (2) the urban/ suburban residential nodes consist of less low-priced house and more medium-priced house. (1) and (2) indicate the differentiation in the provision of different level of residential housing among the three node typologies, therefore, indicate the complementarity among the three node typologies in terms of residential housing price and that people with different preference in residential housing can have more choices within the network than stay in one municipality.

4.3.2 TOD node typologies vs. building uses

Comparing 4.3.1, the inertia of TOD node typologies vs. building uses is relatively lower which indicate the building uses among the three node typologies are relatively closer to the mean profile, whereas, the urban mixed core nodes still have the highest inertia indicating the highest building use diversity, which is consistent with what was shown on table 10.

Table 13, inertia value for the CA of TOD node typologies vs. building uses

Station Type	Inertia
Suburban Residential	0.011
Urban Residential	0.007
Urban Mixed Core	0.017
Total	0.034

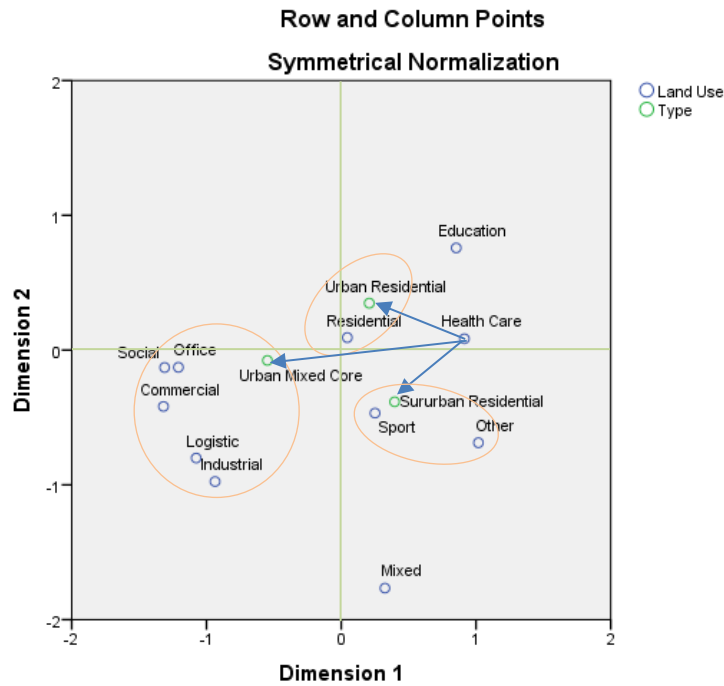


Figure 28, TOD node typologies associated with building use

The visualization of TOD node typologies associated with building use in CA is shown in figure 28 and some patterns are observed. First, the spread-out points can be explicitly grouped into 3 categories according to the node typologies, indicating strong building use differentiation among the three typologies. Compared to the other two, urban mixed core is much closer to the building use points of office, social, commercial, logistic and industrial, which indicates, as expected, a relatively dominant position of this typology in these business and commercial activities. Second, the residential use is the closest to the origin (0,0), meaning the three node typologies have more or less similar proportion of residential building, whilst the residential point is relative closer to urban residential, confirming that urban residential have higher residential proportion. Third, sport uses are closer to suburban residential typology, which implies that suburban nodes have larger tract of land to provide sporting ground. Additionally, health care use should also be noticed, that it is relatively further away from the urban mixed cored nodes in the result graph, indicating more health care facilities are located around residential type nodes.

The distinct differentiation of building uses among the nodes strongly indicates and confirms different roles of the different TOD node types in terms of the provision of activities. Therefore, within the TOD network, the complementarity of activities aroused. Travelling within the TOD network in the City Region of Arnhem-Nijmegen, passengers can access more activities according to their needs.

5. DISCUSSION AND CONCLUSION

5.1. Discussion

In this thesis, a TOD typology was developed to identify the characteristics of different nodes in the transit network. Based on the developed typology, synergy effects between TOD nodes were analysed to understand how their effects contribute to the large-scale TOD network. Three main questions were addressed: (1) whether the TOD-ness values could properly reflect the performance across different nodes; (2) what are the roles of the nodes within the TOD network; and (3) whether there are synergy effects between TOD nodes within a TOD network.

The measurement of TOD-ness in nodes (at the nodes) in the Arnhem-Nijmegen City Region was based on the 5D built-environment dimensions. The results of the analysis indicated variation in TOD-ness among the nodes, as it is similarly demonstrated by Singh (2015). However, when TOD-ness was compared to station ridership, some stations show contradictions in the rankings, as stations that rank low in TOD-ness can still have good performance in term of ridership. This phenomenal ranking difference supports the first claim of the research that a general TOD-ness value might not be able reflect the performance every node. It also indicates that the nodes might not need to be perfect in all the dimensions of TOD.

The above indication leads to second research problem addressed in this study, which was to investigate the roles of the nodes within the TOD network. Latent Class Clustering Method (LCCM) was conducted to develop typologies for TOD nodes. Three typologies were identifiable, and the reason might be that the network is relatively small and dominated by two very strong core stations, which influence the characteristics of the remaining stations in the network. The distribution of the three types of nodes suggests a hierarchical structure of the stations, where the typologies of urban residential and suburban residential serves around the urban mixed core type. The LCCM applied in this thesis allowed us to reduce the complexity inherent to each station environment, by using a means approach to analyse the clustering outputs.

Developing the typology was the first step, to further understand the roles of the nodes within the TOD network; the next step was to identify the interaction between the nodes. Transferring the concept of network synergy from economic field, the interaction between the nodes can be co-operation and complementarity, accordingly, the sub-network are the club type network and web type network. Both interactions between the nodes can contribute to relative network synergy. However, due to the reason that the horizontal synergy is hard to quantify and conditional, this thesis focuses on the vertical synergy of complementarity.

According to Meijers (2005), to achieve complementarity, two fundamental rules should be followed: (1) differentiation in the supplies of activities or places; (2) geographically overlapping market of demands. To measure complementarity between the TOD nodes, the 5D concepts were first considered as a framework to keep consistency with the TOD-ness measurement. However, the rules of complementarity constrain the dimension of design, distant to transit and destination accessibility. As complementarity between the nodes is the complementation of supplies and demands of activities and places, the indicators of residential housing price and building use are selected. And given that Arnhem-Nijmegen City Region runs as a planning body and that the TOD network enables the spatial interaction between the nodes, this thesis argues that measuring complementarity between the nodes can be done by measuring its differentiation. Correspondence analysis was considered to be the right tool to analyse differentiation since it is based on a

probabilistic method to depict the association between two variables of a contingency table. And the result of the analysis of TOD typology versus housing prices (RHP) suggested the urban mixed core nodes offer more choices in lower-price residential housing, which is inconsistent with the usual perception. Since the data is based on the house unit, factors like housing condition or house size are not considered. A good replacement of this data would be the housing type. But due to the data limitation, RHP was adopted to reveal somehow the differentiation in housing choices and trigger discussions. On the other hand, the result of 'TOD typology versus Building Use' suggests strong differentiation between the node types in terms of building uses. As the nodes are connected by the rapid transit service, the differentiation in building use between the nodes add to the total building use diversity of the nodes, which fit well the complementation of diversity. Undeniably, selecting more factors to measure complementarity is necessary to fully demonstrate how the TOD nodes could complement each other between different typologies with the possible spatial interaction enabled by the rapid transit service.

As a result, the nodes interaction based on the network synergy theory indicates the roles of the nodes within a TOD network, that they can be co-operative and contribute to the ridership, they can be complementary in terms of supplies and demands of places and activities. Therefore, with the complementarity from the other nodes, one node does not need to be ideal in some of the dimensions. Outside of the network synergy theory, complementarity between the nodes can also be generally seen as providing services that the other nodes do not have. For example, at the urban mixed core station, there are more trains service, especially the Intercity train travelling outside the region. The residential typologies nodes are complemented as passengers from the residential type station transferring at the urban mixed core station to access the Intercity service. Consequently, the analysis suggested that there are synergy effects among the nodes in Arnhem-Nijmegen TOD network.

5.2. Limitation

To some extent, the results of these analyses are also limited due to the selection of the spatial unit of 800m-radius buffer. This area refers to a 10-minute walking distance. However, the catchment area of a station can be even larger, considering cycling as a feeder mode to transit services. Moreover, since cycling lanes or bus lines are other form of other types of network, the overlay of these networks smooths the rigidity of a single network. Especially in the case of this thesis, bicycle shares 35% of the modal split and the number of bicycles per inhabitant reaches 1.1 bikes per inhabitant, which means averagely every person has more than one bike (Statistics Netherlands, 2015). The reason to conduct the analysis of single railway network is twofold: (1) Considering the relatively higher speed of bicycle, the cycling network can enlarge the buffers and even make the buffers of near stations overlapped. The overlapping will lead to competition of stations in the access trips, which is much influenced by the traveler perception; (2) simplifying the complexity in reality can enable a better understanding of how a regional railway system can promote TOD and achieve network synergy by setting the roles of the nodes.

In this thesis, due to the data unavailability, only the data about passenger count was used to validate the typology, however other measures can be used, namely commute mode share and travel characteristics. Ideally, information about inbound and outbound stations, i.e., the station origin-destination information (the O-D pair of the train trip), would allow the identification of station correlations. However, the Dutch train service provider does not make such information readily available.

5.3. Future study

For future studies, extending the station buffer to simulate the catchment area for bicycle will be recommended. Such an extension will lead to the overlapping of the buffers, which will then lead to the analysis of competition between stations in the access trips. It is vital to understand different relationship between the stations (for example competition or subordination). As the buffers are extended, the unit to calculate built-environment indicator will also be enlarged, including more areas which might contain

different characteristics from the kernel buffers. The increased complexity need to be treated carefully as traveller perception or station level might play a role in assigning the overlapped area to the nodes.

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