Measuring Transit Oriented Development

Implementing a GIS-based analytical tool for measuring existing TOD levels

PEDRAM FARD March, 2013

SUPERVISORS: Dr. ir. M.H.P. Zuidgeest Ir. M.J.G. Brussel

Measuring Transit Oriented Development

Implementing a GIS-based analytical tool for measuring existing TOD levels

PEDRAM FARD Enschede, The Netherlands, March, 2013

Thesis submitted to the Faculty of Geo-Information Science and Earth Observation of the University of Twente in partial fulfilment of the requirements for the degree of Master of Science in Geo-information Science and Earth Observation.

Specialization: Urban Planning and Management

SUPERVISORS: Dr. ir. M.H.P. (Mark) Zuidgeest Ir. M.J.G. (Mark) Brussel

THESIS ASSESSMENT BOARD: Prof. dr. ir. M.F.A.M. van Maarseveen (Chair) Dr. C.J.C.M. Martens (External Examiner, Radboud University Nijmegen)

ADVISOR: Ph.D. Yamini Singh



DISCLAIMER

This document describes work undertaken as part of a programme of study at the Faculty of Geo-Information Science and Earth Observation of the University of Twente. All views and opinions expressed therein remain the sole responsibility of the author, and do not necessarily represent those of the Faculty.

ABSTRACT

Transit Oriented Development (TOD) as a promising planning concept tries to ensure a more sustainable development through integrating land use and transport systems. However, lacking a spatially explicit measurement tool is a recognized drawback associated with the TOD concept. This issue hinders stakeholders, decision makers and practitioners from getting a correct perception of the existing levels of TOD-ness for areas which they are interested to develop, upgrade or maintain.

This study addresses the issue by developing an inherently spatial composite measure called potential TOD Index, which can measure the degrees of TOD-ness in an area-wide approach based on regular tessellation of space.

The research was conducted for the Arnhem Nijmegen City Region in the Netherlands, which faces sustainability issues in terms of utilizing transportation facilities and regional mobility.

Although, the developed method was virtually capable to measure TOD levels by considering functional, economic and built environment aspects, due to data and time constraints just builtenvironment related indicators including various densities, level of mixed use and land use diversity were taken into the consideration.

In order to compute each indicator a geoprocessing model was developed within the ArcGIS platform. Hence, respecting different contributions and importance of indicators into the overall level of TOD-ness for a certain location, using ILWIS SCMA, a Spatial Multi Criteria Analysis tool, was performed to integrate the set of indicators into a composite index map.

Finally, the computed index map was analysed using spatial statistical techniques after which potentially high TOD areas that could be upgraded were identified and few alternative locations were suggested for intervention.

Overall, the procedure worked well and has potential to be adapted for different scales. However, data related issue would be a barrier for implementing a comprehensive spatial measurement.

ACKNOWLEDGEMENTS

It is a pleasure to thank those who made this thesis possible.

First and foremost, I would like to thank my supervisors Dr. ir. M.H.P. Mark Zuidgeest and Ir. M.J.G. Mark Brussel for their constant support and encouragement. I truly appreciate the confidence they had in me that gave me the opportunity to work in my own way. I am very thankful to my advisor Mrs Yamini Singh for her interest and continued support of this research.

I would like to express my appreciation to Dr. Johannes Flacke and Drs. E.J.M. Emile Dopheide for their contribution of data to this study. I am also grateful to the ESRI Nederland for providing the TOP10NL data.

I am very indebted to the European Commission and the Erasmus Mundus program for awarding me the fellowship that allowed me to pursue my graduate studies.

I would also like to thank Dr. David G. Rossiter whose enthusiasm was an inspiration to my research. Finally, I give thanks to my friends and family for their endless encouragement and support.

Pedram Fard Enschede, February 2013 I dedicate this work to Nahide and Mengyi, who are the light of my life.

TABLE OF CONTENTS

1.	INTR	ODUCTION	1
	1.1.	Background	1
	1.2.	Justification	2
	1.3.	Research problem	2
	1.4.	Research objectives and questions	3
	1.5.	Conceptual framework	4
	1.6.	Operational plan	5
2.	LITER	ATURE REVIEW	6
	2.1.	Transit Oriented Development	6
	2.2.	TOD Measurement	6
	2.3.	GIS and Multi Criteria Analysis	8
	2.4.	TOD index	8
	2.5.	Spatial Statistical Analysis and Spatial Clustering	11
3.	Case	Study Introduction	. 13
	3.1.	Study area	13
4.	Meth	odology	. 17
	4.1.	Indicators of measuring TOD	17
	4.2.	Spatial specification of TOD measurement	19
	4.3.	Data collection and preparation	20
	4.4.	Computing indicators	21
	4.5.	SMCA and computing potential TOD index	25
	4.6.	Exploring potential TOD index using visual analysis	27
	4.7.	Spatial statistical analysis	28
5.	Resu	ts and Discussion	. 31
	5.1.	Computed indicators	31
	5.2.	Index value interpretation	33
	5.3.	Visual analysis	35
	5.4.	Upgrading levels of TOD-ness	37
	5.5.	Spatial statistical analysis	38
	5.6.	Alternative locations for intervention	41
6.	Conc	lusions and Recommendations	. 45
Арр	endix	A	. 50
Арр	endix	В	. 51

LIST OF FIGURES

Figure 1: Conceptual framework of the research	4
Figure 2: Operational plan of research	5
Figure 3: Suggested framework of measuring TOD index (Singh et al., 2012)	9
Figure 4: Relative position of the Arnhem Nijmegen City Region in the Netherlands	13
Figure 5: Land use map of the Arnhem Nijmegen City Region	14
Figure 6: Population distribution in the Arnhem Nijmegen City Region	15
Figure 7: Pattern of transportation use for the travels originated, attracted and within the region	16
Figure 8: Average travel distance by mode within the Arnhem Nijmegen city region (MON, 200)7-
2009)	16
Figure 9: TOD measurement indicators discussed in the literature	17
Figure 10: Different possible overlapping patterns of different scale TOD areas overlaid by g	rid
tessellation	19
Figure 11: Application of apportioning method on the variable of interest (e.g. number of houses).	21
Figure 12: Mixed use indicator analysis window; the neighboring area around the given cell	22
Figure 13: Land use diversity indicator analysis window; the neighboring area around the given cell	23
Figure 14: Schematic procedure of computing composite index map based on spatial multi crite	ria
analysis	27
Figure 15: The incremental spatial autocorrelation graph for the potential TOD index	29
Figure 16: Spatial configuration of neighbouring cells for Global Moran's I statistic calculation bas	ed
on the threshold distance of 500 meters	29
Figure 17: Maps of residential and commercial density, mixed use and land use diversity indicators	31
Figure 18: Map of the business density indicator	32
Figure 19: Potential TOD Index Map	33
Figure 20: Map of Potential TOD Index (equal interval classes)	35
Figure 21: Map of Potential TOD Index (standard deviation classes)	36
Figure 22: Spatial autocorrelation analysis result (Global Moran's I statistics)	38
Figure 23: Map of hot spots and cold spots based on the Getis-Ord Gi* Statistic	39
Figure 24: Map of hot spots, clod spots and outliers based on the Anselin Local Moran's I Statistic	39
Figure 25: Anselin Local Moran's I scatter plot	40
Figure 26: The statistically significant hot spots at the confidence level of 95%	40
Figure 27: Frequency distribution of hot and cold spots versus distance to the nearest train station	41
Figure 28: Cumulative relative distribution of hot and cold spots versus distance to the nearest tra	ain
station	41
Figure 29: Bivariate scatter plot of distance to the nearest train station and the rail tracks	42
Figure 30: Proximity to the current railway network	43
Figure 31: Alternative locations to establish new train stations	44

LIST OF TABLES

Table 1: Research objectives and questions	3
Table 2: Criteria table for measuring potential and actual TOD indices	10
Table 3: Adapted list of indicators for measuring potential TOD index	18
Table 4: Indicators standardization scheme	26
Table 5: Criteria weights table	27
Table 6: The descriptive statistics of the computed indicators	32
Table 7: Equal interval classes of index value in relation with the associated initial indicators	34
Table 8: Summary statistics of distances to the railway network	42
Table 9: Attributes of the alternative locations to establish new train stations	44

1. INTRODUCTION

This chapter offers an introduction to the research and justifies the purpose of the study, then describes the research aim, objectives and questions and ends up with a conceptual framework and its operational plan.

1.1. Background

In an increasingly urbanized world, cities face various sustainability challenges like suburban sprawl, inefficient infrastructure utilization and land resource allocation, traffic congestion and environmental pollution etc. the integration of land use and transportation planning is a widely proposed solution, which can contribute to a more sustainable future (Bertolini, le Clercq, & Kapoen, 2005).

In the meantime, different planning theories and concepts have tried to formulate this integration in their specific ways. The concept of *accessibility* as an interface between transport and land use interactions is one of the first approaches that has provided a useful framework for the integration of transport and land use planning.

Another comprehensive approach that pursues such integration is the *Transit Oriented Development* (TOD) concept. It tries to steer land use and environment development towards the transport system. In a more widely agreed description of TOD, specific kind of urban environment with high densities, mixed and diverse land uses, located within an easy walkable area around a transit stop can be recognized as a possible TOD.

The TOD idea considers multiple spatial scales (CTOD, 2011) and suggests concentrating urban development around public transport stations and developing transit systems to connect existing and planned concentrations of development (SMART, 2012). The goal of such development is to shape the urban environment in a way that public resources including urban land, infrastructures and energy would be utilized more efficiently and qualitative aspects of urban environment like walkability and liveability would be upgraded (Curtis, Renne, & Bertolini, 2009).

Although TOD has various benefits, the fact is that it would not happen spontaneously. Investigating different experiences all around the world, Curtis et al. (2009) have concluded that to establish and maintain a successful TOD, involvement of the public and private sector and also local communities is an essential element.

Moreover, there should be some conscious interventions to implement a transit oriented development, thus requiring a reliable measurement tool to assess the existing situation and evaluate impacts of planned interventions at other locations.

The outcomes of this research are expected to provide a quantitative measure of TOD levels and based on existing potentials, facilitate prioritization of development interventions.

1.2. Justification

While TOD is becoming a popular concept among planners and many TOD projects have been implemented and are being implemented, the importance of using a practical measurement tools in the planning and evaluation process is getting more attention. In addition, communicating TOD potentials and achievements to the public, government and investors is taking a critical role. Hence, in order to legitimize the public resources and mobilize private investments towards TOD, there is a strong need to quantify and demonstrate the effects of TOD to all actors (Curtis et al., 2009).

However, regarding various evaluation studies that have been undertaken to assess TODs, there is no uniformly accepted method or index which is able to cover different aspects of TOD, particularly its spatial dimension and can measure existing TOD levels entirely. Therefore developing a uniform index to quantify the level of TOD-ness has been encouraged by various professionals and researchers (Evans, Pratt, Stryker, & Kuzmyak, 2007; Singh, Zuidgeest, Flacke, & Maarseveen, 2012).

Moreover, due to the complex nature of such multi-dimensional spatial index, using a multi criteria approach which is capable of integrating multiple indicators into a single index is essential. In addition, in order to perform series of spatial analytical operations developing a GIS based geoprocessing model would be inevitable.

1.3. Research problem

In the absence of a standard measurement framework, different studies have addressed various aspects of the TOD concept and suggested applying several criteria to assess TODs, some mainly focused on the urban form and physical dimension of TOD. While some others emphasized more on the performance-related and functional aspects of it, there are also some mixed approaches which proposed a long list of indicators at different spatial scales (Renne, Wells, & Bloustein, 2005).

These inconsistencies have deprived stakeholders from a reliable measurement framework which could highlight the areas with high potential for successful investments and also could assess validity and impacts of TOD plans. This is the issue that can mislead governments and private investors about the priorities of investment for the future projects and may lead to misuse of rare resources.

In short, existing deficiencies confront us with a non-structured analytical framework and set of noncoherent indicators that have not been quantified and computed in a straightforward manner. Hence, in order to overcome such shortcomings this study attempts to tackle the problem of:

"Lack of an appropriate practical and spatial measurement tool for measuring the level of transit oriented development"

1.4. Research objectives and questions

1.4.1. Aim

Regarding the discussed problem the aim of this research is:

"To develop a GIS-based spatial model as an analytical measurement tool for measuring existing TOD levels"

1.4.2. Objectives and questions

In order to achieve the research aim several objectives planned to be reached as follows:

Objective	Research Questions
To review and adapt the framework of measuring TOD. (Singh et al., 2012)	 What are the characteristics of introduced indicators? Which indicators can measure the TOD levels better? Is there any need to develop new indicators? What is the optimal/practical set of indicators for this study?
To develop a GIS-based spatial model for computing TOD indicators.	 How to adapt selected indicators to be used in a GIS model? In what spatial extent (station level, corridor-wide or areawide) the analysis should be performed? What are the proper spatial resolution and granularity to carry out the analysis? Which data is needed to compute selected indicators?
To perform the spatial multi criteria analysis to obtain the composite index of TOD-ness.	 How to standardize indicator values? In the relevant spatial scale, how to define the relative importance of criteria? How to visualize the quantified TOD index?
To prioritize potential locations for upgrading levels of TOD-ness.	 How to classify and interpret the TOD-ness index values? How to identify the concentrations of significantly high or low TOD areas? Which TOD factor should be modified to improve the levels of TOD-ness, in certain suitable locations?

Table 1: Research objectives and questions

1.5. Conceptual framework

The illustration below shows the conceptual framework of this research which comprises four major components of:

- Reviewing TOD measurement conceptual grounding to define a practical set of measurement indicators and their specifications.
- Data preparation and GIS model development in order to producing indicator maps.
- Performing spatial multi criteria analysis to arrive at composite index.
- Conducting spatial statistical analysis and identifying potential locations for intervention.



Figure 1: Conceptual framework of the research

1.6. Operational plan

The following diagram gives an overall picture of the thesis operational plan and provides a brief description for each step and also shows the relationship between different phases.



Figure 2: Operational plan of research

2. LITERATURE REVIEW

This chapter presents an overview of literature regarding the topics Transit Oriented Development, Spatial Multi Criteria Analysis (SMCA), applications of GIS, spatial statistical analysis and spatial clustering methods. This provides the background for the research problem and sets out a theoretical framework for the study based on previous researches done on related topics.

2.1. Transit Oriented Development

Over the past few decades achieving sustainability as a common concern has been discussed by many researchers and specifically in the context of urban planning, various strategies and tools have been proposed to reach it. Smart Growth and Transit Oriented Development as a means of it are the two powerful tools which have been proven to support sustainability in different aspects (Cervero, Arrington, Dunphy, & Smith-Heimer, 2004).

While there is no single definition of TOD available, a common characteristic of the concept is illustrated by the California Department of Transportation (2002) as follows: "Transit-oriented Development (TOD) is moderate to higher-density development, located within an easy walk of a major transit stop, generally with a mix of residential, employment and shopping opportunities designed for pedestrians without excluding the auto. TOD can be new construction or redevelopment of one or more buildings whose design and orientation facilitate transit use."

2.2. TOD Measurement

Further, due to the different perceptions of the concept, researchers have emphasized various sides of TOD some like Bernick and Cervero (1996) mainly focused on the measures of the built environment and highlighted the role of the "three Ds" (density, diversity, and design) in the success of TOD. This was later followed by destination accessibility and distance to transit as "two more Ds" and demand management, including parking supply and cost, as the "sixth D" and demographics as the "seventh D" (Ewing & Cervero, 2010).

Reconnecting America (2007) which is a US national non-profit that acts to promote sustainable community development, expresses that TOD is able to bring a wide range of benefits to the cities including:

- More sustainability
- More efficient use of land, energy and resources
- Less oil and gas consumption and cleaner air
- Minimizing traffic increases
- Walkability and healthier lifestyles
- Reduces transportation expenditures
- Opportunities to build mixed-income housing and others.

But from the early days of concept initiation by Peter Calthorpe in the early 90's, despite the advantages and attractiveness of TOD idea it has suffered from the lack of spatially explicit measurement tools that could have delivered spatial analysis and visualisation capabilities

(Schlossberg & Brown, 2004) which could quantify and qualify the level of TOD and its impacts. Therefore, due to the diversity of the employed methods in the previously conducted studies corresponding results of them could not lead to comparable outcomes which then could be used to judge about their degree of success.

This lack of proper measurement framework needs more consideration when we find out that public investment in the infrastructure is too often made without fully understanding the outcomes and sometimes leads to no or little improvement on sustainability. Without measuring the TOD outcomes, mistakes in investment strategies will continue to be repeated and lack of coordination between land use and transportation planning can lead to disappointing results (Renne et al., 2005). Cervero et al. (2004) have also stated that while most research has been done to evaluate the transit

ridership and probable effects on the land value, but other aspects remain rather neglected.

Some other researchers believed that although analyzing the built form and physical dimension is necessary, it is not sufficient, hence Belzer and Autler (2002) introduced 30 performance indicators under the six groups as follows to evaluate TOD outcomes:

- 1. Location efficiency
- 2. Value recapture
- 3. Liveability
- 4. Financial return
- 5. Divers choices, in terms of housing, shopping and modes of transportation
- 6. Efficient regional land use patterns

Further to this, as a part of National Cooperative Highway Research Program (NCHRP), Renne et al. (2005) investigated 56 existing indicators (physical as well as performance measures) under the five categories of: travel behaviour, economic, environmental, built environment and social diversity to determine the success levels of TODs, they carried out a survey amongst transport professionals and suggested a list of top ten indicators for evaluating TODs, as below:

- 1. Transit ridership
- 2. Density
- 3. Quality of streetscape
- 4. Quantity of mixed-use structures
- 5. Pedestrian activity and safety
- 6. Increase in property value
- 7. Increase in tax revenue
- 8. Public perception
- 9. Number of mode connections at the transit station
- 10. Parking

In conclusion, the formulation of TOD measurement and corresponding indicator has been well described in amongst others the report of the Transit Cooperative Research Program, in which Evans et al. (2007) suggested to develop a TOD index as "a potential device for considering the degree to which a particular project is intrinsically oriented toward transit."

2.3. GIS and Multi Criteria Analysis

As it mentioned before, lack of spatiality regarding the TOD measurement has already been recognized and addressed by researchers. Hence, Geographic Information Systems (GIS) with its capability to create, update, analyse and visualize spatial data (Wang, 2006) can be a solution to overcome this shortcoming by providing a set of practical and analytical tools to support the TOD measurement.

Woodsong (2005) in his report described how GIS has been utilized to study land uses within a halfmile radius of existing and potential future rail and ferry transit station locations which helped the Metropolitan Transportation Commission (MTC) to shape the regional vision for implementing TOD within the San Francisco Bay Area.

Further, as a part of research project to identify the most appropriate methods to evaluate the likely impacts of smart growth strategies, Sadek, Wang, Su, and Tracy (2011) investigated two approaches which can be applied to improve current modelling tools towards assessing smart growth strategies; the first one involved a GIS-based methodology by which spatial characteristics of the built environment were quantified using over 50 variables based on high-detail data sources, and the second approach was an enhanced travel demand forecasting method to evaluate the impact of smart growth strategies on travel patterns. Findings of this study also encourage developing a GIS-based method for measuring multidimensional indices.

However, dealing with a set of multiple indicators, reflecting relative importance of them and constructing a composite index, requires using an appropriate analytical method. Mori and Christodoulou (2012); Munda (2006) in their studies indicated that Multi Criteria Analysis (MCA) can be an efficient method to perform such analysis.

Though, according to the Jacek Malczewski (1999) a spatial multi criteria analysis essentially involves three main steps of:

- 1. Standardizing criterion maps
- 2. Identifying the weights of criterion importance
- 3. Combining the criterion weights and the standardized criterion

In most cases the first and last steps has to do with GIS.

Hence, in other studies J. Malczewski (2006), Store and Kangas (2001) stated that the two areas of GIS and multi criteria analysis can benefit from each other and the integration of them would bring synergetic capabilities to the practice.

Further, Beukes, Vanderschuren, and Zuidgeest (2011); Keshkamat, Looijen, and Zuidgeest (2009) applied GIS based methods that rely on spatial multi criteria analysis (SMCA) using ILWIS software package and reported this integration as a successful and preferable method in transport planning. Similarly, Sharifi, Boerboom, Shamsudin, and Veeramuthu (2006) employed the same approach in the context of public transport and land use development planning and recommended SMCA as an effective technique.

2.4. TOD index

In a recent research Singh et al. (2012) have reviewed literature and several case studies and concluded that existing methods and criteria to measure and evaluate TOD, have hardly been

operationalized in the practice. They also stressed the need for developing an analytical tool in conjunction with GIS that may be called as TOD measurement index.

They recommended this index not only for assessment of established projects but also and more crucially for assessing existing conditions on the ground. As is presented in Figure 3 the suggested framework comprises of several modules including: defining criteria and indicators sets, data preparation, criteria map production and finally carrying out spatial multi criteria analysis assisted by SDSS.



Figure 3: Suggested framework of measuring TOD index (Singh et al., 2012)

Since existing indicators in literature contain large sets of relatively dispersed items, Singh et al. (2012) have selected most direct and quantifiable indicators to compose the TOD index. Regarding the current location of transit stops they differentiated two types of indices, one has an area-wide scope and another only focuses on the existing transit area (800 meters around stations), which Singh et al. (2012) aptly named the Potential TOD index and the Actual TOD index. The following tables illustrate two separated sets of measurement criteria and corresponding indicators that have been proposed for computing these indices.

	F	Potential TOD index		
	Criteria	Indicators		
1	What are the various densities	Residential density in TOD area		
1.	in catchment areas?	Employment density in TOD area		
		Commercial intensity/density in TOD area		
2.	What is the level of mixed use	Diversity of land uses		
	in catchment area?			
2	How walkable and cafe is the	Level of mixed-ness of land uses		
э.	TOD area?	Quality and suitability of streetscape for walking and cycling		
		Density of signalled intersections/street crossings		
л	What is the current level of	Private investment of zone		
4.	economic development in the	Number of service/retail establishments		
	area?	Tax earnings of municipality		
	urcu :	Unemployment levels		
		Actual TOD index		
1.	What is the current utilization	Passenger Load in peak hours		
	of transit capacity?	Passenger Load in off-peak hours		
		Service frequency LOS of transit service		
2.	How user-friendly or attractive	Connections to different routes (LOS of transit service)		
	is the transit system?	Safety in transit		
		Safety of commuters at the stop/station		
		Information and ticketing systems		
3.	How accessible is the transit	Interchange to other modes of public transport		
	node and what level of	Access to the station/stop		
	accessibility is provided by that	Pedestrian access		
	node?	Location - Accessibility provided by the station/stop		
Δ	What is the parking supply at	Parking supply-demand for cars/four wheelers		
٦.	station/ston for all modes?	Parking supply-demand for cycles		
	stationy stop for an modes:	Reserved car Parking for special commuter groups		
E	What are the various densition	Residential density in TOD area		
э.	in catchment areas?	Employment density in TOD area		
		Commercial intensity/density in TOD area		
6.	What is the level of mixed use	Diversity of land uses		
	in catchment area?			
7	How walkable and safe is the	Level of mixed-ness of land uses		
7.		Quality and suitability of streetscape for walking and cycling		
		Density of signalled intersections/street crossings		
0	What is the surrout level of	Private investment of zone		
ō.	what is the current level of	Number of service/retail establishments		
	economic development in the	Tax earnings of municipality		
	מוכמי	Unemployment levels		

Table 2: Criteria table for measuring potential and actual TOD indices

However, using these criteria tables and computing the output maps of spatial multi criteria analysis either in form of suitability map or TOD index map can provide us with a range of values without specific indication of required actions in practice, luckily, there are some spatial analytical and spatial statistical methods available in the field that can facilitate interpreting such spatial indices, relevant factors and underlying variables. Some of these methods specifically spatial analytical ones are able to reveal probable spatial patterns and explore the determinants of spatial concentration or dispersion of measured variable (Fischer & Getis, 2010).

As one of few studies that tried to put this in practice, Sugumaran, Meyer, and Davis (2010) have employed spatial statistical analysis aligned with a web based multi criteria evaluation method and prototyped as an Environmental Decision Support System to prioritize local watersheds on the basis of environmental sensitivity.

2.5. Spatial Statistical Analysis and Spatial Clustering

According to Fischer and Getis (2010) spatial statistics comprises of a set of techniques for modelling and explaining spatial data by exploring spatial processes and relationships and assessing spatial patterns, distributions and trends in a quantified manner, consequently spatial statistical literature is a vast area and ranging from abstract mathematical foundations (Anselin, 1988; Getis & Ord, 1992) to data mining and knowledge discovery (Mennis & Guo, 2009; Miller, Miller, & Han, 2001) and practical business applications (Fotheringham & Rogerson, 2008). Though what is significant to this research are statistics of spatial association and spatial cluster analysis, the following section aims to investigate these subjects regarding the current research objectives and correspondent questions.

Páez and Scott (2005) in their review article about spatial statistics and urban analysis, investigated several spatial analytical methods and described how spatial statistics can beneficially support both urban and transportation development practices. They presented three local statistics of spatial association as remarkable tools which are capable in detecting spatial concentration of high or low value locations that we call them 'hot' or 'cold' spots. Mitchell (2009) also expressed that identifying spatial clusters helps to get better insight of spatial phenomenon and possible relationships and consequently lead to more efficient actions.

In their paper first the Getis and Ord's Gi index have been introduced, based on Getis and Ord (1992) to assess overall spatial concentration by measuring the proportion of a variable found within a given distance respective to the total sum of the variable in the study area.

Higher values of this index indicates spatial clustering of high values (hot spots) and lower value of index occurs in case of clustering of low values and also negative spatial autocorrelation.

In addition to this, Páez and Scott (2005) described the Anselin's Local Indicators of Spatial Association (LISA) as the other powerful indicator of spatial concentration. LISA has been developed by Anselin (1995) to assess the influence of individual locations on the magnitude of the global statistic, moreover to identify outlier values and local pockets of nonstationarity or hot spots.

Local Anselin Moran's I index is another spatial statistics associated with the local autocorrelation. It has been adapted by Anselin (1995) based on decomposing a global statistic of Moran's I into portion of each location, so it can be employed for diagnosing spatial outliers and finding spatial clusters .

Later, In order to facilitate performing above mentioned spatial statistical analysis and collect separate analytical functions in an integrated toolbox, Anselin, Rey, and Isard (2010) in a collaborative effort developed and released PySAL as an open source python library that can be embedded by researchers in their own projects and other spatial statistical applications.

In addition to PySAL, they have also provided GeoDa and STARS, two software packages with a graphical user interface that support user friendly environment and rich functionality.

Although, recent software development provided better platforms to apply spatial statistical methods but some other challenges still remain, for instance as a part of PhD thesis of Carrasco (2008) reviewed and reported on several spatial analysis and cluster detection methods specifically for the context of poverty mapping. He analyzed advantages and disadvantages of current methods and highlighted challenges such as the effect of varying scales and data aggregation in cluster analysis and also expressed characteristics and difficulties of cluster detection for continuous and discrete data.

Moreover, Liu, Deng, Shi, and Wang (2012) in their research on developing a new density-based spatial clustering algorithm, reviewed current established methods of spatial clustering, considering seven major groups of; Partitioning, Hierarchical, Density-based, Graph-based, Grid-based, Model-based, Combinatorial algorithms and examined the performance of them. Although they reported some deficiencies in all algorithms regarding geometrical properties and attributes of spatial objects, they also pointed out that under the Partitioning method some algorithms like k-means and CLARANS have been successfully employed for spatial analysis, particularly in facility location siting.

Further, Steenberghen, Aerts, and Thomas (2010) proposed a clustering methodology regarding the specific nature of the network, they tried to detect dangerous segments of the roads in the city of Brussels in Belgium. First they calculated a Dangerousness index based on the distance-weighted number of traffic accidents in neighbourhoods, then employed a linear decrease network clustering method to find spatial concentrations of events on the road network. In addition they also employed Monte Carlo simulation to test the statistical significance of spatial clusters of traffic accidents.

Similarly, Prasannakumar, Vijith, Charutha, and Geetha (2011) in their research towards reducing traffic related accidents, carried out various spatial statistical analysis including; Moran's I spatial autocorrelation calculation, Getis and Ord G statistics, hot spot analysis and kernel density estimation for finding concentrations of incidents and understanding spatial clusters of road accidents. They basically performed all spatial statistical analysis using ArcGIS software and presented the ArcGIS capabilities to accomplish such operations.

3. CASE STUDY INTRODUCTION

3.1. Study area

The Arnhem Nijmegen City Region (Stadsregio Arnhem Nijmegen) is one of the eight Netherlands' city regions located near the Randstad metropolitan area (Figure 4) and supposed to become the second biggest economic zone in the country by 2020 (De Stadsregio Arnhem Nijmegen, 2012).



Figure 4: Relative position of the Arnhem Nijmegen City Region in the Netherlands

The region consists of 20 municipalities, out of which 19 are located within the province of Gelderland and seven have a shared border with Germany.

More than 70 percent of the region is covered by forests, natural sites and agricultural lands, and around 15 percent of its area is characterized by residential, commercial and industrial areas.



Figure 5: Land use map of the Arnhem Nijmegen City Region

The region has around 750,000 inhabitants in an area of over 1,000 square kilometres, however, more than 40 percent of its population settle in the two major city municipalities of Arnhem and Nijmegen (Figure 6).



Figure 6: Population distribution in the Arnhem Nijmegen City Region.

Having a developed road infrastructure (motorways: A12, A50, A73, A15, A325), well equipped waterways (Rijn, Waal, IJssel) and specifically the railway network system comprises 21 operational train stations together with a strategically competitive position worldwide, promises a bright future for the region's development.

Considering all these factors, the legal authorities of the region have given high priority to mobility as the driving force of regional development, so by now they have set the following policies to improve and maintain mobility at regional scale (De Stadsregio Arnhem Nijmegen, 2013):

- Aligning public transport with private transport.
- Promoting spatial development of areas around traffic junctions.
- Making public transport into a coherent and distinguishable whole

However, the results of the recent nationwide mobility survey with a fairly representative sample (Mobiliteitsonderzoek Nederland, MON, 2007-2009) show that the current pattern of transportation use in the region (Figure 7 and Figure 8) is not in line with sustainability principles. Cars as the least environmentally friendly mode of transport are increasingly used for more and longer trips, while using public transport is considered to be more sustainable and sensible choice.

The fact is that this issue coincide with the overall mobility situation in the country where cars account for approximately two-thirds of the total distance travelled on Dutch roads (SWOV, 2010).



Figure 7: Pattern of transportation use for the travels originated, attracted and within the region



Figure 8: Average travel distance by mode within the Arnhem Nijmegen city region (MON, 2007-2009)

Regarding the strengths of the region and its development perspective, along with extensive existing transportation infrastructure rethinking and upgrading the role of public transport, particularly through improving rail connectivity can be a key solution to achieve a more sustainable mobility.

4. METHODOLOGY

This chapter describes the methodology of the research and explains the sequential steps of procedure from framework adaptation, data collection and preparation to establishment and application of geoprocessing models, forming the composite TOD index and further spatial statistical analysis.

4.1. Indicators of measuring TOD

Since this study tries to put the measuring TOD framework into practice and obtain an area-wide index to reflect the existing TOD levels, it was required to refine the broad list of relevant indicators which appeared in the literature (Figure 9) into a practical set of quantifiable indicators.



Figure 9: TOD measurement indicators discussed in the literature

So the proposed framework of TOD measurement (Singh et al., 2012) that has provided such set of practical indicators (Table 2, potential TOD index section), was taken as the basis of TOD measurement for this research. However, because of time constraint and data availability issue only those indicators that could be achievable within the research time period were selected to be analysed in further steps. Thus, while it was not practically possible to obtain data for some indicators like quality and suitability of streetscape for walking and cycling, these indicators were skipped. On the other hand, while density related and land use associated indicators that are central to the TOD concept, could be measured using available and feasible data, they were included in the scope of research.

The following section provides an overview on the selected and analysed indicators within this study.

In principle higher residential and commercial densities support higher level of TOD-ness through shortening travel distances and reducing per capita vehicle travel. Higher densities also support profitable public transport use and make high frequency public transport feasible (Ewing & Cervero, 2001). Hence in this study based on the available demographic data, residential and commercial densities were calculated and later integrated under the density criterion.

In addition to densities, various studies (Evans et al., 2007; Pratt, Evans, & Levinson, 2003; Zhang & Guindon, 2006) pointed out that the level of mixed use, specifically mixture of housing and commercial uses can reflect the spatial configuration of urban land use components and determine the degree to which the public and non-motorized transport can perform efficiently. So as a part of TOD measurement the indicator of level of mixed use was selected and computed by considering both residential and commercial land uses.

On the other hand though, residence and workplace locations are important but there are much more activities and land uses over space that generate and attract trips and raise the demand for transit. Depends on the location and spatial spread of these land uses people may have to travel at different distances to satisfy their trip purposes. In an ideal Transit Oriented Development the higher diversity of land uses maximizes efficiency of trips by providing multiple destinations within an easy accessible area (Cervero et al., 2004). Regarding this character of land use diversity and its contribution to the levels of TOD-ness, the land use diversity also was included in this study.

Nevertheless, due to the regional scale of study, applicable level of detail and data availability issues the indicators of "Quality and suitability of streetscape for walking", "Quality and suitability of streetscape for cycling" and "Private investment per unit of area" were skipped and also the indicators of "Density of signalled intersections or street crossings", "Tax earnings" and "Number of service or retail establishments" were eliminated from consideration.

Moreover the "Number of service or retail establishments" that targets the number of specific businesses per area, due to the data constraint was replaced by the proxy indicator of business density. The Table 3 shows the modified list of indicators which were adapted for measuring potential TOD index in this study.

Criteria	Indicators	Type of the Measure
Level of density	Residential density	
	Commercial density	Built
Level of mixed use	Level of residential and commercial mixed use	Environment
Level of diversity	Diversity of land uses	
Level of economic development	Business density	Economic

Table 3: Adapted list of indicators for measuring potential TOD index

4.2. Spatial specification of TOD measurement

There are several spatial definitions for TOD area that appeared in literature which conceptualize transit oriented development at different spatial levels. However most of definitions agree in the common character of walkability in an area with a radius ranging from 250 to 800 meters around high quality transit systems, such areas theoretically can cover 20 to 200 hectares of development which in the context of urban studies can be counted as a medium spatial scale. This scale is usually not subject to typical data collection and aggregation efforts, census organizations and statistics departments generally collect data at a finer spatial scale of land parcels or city blocks and often due to the privacy concerns aggregate the collected data into a coarser spatial scale of neighbourhoods, census tracts or administrative boundaries (Parker & Asencio, 2008).

Hence, the spatial data and variables needed for measuring existing TOD levels most likely have to be disaggregated.

On the other hand, the spatial scale of potential TOD index as an area wide measure should be such that makes it possible to capture and represent the spatial variation of underlying indicators

accurately and at the same time keep the spatial database and computing processes, efficient and manageable. One well-established method to meet these requirements is the tessellation of space (Mitchell, 2009), that can help to model and represent continuous spatial phenomena by an optimum number of spatial features which are denoted by grid cells.

Considering all above, different grid tessellations of 100x100, 200x200, 300x300 and 500x500 meters were created by using the *Fishnet* function of ArcGIS, then the performance of some common spatial analysis functions like *Union, Near* and *Spatial join* were assessed over these different grids.

Finally, according to the coordination between spatial scale of typical TOD area and the cell size of grid, also regarding the computational performance factor the cell size of 300x300 meters were selected as the basic spatial unit for analyses, Figure 10 shows how different scale TOD areas can be virtually overlaid by 300x300 meters grid cells. Overlaying 1000 square kilometres area of Arnhem-Nijmegen region with such grid cells was resulted in more than 12,000 cells of 9 hectares.



Figure 10: Different possible overlapping patterns of different scale TOD areas overlaid by grid tessellation

4.3. Data collection and preparation

According to the regional scale of the study and aligned with the adapted list of measuring TOD indicators (Table 3) and related data requirements, no fieldwork was planned for data collection but all required spatial layers were obtained from secondary sources.

This was done using few credible academic, professional, institutional and online sources including:

- ITC former projects archive
- ESRI Nederland
- CBS websites (Centraal Bureau voor de Statistiek)
- DANS (Data Archiving and Networked Services)
- Open Street Map

However gathering data from these fragmented sources involved with some issues like incomplete map coverage, inconsistent administrative boundaries, conflicting classifications, different map projections and so on, which in most cases problems were solved by comparison between sources and also with the help of third party reference like Google Maps. The table below shows the initial collected data layers and their correspondent source.

Data Source	Features
ITC former projects archive	Land use
CDC	Administrative boundaries
CBS	Demographics data
CCDI Nederland TOD10NI	Cadastral data (building footprints, open spaces,)
ESRI Nederland - TOPIUNL	 Land use Administrative boundaries Demographics data Cadastral data (building footprints, open spaces,) Railways Train stations
0SM	Train stations
03101	Road network
DANS	Mobility statistics

In addition to solving mentioned issues and in order to ensure efficient data management and facilitate further spatial analyses, by importing all existing data layers from various sources and different formats into a unique database an integrated geodatabase was developed for this research. Later all the pre-processed layers like the base grid and the dissolved land use layer, plus the entire geoprocessing models and their outputs were organized within this geodatabase as well.

4.4. Computing indicators

As it was presented in the adapted list of indicators (Table 3), there were two main groups of indicators needed to be obtained to fulfil the TOD measurement, the first group was density related measures and the second one associated with the land use spatial configuration.

The following section describes the methods that were utilized and depicts specifications of the geoprocessing models that were implemented to compute these indicators.

4.4.1. Density indicators

A high density level as an essential character of TOD has been frequently discussed in the literature and various methods were suggested to measure it, some studies tried to use the total floor area as the metric of density while some other counted for the total number of activities in a certain zone.

However, since this study depends on the acquired data from CBS, the total number of interested activities (houses, businesses and commercial activities) in form of absolute number per cell was taken to measure densities. Because CBS data was provided at neighbourhood level it had to be disaggregated to the grid of 300x300 meters square cells.

This operation required a combination of spatial analytical processes including overlay of base grid over the CBS demographics layer, calculating proportion of each variable's (attribute) value for all fragmented features, dissolving all segments of cells based on the unique cell ID and eventually summing up values. This method that is called *Data apportion for non-coterminous polygons* can apportion target variables (attributes) of interest based on a common attribute between two overlapping but not coincided layers.

We implemented this method by developing a geoprocessing model that takes the CBS demographics and base grid layers as inputs, conducts apportioning process based on the common attribute of *area* and returns the total number of houses, businesses and commercial activities for each grid cell. The graph below shows how apportioning concept was applied on the demographics layer to transfer variables of interest into new spatial unit:



Total number of houses within the grid cells

Figure 11: Application of apportioning method on the variable of interest (e.g. number of houses)

4.4.2. Mixed use indicator

Regarding the contribution of mixed use development to the levels of TOD-ness, it was important to apply a proper quantitative method to measure mixture of land uses as a spatial indicator.

The method we used, was adapted from the research of Zhang and Guindon (2006) on assessing transport-related urban sustainability in Canada, they quantified the level of employment-related mixed use in the vicinity of a residential land unit (pixel) as the ratio of:

$$\frac{N_C}{N_C + N_R}$$

Where N_C and N_R are respectively the numbers of commercial/industrial and residential pixels in the neighbourhood around a residential pixel. In their approach, for a given mode of transport they defined a circular zone corresponding to the radius of average travel distance, then for each residential pixel on the map they determined associated neighbourhood an applied the equation. Since this method was developed to make use of raster satellite imagery, it was required to be substantially adjust it to work with the vector land use data. At this stage implementing the vector grid tessellation concept was the key solution to bridge between the raster and vector approaches. Hence, the land use map of Arnhem Nijmegen region was overlaid by the base grid layer and for each and every grid cell the area of underlying land use classes transferred into the corresponding fields (attributes). Then in order to reflect the overall mixed use character of residential cells in context of their easy walking distance zone, the immediate neighbouring cells were identified (Figure 12) and over this neighbouring area the level of residential and commercial mixed use were calculated as the division of:

$$\frac{\sum S_c}{\sum (S_c + S_r)}$$

Where S_c shows the sum of the total area of commercial land use and S_r represents the sum of the total residential land use within the analysis neighborhood.

At the end, while the further analysis requires non-null value cells, for that group of cells lacking commercial and residential land uses simultaneously, we needed to overcome the error of division by zero and replace the mathematically undefined value (Null) with a numeric value. So in the geoprocessing model a conditional expression was defined to return zero as the mixed use level for this group of cells.



The cell containing residential land use (target of analysis)

Figure 12: Mixed use indicator analysis window; the neighboring area around the given cell

4.4.3. Land use diversity indicator

In principle diversity indicator has been formed based on the notion of entropy which comes from the information theory perspective. Entropy was originally introduced as the measure of amount of information, however later it has been widely used in geosciences, landscape ecology and urban studies in order to measure the level of diversity (Yoshida & Tanaka, 2005).

As it was described before, the land use diversity indicator is one of the key measures to compile the TOD index; it can show the level of spatial heterogeneity in terms of proportion of different land use types within an easy walkable area.

However, while the established methods of computing land use diversity have been mainly developed and tuned to work with raster data model -that characterized by representing one dominant land use for each portion of space rather than a set of land uses- for our study it was required to adapt a method to work with the vector data set. In order to do that, considering the research of Ritsema van Eck and Koomen (2008) on urban land use diversity in the Netherlands, a geoprocessing model capable to compute land use diversity based on the vector data was developed by conducting the following steps:

First, regarding the spatial specification of TOD measurement, for each grid cell the adjacent neighbouring area including the cell and a 300 meters buffer around it, was defined as the window of

analysis (Figure 13). Then, for each land use class, the total overlapped area by the analysis window was calculated and values assigned to the analysis window polygon under different fields (attributes).

Since some land uses could not contribute to the diversity in such a way that TOD means, they were excluded from further calculations. These classes were: rivers and water bodies, roads, cycle and pedestrian paths, side buffers.

The map in the (Appendix A) shows the location and extent of excluded land use classes across the region.

The grid cell of interest (target of analysis)

Neighboring area, covers 300 meters around the cell of interest

Upon transferring land use statistics Figure 13: Land use diversity indicator analysis window; the neighboring area around the given cell

parts of the geoprocessing model had to be defined to compute the land use diversity indicator for all analysis windows. Since the entropy formula contains a summation expression which cannot be handled by common geoprocessing functions it was required to implement an expanded form of it to handle the operation, the following equations illustrates how this was accomplished.

$$LU_{d}(i) = \frac{-\sum_{i} Q_{lui} \times \ln(Q_{lui})}{\ln(n)}$$
$$\sum_{i} Q_{lui} \times \ln(Q_{lui}) = Q_{ai} \times \ln(Q_{ai}) + Q_{bi} \times \ln(Q_{bi}) + \dots + Q_{hi} \times \ln(Q_{hi})$$
$$S_{lui}$$

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

 S_i = Total area of the analysis window i

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

n = Total number of land use classes within the analysis window i

This expanded representation clearly shows that for each incorporating land use, the proportion of area $Q_{lui} = \frac{S_{lui}}{S_i}$ and also natural logarithm of Q_{lui} should be calculated. Although the formula is relatively simple, the logarithm function and similarly natural logarithm function can only be defined for positive real numbers and in case of absence of specific land use within an area, the undefined value error would occur and stop the calculation process, to overcome this issue in our geoprocessing model a conditional expression has been applied that sets to return the value of zero for the contribution of absent land uses to the diversity index.

Moreover, for those areas which contain only one land use type, the value of natural logarithm function in the denominator of the formula would be zero $(\ln(n) = 0)$ and causes the error of "division by zero" for entire formula, since having one type of land use essentially means no diversity at all, the model was set to skip calculation for those areas and simply return the value of zero as the land use diversity indicator for such single type land use areas.

4.5. SMCA and computing potential TOD index

It needs to be expressed that due to the nature of multi criteria analysis methods, usually in the common practices Multi Criteria Analysis (MCA) and Spatial Multi Criteria Analysis (SMCA) deal with participatory processes, they are the tools for appraisal of different alternatives when a common output over several points of view and priorities is needed (Tsamboulas, 2007). Nonetheless, in this study SMCA used to construct a composite index map based on the indicator scores and criterion weights which derived from literature review. However, taking such an approach has not changed the structure of multi criteria analysis, so according to the principles it was required to standardize indicators and assign weights to criteria as well (Jacek Malczewski, 1996).

All this was done by utilizing the ILWIS Spatial Multi Criteria Analysis software. At first all of indicator maps which were produced by geoprocessing models, imported into ILWIS raster format.

Then according the adapted list of indicators for measuring potential TOD index (Table 3) the criteria tree was formed and for each criterion relevant indicators were set.

In a SMCA practice, based on the contribution of factors (indicators) to the final suitability map (composite index) factors can be classified into the cost or benefit. A spatial benefit is a factor that contributes positively to the outcome while a spatial cost negatively impacts the results. (Keshkamat et al., 2009).

Moreover, since different factors (indicators) may be measured in different measurement units (e.g. number of houses versus land value) in order to compute their overall performance in a cumulative suitability map it is necessary to standardize the factors. Depends on the original factors value ranges and the applicable cut-off values, several methods such as *Maximum, Interval* and *Goal* can be used to transform initial values of factors (indicators) into the standardized value range between 0 and 1 where 1 indicates the highest utility.

All these operations can be conducted through the standardization function of ILWIS SCME, so upon making the criteria tree ready, respecting the different units and value ranges of the computed indicators (Table 6) the standardization process was carried out as follow:

Since according to the adapted measuring TOD framework (Table 3) most of indicators including residential, commercial and business densities as well as land use diversity were defined in a way that their higher values contribute to the potential TOD index positively, consequently in the standardization phase they were considered as *Benefit* to the composite index.

Also in the absence of agreed standards, the *Interval* method that considers both minimum and maximum values for standardization was chosen to apply on the commercial and business densities plus land use diversity indicator. According to the Bach, Hal, Jong, and Jong (2006) the minimum value of 540 houses per cell (60 houses per hectare) was set as the *goal* value of residential density. In addition due to the changing effects of mixed use indicator on the potential TOD index; it was defined as the combination of cost and benefit whereas value range from 0.2 to 0.6 which represents

balanced mixture of commercial and residential activities, considered as benefit but values out of this range counted as cost.

Indicator	Description	Standardization Method
Residential density	The higher residential and commercial densities the less per capita vehicle travel and the more	Benefit / Goal
Commercial density	efficient public transport would be	Benefit / Interval
Land use diversity	The higher diversity of land uses the more destinations can be accessed by less number of trips	Benefit / Interval
Mixed use	The more mixed-ness of land uses the more efficient non-motorized and public transport would be	Combination / U-Shape Up
Business density	The higher number of established businesses the higher levels of economic development and hence higher TOD levels	Benefit / Interval

Table 4 below shows the summary of the applied standardization scheme.

Table 4: Indicators standardization scheme

After applying the standardization step, criterion weights had to be defined to reflect the relative importance of criteria with respect to the level of TOD-ness. As it was discussed in the literature review some TOD criteria due to their inherent centrality to the concept of Transit Oriented Development (Ewing & Cervero, 2010) and their significant influence on the success of TOD projects (Evans et al., 2007) have got more attention than others. In our study among the computed indicators, *density* and *land use diversity* belonged to this group.

After these two, *mixed use level* indicator with a certain focus on the residential and commercial land uses was the second level important criterion, which some aspects of it have already been described by density and diversity indicators.

Additionally, with respect to the measuring TOD framework (Table 2) since some studies have pointed out that economic performance and level of TOD-ness can reciprocally influence each other (Renne et al., 2005) the *level of economic development* was considered as the marginal criterion in terms of its contribution to the overall index.

Having three ordered levels of criteria, the rank order method was employed to identify criterion weights; this method calculates the weight of each criterion based on the following formula:

$$W_k = \frac{n+1-k}{\sum_{i=1}^{n} (n+1-i)}$$

Where n is the number of criteria and k represents rank of the criterion in the set (52°North, 2012). Table 5 shows the ranked order and calculated weights of criteria together with relevant indicators. Once the weights were set, the composite potential TOD index value for each and every grid cell was computed by adding up the results of multiplication of standardised indicator value by the weight of associated criterion.

Criteria	Rank order	Resulting weights	Indicator	Contribution to criterion	Associated variable
Lovel of density	1	0.35	Residential density	50%	Number of Houses
Level of defisity	T	0.55	Commercial density	50%	Number of Commercials
Level of land use	1 0.35		Land use diversity	100%	Computed Land use
diversity	1	0.55		100%	diversity
Level of mixed use	2	0.20	Mixed use	100%	Computed mixed use
Level of economic	2	0 10	Rusiness density	100%	Number of Businesses
development	5	0.10	busilless delisity	100%	

Table 5: Criteria weights table

This was done through the ILWIS SMCA tool. This operation could conceptually produce values ranging from 0 to 100, Goal where 100 represent the highest level of TOD-ness.

The following graph from the work of Castellanos Abella and Van Westen (2007) shows how this method works for computing composite index map based on the several indicator maps and set of relevant weights.



Figure 14: Schematic procedure of computing composite index map based on spatial multi criteria analysis

4.6. Exploring potential TOD index using visual analysis

Potential TOD index as a dimensionless figure that reflects the degree of orientation of development towards transit is relative in nature and its interpretation requires a measure. However, there is no established scaling system to classify resulting index values directly, in this condition the potential TOD index can only be used for pairwise comparison between locations to determine which location is potentially more transit oriented than the other but the index may not reflect the magnitude of the differences explicitly.

Hence, to get a better understanding of the index scale and reveal the extent of the differences between its values it was required to employ some methods to explore the obtained potential TOD index and its corresponding map (Figure 19).

Identifying the characteristics of index values in relation with the associated initial indicators through using the equal interval classification (Table 7), was the first employed technique.

Moreover, since a previous study in the same context (Shastry, 2010) successfully used the simple visual analysis method to investigate some aspects of Transit Oriented Development, visual analysis and its relevant classification methods were employed to explore the spatial pattern of TOD-ness across the Arnhem Nijmegen City Region.

4.7. Spatial statistical analysis

Although exploring the potential TOD index maps using visual analysis revealed some probable spatial clusters and concentration of similar values, in order to clarify existence, types and intensity of clusters and at the same time to overcome the subjective aspects of visual analysis and arbitrary classification issues, we needed to employ a more robust method to improve the understanding of the potential TOD index values and their spatial distribution, this was done using spatial statistical analysis as follow:

4.7.1. Identifying existence of spatial clusters using spatial autocorrelation analysis (Global Moran's I Statistic)

At first it was required to calculate the *Global Moran's I* statistic for the potential TOD index to check whether clustering exist or not and how significant it is.

This process involved defining the null hypothesis of the analysis, setting the *ArcGIS Spatial Autocorrelation* tool, adjusting the important parameters of *Conceptualization of Spatial Relationship* and finally set the threshold distance. Details of these steps are given below:

Since the Global Moran's I statistic is an inferential statistic with the null hypothesis of complete spatial randomness, it was required to form a null hypothesis for testing the potential TOD index spatial distribution as well, this consonant null hypothesis was made as:

H0: The distribution of potential TOD index values over the study area is completely random and has no pattern.

After defining the null hypothesis and prior to running the spatial autocorrelation analysis the parameter of conceptualization of spatial relationship as a function that determines what should be considered as the spatial neighbour of each feature, had to be selected. There were various choices including:

- Inverse distance
- Distance band
- Zone of indifference (which combines the two previous methods)
- First order polygon contiguity
- Using spatial weights matrix

According to each of them also a reasonable threshold distance should be defined, at this point to select the proper parameter and relevant distance threshold, the other spatial statistical tool called *Incremental Spatial Autocorrelation* was utilized to help adjusting the conceptualization of spatial relationship.

Incremental spatial autocorrelation is an iterative method to identify the proper distance for defining spatial neighbours; it measures the intensity of spatial clusters at multiple distance bands, calculates z-score for each band and illustrates these scores in a line graph.

The peak points in the graph (the mathematical maxima either local or global) show the likely scale of spatial clustering and reveal the corresponding distance "where the spatial processes promoting clustering are most pronounced" (ESRI, 2012). In case of having more than one peak point, the first statistically significant peak point which located within the shorter distance or the maximum peak



with the highest z-score value often represents the scale of spatial clustering better (ESRI, 2012), however, this should be in line with the object of analysis.

Figure 15: The incremental spatial autocorrelation graph for the potential TOD index

As is shown in the figure above, the incremental spatial autocorrelation graph for the potential TOD index across the study area have two statistically significant peak points at the 500 and 1500 meters, but none of these points had the highest calculated z-score and in overall by increasing the distance the z-score rising as well (see also the table in Appendix B).

According to the detected peak points and regarding the distance decay effects involves in transport related spatial interactions (Comtois, Slack, & Rodrigue, 2009) also considering the fixed size of grid cells in our dataset, the *Inverse Distance* method with the threshold distance of 500 meters were set as the Global Moran's I calculation parameters. Figure 16 shows how the spatial configuration of neighbouring cells would be based on this set of spatial parameters.



Figure 16: Spatial configuration of neighbouring cells for Global Moran's I statistic calculation based on the threshold distance of 500 meters

4.7.2. Mapping spatial clusters using hot spot and outlier analyses (Getis-Ord Gi* and Anselin Local Moran's I Statistics)

Since the spatial autocorrelation analysis results (Figure 22) proved that there is intense spatial clustering of index values over the study area, it was necessary to look for the pattern and location of this clustering. Indeed, it was already expected to find spatial clusters of high index values over and near the populated and urban areas because the index has been derived based the key factors that are mainly concentrated there, nonetheless in order to get a better perspective on the clustering details some other statistical analyses are required to be perform.

Thus to map the location of clusters and to find their intensity, the ArcGIS *Hot Spot Analysis* together with the *Cluster/Outlier Analysis* were conducted and relevant statistics of Getis-Ord Gi* and Anselin Local Moran's I were computed for every grid cell across the study area. In addition to this using GeoDa software besides SPSS the local Moran's I scatter plot was constructed to help classifying and interpreting the related statistics.

These methods are classified under the *Local indicators of spatial association (LISA)* and have a similar approach to decompose relevant global statistics. However, because of their different specifications and outcomes both were employed;

Getis-Ord Gi* statistic considers a feature as hot spot when primarily it has a high value and is also surrounded by neighbours having high values, secondly the sum of the values of the feature and its neighbours proportionally compared to the total sum of all features values across the study area reflects a statistically significant difference. The distribution of this proportion which is measured in the form of z-score and p-value can show either if a feature is statistically significant hotspot or not.

Although, Getis-Ord Gi* statistic can reveal clustering in the spatial distribution but it does not provide information about spatial dissimilarities, this is the Anselin Local Moran's I statistic capability to essentially identify either the features are dissimilar to the neighbouring features or are among the homogeneous cluster.

The Anselin Local Moran's I scatter plot as a complementary tool also provides a framework to illustrate the spatial association of a certain feature with its neighbouring features.

spatial Lag	LH Spatial Outliers	HH Hot spots
Spatia	LL Cold spots	HL Spatial Outliers

value of interest (potential TOD index)

According to the position of the feature on the graph, its spatial association in the neighbouring context can be described as:

- HH, means there is a cluster of high values surrounded by high values
- LL, means there is a cluster of low values surrounded by low values
- HL, indicates there is an outlier which has a high value and surrounded by low values
- LH, indicates there is an outlier which has a low value and surrounded by high values

5. RESULTS AND DISCUSSION

5.1. Computed indicators

According to the TOD measurement concept, the measuring indicators are directly or implicitly related to the land use characteristics of an area. Comparative exploration of the land use map (Figure 5) besides the indicators maps (Figure 17 and Figure 18) illustrates how the computed indicators have been influenced by the land use pattern of the region.



Figure 17: Maps of residential and commercial density, mixed use and land use diversity indicators



Figure 18: Map of the business density indicator

As it can be observed, corresponding to the location of extensive agricultural, natural and forest areas across the region, the indicator values are generally low, since these areas cover a huge portion of the region (around 70%). Their high frequency combined with low values can therefore bias the distribution of indicator values. The descriptive statistics table below also reflects this effect. For most of indicators except land use diversity the skewness statistic is greater than zero that indicates the distributions of values is right skewed.

Statistics		Number of Houses	Number of Commercials	Mixed Use Indicator	Number of Businesses	Land Use Diversity Indicator
Average		25.20	1.39	.029	2.37	.383
Median		2.00	.00	.000	.00	.413
Std. Deviation		56.304	4.743	.075	6.394	.155
Skewness		3.401	15.160	3.888	11.229	640
Std. Error: .022						
Kurtosis		16.047	420.895	18.394	249.663	232
Std. Error: .045						
Minimum		0	0	.000	0	.000
Maximum		692	202	.742	235	.993
	25	.00	.00	.000	.00	.296
Percentiles	50	2.00	.00	.000	.00	.413
	75	14.00	1.00	.015	2.00	.494

Table 6: The descriptive statistics of the computed indicators

All these give a hint to be cautious about interpreting the indicators' values over the study area. However, due to the standardization operation during the SMCA process, potential TOD index should not be influenced by this issue or at least its effects should be less.

5.2. Index value interpretation

Figure 19 shows the map of computed Potential TOD Index across the Arnhem Nijmegen City Region, regarding the applied SMCA method; the composite index value can principally range from 0 to 100. Nevertheless, in the study area the computed index value ranges between 0 and 60 [-].





However, the frequency histogram of the index values for the study area shows that within the above range values are not evenly distributed.

According to descriptive statistics (Table 7), average index value for the entire region is 16.69 [-], whilst half of the cells' score is 16 [-] or lower, also three-quarter has index value lower than or equal to 20 [-].

Only nearly ten percent of the cells fall into the range of 30 to 60 [-], while the top one percent are between 40 and 60 [-].



Index value 60 [-] is clearly an outlier and it is better not to be treated as a reference level.

In addition to these frequency figures, the table shows the average index value at different classes and depicts the characteristics of these classes in terms of TOD measurement indicators.

As it can be seen, the land use diversity indicator has a gradual variation between classes. In contrast average residential density shows sudden changes at different points. However, the average mixed use indicator, commercial and business densities have significant changes corresponding to the index value 40 [-], in the other words the difference between levels of TOD-ness for the index values above and below 40 [-] is almost double. According to this, a potential TOD index value 40 [-] can be highlighted as the conclusive levels of TOD-ness and be taken as the base-line.

Index	Index Potential TOD		Land Use Diversity		Mixed Use		
Value	Relative	Inde	ex [-]	Indica	itor [-]	Indicat	tor [-]
Range	Frequency	Average	Standard Deviation	Average	Standard Deviation	Average	Standard Deviation
0 - 4	10.01%	2.31	1.11	0.07	0.03	0.00	0.00
5 - 9	10.95%	7.31	1.42	0.21	0.04	0.01	0.04
10 - 14	19.61%	12.28	1.42	0.35	0.04	0.01	0.04
15 - 19	31.76%	16.94	1.36	0.47	0.04	0.02	0.05
20 - 24	10.23%	21.25	1.27	0.56	0.08	0.04	0.07
25 - 29	3.71%	27.32	1.40	0.43	0.13	0.08	0.12
30 - 34	8.95%	32.07	1.32	0.41	0.07	0.06	0.10
35 - 39	3.67%	36.45	1.38	0.51	0.06	0.11	0.14
40 - 44	0.91%	41.16	1.18	0.56	0.09	0.26	0.17
45 - 49	0.12%	46.33	1.29	0.52	0.11	0.31	0.10
50 - 54	0.07%	52.38	1.30	0.48	0.09	0.30	0.13
55 - 59	0.00%	0.00	0.00	0.00	0.00	0.00	0.00
60	0.01%	60.00	0.00	0.41	0.00	0.00	0.00
Index		Num	ber of	Num	ber of	Numb	er of
Value	Cumulative	Houses	per cell	Commerci	als per cell	Businesse	s per cell
Range	Frequency				Standard		Standard
		Average	Deviation	Average	Deviation	Average	Deviation
0 - 4	10.01%	Average 0.40	Deviation 2.79	Average 0.02	Deviation 0.18	Average 0.05	Deviation 0.31
0 - 4 5 - 9	10.01% 20.96%	Average 0.40 2.23	Deviation 2.79 6.20	Average 0.02 0.10	Deviation 0.18 0.43	Average 0.05 0.26	Deviation 0.31 0.73
0 - 4 5 - 9 10 - 14	10.01% 20.96% 40.57%	Average 0.40 2.23 4.13	Standard Deviation 2.79 6.20 8.39	Average 0.02 0.10 0.24	Deviation 0.18 0.43 0.72	Average 0.05 0.26 0.52	Deviation 0.31 0.73 1.15
0 - 4 5 - 9 10 - 14 15 - 19	10.01% 20.96% 40.57% 72.33%	Average 0.40 2.23 4.13 6.35	Standard Deviation 2.79 6.20 8.39 11.10	Average 0.02 0.10 0.24 0.46	Deviation 0.18 0.43 0.72 1.15	Average 0.05 0.26 0.52 0.88	Deviation 0.31 0.73 1.15 1.76
0 - 4 5 - 9 10 - 14 15 - 19 20 - 24	10.01% 20.96% 40.57% 72.33% 82.56%	Average 0.40 2.23 4.13 6.35 13.89	Standard Deviation 2.79 6.20 8.39 11.10 20.04	Average 0.02 0.10 0.24 0.46 0.76	Deviation 0.18 0.43 0.72 1.15 1.67	Average 0.05 0.26 0.52 0.88 1.57	Deviation 0.31 0.73 1.15 1.76 2.62
0 - 4 5 - 9 10 - 14 15 - 19 20 - 24 25 - 29	10.01% 20.96% 40.57% 72.33% 82.56% 86.27%	Average 0.40 2.23 4.13 6.35 13.89 79.01	Standard Deviation 2.79 6.20 8.39 11.10 20.04 66.27	Average 0.02 0.10 0.24 0.46 0.76 4.12	Deviation 0.18 0.43 0.72 1.15 1.67 3.45	Average 0.05 0.26 0.52 0.88 1.57 7.07	Deviation 0.31 0.73 1.15 1.76 2.62 4.85
0 - 4 5 - 9 10 - 14 15 - 19 20 - 24 25 - 29 30 - 34	10.01% 20.96% 40.57% 72.33% 82.56% 86.27% 95.22%	Average 0.40 2.23 4.13 6.35 13.89 79.01 138.24	Standard Deviation 2.79 6.20 8.39 11.10 20.04 66.27 74.77	Average 0.02 0.10 0.24 0.46 0.76 4.12 5.85	Deviation 0.18 0.43 0.72 1.15 1.67 3.45 4.34	Average 0.05 0.26 0.52 0.88 1.57 7.07 9.96	Deviation 0.31 0.73 1.15 1.76 2.62 4.85 5.85
0 - 4 5 - 9 10 - 14 15 - 19 20 - 24 25 - 29 30 - 34 35 - 39	10.01% 20.96% 40.57% 72.33% 82.56% 86.27% 95.22% 98.89%	Average 0.40 2.23 4.13 6.35 13.89 79.01 138.24 114.37	Standard Deviation 2.79 6.20 8.39 11.10 20.04 66.27 74.77 83.72	Average 0.02 0.10 0.24 0.46 0.76 4.12 5.85 6.22	Deviation 0.18 0.43 0.72 1.15 1.67 3.45 4.34 7.04	Average 0.05 0.26 0.52 0.88 1.57 7.07 9.96 10.23	Deviation 0.31 0.73 1.15 1.76 2.62 4.85 5.85 9.43
0 - 4 5 - 9 10 - 14 15 - 19 20 - 24 25 - 29 30 - 34 35 - 39 40 - 44	10.01% 20.96% 40.57% 72.33% 82.56% 86.27% 95.22% 98.89% 99.80%	Average 0.40 2.23 4.13 6.35 13.89 79.01 138.24 114.37 104.83	Standard Deviation 2.79 6.20 8.39 11.10 20.04 66.27 74.77 83.72 146.47	Average 0.02 0.10 0.24 0.46 0.76 4.12 5.85 6.22 16.81	Deviation 0.18 0.43 0.72 1.15 1.67 3.45 4.34 7.04 25.75	Average 0.05 0.26 0.52 0.88 1.57 7.07 9.96 10.23 22.32	Deviation 0.31 0.73 1.15 1.76 2.62 4.85 5.85 9.43 32.37
$\begin{array}{c} 0 - 4 \\ 5 - 9 \\ 10 - 14 \\ 15 - 19 \\ 20 - 24 \\ 25 - 29 \\ 30 - 34 \\ 35 - 39 \\ 40 - 44 \\ 45 - 49 \end{array}$	10.01% 20.96% 40.57% 72.33% 82.56% 86.27% 95.22% 98.89% 99.80% 99.93%	Average 0.40 2.23 4.13 6.35 13.89 79.01 138.24 114.37 104.83 79.60	Standard Deviation 2.79 6.20 8.39 11.10 20.04 66.27 74.77 83.72 146.47 56.55	Average 0.02 0.10 0.24 0.46 0.76 4.12 5.85 6.22 16.81 11.13	Deviation 0.18 0.43 0.72 1.15 1.67 3.45 4.34 7.04 25.75 21.05	Average 0.05 0.26 0.52 0.88 1.57 7.07 9.96 10.23 22.32 15.53	Deviation 0.31 0.73 1.15 1.76 2.62 4.85 5.85 9.43 32.37 25.08
$\begin{array}{c} 0 - 4 \\ 5 - 9 \\ 10 - 14 \\ 15 - 19 \\ 20 - 24 \\ 25 - 29 \\ 30 - 34 \\ 35 - 39 \\ 40 - 44 \\ 45 - 49 \\ 50 - 54 \end{array}$	10.01% 20.96% 40.57% 72.33% 82.56% 86.27% 95.22% 98.89% 99.80% 99.93%	Average 0.40 2.23 4.13 6.35 13.89 79.01 138.24 114.37 104.83 79.60 138.63	Standard Deviation 2.79 6.20 8.39 11.10 20.04 66.27 74.77 83.72 146.47 56.55 75.61	Average 0.02 0.10 0.24 0.46 0.76 4.12 5.85 6.22 16.81 11.13 25.75	Deviation 0.18 0.43 0.72 1.15 1.67 3.45 4.34 7.04 25.75 21.05 48.68	Average 0.05 0.26 0.52 0.88 1.57 7.07 9.96 10.23 22.32 15.53 32.63	Deviation 0.31 0.73 1.15 1.76 2.62 4.85 5.85 9.43 32.37 25.08 56.94
$\begin{array}{c} 0 - 4 \\ 5 - 9 \\ 10 - 14 \\ 15 - 19 \\ 20 - 24 \\ 25 - 29 \\ 30 - 34 \\ 35 - 39 \\ 40 - 44 \\ 45 - 49 \\ 50 - 54 \\ 55 - 59 \end{array}$	10.01% 20.96% 40.57% 72.33% 82.56% 86.27% 95.22% 98.89% 99.80% 99.93% 99.99%	Average 0.40 2.23 4.13 6.35 13.89 79.01 138.24 114.37 104.83 79.60 138.63 0.00	Standard Deviation 2.79 6.20 8.39 11.10 20.04 66.27 74.77 83.72 146.47 56.55 75.61 0.00	Average 0.02 0.10 0.24 0.46 0.76 4.12 5.85 6.22 16.81 11.13 25.75 0.00	Deviation 0.18 0.43 0.72 1.15 1.67 3.45 4.34 7.04 25.75 21.05 48.68 0.00	Average 0.05 0.26 0.52 0.88 1.57 7.07 9.96 10.23 22.32 15.53 32.63 0.00	Deviation 0.31 0.73 1.15 1.76 2.62 4.85 5.85 9.43 32.37 25.08 56.94 0.00

Table 7: Equal interval classes of index value in relation with the associated initial indicators

5.3. Visual analysis

The map below is a representation of potential TOD index values based on the equal interval classes (Table 7), higher values from 30 to 60 [-] are shown by the yellow to red colours and lower values are presented in a green colour scale. As a general pattern, concentration of high index values in certain areas like close to and around the train stations is observable, nevertheless, near to the borders, the concentration diminishing and only few number of high TOD cells can be dispersedly found. Although, status of the cells and their neighbours can be seen here, identifying their cumulative status and creating overall picture of them is still subjective and depends on a normative judgment.





Figure 21: Map of Potential TOD Index (standard deviation classes)

Moreover, as it can be seen in the map above, due to the sensitive nature of spatial data classification (Osaragi, 2002) choosing different classification methods or defining a different number of classes or even a minor adjustments on colouring parameters may alter the visualization impression and consequently the perception of the results.

5.4. Upgrading levels of TOD-ness

Referring to the definition of TOD (California Department of Transportation, 2002), transit oriented development can be achieved through a certain levels of density, diversity and design plus having a good connection to the transit stop.

The potential TOD index can measure those aspects of TOD-ness related to the density and diversity and design. So, omitting the design characteristics which could not be measured due to the data availability issue, the computed potential TOD index can represent the current levels of TOD-ness in terms of built environment conditions across the region.

It can show where the current levels of TOD-ness are low, medium or high and together with the status of rail transit connectivity can determine whether a location is virtually TOD or not.

However, to encourage the levels of TOD-ness at certain locations within the region, regarding to the spatial scale of the analyses and relevant abstraction level of the measure, it would not be practical to suggest interventions that have a local-scale character. These type of interventions, some things like modifying floor area rates or adjusting zoning rules require a comprehensive consideration of political, social, economic and environmental aspects at a local scale that are not in the scope of this study. At this regional scale what can be analysed and suggested to upgrade, is the general status of accessibility to the rail transit system.

In principle, accessibility to the rail transit system is influenced by several spatial and non-spatial factors, however, according to the Givoni and Rietveld (2007) the distance to the train station is the most significant element among all.

Accordingly, having the potential TOD index for the Arnhem Nijmegen City Region together with the location of railways and existing train stations, we tried to identify the potentially high TOD areas that can be upgraded by locating a new train station; of course for establishment of new train station or development of rail network, conducting various feasibility studies is essential. Nevertheless, at this study our main focus was on the particular spatial aspects.

5.5. Spatial statistical analysis

Although the spatial granularity of the potential TOD index could capture the characteristics and orientation of development in a relatively coarse level of 300 by 300 meter cells, this was still much smaller than the common train station catchment area (Figure 10), which is defined by the radius of 300 to 500 meters around the station and an average population density of 150 person per hectare (Bach et al., 2006).

However, regarding the base spatial unit of the index, a proper spatial concentration of high TOD cells might meet the optimum catchment extent and also population threshold of the profitable transit service. As it was described before, in order to find these probable clusters of high TOD cells, a set of spatial statistical analyses were performed and the following outcomes were achieved:

5.5.1. Global Moran's I statistic

The graph below shows the results of the spatial autocorrelation analysis and the bell curve scheme helps to interpret the resultant values, since the z-score value is so high (174) and associated p-value is highly statistically significant (0.000), the null hypothesis of complete spatial randomness of the index values over the study area can be rejected. In simpler words there is less than 1% likelihood that the clustered pattern of potential TOD index in the region can be the result of random chance, so at the confidence level of 99% the potential TOD index is clustered.



Figure 22: Spatial autocorrelation analysis result (Global Moran's I statistics)

5.5.2. Getis-Ord Gi* and Anselin Local Moran's I Statistics

The following maps and scatter plot show the results of analysis of local indicators of spatial association, as it can be observed in all three maps, there are vast areas of light yellow colour across the region; this shows that statistically significant clustering of index values have not been found there. This can indicate two situations:

- There are dispersed and low density settlements which characterized by a certain level of variation among high, medium and low TOD cells which are randomly distributed.
- There are fairly homogeneous non-urbanized areas which characterized with low variation among the cells in terms of being TOD, also the average level of TOD-ness in these areas compared to the average level of the entire region should be moderate.

The latter case seems to be more likely; however, in both cases these types of areas are not much of interest to be upgraded because in an overall perspective their potential is low.

Moreover, the two maps of Getis-Ord Gi* and Anselin Local Moran's I statistics, display some areas in a blue colour scale. These areas are spatial concentrations of low TOD cells so-called cold spots, which are mainly associated with the non-urban areas and natural sites where due to the absence of residential and commercial activities, TOD does not make sense at their current situation.

These two maps also illustrate some areas in the red colour scale; these areas are the hot spots of the potential TOD index. In this context hot spot represents a high TOD cell which is a part of high TOD cluster, depends on the spatial configuration of the cluster it can be a group of 9 to 21 or even more neighbouring cells (Figure 16) that have a high average index value which is statistically significant higher than the average of the entire region.



Figure 23: Map of hot spots and cold spots based on the Getis-Ord Gi* Statistic

Figure 24: Map of hot spots, clod spots and outliers based on the Anselin Local Moran's I Statistic

The following scatter plot shows distribution of the cells based on their spatial association.

Since concentration of cells with low or zero index value is intense, the definition and number of hot spots might be influenced.

The map below shows the statistically significant hot spots which have been identified based on different methods at the confidence level of 95%, the results are analogical, however, Anselin Local Moran's I recognized more cells as hot spot. While this

method relies on similarity more than magnitude of the values, its result was used for further analysis.



Figure 25: Anselin Local Moran's I scatter plot



Figure 26: The statistically significant hot spots at the confidence level of 95%

5.6. Alternative locations for intervention

Since connecting potentially high TOD areas to the rail transit was determined as the preferred intervention to improve the levels of TOD-ness, two main aspects needed to be considered as follow:

- Distances between potential TOD areas and the current railway network.
- The population and size of TOD area compared with the profitable transit service thresholds.

Distances were important because establishment of a new station close to the current stations, or so remote from the rail tracks is not sensible. The following graphs illustrate frequency distribution of the hot spots and cold spots from their nearest train station based on the Euclidean distance.



Figure 27: Frequency distribution of hot and cold spots versus distance to the nearest train station



Figure 28: Cumulative relative distribution of hot and cold spots versus distance to the nearest train station

These graphs besides the statistic table below simply shows that having the average distance of 2600 meters, 50% of hot spots located within 1900 meters and almost 90% within 5300 meters distance to the nearest train station. Similarly for the nearest distance to the rail tracks, half of hot spots located within 1100 meters and 90% within 4100 meters from the rail tracks, while their average distance is 1700.

Statistics	Distance to the	Nearest distance
Statistics	nearest train station	to the rail tracks
Average	2641	1701
Median	1867	1095
Percentile 90	5346	4110

Table 8: Summary statistics of distances to the railway network

Since to determine whether a TOD hot spot is within the suitable range from railway network or not two cut-off values were required, in absence of an established guideline, considering the frequency distribution of the current hot spots in terms of distance to the nearest train station and nearest distance to the rail tracks, the median values for the both factors were taken as the threshold.

Considering these thresholds, it can be inferred from the graph below that most of potentially TOD areas are already located close enough to the operating train stations and they can be recognized as TOD (Points within the bottom left quadrant). Moreover, there are several potentially TOD areas that are far from the stations but close to the rail tracks, so they can be upgraded to a TOD through a new transit station (Points within the bottom right quadrant).







Figure 30: Proximity to the current railway network

Once the potentially TOD areas were assessed using the factor of distance to the railway network (Figure 29 and Figure 30), it was required to prioritize these alternative locations against profitable transit service threshold which is around 4000 people (Bach et al., 2006). Therefore, the adjacent neighbouring hot spots within the suitable distance range from the railway network were merged to shape a bigger catchment area, and then these new areas were ranked based on the population size.

The locations identified in the map below are the result of the assessment against all the criteria introduced before. These locations (Table 9) performed well in terms of potential TOD index, nonetheless they are not outliers or even in the top 10 percentile group. They are well located near rail tracks and at the same time far enough from existing train stations, eventually their population passed the requirements of the profitable transit service threshold.

However, looking at the attributes and characteristics of the initial cells under the catchment areas shows that; although the cells individually have a moderate TOD characters, their cumulative potential could reach the TOD requirements. This can be considered as the benefit of combining spatial statistical methods together with the potential index computation that made it possible to reveal the overall levels of TOD-ness as well as measure it specifically.



Figure 31: Alternative locations to establish new train stations

Municipality	Population	Area	Average Potential TOD Index
Groesbeek	8409	270	31.5
Nijmegen	6550	243	32.8
Lingewaard	4101	153	32

Table 9: Attributes of the alternative locations to establish new train stations

6. CONCLUSIONS AND RECOMMENDATIONS

This chapter concludes the thesis by providing a summary of achievements and limitations of the study and offers recommendations for further research.

According to the scope of the study, it was supposed to develop an analytical spatial measurement tool to assess existing TOD levels.

Although the list of theoretical contributing factors and therefore set of the relevant measurement indicators was pretty long and extensive, the research successfully achieved its aim within the allotted time frame through the following approaches:

- Focusing specifically on the built environment indicators
- Using a vector based grid tessellation as an interface between raster and vector analyses
- Developing several geoprocessing models to perform intensive spatial analysis operations which were required for indicators computation
- Performing Spatial Multi Criteria Analysis (SMCA) to obtain a composite index map
- Employing multiple yet coherent methods of visual analysis besides statistical inferences to interpret the computed index as a metric of TOD-ness
- Applying spatial statistical analysis to reveal the potential TOD level at the scale of train station catchment area

All this was conducted in an area-wide fashion at the context of Arnhem Nijmegen City Region where cars are becoming the more dominant mode of transport, thus finding opportunities to improve mobility through efficient interventions is emergent.

The research indicated that from the TOD point of view and particularly from the built environment aspect, several locations within the region can be identified as potentially high TOD areas. These areas were evaluated using a relatively straightforward method and then few alternative locations were suggested for establishing new train stations.

However, each step of the research process involved some issues and uncertainties that had to be resolved. Firstly, spatial specifications of the existing criteria and indicators of evaluating transit oriented development were essentially vague and descriptive in the literature, so to implement such indicators in a GIS model some assumptions had to be made and several aspects needed to be justified.

In addition, regarding the spatial scale and extent of the study a large set of spatial data required to be obtained from secondary sources, however, at the time of the research only a few layers were available in a proper format and almost in all cases metadata were not included. This was a challenging issue especially to deal with the land use related data. Moreover, due to the lack of required spatial data some indicators had to be eliminated from the scope or be replaced with a proxy indicator. Also the method used for disaggregating data into grid cells assumed that distribution of features attributes over space is homogeneous which is not necessarily true, so it could cause a certain level of error. According to all these issues, data related adjustments particularly economic and functional indicators are the parts that have much room to improve to achieve a comprehensive indicator.

Considering the scale of study, the performance of the developed geoprocessing GIS models was well; nevertheless, for further applications especially to work with finer spatial scales or larger datasets the models need to be optimized. Implementing the models' interface in a form of user friendly toolbox would be preferable.

This is also important to note that in this study, Spatial Multi Criteria Analysis was essentially employed to compile various spatial indicators into a single composite index based on the indicator scores and criterion weights which have been derived from literature review. However, in order to reflect the different stakeholders' priorities and consequently evaluating the resultant alternative index maps it would be ideal to expand this work to a participatory multi criteria decision making process in the further studies.

Since depends on the basic spatial unit and definition of the neighbouring features the results of spatial statistical analyses can change significantly, therefore, to ensure spatial statistical reliability the incremental spatial autocorrelation operation was performed and proper neighbouring parameter was specified. However, performing a sensitivity analysis to investigate the effects of variation in basic spatial unit size on the final results is suggested for further research.

Eventually, since there was no participatory practice done during the process, it would be advisable to verify the type and alternative locations of intervention by holding a verification workshop to find out the stakeholders' opinions and identify possible divergences.

- 52°North. (2012). ILWIS 3.x User's Guide Retrieved 2012-12-12, 2012, from <u>http://52north.org/communities/ilwis/ilwis-userguide</u>
- Anselin, L. (1988). Spatial Econometrics: Methods and Models: Springer.
- Anselin, L. (1995). Local Indicators of Spatial Association—LISA. *Geographical Analysis*, 27(2), 93-115. doi: 10.1111/j.1538-4632.1995.tb00338.x
- Bach, B., Hal, E. v., Jong, M. I. d., & Jong, T. M. d. (2006). Urban Design And Traffic: A Selection From Bach's Toolbox = Stedenbouw En Verkeer: Een Selectie Uit De Gereedschapskist Van Bach: CROW.
- Belzer, D., & Autler, G. (2002). Transit-Oriented Development: Moving From Rhetoric to Reality: The Brookings Institution Center on Urban and Metropolitan Policy.
- Bernick, M. S., & Cervero, R. (1996). Transit Villages in the 21st Century: McGraw-Hill Companies.
- Bertolini, L., le Clercq, F., & Kapoen, L. (2005). Sustainable accessibility: a conceptual framework to integrate transport and land use plan-making. Two test-applications in the Netherlands and a reflection on the way forward. *Transport Policy*, 12(3), 207-220.
- Beukes, E. A., Vanderschuren, M. J. W. A., & Zuidgeest, M. H. P. (2011). Context sensitive multimodal road planning: a case study in Cape Town, South Africa. *Journal of Transport Geography*, 19(3), 452-460. doi: 10.1016/j.jtrangeo.2010.08.014
- California Department of Transportation. (2002). Statewide Transit-Oriented Development Study Factors for Success in California.
- Carrasco, L. E. (2008). Scale and strategy in environmental assessment of regional development policies. (Ph.D.), Raleigh, NC: North Carolina State University, US. Retrieved from http://www.ots.ac.cr/bnbt/34614.html
- Castellanos Abella, E. A., & Van Westen, C. J. (2007). Generation of a landslide risk index map for Cuba using spatial multi-criteria evaluation. *Landslides*, 4(4), 311-325. doi: 10.1007/s10346-007-0087-y
- Cervero, R., Arrington, G., Dunphy, R., & Smith-Heimer, J. (2004). Transit-Oriented Development in the United States: Experiences, Challenges, and Prospects: Transit Cooperative Research Program, FTA
- Comtois, C., Slack, B., & Rodrigue, J.-P. (2009). The geography of transport systems. GB: Routledge Ltd.
- CTOD. (2011). Planning for TOD at the Regional Scale: The Big Picture: The Center for Transit-Oriented Development.
- Curtis, C., Renne, J. L., & Bertolini, L. (2009). *Transit oriented development: making it happen.* GB: Ashgate Publishing Ltd.
- De Stadsregio Arnhem Nijmegen. (2012). About Arnhem Nijmegen City Region Retrieved August 2012 from <u>http://www.coolregion.nl/business</u>
- De Stadsregio Arnhem Nijmegen. (2013). Mobility and regional development Retrieved January 2013, from <u>http://www.destadsregio.nl/arnhem-nijmegen-city-region/mobility-and-regional-</u> <u>development</u>
- ESRI. (2012). Incremental Spatial Autocorrelation Method, 2012, from http://resources.arcgis.com/en/help/main/10.1/index.html#//005p0000004z000000
- Evans, J. E., Pratt, R. H., Stryker, A., & Kuzmyak, J. R. (2007). Transit Oriented Development (T. C. R. PROGRAM, Trans.) *Traveler Response to Transportation System Changes*: Transportation Research Board.
- Ewing, R., & Cervero, R. (2001). Travel and the built environment A synthesis Land Development and Public Involvement in Transportation: Planning and Administration (pp. 87-114).
- Ewing, R., & Cervero, R. (2010). Travel and the Built Environment. Journal of the American Planning Association, 76(3), 265-294. doi: 10.1080/01944361003766766
- Fischer, M. M., & Getis, A. (2010). Handbook of Applied Spatial Analysis. Berlin, Heidelberg: Springer.
- Fotheringham, A. S., & Rogerson, P. (Eds.). (2008). The SAGE Handbook of Spatial Analysis. GB: Sage Publications Ltd.
- Getis, A., & Ord, J. K. (1992). The Analysis of Spatial Association by Use of Distance Statistics. Geographical Analysis, 24(3), 189-206. doi: citeulike-article-id:5806900

- Givoni, M., & Rietveld, P. (2007). Developing the rail network through better access to railway stations summary of findings from the IBRAM research: Department of Spatial Economics, Free University Amsterdam.
- Keshkamat, S. S., Looijen, J. M., & Zuidgeest, M. H. P. (2009). The formulation and evaluation of transport route planning alternatives: a spatial decision support system for the Via Baltica project, Poland. *Journal of Transport Geography*, 17(1), 54-64. doi: 10.1016/j.jtrangeo.2008.04.010
- Liu, Q., Deng, M., Shi, Y., & Wang, J. (2012). A density-based spatial clustering algorithm considering both spatial proximity and attribute similarity. *Computers & compton Sciences*, 46(+), 296-309. doi: 10.1016/j.cageo.2011.12.017
- Malczewski, J. (1996). A GIS-based approach to multiple criteria group decision-making. International Journal of Geographical Information Systems, 10(8), 955-971. doi: 10.1080/02693799608902119
- Malczewski, J. (1999). GIS and Multicriteria Decision Analysis: Wiley.
- Malczewski, J. (2006). GIS-based multicriteria decision analysis: a survey of the literature. International Journal of Geographical Information Science, 20(7), 703-726. doi: 10.1080/13658810600661508
- Mennis, J., & Guo, D. (2009). Spatial data mining and geographic knowledge discovery—An introduction. *Computers, Environment and Urban Systems, 33*(6), 403-408. doi: 10.1016/j.compenvurbsys.2009.11.001
- Miller, H. J., Miller, H. J., & Han, J. (Eds.). (2001). Geographic data mining and knowledge discovery. GB: CRC Press Inc.
- Mitchell, A. (2009). ESRI guide to GIS analysis : Vol 2. Spatial measurements and statistics. Redlands: ESRI.
- Mori, K., & Christodoulou, A. (2012). Review of sustainability indices and indicators: Towards a new City Sustainability Index (CSI). Environmental Impact Assessment Review, 32(1), 94-106. doi: 10.1016/j.eiar.2011.06.001
- Munda, G. (2006). Social multi-criteria evaluation for urban sustainability policies. Land Use Policy, 23(1), 86-94. doi: 10.1016/j.landusepol.2004.08.012
- Osaragi, T. (2002). Spatial clustering method for geographic data. London, UK: Centre for Advanced Spatial Analysis (UCL).
- Páez, A., & Scott, D. (2005). Spatial statistics for urban analysis: A review of techniques with examples. *GeoJournal*, 61(1), 53-67. doi: 10.1007/s10708-005-0877-5
- Parker, R. N., & Asencio, E. K. (2008). GIS and Spatial Analysis for the Social Sciences
- Coding, Mapping and Modeling: Routledge.
- Pratt, R. H., Evans, J. E., & Levinson, H. S. (2003). Pedestrian and Bicycle Facilities (T. C. R. PROGRAM, Trans.) Traveler Response to Transportation System Changes: Transportation Research Board.
- Reconnecting America. (2007). Why Transit-Oriented Development And Why Now: The Center for Transit-Oriented Development.
- Renne, J. L., Wells, J. S., & Bloustein, E. J. (2005). Transit-Oriented Development: Developing a Strategy to Measure Success Research Results Digest: Transport Research Board.
- Ritsema van Eck, J., & Koomen, E. (2008). Characterising urban concentration and land-use diversity in simulations of future land use. *The Annals of Regional Science*, 42(1), 123-140. doi: 10.1007/s00168-007-0141-7
- Sadek, A. W., Wang, Q., Su, P., & Tracy, A. (2011). Reducing vehicle miles traveled through smart landuse design: the Department of Civil, Structural and Environmental Engineering at the University at Buffalo (UB), the State University of New York (SUNY).
- Schlossberg, M., & Brown, N. (2004). Comparing transit-oriented development sites by walkability indicators Transit Planning and Development, Management and Performance, Marketing and Fare Policy, and Capacity and Quality of Service (pp. 34-42). Washington: Transportation Research Board Natl Research Council.
- Sharifi, M. A., Boerboom, L., Shamsudin, K. B., & Veeramuthu, L. (2006). Spatial Multiple Criteria Decision Analysis in Integrated Planning for Public Transport and Land Use Development Study in Klang Valley, Malaysia Paper presented at the Proceedings of the 2006 ISPRS Technical Commission II Symposium, Vienna.
- Shastry, S. (2010). Spatial assessment of transit oriented development in Ahmedabad, India. Retrieved from http://essay.utwente.nl/59707/
- Singh, Y. J., Zuidgeest, M. H. P., Flacke, J., & Maarseveen, M. F. A. M. v. (2012). A design framework for measuring transit oriented development. Paper presented at the Urban transport XVIII: Urban transport and the environment in the 21st century, A Coruña, Spain.

- SMART. (2012). Inquiry into the utilisation of rail and infrastructure corridors: The SMART Infrastructure Facility at the University of Wollongong.
- Steenberghen, T., Aerts, K., & Thomas, I. (2010). Spatial clustering of events on a network. *Journal of Transport Geography*, 18(3), 411-418. doi: 10.1016/j.jtrangeo.2009.08.005
- Store, R., & Kangas, J. (2001). Integrating spatial multi-criteria evaluation and expert knowledge for GISbased habitat suitability modelling. *Landscape and Urban Planning*, 55(2), 79-93. doi: 10.1016/s0169-2046(01)00120-7
- Sugumaran, R., Meyer, J., & Davis, J. (2010). A Web-based Environmental Decision Support System for Environmental Planning and Watershed Management. In M. M. Fischer & A. Getis (Eds.), *Handbook of Applied Spatial Analysis* (pp. 703-718): Springer Berlin Heidelberg.
- SWOV. (2010). Mobility on Dutch roads. Leidschendam, the Netherlands: SWOV.
- Tsamboulas, D. A. (2007). A tool for prioritizing multinational transport infrastructure investments. *Transport Policy*, 14(1), 11-26. doi: 10.1016/j.tranpol.2006.06.001
- Wang, F. (2006). Quantitative Methods and Applications in GIS. GB: CRC Press Inc.
- Woodsong, G. G. (2005). GIS for TOD: Transit Oriented Development in the Bay Area: Metropolitan Transportation Commission.
- Yoshida, T., & Tanaka, K. (2005). Land-use diversity index: a new means of detecting diversity at landscape level. Landscape and Ecological Engineering, 1(2), 201-206. doi: 10.1007/s11355-005-0022-0
- Zhang, Y., & Guindon, B. (2006). Using satellite remote sensing to survey transport-related urban sustainability: Part 1: Methodologies for indicator quantification. *International Journal of Applied Earth Observation and Geoinformation*, 8(3), 149-164. doi: 10.1016/j.jag.2005.08.005

APPENDIX A



APPENDIX B

Summary of the incremental spatial autocorrelation table

Global Moran's I Summary by Distance

Distance	Moran's Index	Expected Index	Variance	z-score	p-value
300.00	0.000000	-0.000083	0.000000	1.000188	0.317220
400.00	0.842605	-0.000083	0.000043	129.055277	0.000000
500.00	0.803594	-0.000083	0.000021	173.584786	0.000000
600.00	0.537885	-0.000083	0.000010	173.163451	0.000000
700.00	0.711663	-0.000083	0.00009	241.549274	0.000000
800.00	0.711663	-0.000083	0.00009	241.549274	0.000000
900.00	0.590365	-0.000083	0.000005	254.711381	0.000000
1000.00	0.636419	-0.000083	0.000005	288.130166	0.000000
1100.00	0.609215	-0.000083	0.000004	304.194258	0.000000
1200.00	0.559279	-0.000083	0.000003	303.822129	0.000000
1300.00	0.566274	-0.000083	0.00003	328.875281	0.000000
1400.00	0.549273	-0.000083	0.00003	339.024615	0.000000
1500.00	0.468401	-0.000083	0.000002	337.928924	0.000000
1600.00	0.511921	-0.000083	0.000002	358.053618	0.000000
1700.00	0.493843	-0.000083	0.000002	367.460878	0.000000
1800.00	0.465836	-0.000083	0.000002	372.483976	0.000000
1900.00	0.458759	-0.000083	0.000001	384.580019	0.000000
2000.00	0.450516	-0.000083	0.000001	388.911835	0.000000
2100.00	0.431016	-0.000083	0.000001	392.540463	0.000000

Global Moran's I Summary by Distance (Cont.)

p-value	z-score	Variance	Expected Index	Moran's Index	Distance
0.000000	406.082617	0.000001	-0.000083	0.415471	2200.00
0.000000	409.071147	0.000001	-0.000083	0.409691	2300.00
0.000000	411.378836	0.000001	-0.000083	0.395888	2400.00
0.000000	420.667511	0.000001	-0.000083	0.386659	2500.00
0.000000	426.340056	0.000001	-0.000083	0.375841	2600.00
0.000000	428.201064	0.000001	-0.000083	0.366088	2700.00
0.000000	435.124759	0.000001	-0.000083	0.358759	2800.00
0.000000	438.870410	0.000001	-0.000083	0.352205	2900.00
0.000000	440.972253	0.000001	-0.000083	0.334846	3000.00
0.000000	448.299403	0.000001	-0.000083	0.334515	3100.00
0.000000	451.243254	0.000001	-0.000083	0.329379	3200.00

First Peak (Distance, Value): 500.00, 173.584786

Max Peak (Distance, Value): 1400.00, 339.024615

Distance measured in Meters