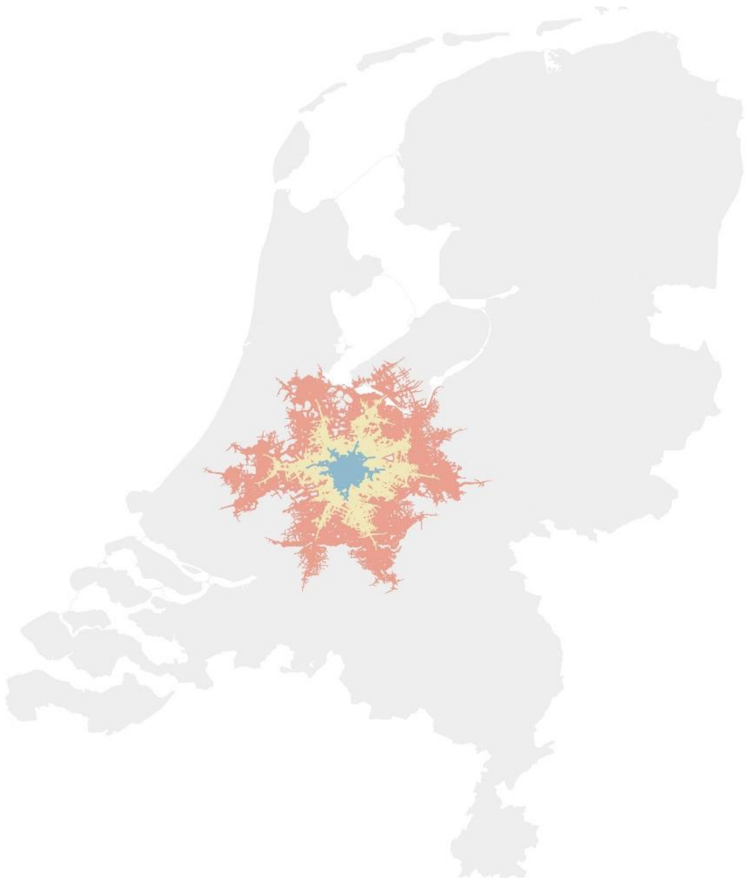
GIMA

Geographical Information Management and Applications

Towards a Dynamic Isochrone Map:

Adding Spatiotemporal Traffic and Population data



March 2017

Joris van den Berg

Supervisor: Drs. Barend Köbben

External Supervisors: Sander van der Drift

Luc Wismans

Universiteit Utrecht

TU Delft

UNIVERSITY OF TWENTE.

WAGENINGEN UR

dat. mobility

Colophon

GIMA MSc Thesis
March 2017

This master thesis is commissioned by the University of Utrecht, University of Wageningen, University of Twente, and the Delft University of Technology as part of the Geographical Information Management and Applications (GIMA) Master of Science.

Responsible Professor:
Prof. Menno-Jan Kraak

Supervisor:
Drs. Barend Köbben

External Supervisors DAT.Mobility:
Sander van der Drift
Luc Wismans

Contact information:
Joris van den Berg
Europaplein 774
3526 WP Utrecht
jorisvdberg@live.nl

UU student number: 3864847
ITC Student number: s6026028

Summary

New available data, new visualization techniques and an increased interest in dynamics through time lead to research increasingly focusing on variations through time. Spatiotemporal traffic data containing average driving speeds for different times allowed to calculate routes or isochrones throughout the day, and mobile data – being GPS tracking, mobile phones and locative media worldwide – lead to new opportunities in accessibility studies. Mobile data can give a more accurate way in the spatiotemporal distribution of the population and can be used to dynamically estimate the number of people within certain areas throughout the day.

This research combines these spatiotemporal traffic data and spatiotemporal population distribution data in a dynamic isochrone map. This allows to explore – through time – what areas can reach a given point within a given time and the number of people within that particular area.

We first researched the historical use of isochrone maps. Hereafter, using the studied literature, we designed a generic flowchart which divides the construction of an isochrone map in smaller sub-steps. First, decisions are made regarding the use and purpose of the isochrone map. These decisions influence what data, calculations and visualizations are suitable for that specific purpose. Secondly, the required input data is selected which is of influence on the calculations that can be used. Which brings us to the third step: isochrone calculations. In this step a method is developed to calculate isochrones that serve the purpose formulated before, using a calculation that is suitable for the data available. The resulting isochrones can then be visualized resulting in an isochrone map.

Though isochrone visualization seems like a relatively easy step, there are different ways of visualizing isochrone maps, depending on its purpose. Isochrone visualization, here, means not only colors used but also the shape chosen to represent the isochrones calculated. Examples include visualizing isochrones by coloring the network within reach, coloring the points in reach or by constructing an isochrone area. There are different ways to construct an area out of isochrone networks or isochrone points, each resulting in different shapes. Simple shapes might be more accurate for visualizing an isochrone, whereas more complex shapes might be more accurate for determining the number of objects within an isochrone area.

We have developed a methodology and visualization that allows users to interactively explore the spatiotemporal data online. The isochrone areas calculated were visualized using QGIS. Using the TimeManager plugin we were able to efficiently export the ten, twenty and thirty minute isochrones per fifteen minute interval. The resulting ninety-six images were then loaded in a HTML file and using JavaScript we generated an interactive animation out of the static images. The population distribution, consisting of the residents, visitors and total number of people, was added to the HTML file as a video using Microsoft Excel and PowerPoint.

Using a specific case study, we have proven that spatiotemporal traffic and population distribution data can be combined in a dynamic isochrone map to produce more accurate results compared to static methods. The IKEA isochrone map displays the areas which can reach an IKEA store within ten, twenty and thirty minutes in the Netherlands, throughout the day. It also displays the number of people within the thirty minute areas per IKEA store.

Acknowledgements

First of all and most importantly, I would like to thank my supervisors for their incredible help during the research process. Barend, with his extensive knowledge on web maps helped me realize one of my goals: creating an online dynamic isochrone web map. Sander, whom I could always approach for a nice chat or if I was stuck with one my SQL queries again. Luc, for critically reading my work and with your sharp and on point ideas and comments pushing my work to a higher level. Thanks!

I would also like to express my sincere gratitude to everyone at DAT.Mobility, for providing me the opportunity to write my thesis during a research internship using their facilities, data, inexhaustible knowledge and enthusiasm.

During the research it was often uncertain to what extent I would be able to actually create a dynamic isochrone map. I was unfamiliar with some of the necessary tools and often in doubt how and when I would finish this research. Fortunately, with the incredible help and support of my supervisors I have been able to construct a master thesis and dynamic isochrone map with which I am very satisfied. Besides, I have learned a lot from the whole research process and my time at DAT.mobility.

Contents

List of tables

List of figures

Chapter 01

Chapter 1: Introduction

1.1 Context

We live in a world in which we are constantly on the move. We travel for work, for leisure, for holidays and for our daily groceries. And, depending on the number of people that travel at the same time, we get in each other's way. By all travelling at the same time we cause delays, traffic jams and fill up public transportation thereby quite effectively diminishing the distance we can travel and the access to activities within a given time. Until recently, we lacked insight in where people are travelling and how the delays we cause influence accessibility through space and time. Contemporary accessibility studies focus on 'smart growth', trying to research how to maximize the number of places of activity that can be reached (Bertolini, le Clercq & Kapoen, 2005), maximizing the number of people that can possibly reach these places within a given travel time (Li et al., 2011; O'Sullivan et al., 2000). Boosted by an increase in the potential of spatiotemporal data, advancements in GIS (Geographic Information Systems) and Cartography, accessibility studies increasingly focus on dynamics and change through time (Innerebner et al., 2007).

A way of analyzing and gaining more insight into accessibility is through isochrone maps (figure 1.1). An isochrone map logically displays isochrones which are the points, lines or areas that can be reached from a given location, within a given time (Bauer et al., 2008; Efentakis et al., 2013; Marciuska & Gamper, 2010). In Greek, 'chronos' means time and 'iso' is a prefix for 'similar', so of similar time. Isochrone maps have mostly been used for urban planning and transport geography for the past few decades to gain more insight into cities' accessibility, reachability and coverage of public services (Marciuska & Gamper, 2010). Besides visualizing points, lines or areas that are within reach from a given location within a given time, the number of people within an area can be determined by combining the isochrone area with population distribution data. This determines the number of people that could theoretically reach or be reached from a given place within a given time.

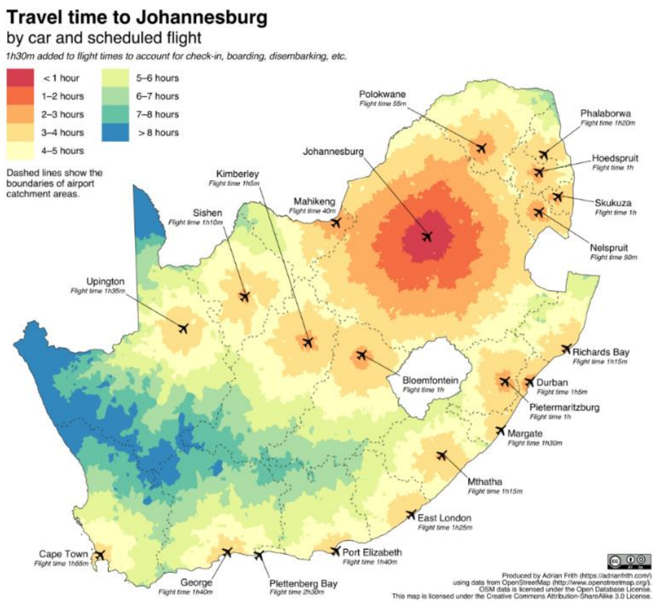


FIGURE 1.1 EXAMPLE ISOCHRONE MAP OF TRAVEL TIME TO JOHANNESBURG

1.2 Research Problems

One of the major problems with most contemporary isochrone maps is that static travel speeds are assumed when calculating isochrones. In other words: different locations are assumed to have the same travel-speed throughout time (Miller & Bridwell, 2009; Shaw, 2006). However, traffic conditions change significantly over space and time (Li et al., 2011). Using static travel time in accessibility studies and isochrone maps means that significant variations in accessibility through time and space would be ignored. Traditional work focused particularly on space constraints whereas time constraints have been mostly disregarded (Li et al., 2011). A possible solution would be to use spatiotemporal – changing through space over time (Andrienko et al., 2013, p. 382) – traffic data to calculate isochrones as done by Lee et al. (2009). While research on spatiotemporal traffic data has gained attention in route computation research, spatiotemporal traffic data for calculating isochrones have not received the same consideration (Baum et al., 2015).

Moreover, researches that determine the number of people in isochrone areas (Efentakis et al., 2013; Innerebner et al., 2013) fall short on one crucial point. While in these studies the relevance and need for spatiotemporal traffic data is claimed to be absolutely necessary, taking into account spatiotemporal variation in population distribution and movement is completely absent. Conclusions and business intelligence decisions in the work of Efentakis et al. (2013) are for example based on the assumption that people do not move, something that does not hold in the real world. The number of potential customers within fifteen minutes is determined in different traffic situations and Efentakis et al. (2013) showed that the number of potential customers varied between the twenty and forty percent depending on traffic, these variations seem to be quite significant.

Currently, mobile data, being GPS tracking, mobile phones and locational media worldwide, provide new opportunities for research into the movement of individuals and population distribution (Zook et al., 2015). To provide more accurate results and conclusions there is room for improvement regarding spatiotemporal population distribution using mobile data and showing the actual distribution of people through time and space instead of assuming that people are 'sleeping residents' remaining within their houses night and day (Järv et al., 2016).

Assuming static travel speeds and static population distribution has different consequences: users of isochrone maps can make decisions or interpretations based on assumptions, leading to overly simplified or erroneous images of the realities of accessibility (Tenkanen et al., 2016). Isochrone map users, like urban planners, would carry a risk of over- or underestimating accessibility or the number of people within reach in peak hours. Social equity is another related field where problems could occur when using static traffic data (Li et al., 2011; Shaw, 2006). People who live relatively close to facilities but suffer from traffic congestion have more difficulties accessing certain facilities than others who are not experiencing traffic congestion. This is especially true in urban areas (Melhorado et al., 2016). Errors could also occur in areas which are not inhabited but are crowded, like airports or business areas. Because officially no one is registered to live in these areas, using static population distribution data in accessibility studies would assume that no one is present in those areas, whereas in the real world significant numbers of people travel to these places.

Despite possible benefits spatiotemporal data might have when implemented in isochrone maps, the implementation of spatiotemporal data can cause new problems. Problems both technically, how to calculate isochrones using vast amounts of spatiotemporal data, as well as how to visualize dynamics in isochrone maps. More data does not necessarily mean more accurate or better results. Ironically, more (spatiotemporal) data means more complications and more effort to conduct useful research (Zook et al., 2015). According to Ullah and Kraak (2015), spatiotemporal data needs interactive geovisual analytical representations to produce useful insights. Although a lot of effort has been put in developing visualization methods that meet the needs to analyze and understand spatiotemporal data (Zenget al., 2014), options that effectively deal with temporal data in cartography still have not been developed sufficiently (Andrienko et al., 2010; Li & Kraak, 2008). Moreover, using spatiotemporal traffic and population distribution data in isochrone maps has not been researched before. It is unclear if and how the data can be combined and especially what potential these data actually has for use in isochrone maps. Besides, the relative novelty of these data means that there is a lack of research into best practice (Zook et al., 2015).

Lastly, the strength of isochrone maps is to visualize accessibility (Doling, 1979; O'Sullivan et al., 2000). Still isochrone maps have been used infrequently in the literature and are often absent from well-known studies on accessibility (O'Sullivan et al., 2000). Besides isochrone maps being potentially undervalued in contemporary literature, little attention has been given to the possible value isochrone maps can have when enriched with spatiotemporal data. Efentakis et al. (2013) conducted one of the few researches that used static and dynamic traffic data to research differences between the two. They concluded that spatiotemporal traffic data have a 'huge' impact to informed business intelligence decisions. Jihua et al. (2013) created accessibility profiles to display variations in accessibility throughout the day. By plotting the isochrone area in square kilometers versus different hours a day, a better insight in the accessibility of a place was realized.

1.3 Research Focus

This research focuses on the incorporation and potential use of spatiotemporal traffic and population distribution data in a dynamic isochrone map. The main Research Objective (RO) of this research is:

RO: To incorporate spatiotemporal traffic and population distribution data in a dynamic isochrone map

In the main objective spatiotemporal is referring to both traffic data and population distribution data and their changing nature through space and time. Dynamic in isochrone map refers to the ability of interactively exploring dynamics and changes in spatiotemporal data. In order to do so, a general understanding of isochrone maps is needed first. Therefore, historic work regarding isochrone maps and how they have developed over time are discussed first. Since this research focuses not only on isochrone maps, a literature review covering all relevant concepts within the fields of accessibility and cartography studies is conducted as well.

O1: To review historic and current scientific literature related to isochrones and spatiotemporal traffic and population distribution data in accessibility and cartography studies

After formulating the theoretic framework in which this research is situated, various concepts are combined. Firstly, spatiotemporal traffic and population data need to be pre-processed in order to determine the usability in isochrone maps. Data pre-processing is defined as: 'A step (…) where data are prepared before analysis methods can be applied. This step may include data cleaning (removing noise and/or outliers, handling missing values, resolving inconsistencies), integration, formatting, reduction etc.' (Andrienko et al., 2013).

O2: To pre-process spatiotemporal traffic and population distribution data for combined use in dynamic isochrone maps

To actually make sense out of spatiotemporal data, options to dynamically visualize spatiotemporal data are explored:

O3: To dynamically visualize isochrone maps containing spatiotemporal traffic and population distribution data

Lastly, the usability of spatiotemporal traffic and population distribution data in a dynamic isochrone map are tested using a specific case study (paragraph 1.7).

O4: To review the usability of spatiotemporal traffic and population distribution data in dynamic isochrone maps using a specific case study

1.4 Research Questions

The main question in this research is:

RQ: How can spatiotemporal traffic and population distribution data be incorporated in a dynamic isochrone map?

Sub questions are formulated to on the one hand help answering the main question by breaking it into smaller parts, and on the other hand solve related problems and questions directly contributing to answering the main question. The sub questions are subsequently:

Q1: To what extent have isochrone maps, spatiotemporal traffic and population distribution data been researched in accessibility and cartography studies?

Q2: How is spatiotemporal traffic and population distribution data pre-processed for combined use in dynamic isochrone maps?

Q3: How can spatiotemporal traffic and population distribution data be visualized dynamically in isochrone maps?

Q4: What potential does including spatiotemporal traffic and population distribution data in dynamic isochrone maps have when applied to a specific case study?

1.5 Social and academic relevance

This research has both social and academic relevance. The academic relevance is that problems regarding isochrone maps and spatiotemporal data in accessibility studies and cartographic studies are addressed. Firstly, problems identified in accessibility studies regarding static traffic data and static population distribution data are addressed by researching incorporation of spatiotemporal, dynamic data. Secondly, researching the potential use and best-practice of spatiotemporal data adds to the overall scientific knowledge. Besides that, methods to dynamically visualize change through time adds knowledge and raises awareness to pressing questions in cartographic studies: How to effectively visualize time?

The social relevance becomes apparent when discussing several possible use-cases of a dynamic isochrone map that uses spatiotemporal traffic and population data. Calculating isochrone maps using spatiotemporal traffic data eventually allows insight in dynamic change in accessibility. Questions that could be solved include: What happens to the accessibility of a city center during rush hours? During what time intervals can suppliers best supply me? How did an accident on the highway affect accessibility this morning?

By combining isochrone maps with spatiotemporal population distribution data a whole new range of interesting questions can potentially be answered. Spatiotemporal population distribution data are used for roughly determining the number of people within areas at a given time. Since the movement of people is a dynamic phenomenon, spatiotemporal population distribution data can possibly give a more realistic count of the number of people within an area compared to using static population data. Also, knowing where people cluster, and at what times, allows businesses to adjust their opening hours, schedule of events and optimal location (Steenbruggen et al., 2015). The rise of alternative ways to track the movement of people, and the spatiotemporal distribution of populations is particularly interesting in accessibility studies, and until recently has not been used (Järv et al., 2016). The relative newness of these sorts of data means that no best-practices have been developed yet (Zook et al., 2015).

To dynamically visualize isochrone maps incorporated with spatiotemporal data means a more efficient visualization of spatiotemporal change (Innerebner et al., 2013). Besides, it also provides a possibility to display interactive statistics allowing easier interpretation of the presented results. As Ullah and Kraak (2015) mentioned, there is a need for interactive geovisual analytical representation of the produced spatiotemporal data in order to produce useful insights and to make sense out of the data.

Using spatiotemporal traffic data has already proven to be successful in several accessibility studies (Jariyasunant et al., 2010; Jihua et al., 2013; Innerebner et al., 2013; Li et al., 2011; Marciuska & Gamper, 2010). Also, there are technological opportunities like mobile data that can have additional value for isochrone maps and reachability studies. This research aims to exploit those possibilities.

1.6 Research Limitations

This research limits its scope to the use of isochrone maps and spatiotemporal traffic and population distribution data in accessibility and cartographic studies, although the potential use of these concepts is not limited to these two fields. Another limitation is the case-study introduced (paragraph 1.7). There is a variety of cases in which a dynamic isochrone map using spatiotemporal traffic and population distribution data could be used each with slightly different requirements. By choosing one particular case-study specific choices regarding data used and methodology have been made. However, the case-study serves as a proof-of-concept and eventually shows the potential use of spatiotemporal traffic and population distribution data in isochrone maps. Lastly, no actual end-users have been involved in the process. Therefore, the actual needs and requirements of end-users are not taken into account. The potential value in a specific case study (Q4) is described by the researcher. This limitation is elaborated in the discussion (chapter 9)

1.7 Introduction Case Study

To research the potential practical use of spatiotemporal traffic and population distribution data, a case study was chosen. The case study used in this research is the dynamic accessibility of Ikea in the Netherlands. Ikea is a furniture retailer aiming to provide people with affordable design (IKEA, 2016). Developing a dynamic isochrone map using spatiotemporal traffic and population distribution data is potentially interesting to dynamically analyze the areas and the number of people that can reach an IKEA store within a given time. This might also lead to identifying potentially interesting locations for a new store.

The Dutch IKEA manager Kristina Johansson claims that 90% of the Dutch population is currently within a one-hour drive of an Ikea store, and nearly half of the Dutch population even lives within 20 minutes (Rietveld, 2015). This statement can be analyzed using spatiotemporal traffic and population distribution data. Firstly, calculating isochrone areas using spatiotemporal traffic data allows to dynamically explore what areas have access to Ikea stores and how this access fluctuates throughout the day. By combining these areas with spatiotemporal population distribution data, a more realistic number of potential customers within the areas can be calculated. Also, by calculating areas which can reach an Ikea store within a certain time, areas out of reach can be identified.

We formulated some assumptions. First of all, IKEA service areas and potential new store locations are limited to the Netherlands. With the data used in this research, network and population analysis are limited the Netherlands and people and roads outside of that are not taken into account. Furthermore, since 95% of the people visiting Ikea do so by car (Heede, 2016), this case study is based on the assumption that all people visiting Ikea do so by private car. The isochrones are therefore calculated using a road network as input.

Lastly, we would like to emphasize that IKEA was in no way involved in this research. The analysis of IKEA stores serves only as a proof-of-concept that incorporating isochrone maps with spatiotemporal traffic and population distribution data in a dynamic web map can lead to relevant and useful insights regarding accessibility.

1.8 Thesis structure

The structure of this thesis is as follows (figure 1.2): The first part (in the yellow box) consists of an extensive literature review (steps 1, 2, 3, and 4). The literature review provides the context of what this research is about as well as what has been done so far. The literature review is spread over the chapters 2, 3, 4 and 5. These chapters subsequently discuss the four most relevant concepts in this research: isochrone map history, isochrone map construction, accessibility studies and cartography. A result of the literature review is a conceptual model that is presented in chapter 6 and links the four concepts discussed.

The second part (in the red box) consists of the methodology used to create a dynamic isochrone map. The first steps consist of calculating isochrones (5, 6, and 7). The steps hereafter consist of processing spatiotemporal population distribution data (8), and combining this data with the isochrones calculated (9). The resulting maps (10) are visualized (11) with interactive elements (12) and tested for functionality (13). This is described in detail in chapter 7.

After describing the results (chapter 8) the thesis is finalized with a discussion (chapter 9) which reflects on the research process and the methods and data used. This discusses how the context and way in which this research is set up is of influence on the results and conclusion (Rossiter, 2008). Finally, the conclusion (chapter 10) answers the main question and draws more general conclusions taking into account the points mentioned in the discussion. Recommendations for future research are also included, encompassing both parts that could have been done better and unexplored interesting questions to be researched in future work.

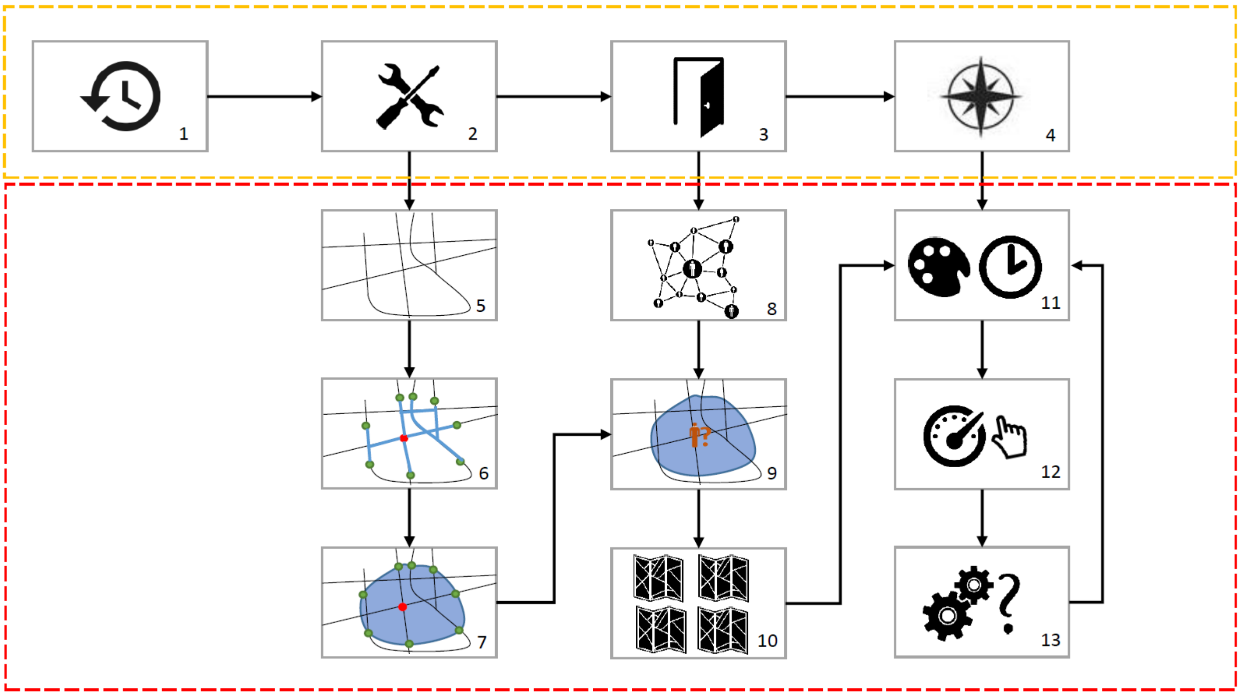


FIGURE 1.2 DESIGN SCHEME

Chapter 02

Chapter 2: Isochrone maps

One particular sort of map plays a central role in this research: the isochrone map. This chapter provides an elaborate overview of the isochrone map. We first work our way through history and see how isochrone maps were used and how they have developed overtime. Accordingly, we explain how isochrones and isochrone maps are constructed, since there is a variety of ways to do so. Isochrones are defined as: 'The set of all space points from which a query point is reachable within a given timespan' (Bauer et al., 2008; Efentakis et al., 2013; Marciuska & Gamper, 2010).

Using isochrone maps has several advantages. They are especially useful in analyzing the number of destinations accessible within a given travel time (Wang et al., 2016) and are useful in visualizing accessibility. People, when travelling, tend to think of accessibility more in terms of time rather than in terms of the actual distance (Ullah & Kraak, 2015). It is more relevant to know the time it takes to get somewhere than the actual distance to that same place. It can be interesting and useful for users to see the time it takes to get to a place, since most maps display geographical distance and not time. Besides that, distance-scaled maps can often be misleading, it can for example occur that a place – which is geographically closer by – takes longer to reach time wise than a place geographically further away. This can be caused by poor connections or differences in speed limits in the road network. Isochrone maps help users to gain a better understanding of their accessibility. It visualizes accessibility using time rather than distance and it provides a realistic way of visualizing transport options available and opportunities within reach (O'Sullivan et al., 2000; Doling, 1979).

It is important to distinguish the terms isochrones and isochrone maps. Isochrones are a collective term for isochrone points, isochrone networks and isochrone areas. All of them can be calculated using the same technique but their representation as a spatial object is different, they can be represented using points, lines or areas. By for example connecting all space points, an isochrone area is created. An 'isochrone area refers to the set of all points contained within an isochrone which are reachable in the specified time or less' (O'Sullivan et al., 2000). Isochrone maps simply refer to maps visualizing isochrones, and have nothing to do with isochrone calculations. Isochrone maps are the resulting product of calculations and choices made (figure 2.1). This is discussed in more detail in chapter 3.

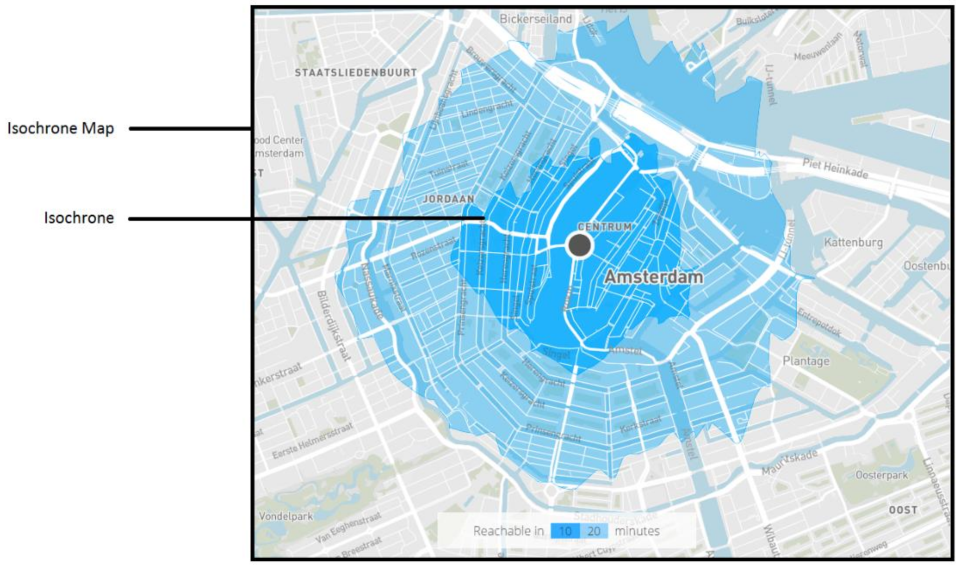


FIGURE 2.1 EXAMPLE OF AN ISOCHRONE AND ISOCHRONE MAP (URBICA DESIGN, 2016)

2.1 Isochrone maps drawn by hand

The first known isochrone map was produced in 1881 by Francis Galton (figure 2.2, Galton, 1881). It displays travel times from London to the rest of the world. In the following decades, more isochrone maps appeared. The John Bartholomew and Son Map Publishing Company improved and further developed and expanded the isochrones audience. Isochrone maps became more detailed and were drawn on country and city level. Since cars were not that common, isochrone maps were drawn based on public transport. Examples include 1920's isochrone maps of Manchester (Mapping Manchester, 2013) and Melbourne (MCCTD, 1914) rail transport travel times. First, travel times to different stations were determined, using measurement data or interviewees' description of a journey (Brainard et al., 1997). Hereafter, buffers were drawn around stations taking into account the distance a person could still travel while walking. For more details on how isochrones were calculated, see the work of Riedel (1910).

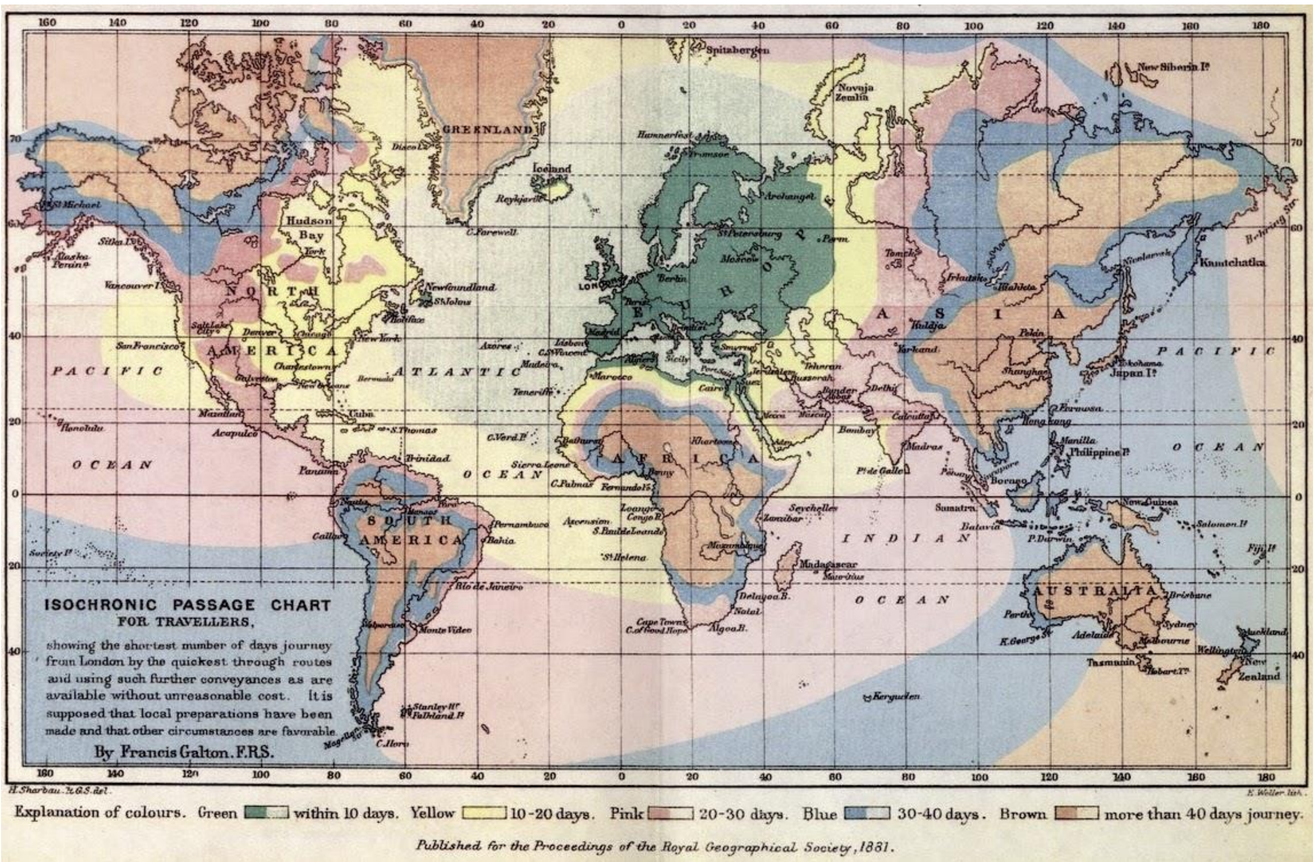


FIGURE 2.2 ISOCHRONIC PASSAGE CHART (GALTON, 1881).

Most of these maps are related to travel time, however, other uses were developed as well. An example is the ‘Springtime Begins’ map, published around 1930 (figure 2.3, Lange-Diercke, 1930). It shows during what times spring begins in different geographical places. Though the majority of isochrone maps visualizes travel times and reachability, one should keep in mind other possibly interesting applications for isochrone maps. It is not uncommon to use isochrone maps for visualizing natural phenomena (also see: Birks, 1989).

These early examples of isochrone maps were mostly used to assist urban planners by giving them more insight into accessibility (Kok, 1951; Rowe, 1953; Forer & Kiveli, 1981; Getis & Getis, 1972). Apart from these examples isochrone maps appeared to not be used that frequently anymore. This presumably had to do with the laborious and intricate nature of drawing isochrones. It was not until the development of computers and GIS that isochrone maps regained interest due to new possibilities (O’Sullivan et al., 2000).

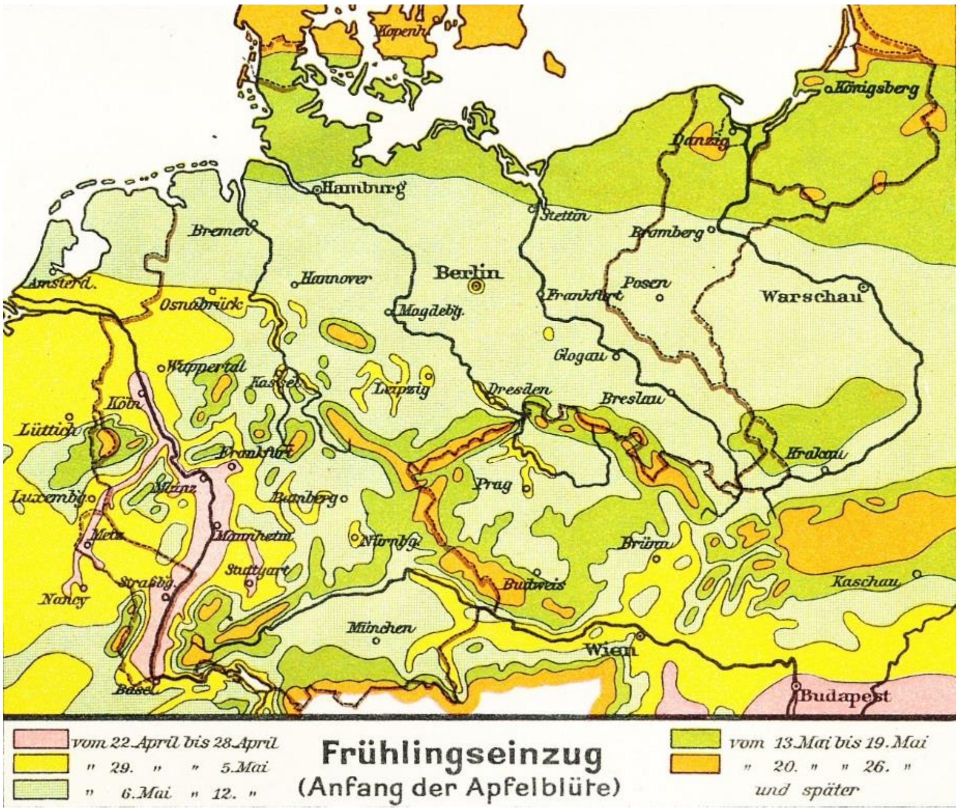


FIGURE 2.3 ‘SPRINGTIME BEGINS’ (LANGE-DIERCKE, 1930)

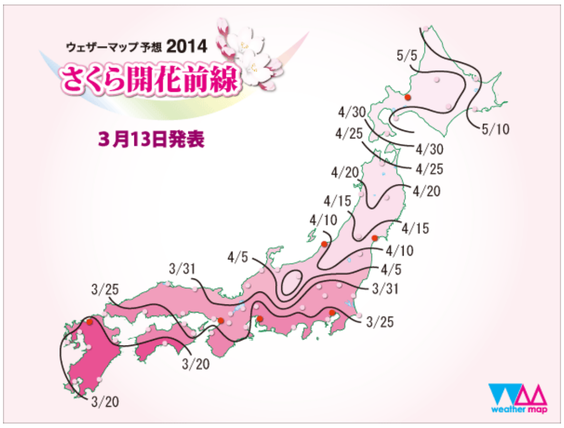
2.2 Isochrone maps on a desktop GIS

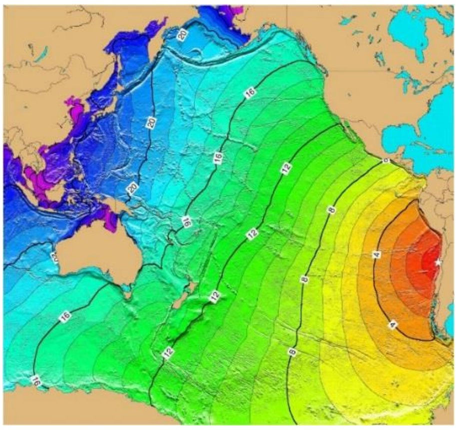
O'Sullivan et al. (2000) and Brainard et al. (1997) are amongst the first researchers that published articles regarding calculation of isochrones using GIS. Using GIS allowed complex calculations that are either too time-consuming or impossible for humans to execute. Travel times for example, were previously determined based on an interviewees' description of a journey, a GIS approach could now produce more precise estimates of distance and travel time. This is only one of the advantages.

Drawing an isochrone map on paper was not very efficient. Fixing mistakes or drawing a new isochrone map was very time-consuming. With the introduction of GIS, the flexibility of drawing isochrone maps was increased. Brainard et al. (1997) mention that GIS made it possible to more quickly and easily generate isochrones. Where isochrone calculations using GIS in the early 2000's were still quite basic, developments in computational power, GIS functionalities and more geographical data allowed more complex and precise isochrone calculations. The first generation of network GIS analysis often assumed travel by private transport over a road network, whereas later work of for example O'Sullivan et al. (2010) focused on multi-modal transport (see paragraph 3.2.1), using different modes of transport. Taking into account for example different bus lines, and walking distances to bus stops increased calculations' complexity.

Soon, isochrone maps developed further: isochrones were combined with other spatial datasets leading to new interesting results. Isochrone maps were more frequently used in accessibility studies to determine what could be reached from a given point in space, within a given time or to determine the number of people within reach (O'Sullivan et al., 2010; Bauer et al., 2008; Bertolini et al., 2005), and the modes of travelling based on travel schemes became increasingly precise. Also, the use of static traffic data shifted towards more advanced, dynamic methods driven by new datasets (Jariyasunant et al., 2010; Jihua et al., 2013; Hudeček, 2011; Lee et al., 2009; Li et al., 2011; Messelodi et al., 2009; Roanes-Lozano, 2012). New techniques allowed the calculation of actual travel speeds at a given time, giving a more realistic view of accessibility using isochrone maps.

While the majority of scientific researches on isochrone maps were related to networks and travel times, some other uses outside of the academic world were created as well. Private and public sectors used isochrones to map natural phenomena, such as a cherry blossom forecast in Japan (figure 2.4a), and estimated tsunami waves travel times (figure 2.4b).





(a)
Cherry Blossom (Weather Map, 2014)

(b)
Tsunami Waves (NOAA, 2016)

FIGURE 2.4 OTHER ISOCHRONE MAP USES

2.3 Isochrone maps on a web GIS

Simultaneously with the development of web maps (see chapter 5), it did not take long for isochrone maps to appear on the web (Biazzo, 2015; Efentakis et al., 2013; Gortana et al., 2014; Innerebner et al., 2013; RPA, 2011; Simplefleet, 2014; Urbica Design, 2016; Waag Society, 2014; Wehrmeyer, n.d.). Through the internet, isochrone maps became available for the public. First isochrones were static: they were merely images of an isochrone map displayed on a website, interaction was not possible (Cartwright, 2008). Later, interactive isochrones were developed. It was now possible to check what places could be reached within a given time, using different modalities with a simple click (figure 2.5). The flexibility in selecting what points should be used as input – along with other parameters – proved to be a major advantage over previous isochrone maps in which the creator determined what the input was. No longer powerful desktops and often expensive GIS application software were required to analyze reachability and no longer experts were required to create an isochrone map that fitted personal needs. As a result, more and more online isochrone maps were launched. Where a first generation of online isochrone maps focused on reachability using different modalities, more recent online isochrone maps combined isochrone areas with other spatial datasets for example to determine the number of jobs within reach (RPA, 2011).

Although it cannot be denied that these online interactive isochrone maps have proven to be useful to gain a better understanding and insights into reachability, issues have occurred as well. Most online isochrone maps provide little to no information regarding methods and data used by the creator. What travel speeds were used as input in the calculation? What road network is used and how accurate is it? Where did other spatial datasets come from and what is their accuracy? How have isochrone areas been determined? These are all questions that are crucial when a user wants to draw valid conclusions based on a presented isochrone map. This is not exclusively true for isochrones in web maps but also for isochrones created using a desktop GIS. Nearly anyone has access to and can create isochrones on the web since isochrone maps became available online. At the same time this poses a problem: not all of these isochrone maps have the same detailed calculations and it is hard to validate their accuracy.

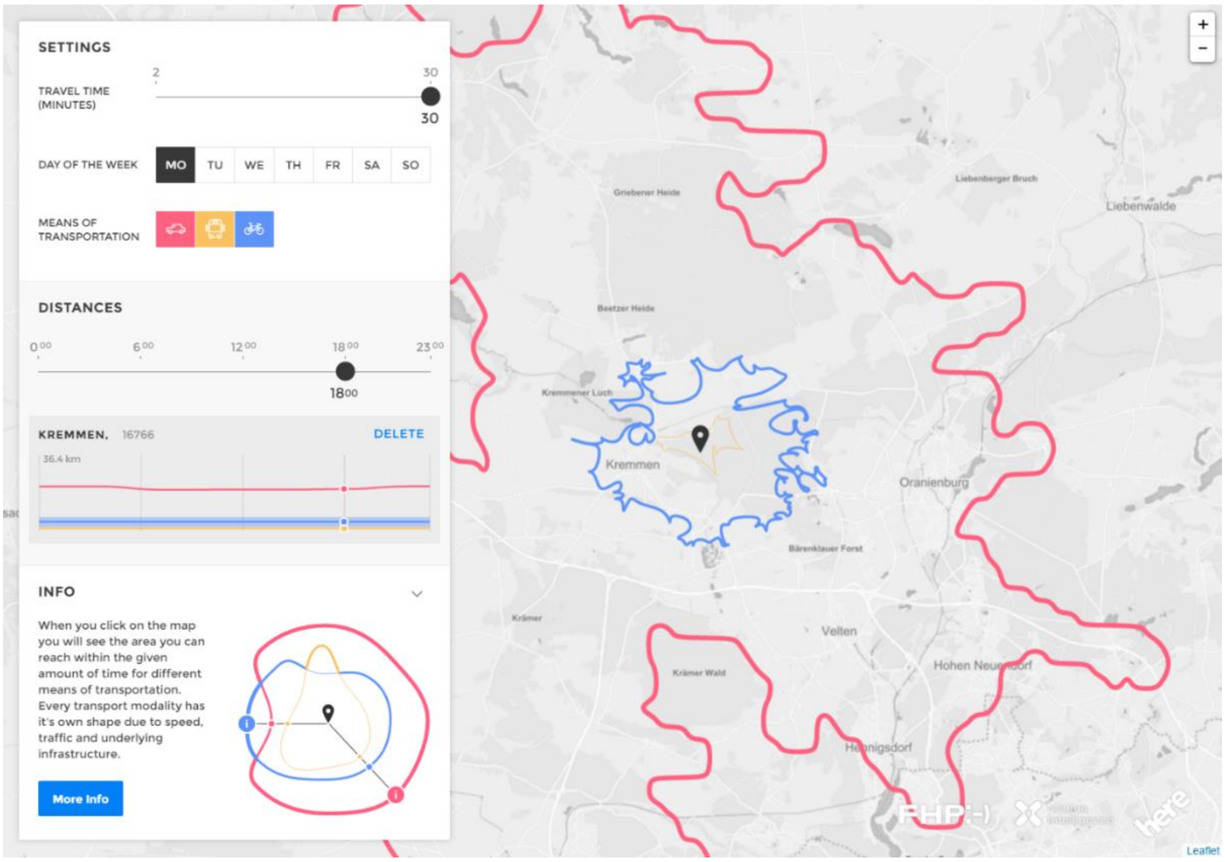


FIGURE 2.5 ISOSCOPE APPLICATION FOR DIFFERENT MODALITIES (URBICA DESIGN, 2016)

Chapter 03

Chapter 3: Constructing isochrones

Although most of the isochrones discussed here have in common that their goal is to display the set of all space points from which a query point is reachable within a given timespan (Marciuska & Gamper, 2010), there is a variety in methods to construct them (Bauer et al., 2008; Efentakis et al., 2013). Figure 3.1 introduces a basic workflow used when constructing isochrones. This chapter covers the most important decisions that have to be made when constructing isochrones. These decisions determine the calculation that has to be used. Accordingly, the data used as input for the calculation can differ which influences the resulting isochrone. Finally, there are different ways of visualizing isochrones. Visualizing refers to both the lay-out of an isochrone map as well as its representation as spatial object. Discussing all of these topics provides an overview of differences in isochrones and isochrone maps. Note that in line with this research, these terminologies all relate to isochrones and isochrone maps being used for reachability studies and are constructed using GIS. Also, one method of constructing an isochrone is not necessarily better than others. It fully depends on the intended use.

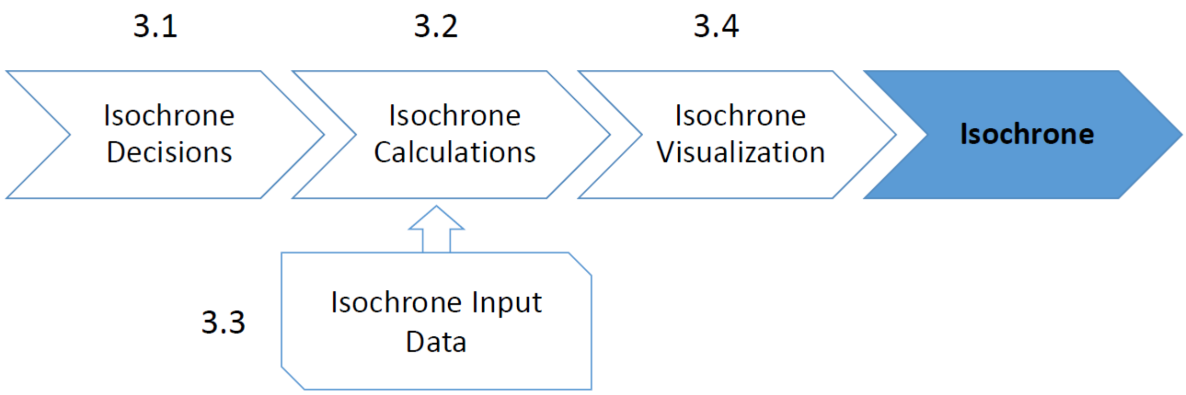


FIGURE 3.1 ISOCHRONE CONSTRUCTION WORKFLOW

3.1 Isochrone decisions

3.1.1 Network vs as the crow flies

A very simple example of an isochrone would be to see what area people can reach from their house within fifteen minutes. In this case two versions of an isochrone can be constructed: the first one assumes that people can move in all directions walking in an equal pace. Circles of various radii, depending on peoples walking speed, are in this case be formed around people's houses. Figure 3.2 displays a situation in which a river is next to the starting point. Drawing a circle around it would mean that places on the water are reachable as well, and in case there were no bridges, areas on the other side of the river would be falsely included as well. Since drawing circles around a given point in some cases is insufficient, another option is available: to base isochrone calculation on the street network. This way, different walking speeds per road and time penalties at junctions with traffic lights could be added as well. This can lead to a higher accuracy (O'Sullivan et al., 2000). This research focusses particularly on calculating isochrones using road networks.

FIGURE 3.2 AS THE CROW FLIES ISOCHRONE (URBICA, 2015).

In order to fully understand how isochrones are calculated on a network, a partial understanding on spatial networks is needed first. A network is defined as: 'a set of interconnected linear features through which materials, goods and people are transported or along which communication of information is achieved' (Heywood et al., 2011). In GIS, networks are used to model reality. A network is represented as a set of lines and points but with additional special attributes. Topological relationships define how these lines are connected (Longley et al., 2011). The lines serve as network links or edges (figure 3.3), they represent 'roads, railways and air routes of transport networks, the power lines, cables and pipelines of the utilities networks, or the rivers and streams of hydrological systems' (Heywood et al., 2011). Links or edges can be either directed or undirected, meaning directions are specified per link (directed) or that it does not matter in what direction the link is traversed (undirected). This is further discussed in paragraph 3.3.2.

Points are used as nodes or vertices (figure 3.3), they represent network nodes, stops, centers and turns. They can also model real-world things like junctions, bus stops, river deltas etc. Heywood et al. (2011) describes stops as: 'points where goods, people or resources are transferred to and from some form of transport system.' Centers are discrete locations on a network which have some form of attraction. However, stops and centers for this research are irrelevant. More important are nodes or vertices that represent turns. Turns are transitions between edges or links and represents relationships between them that affect movement through the network (Heywood et al., 2011). A turn might for example contain information about traffic lights at a junction.

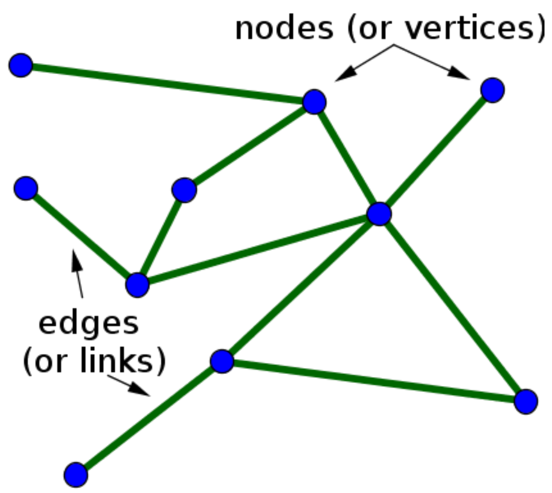


FIGURE 3.3 SIMPLE NETWORK REPRESENTATION
(MATH INSIGHT, 2016)

Another important term for network features is impedance. Network features are primarily based on impedance. Impedance is the cost of travelling between nodes along a network and the costs of making a turn and/or stop based on local conditions. These are important in determining the outcome of for example route finding. (Heywood et al., 2011, p. 97). Impedance is crucial in different network operations. Impedance can be expressed in different forms. Link impedance for example, is about involved costs when traversing a link. Costs can be expressed in whatever unit a user is interested in. Costs can for example be money, time, fuel, or a driver's salary. Sometimes costs are specified for both directions of the same link. If for example a road is on a slope, it costs more fuel to drive up that road compared to when you drive down (For an example, see: Dannenberg et al., 2011). This is also referred to as cost and reverse cost. Lastly, turn impedance is about involved costs on a turn. It is possible that a right turn is prohibited, or more expensive than a left turn. Lastly, stop impedance is similar and is about involved costs when making a stop. In some places on a road it is either impossible or not allowed to make a stop (Heywood et al., 2011).

3.1.2 Road network

A network dataset, like other spatial datasets, is often stored in a spatial enabled database. This database stores information about the network. Nodes, links impedances and their geometry is stored in such a way that they can be visualized and analyzed. The shortest path problem is a well-known problem in network analysis and of importance to be able to determine isochrones. It deals with the question how to get from point A to point B at the lowest possible cost. Despite the fact that the problem is called the 'shortest' path, the actual calculation can be based on whatever impedance unit connected with the network. As a result, different costs can be combined allowing different formulations of a shortest path. For a driver it might for example be relevant to select the fastest or the simplest route rather than the shortest one (Sacharidis & Bouros, 2013). Based on the chosen definition of cost various algorithms like the Dijkstra algorithm (1959) can be used to solve the shortest path problem to determine the 'cheapest' option, being the route with the least impedance. Other uses of network analysis include the travelling salesman problem, location-allocation questions and route tracing (Heywood et al., 2011).

3.2 Isochrone calculations

The essence of calculating isochrones is relatively simple; shortest path calculations on a road network are a first step towards calculating isochrones. So rather than calculating costs 'shortest' paths from point A to point B, point A is given and respectively all possible routes in all possible directions to or from point A are calculated until the maximum given timespan is reached. Eventually, the computer returns all nodes and edges that are located within a given maximum timespan. Besides the location, the cumulative costs that were already made when reaching a given point or edge are stored as well. Note that isochrone maps are always using time as cost, which is why they are called isochrones.

The above description is the essence of all isochrone calculations. However, calculations become more complex once different modalities and more accurate datasets are added. While the core remains the same, the actual algorithms calculating the isochrones are vastly different. The equations used in these algorithms are not discussed more in depth in this theoretical framework since they are not the focus of this research. Instead there is a focus on why there is a need for differences in isochrone calculations. For those who do want to read more on isochrone algorithms, see Bauer et al., (2008), Baum et al., (2016), Baum et al., (2015), Jariyasunant et al., (2010), Efentakis et al., (2013), Gamper et al., (2012), Specht et al., (2014) and Marciuska & Gamper (2010).

3.2.1 Single modal vs multimodal

Isochrone calculations can take different modes of transport into account as well. To start, a decision has to be made how many modalities are taken into account. There are basically two options: single modal and multimodal. Single modal networks are based on the simple assumption that only one transport system is used; either walking, public transport or car. Whereas multimodal networks permit several transport systems (Gamper et al., 2012). For example walking in combination with public transport. This further complicates isochrone calculations since the option to switch transport has to be taken into account (O'Sullivan, et al., 2000). In this research, single modal is used.

3.2.2 Discrete vs continuous in time and space

Networks can be continuous or discrete in both time and space. Networks continuous in time can be traversed at any point in time, discrete time networks follow an associated schedule (Gamper et al., 2012). Ullah & Kraak (2015) refer to this as scheduled or non-scheduled movements. Scheduled movement is tied to time-tables, while a non-scheduled movement is not. Scheduled could for example include trains or airplanes which are bound to a time table, whereas non-scheduled could include biking or travelling by private car. Again, this has an impact on isochrone calculations since in scheduled or discrete time networks the departure or arrival time has to be taken into account. The departure or arrival time determines whether there is waiting-time at certain bus stops or train stations. Continuous or discrete in space has to do with the chosen modality as well. Continuous in space means that a stop can be made anywhere along a road. In retrospect, discrete in space means that a stop can only be made along points that connect the roads (Gamper et al., 2011; Gamper et al., 2012). A car can theoretically stop anywhere along most roads, should the driver desire. People taking a bus do not possess the same luxury, they can only stop or get off at given bus stops.

3.3 Isochrone Input Data

Basic road networks contain information on nodes and edges and typically have impedances, 'costs' to traverse parts of the network. These provide a basis for isochrone calculations. However, road networks have become more accurate to better resemble real world situations. In isochrone calculations it is possible to include more accurate information leading to more accurate isochrones. The differences in road network datasets and its implications on the resulting isochrones are discussed in the upcoming paragraph.

3.3.1 Static vs dynamic

In order to calculate how far an individual can travel within a given time, two components are crucial: the road length and the average speed driven. Using the combination of these two components in a calculation can determine how far an individual can get in a given time. The road length is static, in a road network the length only has to be calculated once and this length remains the same until the road is physically changed. On the contrary, the average travel speed is dynamic and dependent upon a lot of variables. Travel speed is affected by traffic and non-traffic related factors, such as speed limits, traffic volume and traffic facilities (e.g. signals) and non-traffic factors including traffic weather, road construction (Lee et al., 2009).

Traditionally, isochrone maps were limited to a single snapshot in time, creating a static image of accessibility. Speed limits were often used as average speed in calculating isochrones or an average speed driven that day. However, traffic changes significantly through space and time (Li et al., 2011). Ultimately, isochrones can be calculated using static or dynamic traffic data as input. Static traffic data has only one value for the average speed driven on a road segment whereas dynamic data contains average speeds that vary over time and in space.

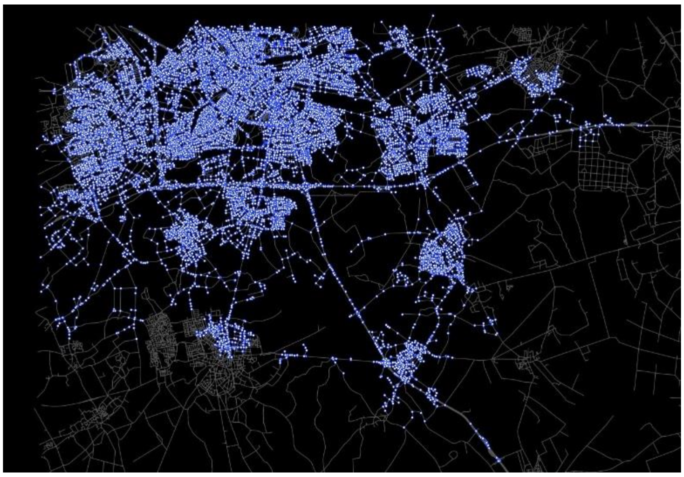
3.3.2 Directed vs undirected

Paragraph 3.1.2 already briefly discussed directed and undirected networks. Network data used in isochrone calculations should ideally be directed. Undirected networks could result in inaccurate results since these cannot deal with one-way streets which could for example result in paths in which one-way streets are traversed in the wrong direction. However, there are solutions to resolve this problem. It is possible that a road is stored in a database as two lines, one for each direction each with its cost. Another way is to store a cost and a reverse cost on one line segment. It is possible that costs to traverse a road segment from A to B are different from traversing the same road segment from B to A, some road networks include only one cost field per road segment for both directions. This can for example be a speed limit that is the same for both directions. In the real world it is common that travel speeds in one direction are different than travel speeds in the other direction. Some road networks include both costs and reverse cost and can result in more accurate calculations. These are also important when deciding to calculate to or from a given point. Moreover, costs and reverse costs can also determine whether the calculations is directed or undirected. By entering divergent values, depending on the tool used, for road segments that cannot be traversed in a particular direction the network becomes directed.

3.4 Isochrone Visualization

3.4.1 Isochrone points and lines

Isochrones are a collective term for isochrone points, isochrone lines and isochrone areas. All three are calculated using the same technique and are referred to as isochrones, but their representation and visualization on an isochrone map is different. Visualization here refers not only to the lay-out of the map but also the representation of an isochrone, so as points, lines or areas. A logical choice would be to visualize isochrones as a set of points, since these are determined by calculating isochrones. Isochrone points can be visualized to display what points can be reached over a network, within a given time (figure 3.4a). Likewise, isochrone lines can be displayed by visualizing the edges which are determined in the isochrone calculation (figure 3.4b). Simply put, edges belonging to nodes within reach are drawn, forming a network within reach of a certain time. This is a basic visualization with limited information, additionally the isochrone points or isochrone network could be colored according to the cumulative costs so that a difference within the given time can be visualized.



(a) Isochrone points

(b) Isochrone network

FIGURE 3.4 ISOCHRONE POINTS AND ISOCHRONE NETWORK

3.4.2 Isochrone areas

Isochrone areas differ slightly; where geometries for isochrone points and isochrone networks are already given, geometries for isochrone areas are not. Additional steps have to be taken to calculate isochrone areas, and these steps can be performed in different ways. Creating an area from a set of points or lines proves to be problematic. Although the amount of research done regarding the calculation of isochrone areas is limited, some problems have been addressed by Marciuska and Gamper (2010) and Baum et al., (2016). This paragraph gives an overview of available techniques concerning calculating isochrone areas along with problems related to those techniques.

An isochrone area is useful for two major reasons: Objects within the area might not be exactly bordering the isochrone network and isochrones visualized as areas can be easier interpreted by users (Marciuska & Gamper, 2010). The challenge lies especially in constructing a minimal area around the isochrone network which represents all space points within the isochrone. As can be seen in figure 3.4, it can be hard to determine exactly which areas are reachable and which are not. Visualizing an isochrone as an area allows easier interpretation, and is most widely used (Doling, 1979; O'Sullivan et al., 2000).

The easiest way to visualize an isochrone area is by connecting the set isochrone points. This leaves a polygon area in which all points within a given timespan are reachable. This basically is what happens in a Convex Hull and Concave Hull algorithms; it connects all outer dots forming an area (figure 3.5a). The Convex Hull approach can be compared to wrapping a rubber band around all points. As can be seen, some problems arise. Entire areas that are within the convex hull are actually well out of reach. This can lead to wrong conclusions as to which areas are reachable and can give false information regarding the number of objects within reach when using isochrone queries, which is discussed in paragraph 3.5. The Concave Hull algorithm is more like vacuum sealing the set of input points. A percentage can be set as parameter which determines how similar the Concave Hull calculation should be compared to the Convex Hull. The lower the percentage the smaller the Concave Hull area is compared to the Convex Hull approach (PostGIS Documentation, 2017). Figure 3.5b displays a convex hull calculation on the same set of points used in figure 3.5a. Note the areas on the right and lower side that were included in figure 3.5a and are now excluded from the area.

(a) (b)

FIGURE 3.5 CONCAVE HULL AND CONVEX HULL ALGORITHM

Another common approach is calculating an Alpha shape. An Alpha shape algorithm is to 'draw circles with a radius of 1/alpha such that they touch at least two points and none of the other points is inside those circles. All points that touch a circle are selected and connected' (Marciuska & Gamper, 2010). Figure 3.6 displays an Alpha shape calculation on the example network. The Alpha shape is quite comparable to the output of the concave hull approach in figure 3.5b. The major difference being the area on the right side. When comparing the Concave and Alpha, the latter performs better in this case given the more accurate shape of the area covering the isochrone network.

FIGURE 3.6 ALPHA SHAPE ALGORITHM

The algorithms mentioned above have points as input while these points do not necessarily cover a network area. Marciuska and Gamper (2010) identify that edge information is lost in the process which can result in large errors. They argue that it is almost impossible to find the right parameters to obtain correct areas. Besides, the transformation of a network into a set of points leads to information loss which is illustrated in figure 3.7.

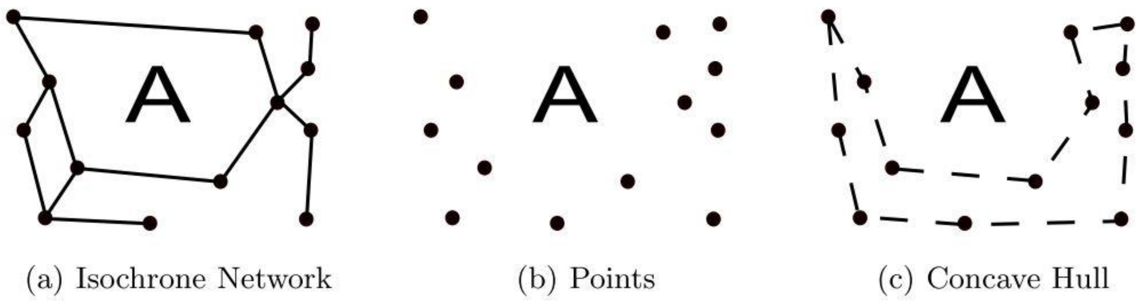


FIGURE 3.7 TRANSFORMATION FROM NETWORK TO AREA USING POINTS

Besides connecting isochrone points there are other ways of determining an isochrone area. Marciuska and Gamper (2010) propose two different solutions: the link-based approach and the surface-based approach. The link-based algorithm draws a buffer around each individual link of the isochrone network. It then combines these buffers and returns is to the user as an isochrone area. This approach could be a possible solution for areas that are unreachable over the network but are included when using point area based calculations discussed above. Figure 3.8 provides an example; parts of the isochrone area are not included since they are not reachable over the network, leaving holes in the isochrone area. It is debatable whether those holes in the isochrone areas can still be reached using other modalities but this depends on the use-case and the definition of reachability.

FIGURE 3.8 LINK-BASED APPROACH

Though not mentioned by Marciuska and Gamper (2010), a buffer can also be drawn around isochrone points (Figure 3.9). There is one obvious problem: once network edges become longer in distance, the network nodes are geographically further apart. It is possible that a buffer area leaves holes in between nodes that are actually connected through a link. The piece of buffer on the lower right side of figure 3.9 illustrates this problem. Though the error in this example is minimal and might not seem important, larger errors can occur once the network links become longer in distance. A possible case where buffers around points are useful is in the London underground. It is impossible to get off the subway somewhere along the link, so places in between stops are unreachable. But from the subway stations within reach someone can still walk or bike using the time that is left before reaching the max. Drawing a buffer around network nodes would in this case give more accurate results. Since it is impossible to stop somewhere along a link, it would be incorrect to draw a buffer around an isochrone network and in this method points are used instead.

The surface-based approach offers an alternative that leaves no holes in the calculated polygons. It first computes a polygon around the entire network and accordingly creates a buffer around this polygon. This is especially useful when trying to identify objects within an isochrone area, which might not necessarily be on the network but near. By drawing a buffer around a polygon that covers the isochrone area, objects in near vicinity of – but not on the network itself – are still included (Figure 3.10; Marciuska & Gamper, 2010).

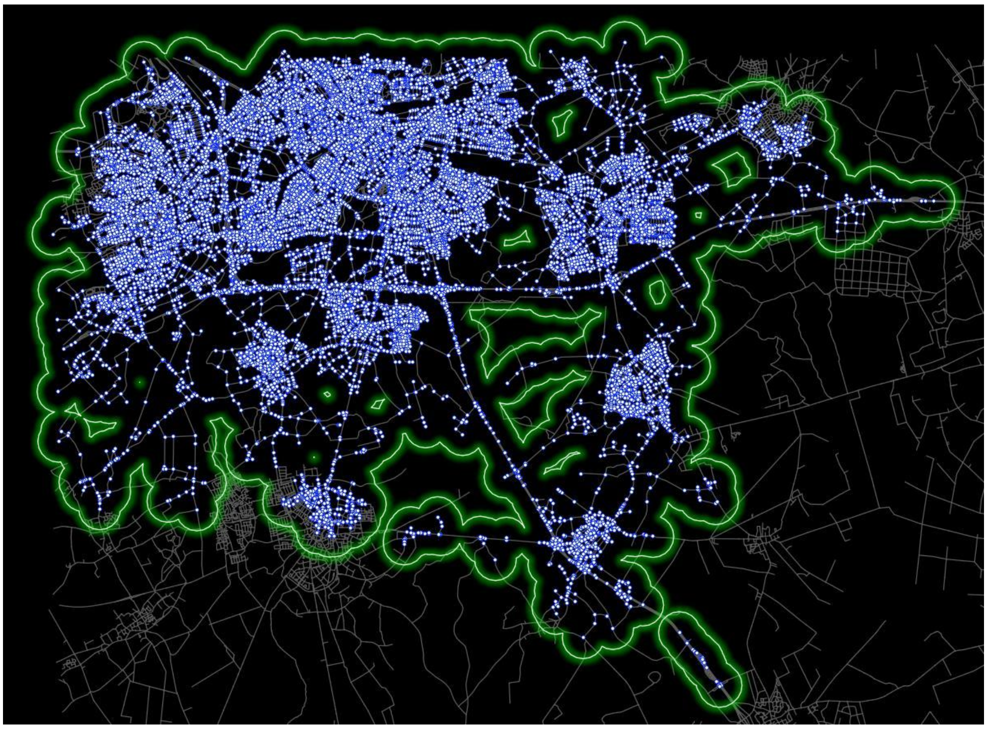


FIGURE 3.9 BUFFERS DRAWN AROUND ISOCHRONE POINTS

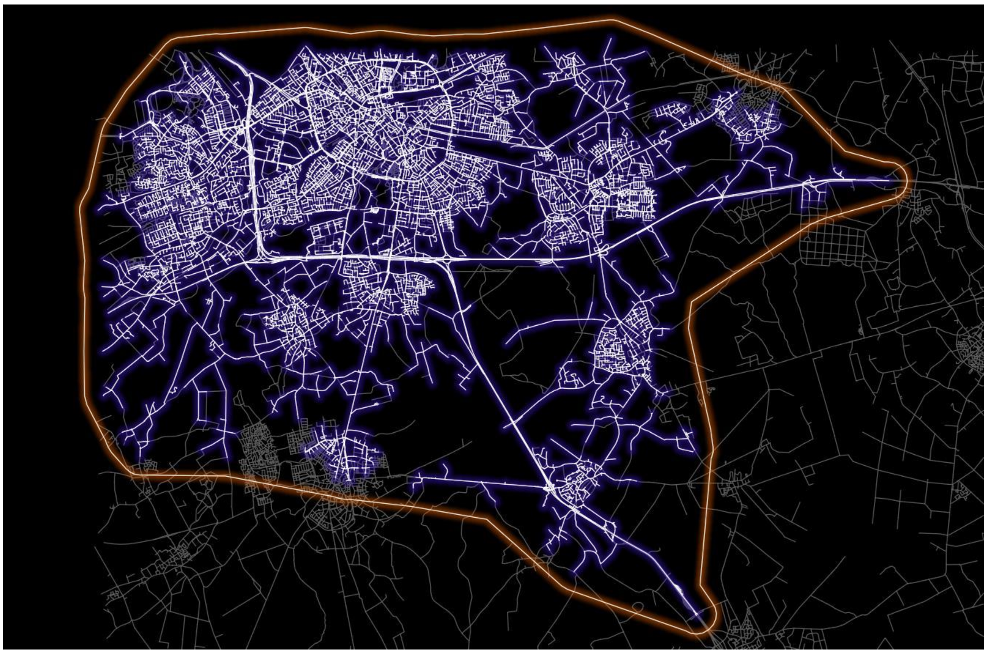
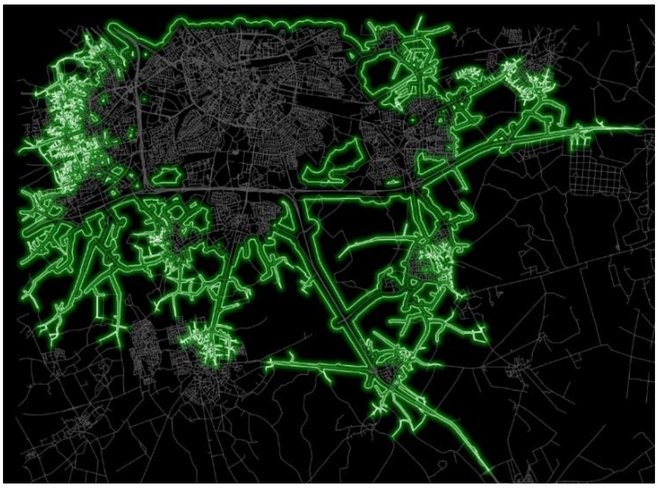


FIGURE 3.10 SURFACE BASED APPROACH

An issue not addressed by Maricuska and Gamper (2010) is that the outermost parts are extended by the given size of a buffer, both in the link-based and surface-based approach. A maximum time is given as cost for calculating the isochrone, which means the outermost points represent this maximum time. A buffer creates areas which are actually out of reach because there is no time left. Throughout the isochrone area shown in figure 3.10 grey parts of the road network, parts that are out of reach, are within the isochrone area. There are two options available to solve inclusion of areas in outermost parts that are actually out of reach. One option (figure 3.11a) is to change the configuration of the buffer construction. This causes that buffer distances are not drawn at the end of the network, but stops where the network stops. Figure 3.11b displays a second solution. A buffer can be drawn according to the aggregated costs of isochrone points or isochrone networks, a so-called variable distance buffer. In other words: time already spent can be taken into account when drawing a buffer. The more time is spent, the smaller the buffer size.

(a)



(b)

FIGURE 3.11 ALTERNATIVE BUFFERS AROUND ISOCHRONE NETWORK

As explained earlier, isochrones can be both single- and multimodal, and can be continuous or discrete in both time and space. Each methodology explained above has advantages and disadvantages for different types of isochrones and the questions that are being asked. For only visualizing an isochrone area, a concave hull approach might be sufficient whereas for determining objects within isochrone areas, variable buffers might be a better approach. How exactly to determine objects within a chosen isochrone area is discussed in the next paragraph.

3.5 Isochrone queries

There is a variety of queries in spatial network databases, of which isochrone queries is a specific type. Closely related are range queries, 'A range query determines all objects (of a specific type) that are within a specific distance from a query point' (Marciuska & Gamper, 2010). The main differences are that isochrones represent areas which are used to calculate nearby objects whereas range queries calculate all objects within a given distance. Range queries use Euclidean distance in a circle around the query points, isochrones are calculated over a network, leading to a higher accuracy. Another advantage of isochrone queries over range queries is that it allows an isochrone to be intersected with different types of objects without the need to recompute distances to individual objects from scratch (Marciuska & Gamper, 2010; Innerebner et al., 2013). By combining spatial datasets with isochrone areas, interesting questions can be answered. Examples include the number of supermarkets, restaurants people or other spatial objects within a certain time from a given query points can be calculated.

A disadvantage of isochrone queries is that they are heavily dependent upon the method used to determine the isochrone area. We have shown in paragraph 3.4.2 that there are different ways to determine areas, and each way has different results. The Convex Hull approach for example, could include spatial objects that are not actually within reach. The main challenge when performing isochrone queries is to construct a minimal area around the isochrone network which represents all space points within the isochrone (Maciuska & Gamper, 2010).

Chapter 04

Chapter 4: Accessibility Studies

Isochrone maps can be seen as a part of accessibility studies (Li et al., 2011), and to understand isochrone maps and their use, a general understanding of accessibility is required as well. Accessibility studies form the context in which isochrone maps are situated and one cannot be seen apart from the other. Though isochrone maps cover only a small part of accessibility studies, this chapter gives a required introduction to accessibility studies, after which the focus shifts towards a more current and specific topic in accessibility studies which influenced the development of isochrone map.

4.1 Accessibility

Accessibility is an abstract and complex term. It is used in a wide variety of disciplines and has a lot of different definitions. The concept of accessibility has originally been introduced in the transportation planning literature, but is inherently interdisciplinary. It is used in many other scientific fields such as urban geography, network and spatial economics, regional science and geographical analysis (Cascetta et al., 2016). The variety of uses and definitions has led to an even more complex classification of different accessibility indicators. Most of the definitions of accessibility are beyond the scope of this research and are not discussed. The general definition of accessibility that is within the scope of this research is: 'The amount and the diversity of places of activity that can be reached within a given travel time and/or cost' (Bertolini et al., 2005). One major difference being that places can also be replaced by the number of people. For more work and an extensive overview of definitions and classifications on accessibility see: Melhorado et al., (2016) and Li et al. (2011).

Often, accessibility is split in two: active and passive accessibility, also referred to as place or people accessibility. Passive accessibility visualizes area-based access measurement in a region while ignoring disaggregate and individual complexities (Li et al., 2011). Cascetta et al. (2016) elaborate by referring to passive accessibility as the ease with which an activity can be reached. Active accessibility on the contrary centralize individuals. Active accessibility reflects the ease of a traveler to reach places in the study area (Cascetta et al., 2016). Individuals have certain characteristics that can be taken into account, differentiating active from passive accessibility. These characteristics can for example include the ability of an individual to travel or specific needs or requirements of places and activities to be visited. Active accessibility is regarded to complement passive accessibility because accessibility in general is closely related to the movement of individuals and their needs (Li & Kraak, 2008). Isochrone maps do not take into account characteristics of individuals and can therefore be placed under passive accessibility.

Traditionally, most researches using spatiotemporal data, including accessibility research, used by Peuquet's (1984, in Li & Kraak, 2008) triangle to structure spatiotemporal questions (Figure 4.1). The question 'what?' and 'where?' were most important in answering questions regarding accessibility since they could be visualized on a map. A third dimension 'when?' was mostly disregarded and gained relatively minor attention (Shaw, 2006). Moreover, in most visualization methods, time is considered linear and one-dimensional as well (Li & Kraak, 2008). This is also related to a lack of methods to visualize the combination of these three dimensions. As can be seen in figure 4.1, there are existing methods to visualize two of the three spaces. Since the location- and attribute space are typically used on maps, the time space was disregarded or generalized. This happened not only in accessibility studies, but throughout social sciences. Soja (1989, in Steenbruggen et al., 2015) *'highlights how, in the past, planning and geography have understood space as a dead, fixed, immobile, and undialectic entity, which is based on passive measurements instead of on actions and meanings.'*

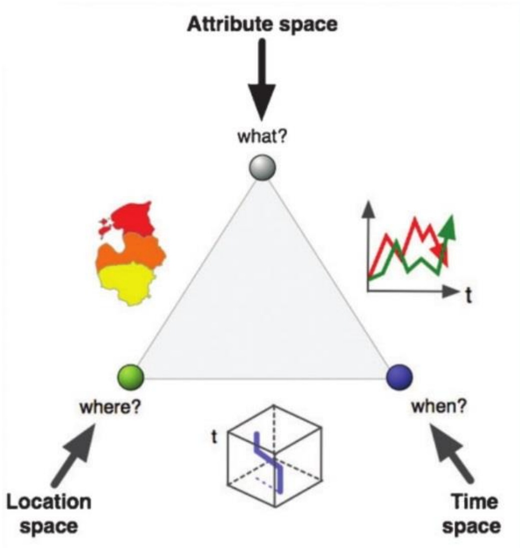


FIGURE 4.1 PEUQUET'S TRIANGLE (1984, IN LI & KRAAK, 2008)

4.2 New mobilities paradigm

The use of dynamics through time in accessibility maps partly changed when Sheller and Ury introduced the new mobilities paradigm in 2006. Sheller and Ury especially criticized the lack of mobility, people movement and travel in social science. The time space could no longer be generalized since the movement of people, goods and information is inextricably connected to the time space. This also meant that accessibility research needs to move beyond static measures and increase attention to the temporal dimension in accessibility research. The mobility paradigm was triggered by a combination of interrelated developments in different fields. Figure 4.2 is an interpretation of the mobilities paradigm described by Sheller and Urry (2006).

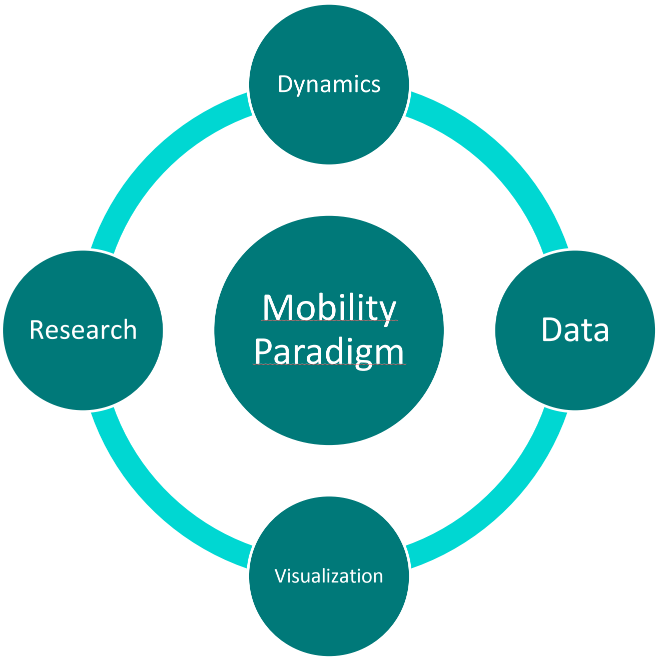


FIGURE 4.2 INTERPRETATION MOBILITY PARADIGM

4.3 Traffic dynamics

Dynamic visualizations of spatiotemporal traffic data were rarely used in accessibility studies. Travel times used in calculations were mostly static, inevitably ignoring variations in accessibility which could help understand dynamics of different locations, times and individuals. Space constraint were taken into account whereas time constraints were mostly disregarded, despite the fact that traffic conditions vary significantly over space and time (Li et al., 2011). This partly had to do with a lack of technologies and data to include the time component. Gradually, innovative ways to include dynamic traffic data in accessibility studies were developed, one being so-called Floating Car Data (FCD). FCD 'refers to the data being collected (continuously) by a fleet of vehicles, which can be considered as a distributed network of sensors, i.e. FCD is an embedded traffic measurement system' (Messelodi et al., 2009). This method allowed the average travel time or speed in certain links of the road network to be determined.

4.4 Population distribution dynamics

Despite the fact that maps and researches including dynamics in traffic have been around for a while, dynamics in population distribution has only recently gained more attention. Kwan (2013) argues that mobility is an essential element of people's spatiotemporal experiences. According to him, these experiences cannot be researched or understood by just looking at where people live. Again, the lack of knowledge in this field goes hand in hand with underdeveloped technology. Besides residential information, where do people live, information on dynamic movement has been limited. This changed with the rise of big data and mobile data. Through increased use of mobile devices, such as mobile phones and geo-located social media posts, more information on population distribution that changed through time became available and provide new and better ways to providing new ways of understanding and visualizing accessibility (Järv et al., 2016; Zook et al., 2015).

Examples of using geo-located social media posts to track people movement include work of van den Berg et al. (2015) and van der Drift (2015). Through harvesting social media content, geo-locations could be determined which allowed researchers to discover individual movements and dynamic population distribution. One of the downsides of using social media content to track people movement is that it is partly biased. Only people actually making use of social media platforms and enable their location to be shared are included. Besides this, the amount of social media content is very limited for some platforms (van den Berg et al., 2015). Furthermore, serious questions regarding privacy issues have been raised (Zook et al., 2015).

Another way to monitor population distribution is through the usage of mobile phones (Ahas et al., 2010; Steenbruggen et al., 2015). Since the usage of mobile phones is widespread, this provides an interesting source for monitoring population distribution. Ahas et al. (2010) researched the usefulness of mobile position data to produce meaningful locations to users of this data through mobile positioning: 'Mobile positioning means tracing the location coordinates of mobile phones'. Mobile positioning can be roughly divided in passive and active positioning. Active mobile positioning is monitoring real-time mobile phone positions using special queries like radio waves to 'ask' the current location. On the contrary, passive mobile positioning is the data stored in memory or log files of mobile phone operators automatically. Basically any use of a mobile phone is logged: calls, text messages, GPRS etc. and connected with mast information (Ahas et al., 2010).

This passive mobile positioning data has gained much popularity in geography studies due to the availability of large samples (Steenbruggen et al., 2015; Meppelink et al., 2015). In so-called billing-logs or Call Detail Records (CDR) mobile phone operators store all phone activity in their network. These records have an attribute, linking the mobile phone to the connected network cell. This cell is also known as the Cell Global Identity (CGI) where a cell means: 'the geographical area where it is possible to connect to one transceiver of a base station.' Each cell has only a limited capacity (Vajakas et al., 2015), causing a variety in cell tower density between urban and rural areas affecting the accuracy of mobile positioning (Steenbruggen et al., 2015). Also, the time between logged activities can be hours leading to further inaccuracies (Vajakas et al., 2015; Zook et al., 2015; Steenbruggen et al., 2015).

Since information stored in CDR's is linked to individual phones and phones in turn are linked to owners, billing logs are extremely privacy sensitive. Network operators, individuals and governments likewise are not likely to allow usage of this sort of data in commercial or research context. To resolve this privacy issue, mobile operators can extract anonymous geographical data from the log files. Historic location points or movement lines are extracted and accordingly sold or distributed for commercial and scientific purposes (Ahas et al., 2010).

Chapter 05

Chapter 5: Cartography

5.1 Visualize dynamics

The increased interest in dynamics and use of spatiotemporal data lead to new problems. Partly because of a relative absence of time in maps, ways to include time were underdeveloped in cartographic work. Traditionally, most maps limited themselves to one moment in time and for most geographic maps this was fine since there was no dynamic time attribute. However, a wide range of geospatial data does have a time component and methods of displaying a time attribute were limited. Geographical processes or events can no longer be successfully researched without considering time as well. The most important challenges and questions facing society today require time to detect and analyze trends and changes (Kraak & Ormeling 2010, p. 152).

Ways to visualize geographical data with a temporal component are increasingly explored and many scientists are occupied with the challenges raised by visualizing spatiotemporal data (Andrienko et al., 2014). However, the amount of data, that also depends on the length of a time period that needs to be covered, quickly becomes too complex to visualize. On the one hand because the enormous amounts of information and data that is collected, stored, processed and presented has never been as high as today (Li & Kraak, 2016). On the other hand, cartographers are struggling with effective methodologies to visualize the time component of the data. Different diagrams and map-like representations try to visualize spatiotemporal data, which all deal with the spatial component well, but the temporal component is not sufficiently developed (Ullah & Kraak, 2015; Andrienko et al., 2010; Li & Kraak, 2008). Besides, some of the maps and diagrams that do visualize the temporal component are not scalable and/or difficult for users to understand.

Essentially, mapping time is equal to mapping change. This change can occur in a feature's existence or changes in geometry, in attributes or in both. Change in a feature's existence refers to elements appearing or disappearing, a glacier melting in summer and expanding in winter would be an example. Changing boundaries are an example of change in geometry and changes in road traffic intensity is an example of an attribute change. Based on these changes three temporal cartographic depiction modes are proposed by Kraak and Ormeling (2010, p.154):

- Single static maps. This comes down to a single map in which graphic variables and symbols represent change in time. Figure 5.1 provides an example of a single static map. It displays urban expansion in the Netherlands from around 1800 to 2005. In this case, different colored variables refer to different construction years. The map is quite useful for determining areas that are predominantly built around certain times. It is however quite hard to compare expansion between different years, and one can imagine this is not an ideal solution once data covers a longer or more frequent time interval.

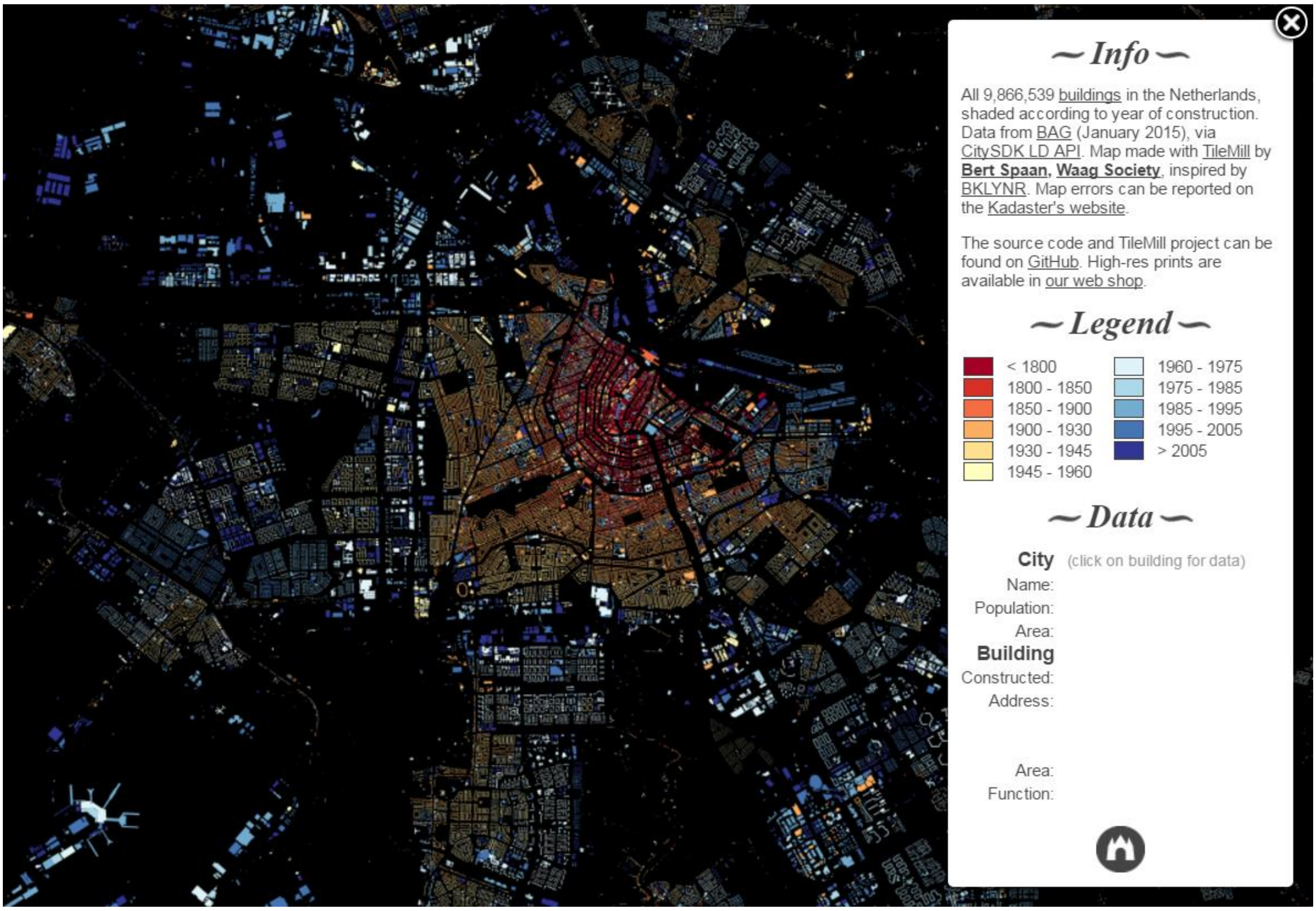


FIGURE 5.1 SINGLE STATIC MAP (WAAG SOCIETY, 2015)

- Series of static maps. Creating a series of maps that all display a snapshot in time partly takes away the complexity of a single static map. Together, the individual snapshots tell a story. By sequencing the static snapshots chronologically, users can perceive the temporal variation. A well-known example is a series of changing glaciers (figure 5.2). Seasonal differences and yearly differences in the glacier size are displayed. A series of static maps is limited in its use because once the number of years or time displayed increase, the images quickly become too complicated.

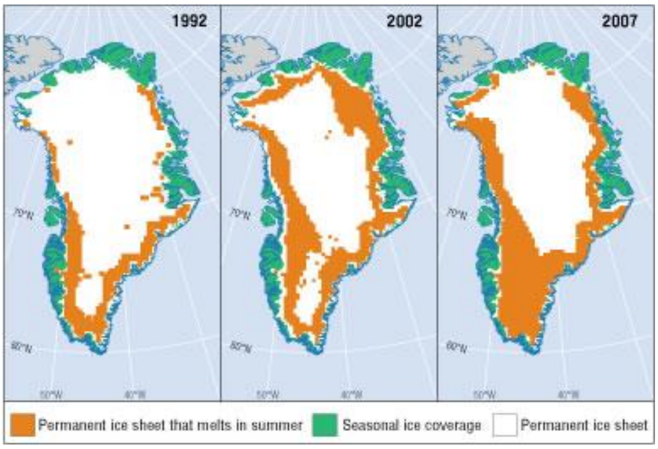


FIGURE 5.2 SERIES OF STATIC MAPS (HAMRICK, 2010)

- Animated maps. Animated maps show different snapshot in time in one single frame. One image appears after the other, allowing users to see change. Since change occurs in one frame, it is impossible to visualize in a static document. Animations are mostly used in web pages, and can be further divided in two: interactive and non-interactive animations. Non-interactive animations display a repeating sequence of images, over which users have no control. On the contrary, interactive animations refer to animations in which the user does have control. Users can for example control the speed in which images are displayed or pause and play the animation. Another well-known example is Google Earth, in which users can interactively explore the world.

Of the three temporal cartographic depiction modes proposed, animations seem to be the best solution. However, issues regarding animations have also occurred. In particular with non-interactive animations since users where in some cases overwhelmed by the amount of information with which they were presented (Kraak & Ormeling, 2010). In order to process and analyze spatiotemporal data, interactive tools are required (Kraak & Ormeling, 2010). Not all cartographers master the skills to create animated maps, let alone interactive animated maps. Vice versa, the people that do master skills to create interactive animated maps might not be up to date on cartography. This is discussed more thoroughly in paragraph 5.3.

5.2 Web Mapping

Isochrone web maps were already briefly introduced in paragraph 2.3. Since time and dynamics in maps can be animated and web maps have proved to be a suitable platform for doing this (Kraak & Brown, 2001), a brief introduction to web mapping is given here. Web mapping technologies are defined as: 'The compilation of APIs, frameworks, libraries, services etc., that all together enable the creation and dissemination of web maps' (Peterson, 2003).

As is the case with online isochrone maps, the first generation of web maps were static. Online maps were primarily static. Besides the fact that they were displayed online they had no additional values compared to ordinary paper maps (Kraak & Ormeling, 2010; Cartwright, 2008). Roth et al. (2014a) sum up the functionalities web maps have today that differentiates them from the first generation of web maps. Web maps commonly are adaptive, interactive, mobile, multiscale, and/or updated in real time.

There is a wide variety of web mapping technologies available which is expanding rapidly, new releases and substantial updates to web mapping technologies occur almost on a daily basis (Roth et al., 2014a). This is a major advantage since new opportunities arise for cartographers and geographers alike, there are more possibilities than ever before. At the same time however, these ever increasing possibilities and technologies are making it hard to keep up to date with all possibilities.

5.3 Web map Design

Designing a map is an important step in effectively visualizing a story creators want to tell with their map. Web map design is essentially the same, except that it offers some extra possibilities and has some limitations that should be taken into account in the design as well. Besides, there has been a gradual shift in who creates web maps. The role of cartographers is declining in web map design.

Well-designed interactive maps are characterized by their relative 'emptiness', meaning that every part or element of the image visualized on screen should be legible (Kraak & Ormeling, 2001, p. 79). The interactive map can be extended with additional 'hidden' information which can be accessed by the map user through interaction. This way, only information relevant for the user appears on screen.

Another point to consider are the file and display size. Since loading times of interactive maps are dependent on a user's internet speed, users might dislike waiting for relatively long downloads. Furthermore, it is possible that the interactive map is used on multiple devices with internet access, each with their own screen size. This should be taken into account when developing an interactive map.

Besides these smaller points that are especially relevant for cartographers, another development has led to changes in the way web maps are designed. Since web mapping requires a fair share of different scripting languages, cartography and coding are increasingly intertwined. Some cartographers have tried hard to update their coding skills with varying results. The creation of especially web maps is shifting towards people who know how to code rather than people that know how to correctly design a map (Roth et al., 2014b).

According to Roth et al. (2015), coders with limited knowledge on maps and cartographers with limited knowledge on coding have created problems causing web maps to increasingly fail. Especially cartographic design rules for generalizing, normalizing, classifying symbolizing and visualizing can be done incorrectly by coders due to a lack of cartographic knowledge. Also the interface of the map and its functionalities can lead to ineffective and frustrating user experiences.

To possibly resolve problems of cartographic incorrect web maps and unhelpful and ineffective web maps, Roth et al. (2014b) recommend a special role for cartographers. Since cartographers do have experience and the required knowledge to create correct (web) maps, they should (in addition to or besides contributing to the coding part) be involved in the design and evaluation of prototypes to streamline the development and promote a positive user experience with the web map or application built.

Chapter 06

Chapter 6: Conceptual Model

In chapters 2, 3, 4 and 5 we have provided an extensive overview of relevant concepts. In this chapter we summarize the most important findings particularly relevant for this research, and display how these concepts are related in a conceptual model (figure 6.1). Through summarizing, relationships between concepts are made clear as well.

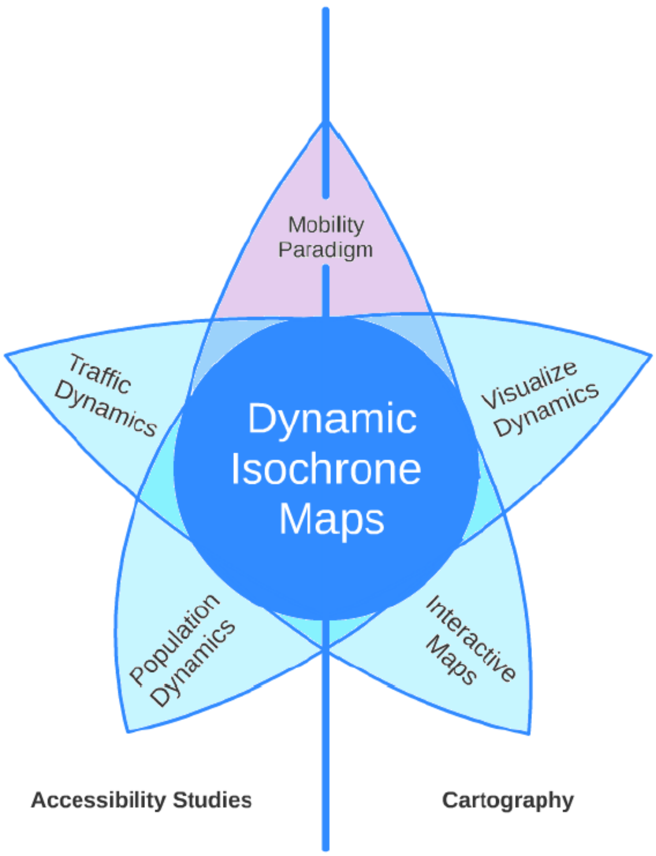


FIGURE 6.1 CONCEPTUAL MODEL

This research is placed in two particular fields of research: accessibility studies and cartography. Isochrone maps, more specific: dynamic isochrone maps, are of central importance throughout this research. Dynamic isochrone maps are situated in both accessibility and cartography and are therefore placed in the middle of the conceptual model. The concepts surrounding dynamic isochrone maps are all interrelated and in the middle is where these concepts come together. Furthermore, surrounding concepts are placed in either the accessibility studies (Chapter 4) field on the left, or the field of cartography (Chapter 5) on the right. All but the mobility paradigm in purple, which has had an impact on both accessibility studies and cartography. The latter is the starting point of this research.

Through the new mobilities paradigm (Paragraph 4.2), attention regarding time and dynamics in social science increased. The time component is increasingly used in accessibility studies, and more specific in isochrone maps as well. At first, accessibility studies and isochrone maps alike included new ways of adding dynamics in traffic (Paragraph 4.3) through for example Floating Car Data (FCD). Later, dynamics were further extended to dynamics in population distribution and people movement (Paragraph 4.4), measured through social media platforms and mobile phone data. The new mobilities paradigm also urged (new) ways of effectively visualizing dynamics (Paragraph 5.1). Cartographic studies struggle with effectively visualizing time. Out of several options, animations in general seemed most applicable for most use cases. Ways to visualize time in interactive and non-interactive animations are increasingly used.

Despite the fact that all relevant concepts come together through isochrone maps, we would like to again emphasize that all concepts are interrelated. Developments in one field led to new possibilities in another and vice versa. This continuous slew of developments has provided us with a starting point for a research combining all these new possibilities. Using web mapping technologies, dynamic visualizations of time, dynamic population distribution and dynamic traffic data, an isochrone map suitable for dynamic accessibility studies is created. Using the combination of knowledge gained from different study areas, this is one of the first researches to create an isochrone map that includes dynamic traffic data and dynamic population distribution. We have shown different sort of isochrones and their calculation methods. Using the theoretical insights, the methodological chapter hereafter further explains how a dynamic isochrone map was constructed and justify specific choices made.

Chapter 07

Chapter 7: Methodology

As outlined in the workflow in chapter 1 (figure 1.2), this research is split in two parts: a theoretical part and a methodological part. The literature study conducted in the previous chapters has provided the background of this research and serves as a starting point and input for the remainder of this research, the methodological part. The methodology is subdivided in three paragraphs each dealing with a distinctive part of the methodology.

The first paragraph (7.1) describes all steps taken that involve the dynamic road network used in this research. Firstly, the road network is pre-processed in order to perform routing which allows calculation of isochrone points and lines. Accordingly, paragraph 7.2 describes the steps taken regarding the spatiotemporal population distribution data used. The way this data is collected and pre-processed is discussed first. Hereafter, we explore the spatiotemporal population distribution data used to demonstrate what can be done and to come to a deeper understanding of the data presented. We then describe how the spatiotemporal population distribution data is pre-processed for use in this research. The third paragraph (7.3) consists of a description how the spatiotemporal traffic data and spatiotemporal population distribution data are combined. The steps undertaken to effectively communicate the results are described as well. We describe how the data is visualized in order to bring across a clear message and effectively visualize differences through space and time.

7.1 Isochrones

A workflow to construct isochrones is presented back in chapter 3 (figure 7.1). This paragraph uses the same framework for constructing isochrones.

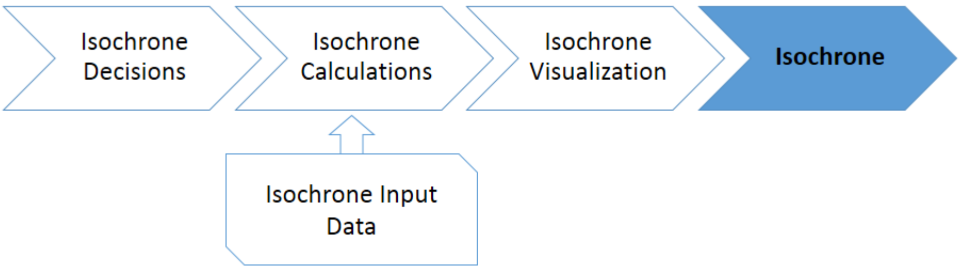


FIGURE 7.1 ISOCHRONE WORKFLOW

7.1.1 Isochrone decisions

Isochrones calculated in this research are used to determine the number of people that can reach an IKEA store in the Netherlands within a given time. The majority of IKEA visitors (95%) travel to IKEA by car (Heede, 2016). We decided to focus exclusively on this group of IKEA visitors and exclude visitors who use other modes of transport. As a result, a unimodal network is sufficient to calculate isochrones.

7.1.2 Isochrone Data

The data used in this research, which meets the requirements based on the isochrone decisions, are the Traffic Patterns data from HERE (HERE, 2017). HERE Traffic Patterns offers extensive average traffic speed data for 83 different countries. These data are collected by billions of observations on every type of road. This type of data was introduced in paragraph 4.3 as Floating Car data.

FIGURE 7.2 HERE ROAD NETWORK THE NETHERLANDS

The HERE traffic patterns data used in this research contain average driving speeds for every road in the Dutch road network (figure 7.2). Through FCD and observation stations on Dutch roads average speeds have been measured during three years. The information on how many observations are used per road is limited. However, the total number of observations, called probes, in the Netherlands has increased in the last few years (figure 7.3). In general, the busier the road, the more probes are on that road. For each road the mean speeds driven during this period are linked to one of the around 20.000 speed patterns which most closely resembles the observed speeds. Each road in the Netherlands is linked to seven speed patterns, one speed pattern for every day of the week. Each speed pattern contains 96 speeds a day, one for every 15 minutes. For example, all probes observed on a Monday between 08:15 and 08:30 are averaged and linked to a resembling speed pattern for Monday 08:15. These speed patterns do not exceed the maximum allowed speed on that specific road. This is because HERE traffic patterns are mostly used for navigation systems and trip planners, and these should not encourage users to exceed the maximum allowed speed.

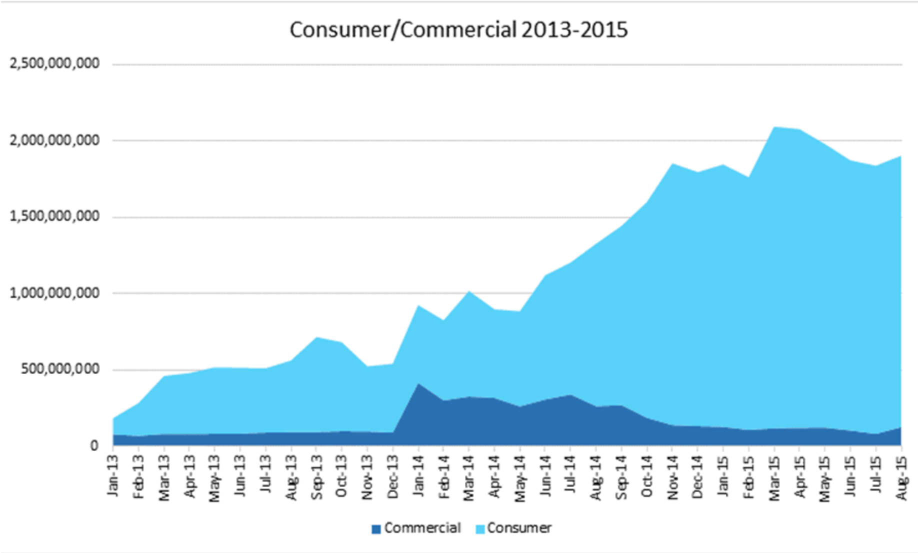


FIGURE 7.3 NUMBER OF MONTHLY PROBES IN THE NETHERLANDS

Because this traffic dataset is large, the road network data are stored in a PostgreSQL database. This database is managed through the open-source software pgAdmin and extended with PostGIS and pgRouting. PostGIS is a spatial extension for PostgreSQL, it adds support for geographic types and functions (PostGIS, 2016). pgRouting is an extension which offers a library of network functions which can be performed on a database (pgRouting, 2016). The combination of PostgreSQL, pgAdmin, PostGIS and pgRouting allows spatial computations on large network datasets.

Before actually performing network calculations, first the HERE network needs to be pre-processed. This is a time-consuming task. The dataset consists of two separate datasets which need to be joined: the road network itself and speed patterns per road link, per 15 minutes, per average week day and per direction. Both of these datasets contain patterns and parts of roads which are not accessible by car. These are filtered out first. Network links that represent ferry lines are also filtered out, since it is unclear if waiting times and possible costs involved are included in the links that represent ferry lines. The resulting tables are joined, forming a table with speed patterns for all roads accessible by car in the Netherlands. This results in 1.5 million rows, each containing 1354 columns with a total of 2 billion fields and 11GB in size. Once this table is prepared, routing calculations can be performed.

7.1.3 Isochrone Calculations

One of the calculations that is a part of the pgRouting extension is pgr_drivingdistance. This function calculates all nodes and edges in the network that have costs less than or equal to a given cost. A starting point is entered and the function calculates in all possible directions how far the network can be traversed within a given cost. A differentiation from or to the given input point is possible as well. The input cost in the function can be differentiated as well. Possible costs include distance travelled, fuel cost or, as in this research, driving time.

To determine the points from which to calculate isochrones, the coordinates of different IKEA stores have been identified. Currently, there are 13 IKEA stores in the Netherlands (figure 7.4). These IKEA stores serve as starting points for the driving distance calculation. Since the driving distance function requires a node on the network as input, the IKEA coordinates (Google Maps, 2016) are snapped to the closest network node and used as input.

FIGURE 7.4 IKEA STORES IN THE NETHERLANDS LOCATED USING COORDINATES (GOOGLE MAPS, 2016)

Moreover, the driving distance function requires a field that represents the cost and reverse cost per road segment. The difference between cost and reverse cost is the direction in which a road is traversed as explained in paragraph 3.3.2. Since the average speeds are stored in the HERE network data and the road length can be calculated, we created a function that calculates the time it takes to traverse a road segment. This function uses PostGIS' function ST_Length which calculated road lengths using the geometry field stored in the database. By combining average driven speeds and the road length, the time it takes to traverse a road can be calculated.

Normally, the driving distance function calculates what parts of the network can be reached from a given point. However, in this research we are interested in how many people can potentially drive to an IKEA store. So instead of IKEA stores being a start point, we rather want IKEA stores to be an end point. This is achieved by switching the cost and reverse cost values. This causes the driving distance function to calculate and choose roads that are directed towards IKEA stores instead of away from IKEAs.

Column	Meaning
seq	Order in which roads are traversed.
from_v	ID of the nodes used as starting points (in case of multiple points in one calculation)
node	ID of nodes within max given cost
edge	ID of edges within max given cost
cost	Cost to traverse road
agg_cost	Aggregate cost from start to current road.

TABLE 7.1 RESULTING COLUMNS PGR_DRIVINGDISTANCE CALCULATION

After the driving distance calculation is completed, a table is created (table 7.1). However, this output table does not contain any geometry. A final step before being able to visualize calculated isochrones is to join the output table with the original road network table. The result is a table of all roads within reach, containing a geometry field which can be visualized in for example QGIS (figure 7.5). This example displays parts of the network that are able to reach one of the IKEA stores within 30 minutes on a Tuesday night at 00:00. The same calculation is repeated for every 15 minutes of the day. The complete workflow is visualized in figure 7.6.

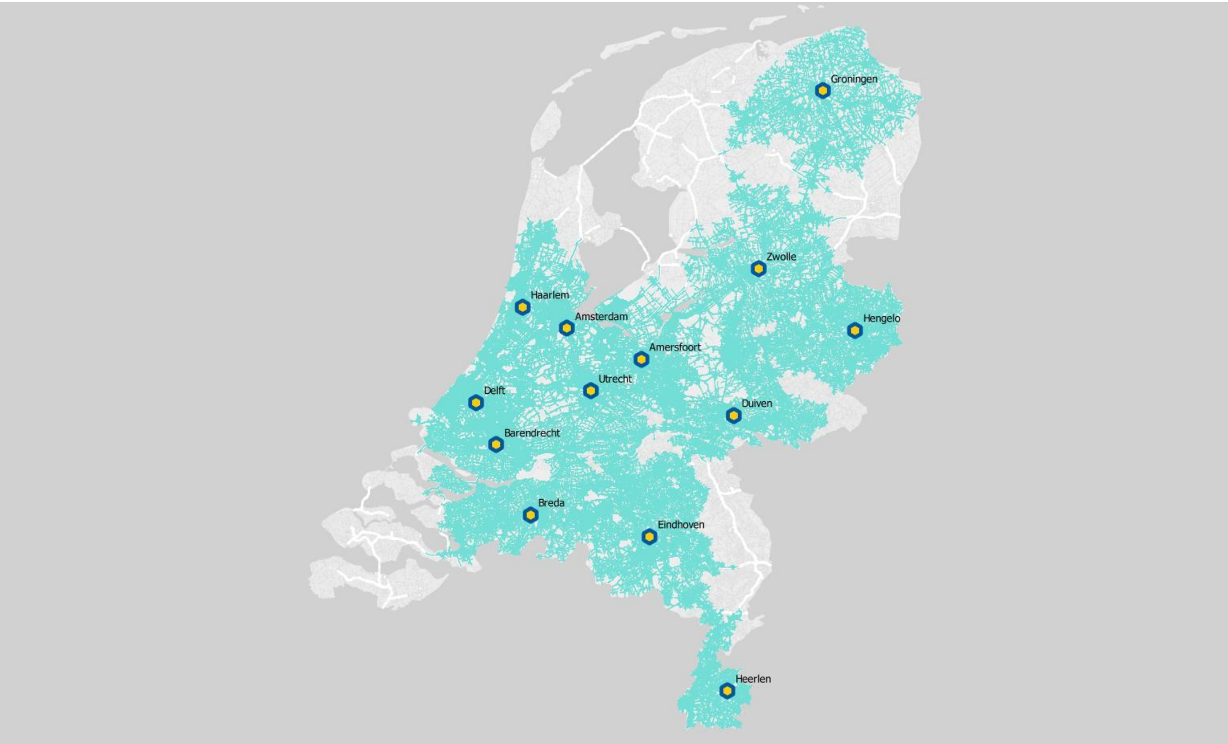


FIGURE 7.5 ISOCHRONE NETWORK WHICH DISPLAYS THE PARTS OF THE NETWORK WHICH CAN REACH AN IKEA STORE WITHIN 30 MINUTES ON AN AVERAGE TUESDAY 00:00 IN THE NETHERLANDS.

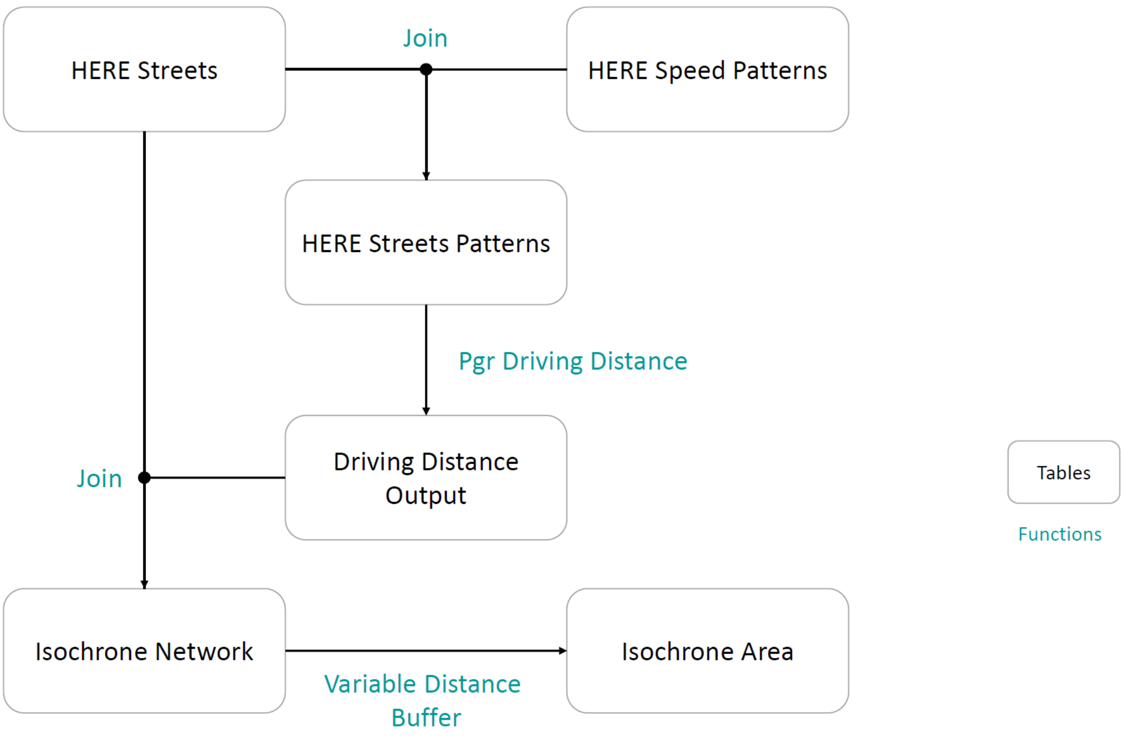


FIGURE 7.6 FLOWCHART ISOCHRONE AREA CONSTRUCTION

Despite the fact that pgRouting is fit for handling complex routing computations on extensive network datasets, there are two limitations. When for example calculating the driving distance for one hour, pgRouting uses data from one input column for costs. Since one column represents one time step, inaccuracies can occur. If for example average speeds from 9 o'clock with a maximum cost of one hour are used in a driving distance calculation, the computer uses the 9 o'clock data during the whole calculation. Ideally, the calculation would have a Time Dependent Dynamic Shortest Path algorithm (TDDSP).

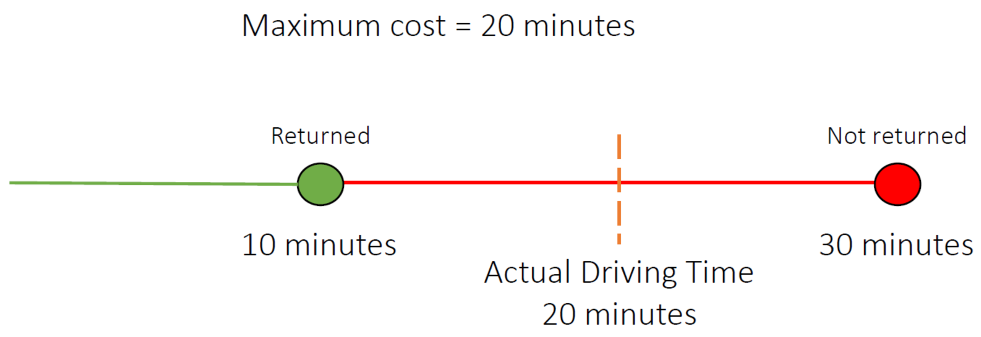


FIGURE 7.7 NODE PROBLEM

Another limitation is illustrated by figure 7.7. The pgr_drivingdistance function by default returns the node and edge which do not exceed the maximum given cost. Some road segments are relatively long. If for example they have a node at each end of which one exceeds the maximum cost and one does not, only the latter is returned whereas in reality part of the road segment could still have been travelled before exceeding the maximum cost. Currently, both of these problems cannot be solved with the default pgRouting functions. Obe and Hsu (2017) have identified this problem as well and describe a possible solution called 'node injection'. Since the solution is specific for the case they described, it cannot be applied to the case study used in this research.

7.1.4 Isochrone visualizations

As described in chapter 3. there are numerous ways to construct isochrone areas using nodes or lines as input partly depending on the purpose of the isochrone map. Since the isochrone area is used to calculate the number of people in reach, it is important to draw an area which is as accurate as possible. Therefore, in this research the variable distance buffer is chosen. The alternatives described in chapter 3 are not accurate enough and would have included areas and therefore people that were out of reach. One of the problems with isochrones remains: a fixed border has to be drawn somewhere. It is always debatable whether points which are located just outside of a isochrone area can still be reached within the given cost or not but a choice has to be made. In this particular case the variable distance buffer is the most accurate.

7.2 Population Distribution Data

In chapter 4 different ways to monitor population distribution or movement have been discussed for example using social media or by tracking mobile phone usage. Both methods have advantages and disadvantages.

Social media data for example, is partly biased since it exclusively consists of people using social media. On the contrary, social media datasets are extensive, publically available and therefore easily accessible.

Active mobile positioning would be a less biased way of analyzing population distribution compared to Social media data. Nowadays, the mobile phone is integrated in our lives and in 2015 80% of the Dutch population owned a mobile phone (Statista, 2016 in: Meppelink et al., 2015). Through active mobile positioning (paragraph 4.4) phones are tracked with 500 meter accuracy (Zhang et al., 2014). The major disadvantage is that people have to install an app or grant permission to be followed causing the sample size to be relatively low compared to social media data.

Passive mobile positioning includes working with Call Detail Records (paragraph 4.4). The major advantage of passive mobile positioning is a big sample size since the service provider stores all phone usage, but the downside is a relatively low accuracy. Areas in which phone usage is registered are varying in size depending on the number of people, existing administrative boundaries and the number of cell towers in the area.

In this research we have chosen to work with passive mobile positioning data because out of the alternatives mentioned above it provides the most realistic data on population distribution. The passive mobile positioning data is provided by the company Mezuro. The passive mobile positioning data used in this research is aggregated; it originates from CDR's collected by a single network provider but is pre-processed by another company using a complex algorithm to approximate and classify the number of people within areas instead of just phone activity of one specific network provider. The algorithm takes into account different factors such as the number of people within a GSM area subscribed to the network provider, the number of active phones of subscribers per area and the number of inhabitants per area. In the remainder of this research when mentioning numbers of people, residents and visitors, these are actually estimations on the number of people based on the observed phone activity in areas.

As mentioned briefly in paragraph 4.4, GSM data is privacy sensitive. In theory it is possible to track someone's movements. To secure the privacy of mobile phone owners, the CDR's are anonymized. This means that data of individual phones remain with the network operator. Also, it is not possible to track or filter individual phones out of the provided data. At least 16 phones have to be in the same area before they are registered in the final dataset (Meppelink et al., 2015). Moreover, little attention has been given to the possible bias in, and accuracy of mobile phone data. The CDR's are aggregated and in this research we use the numbers which result from the aggregation algorithm as the number of inhabitants or visitors, but since they originate from a single network operator's CDR's there is a possible bias.

7.2.1 Data Exploration

The aggregated GSM data, from here on simply referred to as GSM data, consists of two tables: one table contains the administrative areas used (figure 7.8). The Netherlands is divided in 1261 areas in which phone activities have been registered. This table does not contain any information on the number of people in that area yet. It merely serves as a spatial reference to the GSM areas. The second table holds the 'raw' numbers, including further classified population groups in areas for a given month (table 7.2).

Column name	Meaning
bag_id	Identifier for administrative Area
datum	Date
uur	Hour
aantal	Total number of people in area
dagsoort	Sort of day (Monday, Tuesday etc.)
ninwplaats	Number of assumed residents in area
nbezplaats	Number of total visitors in area
freqbez	Number of frequent visitors in area
regelmbez	Number of regular visitors in area
Incidbez	Number of incidental visitors in area
bgast	Number of foreign visitors in area

TABLE 7.2 COLUMNS GSM DATA

FIGURE 7.8 GSM AREAS IN THE NETHERLANDS

The GSM data are classified using observations from the given month. Assumed residents for example, are people that have been observed in the same area during most of the nights in the given month. Regular visitors are observed in a specific area at least 10 times a month. There is a possibility that these people visit these areas because of their job or school.

Frequent visitors are people which are observed 3 to 9 times in a GSM area per month. It is hard to determine the goal with which frequent visitors travel to certain areas. It could for example be visiting friends or families once a week. The same goes for incidental visitors; People which are observed one or two times a month in a GSM area. It could for example be people visiting special events, or recreating in or outside the city.

GSM data provides a more accurate and, more important, dynamic insight in population distribution compared to traditional static measures. Figure 7.9 displays the number of residents according to GSM data at Thursday 15-09-2016, and the number of residents according to static PC6 data. A drop in the number of residents – which at its maximum consists of almost 10.000 people – can be observed starting around 5 in the morning. Especially during work hours (9-17) the drop in the number of residents is most apparent.

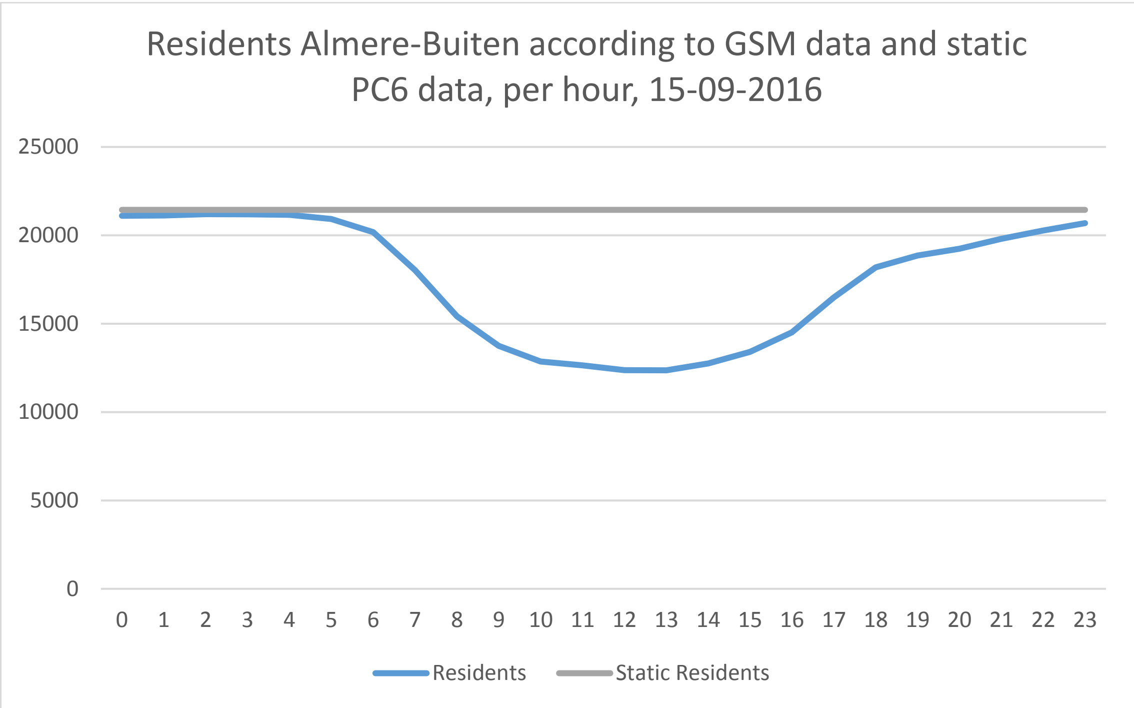


FIGURE 7.9 RESIDENTS ALMERE-BUITEN OER HOUR ON 15-09-2016 USING PC6 DATA AND GSM DATA.

7.2.2 Data pre-processing

For this specific research we are interested in the number of people which are located in an isochrone area at a specific time during the day. It is interesting to see which places are most crowded throughout the day. A differentiation is made between inhabitants and visitors within the isochrone areas. The number of inhabitants and visitors are calculated using different calculations because we can further increase accuracy for inhabitants using PC6 points.

PC6 points (figure 7.10) are points per PC6 area containing the (static) number of residents in that postal code zone represented as points and are more detailed than the GSM areas. By intersecting the PC6 points with the GSM areas we determine the static total number of inhabitants within a GSM area (p_t). So the sum of all PC6 points in a GSM area. By dividing the number of residents for each individual PC6 point (p_p) by the total static number of residents in the GSM area we have the fraction of the total population per PC6 point. Using these fractions we have more information on the distribution of inhabitants within the GSM areas. Assuming that this distribution remains the same through time, we can multiply the fraction of each PC6 point which is located in the isochrone area (I_{gsm}) which results in the dynamic population per PC6 point. The sum of these PC6 points is the total dynamic number of inhabitants in the isochrone area (I_{DT}).

$$I_{DT} = \sum \left(\left(\frac{p_p}{p_t} \right) \times I_{gsm} \right)$$

I_{DT} = Total dynamic inhabitants in isochrone area.

p_p = Population PC6 Point.

p_t = Total PC6 population GSM area.

I_{gsm} = Dynamic inhabitants in isochrone per GSM area.

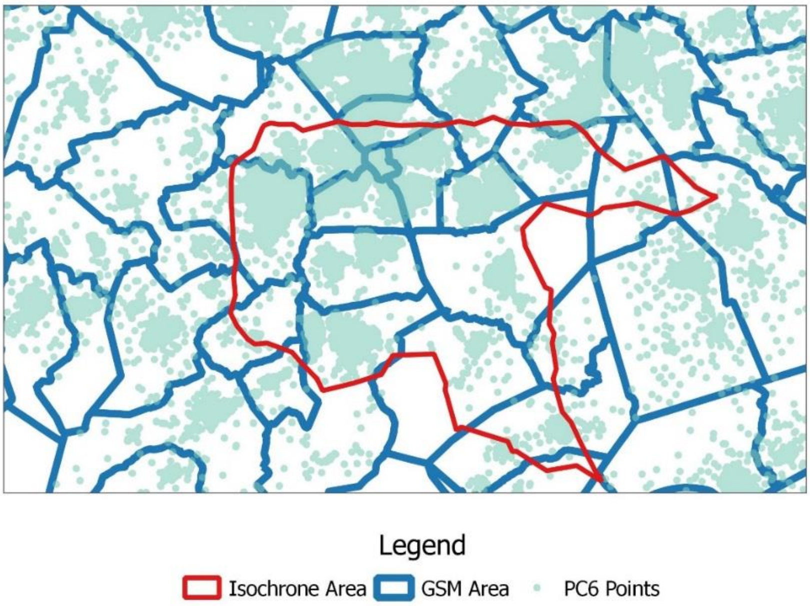


FIGURE 7.10 INTERSECTION BETWEEN ISOCHRONE AREA, PC6 POINTS AND GSM AREAS.

The distribution of inhabitants using PC6 points cannot be applied to visitors since we do not know exactly where in the area visitors are located and we do not have a method to more accurately determine their location. Another possibility is to use the isochrone and GSM areas' surface area. First, isochrone areas calculated before are intersected with the GSM areas (figure 7.10). The share of the isochrone area (A_{iso}) within the GSM area (A_{gsm}) can be used to calculate the relative number of visitors in that particular area (V_{gsm}), assuming that the visitors are distributed equally. The sum of these relative visitors per intersected isochrone GSM area are the total number of visitors within an isochrone area (V_T). The workflow for calculating the number of people in an isochrone area is presented in figure 7.11.

$$V_T = \sum\left(\left(\frac{A_{iso}}{A_{gsm}}\right) \times (V_{gsm})\right)$$

$V_T = Total\ dynamic\ Visitors$

$A_{iso} = Area\ isochrone\ within\ GSM\ area$

$A_{gsm} = Total\ area\ GSM\ area$

$V_{gsm} = Dynamic\ visitors\ GSM\ area$

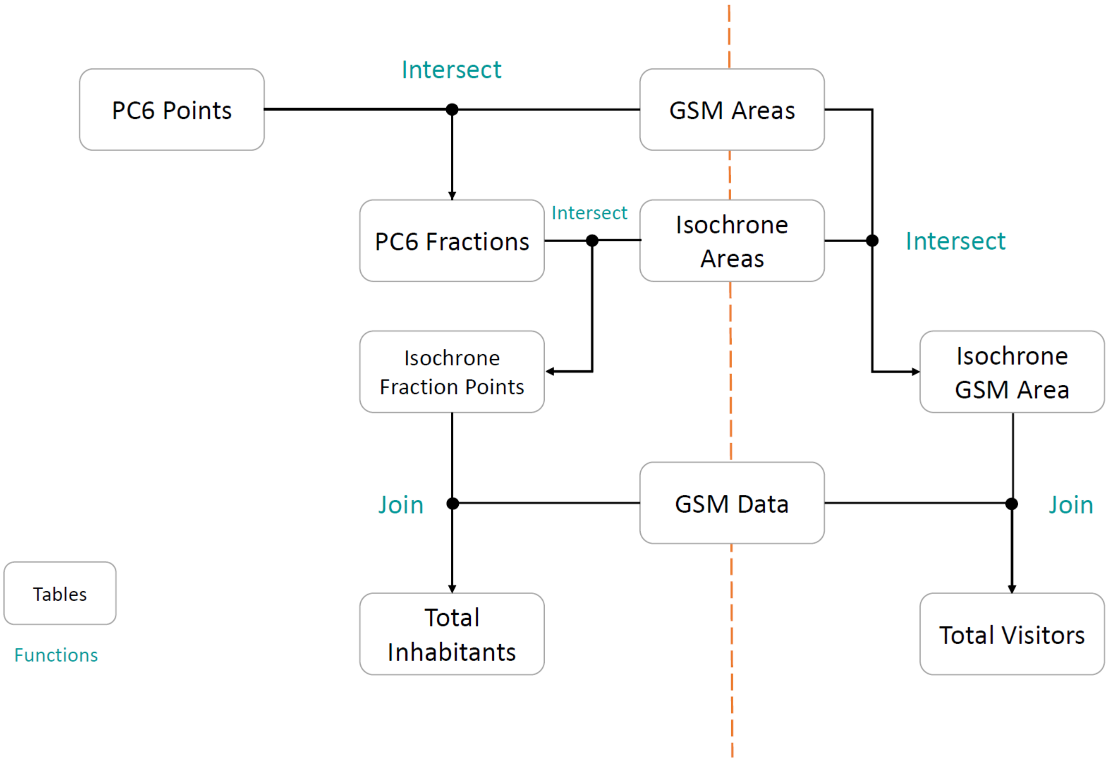


FIGURE 7.11 FLOWCHART GSM DATA

Figure 7.12 displays the resulting data for Utrecht. Note that during the morning and evening rush hour we observe a drop of around 500.000 people because the isochrone area has shrunken due to traffic. Also, we can see that the line representing the inhabitants and the line representing the visitors are ragged. This is because of the mixed use of datasets. The GSM data are on an hourly basis whereas the HERE data to calculate the isochrones are per 15 minutes. Because the isochrone areas and the GSM data have a different time interval, every once in a while the number of inhabitants and visitors 'jumps' to the next hour.

FIGURE 7.12 TOTAL NUMBER OF INHABITANTS, VISITORS AND PEOPLE IN 30 MINUTE ISOCHRONE AREA UTRECHT CALCULATED USING AGGREGATED GSM DATA

7.3 Visualization

Introducing a spatiotemporal dimension to a map leads to challenges. The amount and the complexity of the data used in this research made it more challenging to process, store, analyze and visualize the spatiotemporal data compared to static data for one moment in time. In chapter 5 we discussed different methods to visualize spatiotemporal data. Since we are visualizing isochrone areas and the number of inhabitants and visitors per 15 minutes a day, an animation is considered the most suitable method to visualize the generated spatiotemporal information. Furthermore, one of Kraak and Ormeling's (2010) conclusions was that interactive tools were required in order to process, analyze and make sense out of spatiotemporal data.

In order to produce an animation, a series of static images is produced first. The spatiotemporal information stored in our spatial database cannot be visualized using PGadminIII. To visualize the data we use QGIS which is a free and open-source Geographic Information System (QGIS, 2017). QGIS has a database plugin which allows direct communication with the PostGIS database. Tables containing spatial objects can be loaded and visualized in QGIS directly.

The two major components which are visualized in the web map are the isochrones and the population distribution data. First, the table containing the geometry of the isochrones is imported in QGIS. QGIS by default draws the isochrones on top of each other for every 15 minutes of the day. However, we want to visualize the isochrones per 15 minutes. The QGIS TimeManager (QGIS plugins, 2017) plugin offers a solution: it allows visualization based on a time attribute in a selected table. By selecting the attribute field in a table in which time is stored, the TimeManager filters out and visualizes specific times creating an image of a specific time with the related polygon instead of drawing them on top of each other. Besides, the TimeManager plugin allows users to export images per time step. Using this function, 96 static maps for every 15 minutes of the selected day are exported.

As a next step we need a tool which can generate an interactive animation out of several static images. By interactive we mean a tool which can play the animation at different speeds but also allows the user to 'slide' through time at will. JavaScript code, written by Barend Köbben (2016) and originally used for a Gondwana animation, is used and slightly adjusted to provide the functionalities mentioned (figure 7.13).

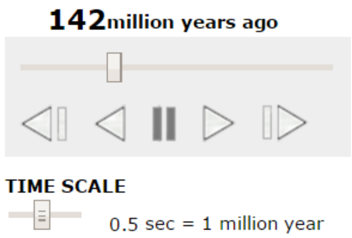


FIGURE 7.13 JAVASCRIPT TIME SLIDER CONTROL FROM GONDWANA WEBMAP (KÖBBEN, 2016).

The second component that is visualized is the spatiotemporal population distribution data. We have chosen to visualize this data in a line graph to allow the user to see possible trends throughout the day. The number of inhabitants, visitors and total number of people are loaded in excel and visualized as a line graph (Figure 7.12). Using PowerPoint, an animation effect is added to the line graph as well. The runtime of the animation equals the runtime of the isochrone animation. These components are all entered in a HTML (Hyper Text Markup Language) file and styled using CSS (Cascading Style Sheets). This HTML file can be opened using a web browser which brings together all individual elements and creates the dynamic IKEA isochrone map.

Chapter 08

Chapter 8: Results

The result of this research is the dynamic isochrone map constructed and designed for a specific IKEA case study. The dynamic isochrone map is accessible on the website www.kartoweb.itc.nl/students/isochronesmap. The introduction page contains all IKEA isochrones combined in one animated map (figure 8.1). On the right side is some additional information on the construction of the dynamic isochrone map, the structure of the website and how the animation can be controlled. On the left hand side there is a menu with all thirteen IKEA stores which link to individual pages that zoom in to a specific IKEA store.

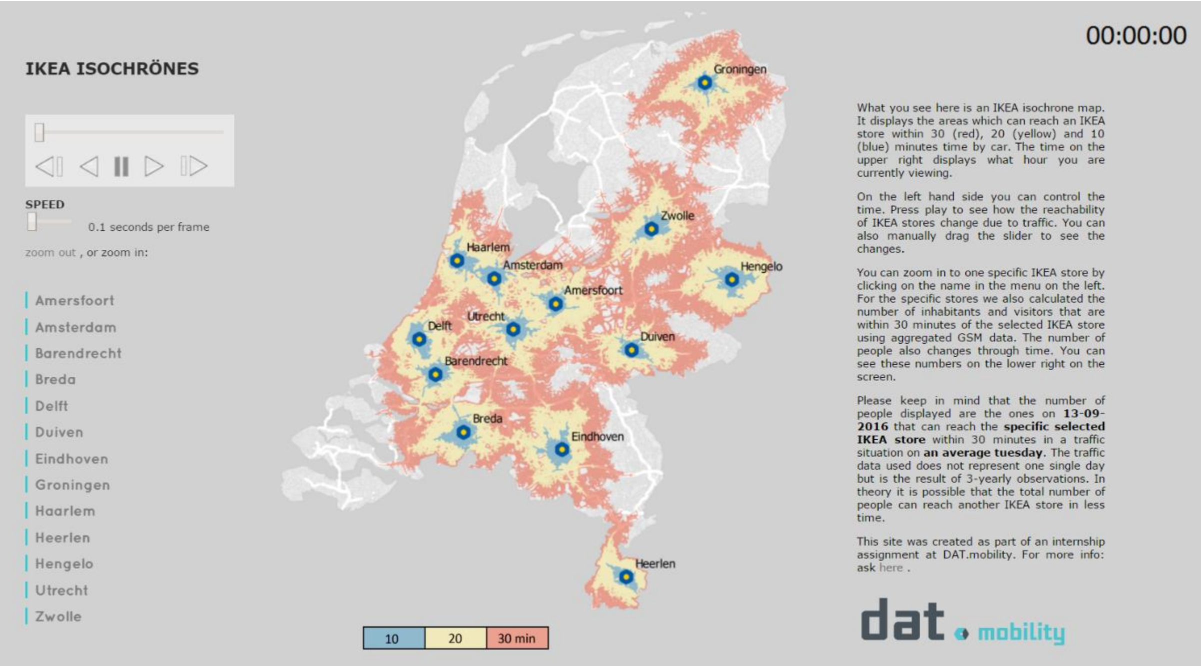


FIGURE 8.1 HOME PAGE DYNAMIC ISOCHRONE MAP

An example of a store specific page can be seen in figure 8.2, in this case Utrecht. As soon as the page is opened, the animation starts playing. The time in the upper right corner indicates the time that belongs to the time step visualized. The graph on the lower right corner displays the total number of people (black), the total number of inhabitants (orange) and the total number of visitors (green) which can reach the IKEA store within thirty minutes on the 13th of September 2016. The legend is positioned at the bottom of the map. On the left side other stores can be selected and the time slider can be controlled. The user can control the speed of the animation, the direction It plays, can forward or backward it one frame per click or can slide at will.

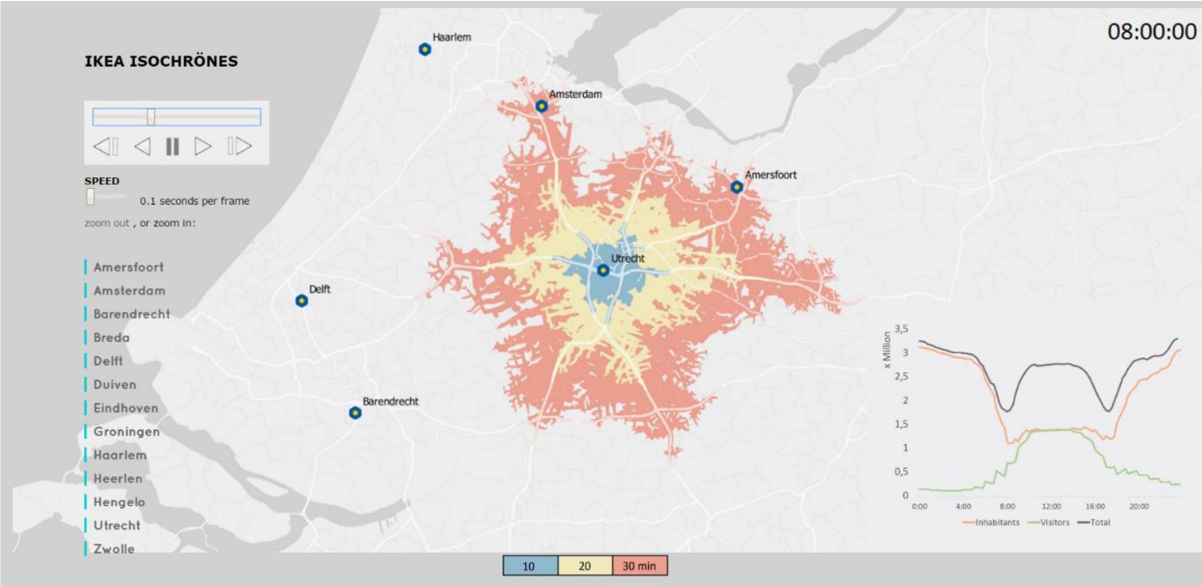
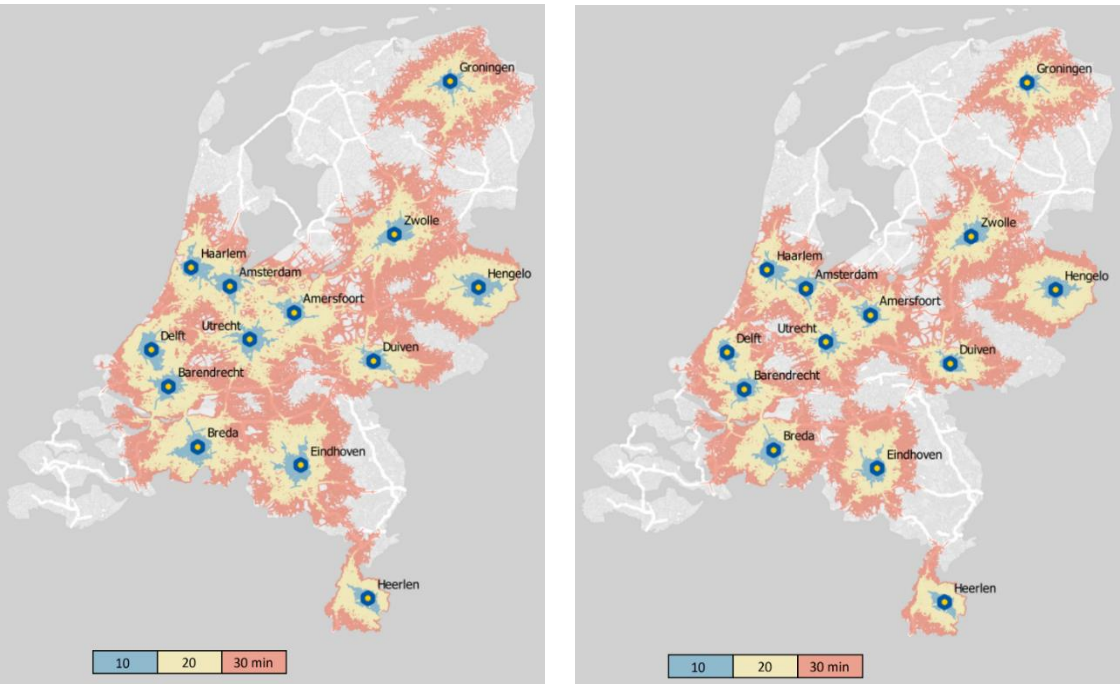


FIGURE 8.2 IKEA UTRECHT ISOCHRONE, 08:00.

There are a couple interesting results regarding the specific IKEA case study. As can be seen on the dynamic isochrone map (figure 8.3a), the majority of the Netherlands is within a 30-minute drive of an IKEA store. Especially in the more populated areas there are more IKEA stores on a relatively smaller surface causing a good reachability even during rush hour (figure 8.3b). It is hard to see differences between cities and how accessibility to individual IKEA stores changes throughout the day. When zooming in on a specific store we can observe more detailed results, such as the number of people that can reach an IKEA store within 30 minutes.

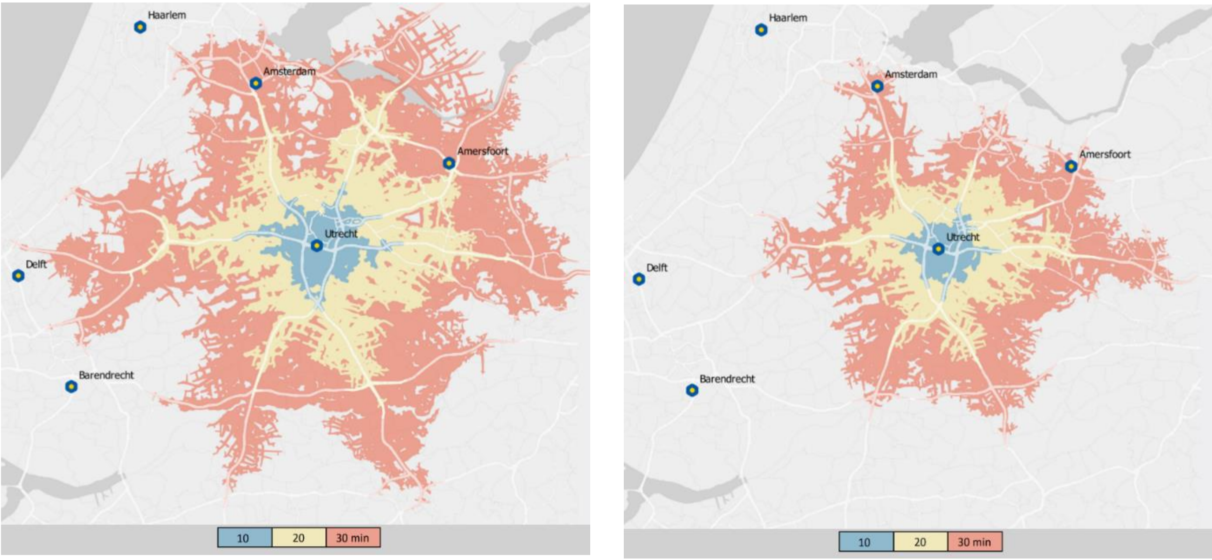


(a) (b)

FIGURE 8.3 IKEA ISOCHRONES THE NETHERLANDS AT 00:00 (A) AND 08:30 (B)

When zooming in on the IKEA Utrecht, we observe differences in the areas that can reach IKEA Utrecht within given times. At 06:00 in the morning we see a decline in the areas with access to IKEA Utrecht. This decline does not stop until 08:15, after which the area gradually starts to grow again. It is not until 10:45 that the area is stable again and not noticeably declining or expanding. We observe a similar pattern at the end of a working day. The area starts declining around 16:00 until 17:15 after which it grows back to a stable state around 20:00. The same patterns are observed for other IKEA stores in the Netherlands for both morning and afternoon rush hours, although the absolute differences in areas vary between cities.

To illustrate the difference through time, figure 8.4a show areas with access to IKEA Utrecht within given times at 00:00 and figure 8.4b shows the same areas at 08:15. During the rush hours mentioned above, the areas which can reach an IKEA store within ten, twenty and thirty minutes are noticeably smaller than outside the rush hours. Areas from which an IKEA could be reached in 30 minutes before rush hour might not be able to so during rush hours.



(a) (b)

FIGURE 8.4 ACCESSIBILITY TO IKEA UTRECHT AT 00:00 (A) AND 08:15 (B)

Besides seeing the spatiotemporal differences in the areas which can reach an IKEA store within a given time, it is interesting to see the spatiotemporal variation in the number of people within those areas. We see the same trend for all IKEA stores (figure 8.5): starting at 00:00 the number of inhabitants in the isochrone areas are relatively high and the number of visitors in the isochrone area are relatively low. Simultaneously with the start of the morning rush hour (06:00) the number of inhabitants starts decreasing and the number of visitors starts increasing indicating that people are on the move. Around 10:00 the number of inhabitants and visitors stabilize again until the morning pattern reverses and people start going home around 16:00. The number of inhabitants in the areas increases, whereas the number of visitors decreases. We do see that the increase and decrease of the number of inhabitants and visitors during the evening is more gradual compared to the increase and decrease in the morning. This can probably be explained by the fact that most people are sleeping in the early morning whereas they are still active during evening hours.

Furthermore, we also see that the number of visitors does not surpass the number of inhabitants in the IKEA isochrone areas throughout the day, except for Amsterdam (figure 8.6) and Haarlem. From around 10:15 until 15:15 the number of visitors in the Amsterdam and Haarlem IKEA isochrones surpasses the number of inhabitants. Also the total number of people increases during this time interval. We do not have enough information to further explain why this is happening in Amsterdam and Haarlem.

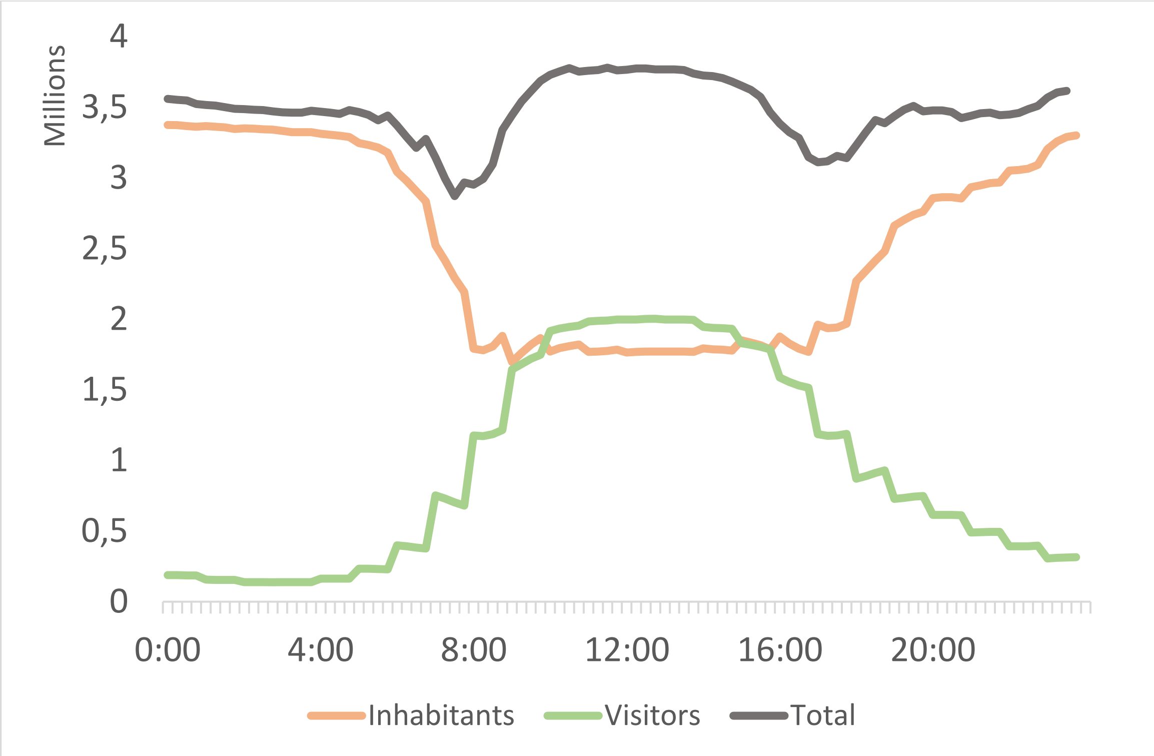


FIGURE 8.6 TOTAL NUMBER OF INHABITANTS, VISITORS AND PEOPLE IN 30 MINUTE ISOCHRONE AREA AMSTERDAM CALCULATED USING AGGREGATED GSM DATA

Lastly, during rush hours, we see significant drops in the total number of people for the IKEA isochrones located in relatively busier cities like Amersfoort, (figure 8.7), Amsterdam, Barendrecht, Breda, Delft, Duiven, Eindhoven, and Utrecht. The total number of people within the isochrone areas are relatively more stable in Groningen (figure 8.8), Haarlem, Heerlen, Hengelo and Zwolle. We see the decreases in the total number of people simultaneously with the declining isochrone areas observed earlier. Because the areas are smaller during rush hours, the total number of people most likely decreases since areas in which people were capable of reaching an IKEA within a given time are now not.

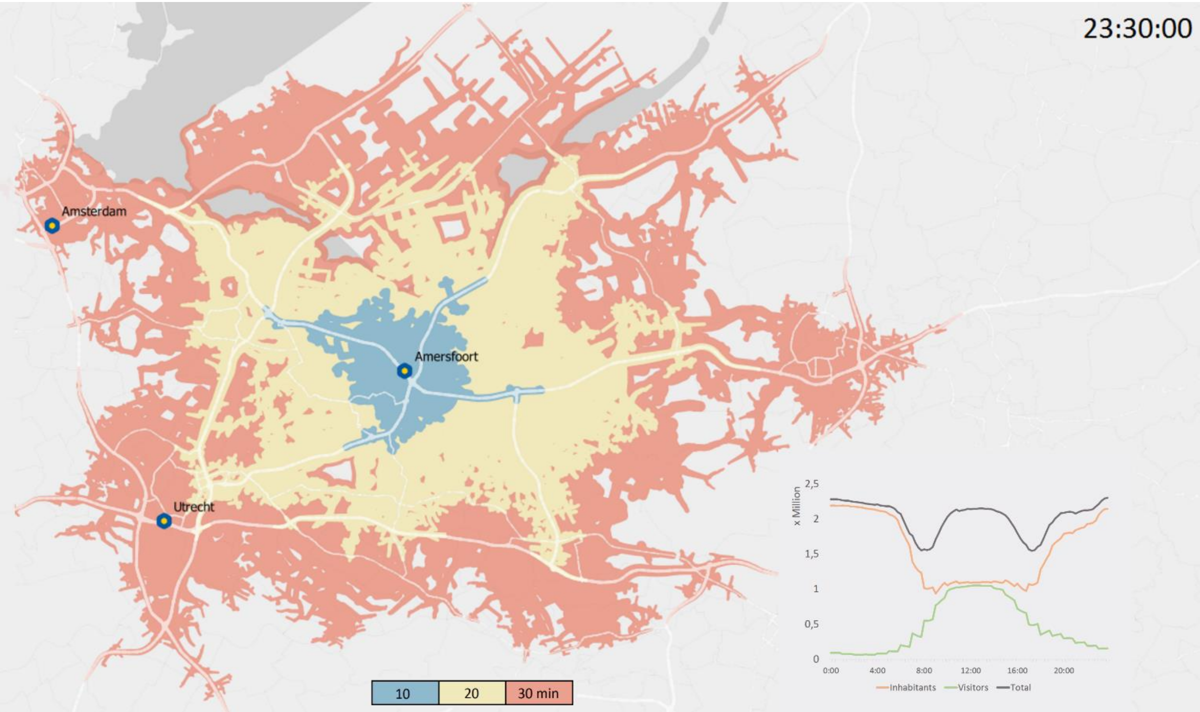


FIGURE 8.7 IKEA AMERSFOORT ISOCHRONE 23:30.

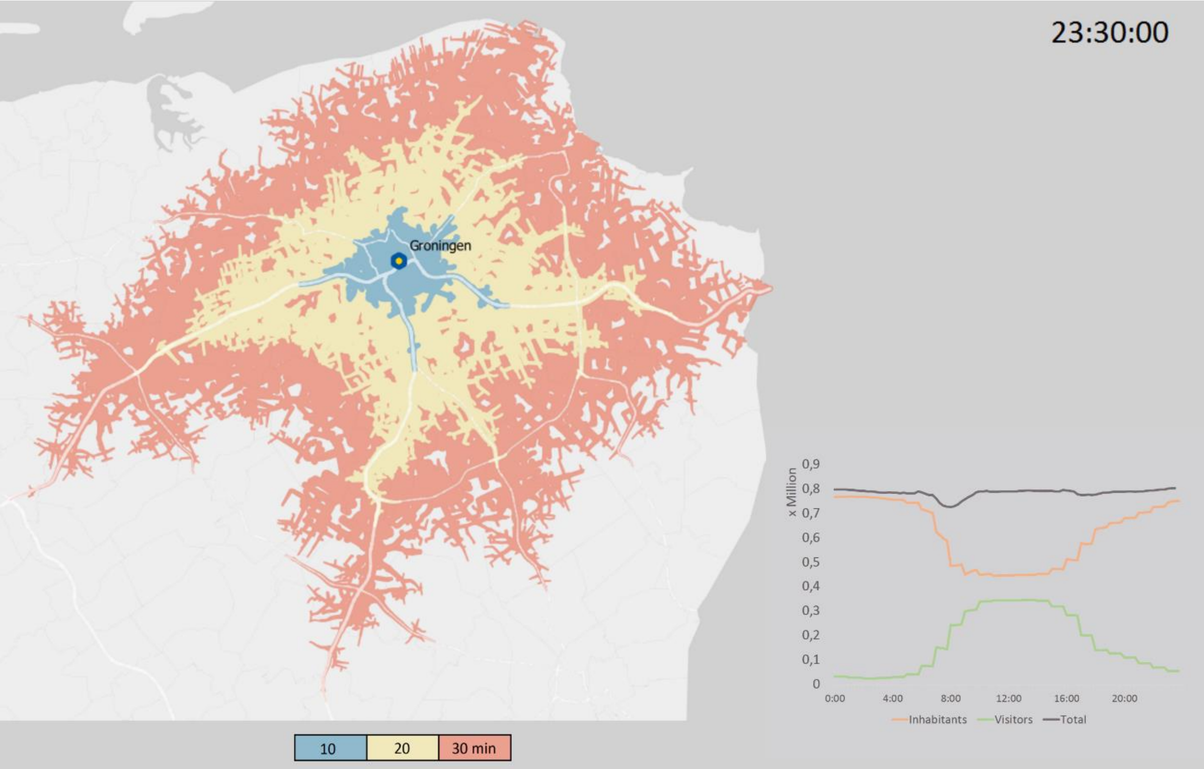


FIGURE 8.8 IKEA GRONINGEN ISOCHRONE, 23:30

Chapter 09

Chapter 9: Discussion

This research is amongst the first to combine spatiotemporal traffic and population distribution data in a dynamic isochrone map. Using open source software, a methodology to pre-process the data, perform (network) calculations and to visualize spatiotemporal data has been developed. Due to the relative novelty of this research the methodology has been exploratory, and without a doubt there are other ways to achieve the same or at least similar results. Because of the fact that only free and open source software has been used in this research, we do believe the method developed in this research can be a good starting point for further research. Still, there remain some assumptions and flaws in the methodology which can possibly be improved in further research. In this discussion we evaluate the methodology, software and data used in this research.

9.1 Methodology

As discussed in chapter 3, a point which can always be discussed when using and constructing isochrone maps is where and how to draw a boundary. Since we have calculated isochrone areas using a network and wanted to use these isochrones to identify the number of people, an area still had to be constructed from the isochrone network. We reviewed different options and eventually chose for a variable buffer method which in our opinion is the best option for this specific study. Although the isochrone area does look a bit strange it effectively reduces the buffer size once roads are further away from the starting point successfully eliminating people living close to a road but not close enough to be taken into account.

To calculate the number of inhabitants we used a different method than for the number of visitors. This is because we had access to PC6 points which contained more detailed information on (static) population distribution. By assuming that this distribution over the PC6 points remains the same throughout the day we could allocate inhabitants more accurately. However, we did not conduct any validation and for now have to assume this is the best method available. Likewise we assumed that visitors were distributed evenly throughout GSM areas.

9.2 Software used

As mentioned, PostgreSQL extended with postGIS and pgRouting works excellent on network tables, but during the work we identified two shortcomings. First of all, pgRouting by default does not support instantaneous driving time, also called Time Dependent Dynamic Shortest Path algorithms. The functions used in this research are designed for static input data and are therefore not as accurate as they would have been when TDDSP's would have been used. Some pgRouting users already altered the default functions to support TDDSP. In this research we chose not to alter the default functions due to a lack of time and skills. TDDSP's are likely to be added to the default pgRouting functions in the near future.

Furthermore, pgRouting returns nodes and edges which do not exceed the maximum given cost. We described in paragraph 7.1.3 that it is possible that a road segment can still be traversed further but because there are no nodes along the road only a starting point is returned. This problem has been addressed by Obe and Hsu (2017) as well, but is not yet supported in the default pgRouting functions either.

QGIS proved to be very useful in this particular research. One of the major benefits is that it communicates with the PostgreSQL database easily, making the visualization of spatially enabled tables easy and quick. Besides, the TimeManager plugin extends QGIS with necessary tools to work with spatiotemporal data. It automatically filters and displays spatial objects based on a time column and users can export the resulting images to their liking. A small disadvantage however is that users cannot export images with a legend or additional text when using the TimeManager. Using the atlas function in the QGIS print composer might be an alternative approach for exporting images but is not used in this research. All in all, the combination of PostgreSQL, PGAdminIII, postGIS, pgRouting and QGIS has worked out well in this research. Lastly, the software packages used are all free and open source.

9.3 Data used

9.3.1 HERE Traffic Patterns

The spatiotemporal traffic data used also have some limitations. We mentioned that the speed patterns do not exceed the maximum allowed speed on that road. In theory it is possible that observations exceed the maximum allowed speed. However, since there are no patterns which exceed this maximum speed, these are not in the dataset. This is because HERE traffic patterns are mainly used in navigation systems.

The information on the number of observations and the coverage of all Dutch roads is limited. It is possible that some roads contain only a few observations for a few moments a day. Obviously the patterns would better resemble reality if there would have been more observations.

9.3.2 Aggregated GSM Data

We argued the GSM data used currently are the most accurate way to gain insight into the spatiotemporal dynamics of population distribution. This does not mean that GSM data have no disadvantages. GSM data originates from the CDR’s of one network provider which could lead to a bias. There are three major network operators in the Netherlands and there is a possibility that certain demographic groups are under or over represented by one network provider. Since the CDR’s are aggregated this could lead to biased results in the GSM data used. Again, there is no real way of validating these results yet. However, at the moment GSM data are the best option to gain more insight in the dynamic distribution of the Dutch population.

Also, there is a lack of research on the accuracy of GSM data. There is no way of validating the numbers of inhabitants and visitors within the isochrones presented in this research. We argue that at the moment of writing this is the most accurate way of determining dynamic population distribution and the variation through time is more accurate than traditional static measures. We should however keep in mind that these numbers have not been validated yet and went through a process from raw CDR’s, which might already contain minor errors, to complex algorithms which all influenced the final data. Users should be aware of these facts and potential inaccuracies and should hold the numbers presented as an indication.

Another flaw is the result of using two different datasets. The HERE Traffic Patterns data are available in 15 minutes intervals whereas the aggregated GSM data are on an hourly basis. This causes the number of inhabitants and visitors to take a 'jump' sometimes. Also, the GSM data are specifically for the 13th of September in 2016. The HERE Traffic Patterns are the result of 3-year averages. The displayed number of inhabitants and visitors are therefore an estimation assuming that no incidents occurred on the Dutch roads and the travel patterns in the dataset resemble the actual average speeds driven that day.

9.3.3 Final results

The final product is presented on a website which has interactive elements but is quite limited in terms of functionality. For potential users it might be more useful if the isochrone were presented in a web map, which allowed panning and zooming on the map. If these functionalities would in fact be of additional value is questionable. The potential social value is strongly related with one final point of discussion; the usability of the dynamic isochrone map created during this research. Because no actual end-users have been involved during the development or testing of the dynamic isochrone map, it is unknown whether the functionalities developed fit the user needs. However, from a scientific point of view we have succeeded to bring together spatiotemporal traffic and population distribution data in a dynamic isochrone map, which have led to interesting insights regarding accessibility.

Chapter 10

Chapter 10: Conclusion

In this thesis, we researched how spatiotemporal traffic and population distribution data can be incorporated in a dynamic isochrone map. We did this by first exploring existing literature to find to what extent isochrone maps, spatiotemporal traffic and population distribution data have been researched in accessibility and cartography studies. We then continued with pre-processing the spatiotemporal traffic and population distribution data to make it suitable for combined use in a dynamic isochrone map. After pre-processing, we explored ways to visualize the spatiotemporal traffic and population distribution data. As a final step we explored the potential of combining spatiotemporal traffic and population distribution data in a dynamic isochrone map, using a specific IKEA case study.

To answer Q1, 'To what extent have isochrone maps, spatiotemporal traffic and population distribution data been researched in accessibility and cartography studies?' There have been researches which either discussed isochrones, dynamic isochrones, spatiotemporal traffic or spatiotemporal population distribution data. However the combination of these subjects has barely been researched. By individually researching existing literature on isochrone maps, spatiotemporal traffic data and spatiotemporal population distribution data, this research explores what possibilities the combination of these different subjects might have.

After the literature study we started pre-processing the data used in our case study to answer Q2; 'How is spatiotemporal traffic and population distribution data pre-processed for combined use in dynamic isochrone maps?' Both datasets were stored in a spatially enabled database. The spatiotemporal traffic data are used to calculate isochrone areas per fifteen minutes for an average Tuesday. The spatiotemporal population distribution is then joined with the isochrone areas and used to calculate the number of inhabitants and visitors within these areas.

A final methodological step was to visualize the isochrone areas and the population distribution data. This provides an answer to Q3: 'How can spatiotemporal traffic and population distribution data be visualized dynamically in isochrone maps?' We chose to visualize isochrone areas using QGIS and exported static images using the TimeManager plugin. Using JavaScript we created an interactive animation out of the static images to dynamically visualize the isochrone map. The population distribution data is presented as a synchronized video, created using Microsoft Excel and PowerPoint.

The question remaining is Q4: 'What potential does including spatiotemporal traffic and population distribution data in dynamic isochrone maps have when applied to a specific case study?' The impact of combining spatiotemporal traffic and population distribution data in a dynamic isochrone map is that, applied to this specific case study, more realistic results regarding the areas which can reach an IKEA and the number of people within these areas can be achieved as compared to isochrone maps using static data. We have seen a decline in the area which can reach an IKEA store within given times during morning (06:00-10:45) and afternoon rush-hour (16:00- 20:00). Using the dynamic isochrone map we determined that 08:15 and 17:15 are the times at which the areas that can reach an IKEA store within ten, twenty and thirty minutes are the smallest. At these times we simultaneously observed decreases in the total number of people that can reach an IKEA stores within the given times, varying for each IKEA store.

The combination of these research questions answers the main question: 'How can spatiotemporal traffic and population distribution data be incorporated in a dynamic isochrone map?' First, a methodology has to be developed on how an isochrone map is constructed and with what use. Part of this methodology consist of pre-processing the spatiotemporal data that is used. As a final step the input data is used to calculate isochrone areas and the number of people within the areas, and interactively visualized to create a dynamic isochrone map.

The method used in this research is easily scalable and can be used for similar cases without the need to redevelop the methodology. The maximum driving time can easily be adjusted, along with the starting points and whether the calculation should be to or from a given facility or place. The combination of spatiotemporal traffic and population distribution data is particularly interesting for calculating dynamic service areas which can be used in different fields. A specifically interesting potential use would be the optimization of potential locations for new stores or facilities. By entering potential points as input, statistics on the number of people in reach through time can be analyzed and the most optimal one can be chosen. In this application especially the dynamic distribution of people is interesting. Where static population distribution measures only included information on where people live, GSM data reveals historical spatiotemporal distribution patterns. By using this information a more optimal location can be chosen in which the number of people in reach at certain times is maximized, potentially increasing profits. Urban planners could also benefit from a dynamic isochrone map by for example choosing a new location for a train station taking into account the number of people within reach.

10.2 Recommendations

The results of this research are promising although some points can be improved in future research. First of all, pgRouting by default is more focused on the use of static input data for network calculations. Time Dependent Dynamic Shortest Path algorithms (TDDSP) and a method to increase the accuracy of the nodes returned by pgRouting, for example, would increase the overall accuracy of the isochrone calculations and thus the calculated number of people within these areas. These functionalities can be added by editing the default pgRouting functions.

Besides these methodological points, new, more accurate spatiotemporal datasets might become available in the near future. It would be interesting to calculate isochrone areas using actual traffic speeds of one single day instead of the Traffic Patterns used in this research. Also more research into GSM data should be conducted to draw better conclusions on the accuracy and usability of these data. Higher accuracies could also be achieved by combining GSM data with detailed information on, for example, land use and mobility patterns.

Moreover, the dynamic isochrone map should be tested with actual end-users in future research to evaluate the usability and other potential benefits or shortcomings compared to traditional static isochrone maps. In this research we claim that adding spatiotemporal dynamics to isochrone maps lead to a better and more accurate insight in accessibility but the potential need and use for such an application are not researched.

Although there is always room for improvement, we hope this research encourages new research into dynamic isochrone maps using spatiotemporal traffic and population distribution data. Besides potentially improving the methodology presented in this research or using a different, we hope to see relevant new case-studies in which the benefits of a dynamic isochrone map, as presented in this research, are shown.

References

Ahas, R., Silm, S., Järv, O., Saluveer, E., & M. Tiru (2010). Using Mobile Positioning Data to Model Locations Meaningful to Users of Mobile Phones. *Journal of Urban Technology*, *17*(1), 3–27. https://doi.org/10.1080/10630731003597306.

Andrienko, G., Andrienko, N., Dykes, J., Kraak, M.-J., & H. Schumann (2014). GeoVisual analytics, time to focus on time. *Information Visualization*, *13*(3), 187–189. https://doi.org/10.1177/1473871613487091.

Andrienko, G., Andrienko, N., Bak, P., Keim, D., & S. Wrobel (2013). *Visual Analytics of Movement*. Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-37583-5.

Andrienko, G., Andrienko, N., Dykes, J., Kraak, M., & H. Schumann (2010). GeoVA (t) – Geospatial visual analytics: focus on time. *Journal of Location Based Services*, *4*(3), 141–146. https://doi.org/10.1080/17489725.2010.537283.

Bauer, V., Gamper, J., Loperfido, R., Profanter, S., Putzer, S., & I. Timko (2008). Computing isochrones in multi-modal, schedule-based transport networks. *Proceedings of the 16th ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems - GIS '08*, 2. https://doi.org/10.1145/1463434.1463524.

Baum, M., Bläsius, T., Gemsa, A., Rutter, I., & F. Wegner (2016). Scalable Isocontour Visualization in Road Networks via Minimum-Link Paths, 1–42. Retrieved from http://arxiv.org/abs/1602.01777.

Baum, M., Buchhold, V., Dibbelt, J., & D. Wagner (2015). Fast Computation of Isochrones in Road Networks, 1–27. https://doi.org/10.1007/978-3-319-38851-9.

Berg, J. van den, Ferloni, G., Hoeve, L. van, Passier, K., & R. Schreppers (2015). *Social Media as Geo-Information: Exploring the Usability of Twitter Data*. Utrecht University. Unpublished.

Bertolini, L., le Clercq, F., & L. Kapoen (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*, 207–220. https://doi.org/10.1016/j.tranpol.2005.01.006.

Biazzo, I. (2015). Social Dynamics Lab. Retrieved October 10, 2016, from http://www.socialdynamics.it/resources/citychrone/citychrone.html.

Birks, H. J. B. (1989). Holocene Isochrone Maps and Patterns of Tree-Spreading in the British Isles. *Journal of Biogeography*, *16*(6), 503–540.

Brainard, J., Lovett, A., & I. Bateman (1997). Using isochrone surfaces in travel-cost models. *Journal of Transport Geography*, *5*(2), 117–126. https://doi.org/10.1016/S0966-6923(96)00074-9.

Cartwright, W. (2008). Delivering geospatial information with Web 2.0. In M. P. Peterson (Ed.), *International Perspectives on Maps and the Internet* (pp. 11–30). Berlin, Heidelberg: Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-72029-4_2.

Cascetta, E., Cartenì, A., & M. Montanino (2016). A behavioral model of accessibility based on the number of available opportunities. *Journal of Transport Geography*, *51*, 45–58. https://doi.org/10.1016/j.jtrangeo.2015.11.002.

Dannenberg, P., Kunze, M., & G.M. Nduru (2011). Isochronal Map of Fresh Fruits and Vegetable Transportation from the Mt. Kenya Region to Nairobi. *Journal of Maps*, *7*(1), 273–279. https://doi.org/10.4113/jom.2011.1169.

De Morgen (2016, October 28). Groen niet te spreken over nieuwe IKEA-vestiging, p. 1.

Dijkstra, E. W. (1959). A note on two problems in connexion with graphs. *Numerische Mathematik*, *1*(1), 269–271.

Doling, J. (1979). *Accessibility and Strategic Planning*. Birmingham: Centre for Urban and Regional Studies, University of Birmingham.

Drift, S. van der. (2015). *Revealing spatial and temporal patterns from Flickr photography*. Wageningen University.

Efentakis, A., Grivas, N., Lamprianidis, G., Magenschab, G., & D. Pfoser (2013). Isochrones, traffic and DEMOgraphics. *GIS: Proceedings of the ACM International Symposium on Advances in Geographic Information Systems*, 538–541. https://doi.org/10.1145/2525314.2525325.

Efentakis, A., Theodokaris, D., & D. Pfoser (2012). Crowdsourcing computing resources for shortest-path computation. In *Proceedings of the 20th International Conference on Information and Knowledge Management* (pp. 434–437).

Forer, P., & H. Kivell (1981). Space-time budget, public transport, and spatial choice. *Environment and Planning A*, *13*, 497–509.

Galton, F. (1881). *On the Construction of Isochronic Passage Charts*. *Proceedings of the Royal Geographical Society*. Royal Geographical Society.

Gamper, J., Böhlen, M., Cometti, W., & M. Innerebner (2011). Defining Isochrones in Multimodal Spatial Networks. In *Proceedings of the 20th ACM International Conference on Information and Knowledge Management* (pp. 2381–2384). ACM.

Gamper, J., Böhlen, M., & M. Innerebner (2012). Scalable computation of isochrones with network expiration. In *Lecture Notes in Computer Science* (pp. 526–543). https://doi.org/10.1007/978-3-642-31235-9_35.

Getis, A., & J. Getis (1972). Some Current Concepts, Techniques, and Recent Findings in Urban Geography. *Proquest*, *71*(8), 483–490.

Gonzalez, M. C., Hidalgo, C. A., & A.-L. Barabasi (2008). Understanding individual human mobility patterns. *Nature*, *453*(7196), 779–782. https://doi.org/10.1038/nature06958.

Google Maps (2016). Ikea. Retrieved December 16, 2016 from https://www.google.nl/maps/search/ikea/@52.246146,4.7822063,8.48z.

Gortana, F., Kaim, S., & M. von Lupin (2014). Isoscope. Retrieved October 10, 2016, from http://www.flaviogortana.com/isoscope/.

Hamrick, K. (2010). Greenland and Climate Change. Retrieved from http://www1.american.edu/ted/ice/Greenland.htm.

Heede, A. van den. (2016, November 18). Ikea wil mobiliteitsprobleem oplossen met nieuwe buslijn. *Krant van West-Vlaanderen*, p. 1.

HERE (2017). Traffic Analytics. Retrieved January 26, 2017, from https://here.com/en/products-services/products/here-traffic/here-traffic-analytics.

Het Laatste Nieuws (2016, October 28). Groen niet te spreken over nieuwe Antwerpse IKEA-vestiging, p. 2.

Heywood, D. I., Carver, I., & S. Cornelius (2011). *An introduction to Geographical Information Systems*. Harlow, Engeland: Pearson Education.

Hudeček, T. (2011). Analysis of the Accessibility of Prague in Czechia in the 1918–2020 Period. *Hrvatski Geografski Glasnik*, *73*(2), 93–110.

Innerebner, M., Böhlen, M., & I. Timko (2007). A web-enabled extension of a spatio-temporal DBMS. *Proceedings of the 15th Annual ACM International Symposium on Advances in Geographic Information Systems*, 1–8. https://doi.org/10.1145/1341012.1341056.

Innerebner, M., Böhlen, M., & J. Gamper (2013). ISOGA: A System for Geographical Reachability Analysis, 180–189.

Jariyasunant, J., Mai, E., & R. Sengupta (2010). Algorithm for finding optimal paths in a public transit network with real-time data. *Transportation Research Board 90th Annual Meeting*, 1–14. https://doi.org/10.3141/2256-05.

Järv, O., Tenkanen, H., Salonen, M., & T. Toivonen (2016). Dynamic Spatial Accessibility Modelling: Access as a Function of Time. *AGILE 2016*, 14–17.

Järv, O., Tenkanen, H., Salonen, M., & T. Toivonen (2014). Dynamic Spatial Accessibility Modelling : Access as a Function of Time, 10.

Jihua, H., Zhifeng, C., Guangpeng, Z., & H. Ze (2013). A Calculation Method and Its Application of Bus Isochrones. *Journal of Transportation Systems Engineering and Information Technology*, *13*(3), 99–104. https://doi.org/10.1016/S1570-6672(13)60111-7

Köbben, B. (2016). Gondwana Animation. Retrieved January 31, 2017, from http://kartoweb.itc.nl/gondwana/index.html.

Kok, R. (1951). Isochronenkaarten voor het locale en regionale openbaar personen vervoer van s'Gravenhage. *Tijdschrift Voor Economische En Sociale Geographie*, (XLII), 261–278.

Kraak, M.-J., & A. Brown (2001). *Web Cartography, Developments and Perspectives.* London: Taylor & Francis.

Kraak, M.-J., & F. Ormeling (2011). *Cartography: visualization of spatial data*. Guilford Press.

Kwan, M.-P (2013). Beyond Space (As We Knew It): Toward Temporally Integrated Geographies of Segregation, Health, and Accessibility. *Annals of the Association of American Geographers*, *103*(5), 1078–1086. https://doi.org/10.1080/00045608.2013.792177.

Lange-Diercke (1930). Frühlingseinzug (Anfang der Apfelblüte). Retrieved from https://commons.wikimedia.org/wiki/File:Lange_diercke_sachsen_deutschland_fruehlingseinzug.jpg?uselang=en.

Lee, W.-H., Tseng, S.-S., & S.-H. Tsai (2009). A knowledge based real-time travel time prediction system for urban network. *Expert Systems with Applications*, *36*(3), 4239–4247. https://doi.org/10.1016/j.eswa.2008.03.018.

Li, Q., Zhang, T., Wang, H., & Z. Zeng (2011). Dynamic accessibility mapping using floating car data: A network-constrained density estimation approach. *Journal of Transport Geography*, *19*(3), 379–393. https://doi.org/10.1016/j.jtrangeo.2010.07.003.

Li, X., & M. Kraak (2008). The Time Wave. A New Method of Visual Exploration of Geo-data in Time. *The Cartographic Journal*, *45*(3), 193–200. https://doi.org/10.1179/000870408X311387.

Longley, P. A., Goodchild, M. F., Maguire, D. J., & D.W. Rhind (2011). *Geographic Information Systems & Science*. Hoboken: John Wiley & Sons.

Mapping Manchester (1914). Time zone map, 1914 Melbourne. Retrieved from http://personalpages.manchester.ac.uk/staff/m.dodge/mappingmanchester/iscron.jpg.

Marciuska, S., & J. Gamper (2010). Determining Objects within Isochrones in Spatial Network Databases, 392–405.

Math Insight (2016). Small Undirected Network. Retrieved October 26, 2016, from http://mathinsight.org/image/small_undirected_network_labeled.

Melhorado, A. M. C., Demirel, H., Kompil, M., Navajas, E., & P. Christidis (2016). The impact of measuring internal travel distances on self-potentials and accessibility. *European Journal of Transport and Infrastructure Research*, *16*(2), 300–318.

Meppelink, J., Langen, J. Van, Siebes, A., & M. Spruit (2015). *Know Your Bias: Scaling Mobile Phone Data to Measure Traffic Intensities*. Utrecht University.

Messelodi, S., Modena, C., Zanin, M., De Natale, F., Granelli, F., Betterle, E., & A. Guarise (2009). Intelligent extended floating car data collection. *Expert Systems with Applications*, *36*, 4213–4227. https://doi.org/10.1016/j.eswa.2008.04.008.

Miller, H. J., & S.A. Bridwell (2009). A Field-Based Theory for Time Geography. *Annals of the Association of American Geographers*, *99*(1), 49–75. https://doi.org/10.1080/00045600802471049.

NOAA (National Oceanic and Atmosphereic Administration). (2015). Tsunami Travel Time Maps. Retrieved November 10, 2016, from http://www.ngdc.noaa.gov/hazard/tsu_travel_time_events.shtml.

Obe, Regina O. & Leo S. Hsu (2017). pgRouting: A Practical Guide. Chugiak: Locate Press.

O'Sullivan, D., Morrison, A., & J. Shearer (2000). Using desktop GIS for the investigation of accessibility by public transport: an isochrone approach. *International Journal of Geographical Information Science*, *14*(1), 85–104. https://doi.org/10.1080/136588100240976.

O'Sullivan, D., Morrison, A., & J. Shearer (2000). Using desktop GIS for the investigation of accessibility by public transport: an isochrone approach. *International Journal of Geographical Information Science*, *14*(1), 85–104. https://doi.org/10.1080/136588100240976.

Peterson, M. P. (2003). *Maps and the Internet*. Amsterdam: Elsevier.

Peuquet, D. J. (1984). A Conceptual Framework and Comparison of Spatial Data Models. *Cartographica: The International Journal for Geographic Information and Geovisualization*, *21*(4), 66–113. https://doi.org/10.3138/D794-N214-221R-23R5.

pgRouting (2017). Documentation. Retrieved January 26, 2016, from http://docs.pgrouting.org/.

postGIS (2017). Documentation. Retrieved January 25, 2017, from http://postgis.net/docs/.

QGIS (2017). QGIS. Retrieved January 13, 2017, from http://www.qgis.org/en/site/.

QGIS plugins (2017). QGIS Python Plugins Repository. Retrieved January 13, 2017, from https://plugins.qgis.org/plugins/timemanager/.

Riedel, J. (1910). *Anregungen für die Konstruktion und die Verwendung von Isochronenkarten*. Leipzig: Thomas & Hubert.

Rietveld, A. (2015, May 22). Ikea laat Leiderdorp nog langer wachten. *Leidsch Dagblad*, p. 1.

Roanes-Lozano, E., García-Álvarez, A., & A. Hernando (2012). A geometric approach to the estimation of radial railway network improvement. *Revista de La Real Academia de Ciencias Exactas, Fisicas Y Naturales - Serie A: Matematicas*, *106*(1), 35–46. https://doi.org/10.1007/s13398-011-0050-6.

Rossiter, D. G. (2008). MSc Research Skills Topic: Purpose, structure and logic of MSc research.

Roth, R. E., Donohue, R. G., Sack, C. M., Wallace, T. R., & T.M.A. Buckingham (2014). A process for keeping pace with evolving web mapping technologies. *Cartographic Perspectives*, (78), 25–52. https://doi.org/10.14714/CP78.1273.

Roth, R. E., Ross, K. S., & A.M. Maceachren (2015). User-Centered Design for Interactive Maps: A Case Study in Crime Analysis. *ISPRS International Journal of Geo-Information*, *4*, 262–301. https://doi.org/10.3390/ijgi4010262.

Roth, R. E., Hart, D., Mead, R., & C. Quinn (2014). *Design before you code: Using wireframes in support of interactive and web-based mapping*.

Rowe, K. (1953). *The journey to work on Merseyside*. (Advancement of Science, Ed.). London: British Association for the Advancement of Science.

RPA (2011). Access to Jobs. Retrieved October 10, 2016, from http://fragile-success.rpa.org/maps/jobs.html.

Sacharidis, D., & P. Bouros (2013). Routing Directions: Keeping it Fast and Simple. *SIGSPATIAL ’13:Proceedings of the 21st ACM SIGSPATIAL International Conference on Advances in Geographic Information Systems*, 164–173. https://doi.org/10.1145/2525314.2525362.

Shaw, S.-L. (2006). What about “Time” in Transportation Geography? *Journal of Transport Geography*, *14*, 237–240. https://doi.org/10.1016/j.jtrangeo.2006.02.009.

Sheller, M., & J. Urry (2006). The new mobilities paradigm. *Environment and Planning A*, *38*, 207–226. https://doi.org/10.1068/a37268.

Simplefleet (2014). Simplefleet. Retrieved October 10, 2016, from http://maps.simplefleet.eu/map/berlin.

Soja, E. W. (1989). *Postmodern geographies: The reassertion of space in critical social theory*. London: Verso.

Specht, G., Gamper, J., & N. Krismer (2014). Incremental calculation of isochrones regarding duration. In *Proceedings of the 26th GI-Workshop on Foundations of Databases (Grundslagen von Daenbanken)* (pp. 41–45).

Steenbruggen, J., Tranos, E., & P. Nijkamp (2015). Data from mobile phone operators: A tool for smarter cities? *Telecommunications Policy*, *39*(3–4), 335–346. https://doi.org/10.1016/j.telpol.2014.04.001.

Tenkanen, H., Saarsalmi, P., Järv, O., Salonen, M., & T. Toivonen (2016). Health research needs more comprehensive accessibility measures: integrating time and transport modes from open data. *International Journal of Health Geographics*, *15*(1), 23. https://doi.org/10.1186/s12942-016-0052-x.

Ullah, R., & M. Kraak (2015). An alternative method to constructing time cartograms for the visual representation of scheduled movement data. *Journal of Maps*, *11*(4), 674–687. https://doi.org/10.1080/17445647.2014.935502.

Urbica (2016). Galton. Retrieved October 10, 2016, from http://galton.urbica.co/?&ll=4.893446,52.372732&zoom=13&city=amsterdam_netherlands&mode=foot&page=cities&lang=en.

Urbica Design (2016). Galton. Retrieved October 16, 2016, from http://galton.urbica.co/?&ll=37.63019,55.756389&zoom=13&city=moscow_russia&mode=foot&page=about&lang=en.

Vajakas, T., Vajakas, J., & R. Lillemets (2015). Trajectory reconstruction from mobile positioning data using cell-to-cell travel time information. *International Journal of Geographical Information Science*, *29*(11), 1941–1954. https://doi.org/10.1080/13658816.2015.1049540.

Visscher, Q. (2015, February 18). Zwolle loopt uit voor gedroomde Ikea. *De Trouw*, p. 1.

Waag Society (2015). Buildings. Retrieved from http://code.waag.org/buildings/#52.4158,4.9452,11.

Waag Society (2014). Naar school in Amsterdam. Retrieved October 10, 2016, from http://code.waag.org/scholen/.

Wang, L., Liu, Y., Liu, Y., Sun, C., & Q. Huang (2016). Use of isochrone maps to assess the impact of high-speed rail network development on journey times: a case study of Nanjing city, Jiangsu province, China. *Journal of Maps*, 1–6. https://doi.org/10.1080/17445647.2016.1195296.

Weather Map (2014). Cherry Blossom Forecast Map. Retrieved November 10, 2016, from https://tokyocycling.files.wordpress.com/2014/03/sakura_front_600x450_2014.png.

Wehrmeyer, S. (n.d.). Mapnificent. Retrieved October 9, 2016, from http://www.mapnificent.net/berlin/.

Zeng, W., Fu, C. W., Arisona, S. M., Erath, A., & H. Qu (2014). Visualizing mobility of public transportation system. *IEEE Transactions on Visualization and Computer Graphics*, *20*(12), 1833–1842. https://doi.org/10.1109/TVCG.2014.2346893.

Zhang, Q., Slingsby, A., Dykes, J., Wood, J., Kraak, M.-J., Blok, C. a., & R. Ahas (2014). Visual analysis design to support research into movement and use of space in Tallinn: A case study. *Information Visualization*, *13*(3), 213–231. https://doi.org/10.1177/1473871613480062.

Zook, M., Kraak, M., & R. Ahas (2015). Geographies of mobility: applications of location-based data. *International Journal of Geographical Information Science*, *29*(11), 1935–1940. https://doi.org/10.1080/13658816.2015.1061667.