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Development of a methodology for mobility and accessibility location assessment

Sven Masy

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Prof. Philippe Bouillard

The co-supervision of
Ir. Vincent Gérin

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PREFACE

This document presents the results of the research performed for my master’s thesis in order to receive the master's degree in Civil Engineering at Brussels Faculty of Engineering, the joint program of the VUB Faculty of Engineering Sciences and the ULB Brussels School of Engineering.

I want to thank my supervisors Prof. Philippe Bouillard and Ir. Vincent Gérin for their interest in the proposed subject and for their guidance, as well as all other people who helped me in any way during the process of writing this master’s thesis.

I hope that the research conducted and the developed methodology for location assessment on mobility and accessibility will inspire others in their work, so that they can adopt a similar approach to tackle their own challenges.

Sven Masy

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Sven Masy

Vrije Universiteit Brussel
Pleinlaan 2, 1050 Elsene

Master of Science in Civil Engineering

Brussels Faculty of Engineering

sven.masy@vub.be

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ABSTRACT

The purpose of this study was to develop a quantitative methodology to evaluate locations on mobility and accessibility in the context of the selection of an office building for a company. The geographical scope of the research was the Brussels-Capital Region.

The study involved the development of quantitative, travel time based accessibility and mobility performance indicators that can be evaluated in an automated way. Secondary data on commuting movements to Brussels, obtained from the Belgian federal government, was used to develop the performance indicators for accessibility by public transport and by car. These performance indicators were used in a multi-objective optimisation. The NSGA-II algorithm was used to search for the optimal office building locations in the Brussels-Capital Region, based on accessibility by public transport and by car.

Another part of the research was to look at the possibility to compose an accessibility map for the Brussels-Capital Region. The demand for an accessibility map was formulated in the Brussels-Capital Region's IRIS 2 mobility plan. The maps that were created based on the developed travel time based accessibility indicators provide an answer to this demand.

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1 INTRODUCTION

1.1 PROBLEM STATEMENT

From the perspective of an individual in search for a job, the location of employment, especially the commuting travel time, is an important criterion to consider and might in some cases be a deal maker or breaker in the decision process. On top of this, companies are facing the problem that they often invest a lot of time and other recourses in the processes of recruitment, selection and training of their employees, only to see these employees leave the company when they find another job closer to their place of residence. Job satisfaction and long-term job commitment are in this sense related to commuting travel time. [1]

For a firm, the accessibility of its location by public transportation, car, bike or on foot is thus important to take into consideration when selecting the building to establish its business in. For an office building, a high accessibility to employees will usually be related to high accessibility to clients and other partners visiting the company. In a retail or industrial context, a location that is more accessible for employees, will also be more accessible for suppliers, service providers and customers. An accessible location will thus certainly benefit the company, decreasing costs or increasing revenue within multiple departments.

Moving to a more accessible location will generally result in shorter commuting travel times, but a company or organisation moving from a location with high accessibility by car to a location with high accessibility by public transport might also accomplish a modal shift in its employees' commuting journeys. The choice by a firm for an accessible location may thus reduce internal costs as well as environmental and economical externalities.
It's important to realise that pedestrians and cyclists are generally found to enjoy their way of commuting, but public transport and car users generally don't. Long distance commuters by public transport or car are also found to experience problems related to health and quality of daily life, reporting more symptoms such as stiffness in muscles and joints, lower back pain, tiredness, but also anger and nervousness. [1] Reducing the travel time of employees may therefore reduce stress and other health issues as well.

This thesis addresses the subject of mobility and accessibility based business location evaluation. In the process of choosing the right office building for a company, the accessibility of a location is an important criterion. Accessibility is usually studied qualitatively. The issue with qualitative location evaluation is that several locations will have their own strengths and weaknesses. A certain office building might be located next to a bus stop serving multiple lines, while another building might be located at 300 meters from a major metro station. It's difficult to decide which qualitative features have the biggest impact on a location's attractiveness. A well composed quantitative performance measure for accessibility is needed to address this issue. Comparing locations that exhibit different qualitative strengths that could lead to a high accessibility, would be a good application of such a measure. There are many situations where one alternative clearly outperforms another alternative in terms of accessibility, based on qualitative observations. In these situations, expressing the magnitude of the difference in accessibility can still be required for a multi-criteria evaluation, because other criteria, like financial costs or the quality of the accommodation of a building, might be in favour of the least accessible alternative.

The benefits of a highly accessible location can be large, but an evaluation of accessibility location criteria can't always be performed accurately based only on intuition. Tools that support such an evaluation are certainly useful. Many different mobility and accessibility indicators can be constructed, but the data to compute their numeric values is not always available. Choosing meaningful and effective indicators that can be evaluated in an effective and efficient way themselves may be the most critical part of the process.

1.2 Research relevance

One of the aims of this study is to show the potential of quantitative, travel time based studies in a multidisciplinary and multipurpose context. The objective is to stimulate an increase in travel time based studies in both the private and the public sector.

The research is targeted at developing meaningful and powerful quantitative performance measures for a location's mobility and accessibility. This allows to evaluate a location accurately and in an unprejudiced manner. A performance indicator based on travel times should be highly valued, as travel time is more all-embracing than other mobility or accessibility indicator components. It automatically integrates other parameters that are difficult to study individually. The choice of the parameters considered in a study can significantly affect the results, which unfortunately allows researchers to steer their research results in a certain predetermined direction. In contrast to for example composite accessibility indicators, travel time based evaluation procedures are easy to understand. This contributes to their open and transparent characteristics, which are desirable in many situations.

Travel time based performance indicators enable researchers to avoid detailed and exhaustive individual parameter studies on for example daily traffic delay and infrastructure density, because the effect of these parameters is already included in the computation of the travel times.

The project started off as a project in which decision support systems would be studied in detail, in order to select the system best suitable for office building evaluation. When studying different decision support systems, the observation was made that there was still potential for improvement in the process of evaluating the different (sub)criteria that are usually considered in multi-criteria evaluations. Developing accurate indicators for the performance of the alternatives on every criterion is at least as important as the decision on how to aggregate the performances on individual criteria to a global score and final ranking of the alternatives. The objective of the study evolved towards an in depth quantitative study of the accessibility and mobility related location criteria. This research topic has a high academic-scientific relevance as well as a practical and economic relevance. The developed methodology and its results could serve policy makers. Developing a performance indicator that can be used to take strategic decisions concerning the selection of the best office building for a company is not only relevant in a scientific or business-economic context. The developed indicator could also influence future government policy or spatial planning processes.

The study is performed in an academic context and aims to illustrate the potential of the developed methodology, provide the link with scientific literature and apply the methodology to real-life cases. The purpose is not to develop a commercial tools or service that could be used for similar evaluations.

1.3 Research questions

One central, but very broad research question was formulated: How to use accurate travel time estimations to evaluate the location criteria mobility and accessibility quantitatively? The context in which this research will be conducted, is the evaluation of office building locations. The initial scope will be the Brussels-Capital Region.

Sub-questions:

- How can technology facilitate the evaluation procedure? Can the process of evaluating the developed performance indicators be automated?
- How can a multi-objective optimisation algorithm help to identify the optimal locations for an office building, based on the developed performance indicators? Can the usefulness of the implemented optimisation algorithm be demonstrated based on a practical case study? Are the results satisfying?

Another important part of the research is to look at the possibility to compose an accessibility map for the Brussels-Capital Region. The demand for an accessibility map has been formulated in the IRIS 2 mobility plan. [2] Such a map can serve as a basis for strategic decisions in both the private and the public sector. The IRIS 2 mobility plan shows a strong focus on studying accessibility by public transport, but accessibility by car will be studied as well, since the driving travel mode is still prominently represented in the modal split of commuting displacements towards Brussels.

1.4 STRUCTURE

This document consists of several chapters. A literature study provides the background for the research. The adopted methodology is presented in chapter 3, which introduces how the conceptualised travel time based accessibility and mobility indicators can be evaluated using a web scraping approach. Chapter 4 focusses on presenting different performance indicators and the obtained results, through a case study approach. At the end of this chapter, the developed indicators are used to identify the optimal locations for an office building in the Brussels-Capital Region, based on accessibility by public transport and accessibility by car. Chapter 5 presents the conclusion of this master’s thesis.

2 LITERATURE

This literature review contains a part about accessibility and mobility and a part related to mobility in the Brussels-Capital Region and commuting to Brussels. A third part has been included to introduce the multi-criteria optimisation technique used in this master's thesis.

2.1 ACCESSIBILITY AND MOBILITY

2.1.1 Definitions

In the academic and scientific literature, several definitions for the concepts of mobility and accessibility have been used. The report 'COST Action TU1002 – Assessing Usability of Accessibility Instruments' by the COST program, an intergovernmental framework for European Cooperation and Technology, contains an overview of the evolution of accessibility definitions, as used by different researchers in academic and scientific literature: [3]

- *"the opportunity which an individual or type of person at given location possesses to take part in a particular activity or set of activities"* (Hansen 1959);
- *"the average opportunity which the residents of the area possess to take part in a particular activity or set of activities"* (Wachs and Kumagai 1973);
- *"the accessibility of a point in a system is a function of its location in space with respect to all other points in the system' and 'implies relative nearness either in the sense of a direct linkage or a minimum expenditure of travel cost or time"* (Hack 1976; de Lannoy 1978);
- *"the consumer surplus, or net benefit, that people achieve from using the transport and land use system"* (Leonardi 1978);
- *"the ease and convenience of access to spatially distributed opportunities with a choice of travel"* (Xiaojing et al. 2006);
- *"the extent to which the land use-transport system enables (groups of) individuals or goods to reach activities or destinations by means of a (combination of) transport mode(s)"* (Geurs and Van Eck 2001);
- *"the number and diversity of places that can be reached within a given travel time and/or cost"* (Bertolini, LeClercq and Kapoen 2005);
- *"the ease in meeting one's needs in locations distributed over space for a subject located in a given area"* (Cascetta, Cartenì and Montanino 2013). [3]

2.1.2 Accessibility and mobility

One of the first definitions of accessibility, broadly used in the planning field, was suggested by Walter G. Hansen. [4] [5]

Hansen defined mobility as a measure for the ability to move from one place to another, while accessibility measures the ease of reaching destinations or activities rather than focussing on the ease of traveling. A place with a high mobility does not necessarily have high accessibility and vice versa. [4] The difference between the mobility and accessibility concept is of great importance in past and future research. The idea of pursuing high mobility starts from the assumption that a decrease in travel distance or travel time in the investigated zone (as can be realised by infrastructure works or other policy measures) would be beneficial to the individuals traveling through this zone. One should however try to go the extra mile to evaluate to what extend valued destinations can be reached more easily as a result of the accomplished increase in mobility.

The idea that high accessibility is what should be pursued rather than high mobility does not wipe out the usefulness of a mobility study. A well-constructed mobility measure can have its advantages. An advantage that could be thought of straight away is the difference in complexity and data requirements, which could result in favouring a mobility measure above accessibility measures that can't be evaluated because of insufficient or incomplete data.

The term mobility is also used in a spatial context to study the extent to which people, living in certain areas, (can) move around. In this context, mobility does not only incorporate transportation related components. It can for example be highly influenced by (spatial) parameters driven by individuals or certain groups of people, like wages, as different earnings can result in inequality in access to mobility or mobility poverty.

When mobility is studied as the number of kilometres travelled by people living in a certain area, high mobility is not always a good sign. Although high mobility shows that people have access to transportation, a high number of kilometres travelled also indicates that individuals live far from their valued destinations. It is thus not always a good idea to pursue a high mobility. The definition of a mobility measure, the underlying meaning and their consequences should be chosen wisely and considered in each phase of the study.

In summary, the term mobility is usually used for studying the performance of transportation systems. It can be used for every mode of transport, both individual and public, including walking, bicycling, transit, automobile and intermodal modes of transport. The term accessibility is used to express the ease of reaching valued destinations. The mobility concept studies efficient movement between origin and destination. It assumes that movement is an end by itself, while accessibility looks at the benefits or gains that can be obtained through transportation. Transportation is studied as a means of reaching a destination. [6]

The definition used in this research was adopted from the book "The Geography of Transport Systems" and is the following:

"Accessibility is defined as the measure of the capacity of a location to be reached by, or to reach different locations." [7]

2.1.3 Possible mobility indicators

Since all sort of mobility indicators have been used throughout the years, listing all of them would be a lengthy, but pointless process. Instead, only the mobility indicators that are most relevant to location mobility evaluation are listed below:

- *Average travel distance* (relative to the geographical distance);
- *Average travel time* (per kilometre);
- *Average vehicle minutes of delay*;
- *Travel Rate Index (TRI)* or *Travel Time Index (TTI)*, which indicates how much time is added to a trip during peak conditions compared to free-flow conditions in a relative way. The definition adopted in this document will be the ratio of time needed to reach a destination in respectively congested and uncongested conditions. The term *Travel Time Index* seems to be more common in literature than *Travel Rate Index*, which is why this is the term that will be adopted in this document;
- *User travel cost*. [8]

It's possible to evaluate these mobility indicators for different modes of transport. The selection of an indicator expressed as distance, time or cost depends on the available data and on the application.

From the perspective of an employee, total travel cost is not always a relevant indicator, since travel cost reimbursements might be provided by the employer. The reimbursements provided by the employer might even differ for different modes of travel. For example, in Belgium, it's usual for the public sector not to provide compensation for the cost of traveling to work to employees commuting by car. Compensations are only provided to employees using public transport or bike to get to work. Public transport is in that case effectively free of charge for the employee, either payed by the employer or fully reimbursed, while the reimbursement for commuting by bike are in most cases set to the maximum tax exempt amount. [9]

2.1.4 Components of accessibility

An overview of the accessibility components that can be integrated in an accessibility measure (concept introduced section 2.1.6) was adopted from the 'COST Action TU1002 – Assessing Usability of Accessibility Instruments' report. [3] In 2001, Geurs and Van Eck stated that accessibility consists of the following 4 components: [10]

- *A transportation component*. This component reflects the transport system, expressed as the disutility for a person to cover the distance between an origin and a destination using a transport mode. This component can be studies qualitatively. It can also be quantified in units of distance or time, or even as a cost, quantified in any currency;
- *A land use component*. It reflects the land use system, which consists of the amount, quality and spatial distribution of identifiable opportunities found at each destination. These may be jobs, homes, recreational facilities, …;
- *A temporal component*. This component reflects the availability of opportunities at different times of the day. It can also reflect the time available for individuals to participate in certain activities at different times of the day;
- *An individual component*. The personal needs, abilities (depending on physical conditions, availability of travel modes etc.) and opportunities (depending on income, travel budget, educational level, etc.);

These 4 components need to be kept in mind when constructing accessibility measures. A measure that does not cover all 4 components is not necessarily inadequate. Based on the context of the measure and the availability of context specific data, one can choose whether or not to evaluate a certain component. It is however always useful to specify on the one hand how and to what extent a constructed accessibility measure incorporates the 4 components, and on the other hand which of the components is represented and which are not or only incorporated indirectly.

2.1.5 Evaluating accessibility

Accessibility modelling is not straightforward. Measures suitable for the case or question must be constructed and need to be evaluated within the context of the project, in terms of budget and access to the required data.

The approaches to study accessibility problems can be divided in two different spatial categories:

- *Topological accessibility* studies accessibility in a transportation network, a system composed of nodes, interlinked by paths. It allows to study and measure accessibility only on specific elements of the constructed transportation system. Accessibility can't be measured for points that are not part of the transportation system. Its measures are only suitable for location evaluation in contexts similar to the one of office building evaluation when the network is constructed on a very detailed level, since one needs to be able to evaluate a constructed measure for every possible site location.

- *Contiguous accessibility* allows to study accessibility for any point on the spatial surface. The accessibility measures are function of the spatial structure. A value can be computed for every possible geographical location. Contiguous accessibility indicators are generally less valuable than topological indicators, since the parameters they are composed of are usually more indirectly related to the accessibility perceived by people. The reason to choose for contiguous measures is because constructing a detailed and accurate transportation network is costly. Contiguous measures show the same weakness as topological ones in the sense that the indicators lose their representativeness for reality when the spatial model is not detailed enough, incomplete or outdated. [7]

2.1.6 Accessibility measures

Since accessibility is a concept that has been used in different contexts over time, different accessibility measures have been constructed by different researchers, each of them addressing its own practical application. Measures can be divided into different families, which is done below.

2.1.6.1 Cumulative Opportunity Measure

A Cumulative Opportunity Measure approach counts the number of potential opportunities that can be reached within a predetermined distance, travel time (isochronic measure) or generalised cost. [4] The measure or indicator fits the following expression:

$$A_i = \sum_j B_j \, a_j$$

A_i	Accessibility measured at point i to potential activity in zone j
a_i	Opportunities in zone j
B_j	Binary value, 1 if zone j is within the predetermined threshold and 0 if it's not [4]

This measure has its use for identifying the number of opportunities within a certain distance or travel time from the investigated point i. However, it doesn't consider the actual distance or time travelled to reach the destination or the quality of the reached opportunities. These are issues which are addressed by gravity-based measures (see section 2.1.6.2). [4] A practical example one could think of to illustrate the cumulative opportunity measure family is measuring the number of bus stations within a kilometre of someone's home (point i), without accounting for bus service frequency (quality of the reached opportunities) and the walking distance to the bus stop.

2.1.6.2 Gravity-Based Measure

Gravity-based measures are widely used for assessing accessibility. This family of measures is more complex than the cumulative opportunity measures discussed in section 2.1.6.1 because the measures do take the quality of the reached opportunity and the cost of travel into account. A good general formulation for gravity-based measures is expressed below:

$$A_{im} = \sum_j O_j \, f(C_{ijm})$$

A_{im}	Accessibility measured at point i to potential activity at point j, using mode m
O_j	Opportunities at point j
$f(C_{ijm})$	The impedance or cost function to travel between points i and j, using mode m [4]

The impedance or cost function and the opportunity measure should be composed keeping the desired accessibility indicator's use in mind. In order to construct an accessibility indicator that increases in value for places with better accessibility, high values for O_j should represent highly valued opportunities and the impedance or cost function should decrease for increasing costs. If the cost itself C_{ijm} is expressed in currency, taking positive values, a negative exponential cost function $f(C_{ijm}) = A\, e^{-B\, C_{ijm}}$ could for example be used. When using a cost power function $f(C_{ijm}) = A\, (C_{ijm})^k$, k should take negative values only since the cost function needs to decrease with C_{ijm}.

This kind of measures can for example be used to study the accessibility to primary education at different points i, where the contribution to A_{im} of a primary school decreases with the cost related to traveling from point i to this school. When a new school opens in a neighbourhood, A_{im} will increase.

Constructing an accessibility measure that is minimised for highly accessible places is more complex. Cases similar to the one described directly above can make use of an inversion of the accessibility measure described above, but other cases require a different approach. This is certainly applicable to cases concerning accessibility with a focus on access to a predefined number of opportunities. This will be illustrated through the following example:

A self-employed gardener has been maintaining the gardens of 5 different mansions for a long time. The gardener uses his own equipment, machinery and other tools, which he stores in the van he drives from home to the different work places every day. Due to expiring of the gardener's current rental contract, which couldn't be extended, the gardener must move to a new home. He decides to make the choice of his new home based on the distance to the 5 mansions he travels to on a regular basis. Since the gardener needs to travel to every mansion 4 times a month and back to home, the accessibility measure the gardener uses, will be based on distance to these valued destinations, which he wants to minimise:

$$A_{im} = \sum_j O_j\, f(C_{ijm}) \qquad \rightarrow \qquad A_{i,driving} = 8 \sum_{j=1}^{5} D_{ij,driving}$$

$A_{im} = A_{i,driving}$	Accessibility, measured for house i, to work at locations j, traveling by car
$O_j = 8$	The number of times every mansion must be travelled to or from
$f(C_{ijm}) = D_{ij,driving}$	Travel distance by car between house i and work place j

A lower value of $A_{i,driving}$ indicates better accessibility to the work places of the gardener. This type of indicator can be constructed because the displacements that need to be made are predefined.

More generally formulated: to construct an accessibility measure that is minimised for highly accessible places, once again, high values for O_j should represent highly valued opportunities, but the cost function $f(C_{ijm})$ should increase with the cost C_{ijm}. A regular (positive) exponential function $f(C_{ijm}) = A\, e^{B\, C_{ijm}}$ or a positive power function $f(C_{ijm}) = A\, (C_{ijm})^n$, where n takes only positive values could be considered.

The difficulty in constructing gravity-based measures lies in the need to develop appropriate and meaningful impedance functions $f(C_{ijm})$ and opportunity measures O_j that can be evaluated within the scope or budget of the study.

Another difficulty lies in combining multiple transportation modes. The literature proposes some composite accessibility measures that can be used to combine modes of transport [4], but most of these composite indicators don't combine opportunity and impedance data in a way that fits the needs of this research. The accessibility by transit indicators used in this thesis don't need to overcome the difficulty of combining modes by using composite measures, because the issue of combining modes is addressed in the computation of C_{ijm}.

2.1.6.3 Constraint-based measures

The scientific literature also describes constraint-based accessibility measures or people-based measures, by stating that the amount of time available or the cost that can be spent by individuals to reach specific places or activities might be limited. This could lead to adding a cost constrained to certain gravity-based measures. [4]

2.2 BRUSSELS' MOBILITY

2.2.1 Brussels' mobility policy

The IRIS 2 mobility plan is a strategic document that indicates the direction in which the Brussels-Capital Region's transport policy should evolve by 2015-2020. The plan's publication dates from 2011. It contains some interesting information regarding the investigated topic and confirms its relevance in the eye of the policy-makers. [2] [11]

The document confirms that a location's mobility and accessibility are crucial to its economic vitality. It states that mobility and accessibility have a direct impact on both the social and economic activity of a location. The vitality of the Brussels-Capital Region is determined by the effectiveness of the displacement opportunities of both its inhabitants and visitors. Everyone should be able to move between different parts of the city using the most efficient or most sustainable mode of transport. The attractiveness of a specific location to companies and the international attractiveness of the Region is stimulated by the development of an efficient and sustainable transportation offer.

The report also addresses past mistakes in the planning policy. Already in IRIS 1, which was established in 1998, the need for a planning policy based on accessibility of workplaces and the mobility of companies' employees was emphasised. The document states that the former planning policy failed to achieve a compaction of the areas where public transport was well established. The policy also failed to encourage locating offices in these areas, especially inside the pentagon.

With the IRIS 2 mobility plan, the Region will take accessibility into account in the selection of the zones that need to be developed and their prioritisation, with a focus on accessibility by public transport.

The report also states that an accessibility map for the Capital Region should be generated in the near future. The purpose of this map would be, on the one hand, to be able to evaluate the locations of new projects on accessibility and, on the other hand, to be used in the planning of future infrastructure investments. The article "How to get there? A critical assessment of accessibility objectives and indicators in metropolitan transportation plans" already mentioned that – at the time the article was finalised, October 2016 – "no such map was found". [12]

The Region also invests in improving accessibility from external locations. The improvement of the accessibility of the Region from the Brussels Periphery and from the rest of the country is mentioned explicitly as objective in the plan. [2]

2.2.2 Commuting to Brussels: secondary data

Since the use of secondary data on employment is necessary for the travel time data aggregation process, multiple government authorities were contacted and asked for data from their statistical research, situated in employment and mobility.

Certainly if one wants to develop a representative travel time based indicator for accessibility of possible places of employment, a critical stage in this development will be the definition of a correct measure and the detail of the secondary data source used to aggregate individual travel times.

To aggregate individual commuting travel times, statistical data on employment and commuting is needed. The following sources were considered:

2.2.2.1 The Labour Force Survey (LFS)

The Labour Force Survey (LFS)[1] is a socio-economic sample survey conducted on households by Statistics Belgium[2]. Its main objective is to divide the population at working age in 3 different groups or categories: the working population, the unemployed and inactive population. Afterwards, descriptive and explanatory data is provided for each of these groups or categories. This survey is also conducted in other EU Member States. It is coordinated by the Statistical Office of the European Union, Eurostat. This way, information on (un)employment, employment opportunities and other Labour statistics are gathered in every EU Member State according to the definitions or labour standards of the International Labour Organisation (ILO) and can thus be compared over different EU Member States. Some of the information provided by the Labour Force Survey can't be obtained elsewhere, like formation about labour mobility, motivation for part-time work, the various forms of temporary employment and the education level of the (in)active population. [13]

The Labour Force Survey uses demographic data from the National Register and information gathered by face-to-face interviews, telephone and internet surveys. The survey is performed on a 3-month basis.

In the published data [14], a single table stands out for its usefulness in the aggregation process of individual commuting travel times. The table is titled 'Province and region of the workplace, gender, age and residence'[3]. Both the workplace and place of residence aggregation are performed on national, regional and provincial level, but not on a municipal level. This source can be used to aggregate travel times. The result will be a good indication of reality, but not as representative as when municipal or individual data would be used. However, this will be less data intensive. As a direct result of the lower data requirements, the computation time will be lower.

2.2.2.2 Census 2011

The census is a snapshot of the Belgian population, in this case taken on January 1st 2011. Like the Labour Force Survey discussed in section 2.2.2.1, the government institution responsible is Statistics Belgium. The population consists of all residents living on Belgian territory, registered in the National Registry, regardless of their nationality. Asylum seekers, registered in the waiting register, also belong to this population. The way this population is defined, is in accordance with the standards set by

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[1] - Dutch: Enquête naar de arbeidskrachten (EAK)
- French: Enquête sur les forces de travail (EFT)

The most recent survey data was studied, which contains data from 2016 (publication dated 13 March 2017)

[2] - Dutch: De Algemene Directie Statistiek – Statistics Belgium van de FOD Economie, K.M.O., Middenstand en Energie
- French: La Direction générale Statistique – Statistics Belgium du SPF Economie, P.M.E., Classes moyennes et Energie.

[3] Table T2.007 Provincie en gewest van de werkplaats, geslacht, leeftijd en woonplaats in the Dutch publication or T2.007 Province et région du lieu de travail, sexe, âge, région de residence in the French publication

Eurostat. This allows a comparison between different EU Member States. The Census provides a wide range of demographic, socio-economic, educational and housing data. [15]

Among the available data on mobility there are tables titled “Working population by gender, residence and place of work”, “Employees by gender, place of residence or place of employment”, “Independents or self-employed population by gender”, “Place of residence or place of work” and “Working population by place of work, gender and highest degree (at a detailed level)” [4]. [16] Office building location evaluation could best be performed using the data on employees by place of residence and place of employment.

Both workplaces and places of residence are aggregated on a national, regional, provincial and municipal level. The information is thus more detailed than the available information of the Labour Force Survey.

2.2.2.3 Diagnostics of workers’ commuting movements

The Dutch name of this survey is “Diagnostiek woon-werkverkeer”. The French name is “Diagnostic des déplacements des travailleurs entre leur domicile et leur lieu de travail”. This can be translated to English as “Diagnostics of workers’ movements between their homes and workplaces” or “Diagnostics of workers’ commuting movements”.

This survey gathers information from bigger companies. Participation is mandatory for companies that employ more than 100 employees. The survey’s questionnaire must be filled in for every site occupied by these companies where at least an average of 30 people works. The survey is conducted on a 3-year basis by the Federal Public Service Mobility and Transport. Within its scope, this diagnostic might well be the most complete regarding mobility of workers in Belgium. This makes it a valuable source of information for researchers, policy makers, the companies and employees themselves and for any other party interested in the issue of mobility.

Every employer has access to a customised report on his company’s occupied sites, which contains historical mobility data and suggests possible measures to be taken internally. Global reports are available to the public. [17]

The most recent survey report dates from 2016, using data from 2014. It contains amongst others quantitative data on the modal split for commuting traffic to Brussels, Flanders, Wallonia and the whole country. [18] The data tables published on the official website contain the modal split of commuting movements for employers in different sectors, the modal split for employers based in different municipalities and the modal split per region.

A table that is not published on the website, but could be retrieved on demand, contains a full commuting origin-destination matrix on municipal level, detailed up to the last digit of the postal code, complete with modal split for every origin-destination combination.

2.2.2.4 Company mobility plans of the Brussels-Capital Region

This last secondary source is under supervision of Brussels Environment[5] and supported by Brussels Mobility, the administration of the Brussels-Capital Region responsible for facilities, infrastructure and transport. Any company with more than 100 employees at a single site in the Brussels-Capital Region

[4] These tables are the tables numbered 00.24, 00.24A, 00.24B and 00.24C in [16]

[5] - Dutch: Leefmilieu Brussel
- French: Bruxelles Environnement

is legally obliged to develop a 3-year company mobility plan[6], which must contain some specific mandatory measures to reduce the company's environmental impact and to reduce traffic and congestions in the Region. Measures that facilitate the transition from individual motorised transportation to more sustainable alternatives are highly valued. [19]

A mobility plan consists of two parts:

- An evaluation of the existing mobility;
- An action plan to improve the existing situation.

A full report on the 2014 mobility plans was issued in December 2016. Amongst a lot of other information, it contains data on employees' places of residence and commuting traffic modal split for different activity sectors. [20]

2.3 Multi-criteria optimisation

Since a multi-criteria or multi-objective optimisation will be performed in this study, a short discussion about the optimisation algorithm used, is presented here. A detailed overview of all the families of multi-objective optimisation algorithms will not be included here, although it's certainly interesting for future research to look into alternatives for the method presented here and a way to integrate them in a possible tool.

There are a lot of different multi-objective optimisation methods, all with their own strengths and weaknesses. The methods can generally be divided into 3 classes:

- *A priori methods*, which use preliminary ranking of the objectives (examples: weighted sum, outranking methods, …);
- *A posteriori methods*, which search for the Pareto optimal solutions or the Pareto front;
- *Progressive or interactive methods*, which are methods involving interaction with the decision maker during the optimisation procedure.

A posteriori methods are best suitable for the optimisation that needs to be performed in this research. The reason is that these methods are designed to produce all of the Pareto optimal solutions or at least a number of solutions large enough to have a set that represents the Pareto optimal solutions quite accurately. The decision to select one of these Pareto optimal solutions can be made after the whole set has been identified, based on personal preference or additional criteria. Hence the name 'a posteriori methods'.

2 types of a posteriori methods exist: mathematical programming-based and evolutionary algorithms.

Mathematical programming methods try to find an optimal solution within the design constraints by evaluating different mathematical functions for different input values, while evolutionary algorithms work in a different way: they are developed to try to make an initial population evolve from one generation to the next, mimicking the natural processes of genetic evolution, improving the quality of the population for every generation. The algorithms can for example make use of natural survival-of-the-fittest principles, genetic recombination and mutation.

[6] - Dutch: Bedrijfsvervoerplan (BVP)
- French: Plan de déplacements entreprise (PDE)

The evolutionary algorithm “Non-dominated Sorting Genetic Algorithm II” or “NSGA-II” was selected to be used in this study, because of it wide deployability and because the author of this document had prior experience with this method.

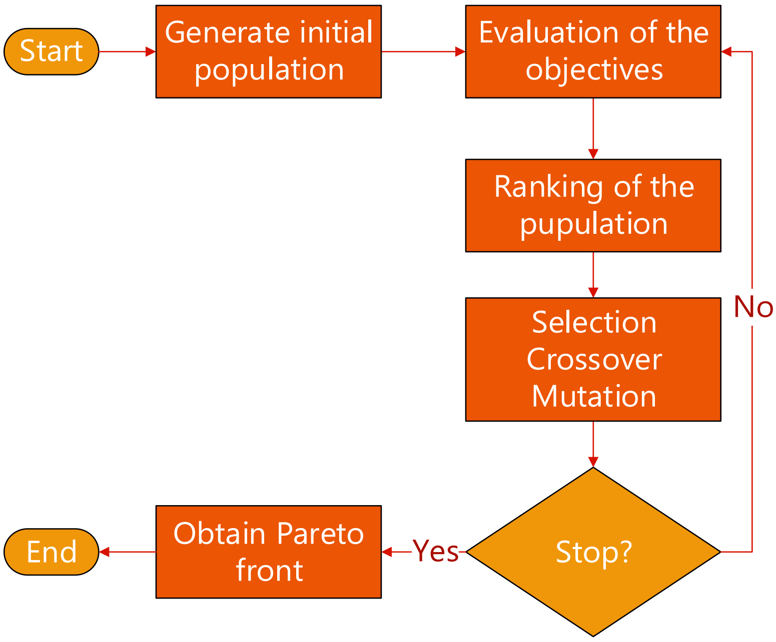

Figure 2-1 NSGA-II procedure: basic flowchart

To define a problem, first the design variables need to be defined. From these variables, a population can be constructed. Next, multiple objectives are defined. The solution scheme of this evolutionary algorithm is as follows: an initial population is constructed within the design space based on the design variables and their constraints. These individual points will be able to reproduce, generating ‘offspring’. By combining the characteristics of the individuals, the new generation can be found through a process of selection, recombination and mutation. For the initial population, the objective functions are evaluated on the considered objectives and the best individuals within the population are used to generate a new offspring. These offspring form the new generation, on which the process is repeated. The algorithm can use processes similar to DNA crossover and mutation. It’s also possible to introduce constraints on the solutions. The very basic flowchart in Figure 2-1 above illustrates the procedure. The stop criterion is usually chosen based on a predefined number of generations, but manual stop decisions or other convergence criteria can be used as well. [21] [22]

2.4 LITERATURE CONCLUSION

All three parts of this literature study are essential for the conducted research. The first two parts of this literature study will be used further on in the text to develop accessibility and mobility performance measures, providing an answer to the central research question. The third part the literature study will be useful when identifying the optimal locations for an office building in Brussels, based on the developed performance measures.

3 METHODOLOGY

3.1 MOTIVATION

Multi-criteria selection techniques often involve a transformation of the results of the evaluation of the gives set of alternatives on different criteria. For example: the ELECTRE[7] family of outranking multi-criteria decision analysis methods uses indexing functions to scale the evaluation data for each alternative on each criterion to a value from 0 to 10, after which a set of thresholds (preference threshold, indifference threshold and veto threshold) is used to transform the data once again. Another outranking method family, PROMETHEE[8] allows using even more complex preference functions. [23] [24] [25]

The multi-criteria analysis is often performed by another person than the one in charge of the evaluation of the alternatives of the different criteria. In an ideal situation, the evaluation data would have a linear relation to the actual cost or gain perceived by the concerned party, so that the person performing the multi-criteria evaluation understands what the data actually represents. It is for example difficult to work with a financial cost that is not expressed in absolute currency or relative return, because the financial data has been transformed already or because the financial criterion has only been studied indirectly. The choice of the indexing function and preference thresholds or functions is not straightforward.

In case the multi-criteria analysis procedure is provided with data that is already scaled and is thus not linear with the actual cost or gain, there is a chance that this data is even further distorted during the process, resulting in a situation where the relationship to the actual cost or benefit is not understood by any of the parties involved in the evaluation process. Using the right measures to assess the performance of the alternatives on the individual criteria is thus of paramount importance for providing proper input data for the evaluation procedure. Otherwise, the sensitivity to certain parameter changes may unexpectedly differ greatly from the desired pattern.

For the example of financial criteria, it is very straightforward to express the evaluation results in a proper way, suitable for any multi-criteria evaluation procedure. Depending on the background, education, experience and capabilities of the people performing the evaluation of the project as well as the available recourses, the selected or constructed measure can easily represent the projected total annual or monthly cost or income, the monetary (net) present value of the project or any other widely established financial indicator.

For other criteria, defining a proper measure and performing the evaluation of the alternatives is often more difficult. Therefore, the aim is to construct a measure for the (sub) criterion accessibility from employees' places of residence in context of the evaluation of an office building on different criteria. The indicator, serving as input for the multi-criteria analysis, should exhibit the valued quality of a linear relation to the actual or perceived cost or benefit as well as the quality of being easy to evaluate.

Many existing measures, like composite mobility or accessibility indicators, are useful in other contexts, but lack these qualities. Evaluating these measures for multiple locations is a work intensive

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[7] - English: ELimination and Choice Expressing Reality
- French: ELimination Et Choix Traduisant la REalité

[8] English: Preference Ranking Organisation METHod for Enrichment Evaluations

and costly process, while the measures are only indirectly related to the actual cost or benefit, which makes them less suitable for the intended use of office building evaluation.

3.2 Methodology development

This section introduces the process of the development of the methodology that provides an answer to the central research question. The developed methodology will be adjusted to meet the requirements of certain case studies in chapter 4.

The goal of this research project is to come up with an open-minded way to evaluate locations on multiple criteria. The criteria that are studied here all represent mobility and accessibility by car and public transportation. Mobility and accessibility will be quantified in the units of time. To achieve this quantification, the mobility and accessibility indicators will be constructed based on point-to-point travel times, which will be obtained using a web scraping approach.

The public transport network in Belgium uses 4 modes: train, tram, metro and bus, which are connected by stops serving multiple lines or even stops that are common for different modes. 4 companies provide public transport services in Belgium, 3 of which operate mainly in specific regions:

- NMBS/SNCB, the National Railway Company of Belgium;
- Brussels Intercommunal Transport Company MIVB/STIB, providing bus, tram and metro services in Brussels;
- Flemish transport company De Lijn, mainly provides bus services in Flanders, but also tram services at specific places and some services in other regions;
- Walloon Regional Transport Company – TEC, mainly providing bus services in Wallonia.

The time schedules of these companies are integrated in Google Maps' transit services.

To be able to perform a study based on travel times, one needs to be able to acquire travel time data. It's important to collect the data in the most sensible way. It would be regrettable not to make use of existing databases of the magnitude and quality of the one Google and other companies or organisations have accumulated over time. Since the acquisition of Waze (an important provider of mapping services) by Google in June 2013, the company has had the opportunity to integrate Waze's crowd-sourced traffic and mapping capabilities within its own services and vice versa, increasing the accuracy of its travel time estimations. [26] [27]

Throughout this study, different types of geospatial data have been calculated, most of them travel times and distances.

Data can be obtained using the Google Maps Distance Matrix API. Google's Distance Matrix service can compute travel distance and journey duration between an origin and destination point using a given mode of transport. A user can retrieve distance and travel time based on input parameters such as origin and destination, departure or arrival time, mode of transport, … [28] In Belgium, public transportation time tables are digitally available for the 4 exploited modes: train, tram, bus and metro. These are integrated in Google Maps.

A specific, well-considered departure or arrival time in the future will always be specified. To avoid any influence of live traffic, the exact date needs to be chosen far enough in the future. In Google Maps Distance Matrix API requests, time must be passed along as a Unix Time Stamp [9].

All car travel time data are acquired using the "best guess" traffic model, meaning that historical traffic conditions are used to give an estimate as close to reality as possible, instead of trying to provide a pessimistic or optimistic travel time estimate.

When using the transit travel mode, no routing preferences, route restrictions or travel mode preferences are included. The used public transport or transit model is an intermodal one. It permits using train, tram, bus, metro and walking as travel modes and transferring between these modes, without preference for one transit mode over the others.

Additional information on these Google Maps Distance Matrix API service parameters can be found in the Google Maps Distance Matrix API Developer's Guide. [29]

Throughout the study, different travel time based accessibility and mobility measures are defined, whereupon these measures are evaluated using Google Maps data. The relation between the measures and the literature discussed in chapter 2 is made by explaining how a defined measure relates to the generic gravity-based measure introduced in 2.1.6.2. The exact methodology for each case is described in detail in the subsections of chapter 4.

The advantage of the defined indicators is that they quantify the accessibility in units of time. Distance data was also collected, but a travel time based study was deemed more relevant as travel time is the parameter that influences a commuter's life directly, while distance is only felt indirectly. The travel time based indicator can be used to compare unimodal and intermodal public transport modes unprejudiced, as time spent walking, waiting for a transition or on public transport result in an equal loss in time for a commuter.

The performance indicators presented in this document can be used for location evaluation within a continuous search space, while in practice, in most cases only a discrete selection of possible locations is taken into consideration. The presented methodology is thus far more elaborate than the method which will mostly be used in a multi-criteria selection process. The ability to evaluate locations in a discrete as well as in a continuous search space allows to go beyond location selection in the domain of multi-criteria evaluation problems, towards a location optimisation procedure in the domain of multi-criteria or multi-objective design problems.

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[9] Unix Time is a way to describe time as the total number of seconds passed since the Unix Epoch, by convention fixed on January 1st, 1970 at 00:00:00 UTC (Coordinated Universal Time). [37] For example: this footnote has been written on 10 April 2017 at 05:53 p.m. in Belgium (CEST) or 03:53 p.m. (UTC). The corresponding Unix Timestamp is "1491839580".
CEST stands for Central European Summer Time and corresponds to UTC+2. It is the clock time during the summer daylight-saving in Belgium and other Central European countries. Central European Time (CET), the clock time in Belgium during winter corresponds to UTC+1. Due to this daylight-saving time issue, during this project, some data was generated using a wrong timestamp. After the bug was detected, these simulations were performed again using the right timestamp and the corresponding sections in this report were adjusted accordingly.

3.3 PRESENTING THE RESULTS

Throughout this document, the choice has been made consciously to use graphical data representations instead of data tables. The advantage is that graphical representations can give the reader a complete view on the presented data in a glance. They can be interpreted easily and by a broad audience. Geospatial data will in most cases be displayed on a map with a continuous colour heatmap overlay. These maps with a colour heatmap overlay, as well as the graphs included in this document, should be regarded as a way to display the obtained data. When a specific value needs to be looked up, this can be done in a small amount of time. Extracting an exact value from a continuous colour heatmap might however prove more difficult. Performing search operations in the data behind the graphical representation will lead to more accurate results.

3.4 STANDARDISATION OF THE DEVELOPED INDICATORS

Since the performance indicators used in this study have been constructed as (weighted) average travel times they have as important quality that their numeric value can be related to the physical world quite easily.

The values of the main mobility and accessibility measures are expressed in minutes. When a specific application would require the transformation of the numeric value of the evaluated measures to a value between 0 and 1, between 0 and 10 or any other pre-set boundaries, the indicators can be standardised by linear scaling to fit within the pre-set boundaries. For this purpose, in a large and static dataset, scaling can be performed based on the minimum and maximum value of the selected indicator throughout the dataset or by using cut-off values. In a small or dynamic dataset, standardisation using minimum and maximum values is not recommended.

A formula to transform an indicator X to a standardised indicator $X_{0\to1}$ can thus be:

$$x_{i,0\to1} = \frac{x_i - x_{min}}{x_{max} - x_{min}}$$

$x_{i,0\to1}$	value of the standardised indicator $X_{0\to1}$
x_i	value of the initial indicator X
x_{min} and x_{max}	minimum and maximum value of X throughout the dataset

Using cut-off values would involve replacing x_{min} and x_{max} in the formula by the chosen values and changing any final values lower than 0 or higher than 1 or to respectively 0 and 1.

At this point, the direction of the indicator can easily be changed by subtracting its value from 1, whereupon a final transformation can be performed to make the indicator's values fit within any predetermined boundaries, like 0 to 10, if needed.

Since standardisation of the indicators involves losing the direct quantitative association of the indicator's value to the physical world, such a standardisation will only be performed once throughout this document, to illustrate what a standardised indicator would look like. This is done in section 4.1.5, where the standardisation is performed using cut-off values, after which the standardised indicator is transformed to a score between 0 to 10.

4 CASE STUDIES

This chapter is dedicated to the development and the evaluation of quantitative accessibility and mobility performance indicators and to the presentation of the results. The link with the literature study provided in chapter 2 will be made to illustrate how the developed indicators relate to the generic definitions provided earlier. A very basic outline for the development of the accessibility and mobility indicators, presented in this chapter, is provided in Figure 4-1. Next to the development of these performance indicators, this chapter also presents how the indicators are used in a multi-objective optimisation, identifying the optimal locations in Brussels for an office building, based on accessibility by public transport and accessibility by car.

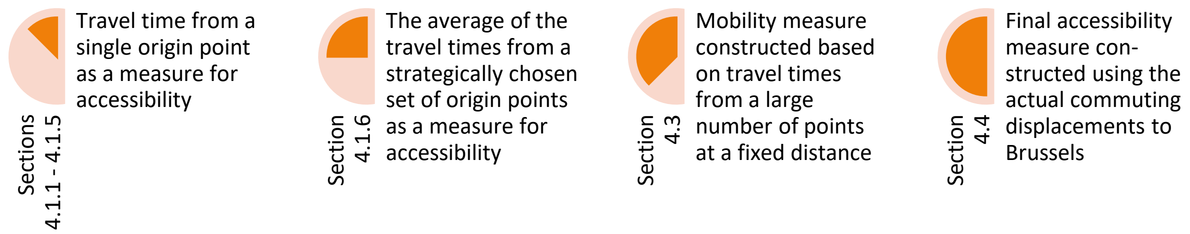


Figure 4-1 Outline of the development of the accessibility and mobility indicators

A fixed heading pattern will be maintained throughout this chapter as much as possible, with a sequence of strategy, accessibility or mobility definition, results and a discussion of the results.

At the end of this chapter, a non-exhaustive list of possible cases is presented. These cases could be studied using an approach similar to the one developed for this study.

4.1 DEVELOPMENT OF AN ACCESSIBILITY PERFORMANCE INDICATOR

4.1.1 A first attempt

4.1.1.1 Strategy

The first attempt consists of gathering travel time data for travelling from Leuven to different points in Brussels. The input used, is as follows: [10]

[10] Since this is the first-time introduction of geographical coordinates in this document, it’s essential to clarify which coordinate system is adopted in this research and accompanying document, because different reference ellipsoids and geodetic systems could result in considerable datum shift when using data across different GIS applications. Keeping this in mind, the choice was made to adopt the World Geodetic System of 1984 (WGS84) datum in this document. The reason is obvious: it’s the current reference system used by GPS and this standard is also used by Google Maps, the data provider selected for this project. [35] Microsoft also uses the WGS84 datum for Bing Maps. [36]

Mode	• Transit
Time	• Arrival time • A Thursday morning in May, 9 a.m. (UTC+2)
Origin(s)	• Point close to the Leuven SNCB train station at Martelarenplein. • Coordinates: 50.8813, 4.7155 or 50°52'52.7"N 4°42'55.8"E

Destination(s)	• 2500 different points in Brussels, arranged in a rectangular grid
	• Latitude and longitude ranging in the intervals:
	  • Latitude interval: [50.8054, 50.8940]
	  • Longitude interval: [4.3196, 4.4446]

List 4-1 Overview of the input used

4.1.1.2 Accessibility definition

This section relates the accessibility measure used here to the gravity-based measure introduced in section 2.1.6.2. The general formulation from section 2.1.6.2 is repeated below:

$$A_{im} = \sum_j O_j \, f\left(C_{ijm}\right)$$

In the case-specific form below, the abstract parameters are concretised:

$$A_{i,\text{transit}} = \sum_j O_j \, f\left(C_{ij,\text{transit}}\right) = \sum_{j \in \{\text{Leuven}\}} 1 \, . \, t_{ji,\text{transit}} = t_{\text{Leuven},i,\text{transit}}$$

$A_{im} = A_{i,\text{transit}}$	Accessibility from Leuven by transit, measured at point i
$O_j = 1$	
$f\left(C_{ijm}\right) = t_{ji,\text{transit}}$	As cost function, the travel time by transit from Leuven (point j) to point i is used

At this point, the abstract gravity-based formulation has not been used up to its fullest potential.

It might feel odd to set the opportunity at point j to 1, because traveling from Leuven to Brussels early on the day would intuitively be related to the opportunity being located at Brussels. However, when reversing the route, traveling back home from Brussels to Leuven, the opportunity or valued destination of the traveller is his home. Or from the perspective of a company in search the ideal building to locate its business: the valued destinations are the places of residence of its employees (office building, workplace) or customers (retail space).

4.1.1.3 Results

Figure 4-2 shows the travel time by transit from Leuven to different points in Brussels. As will often be the case throughout this document, the results are displayed on a map with a continuous colour heatmap overlay.

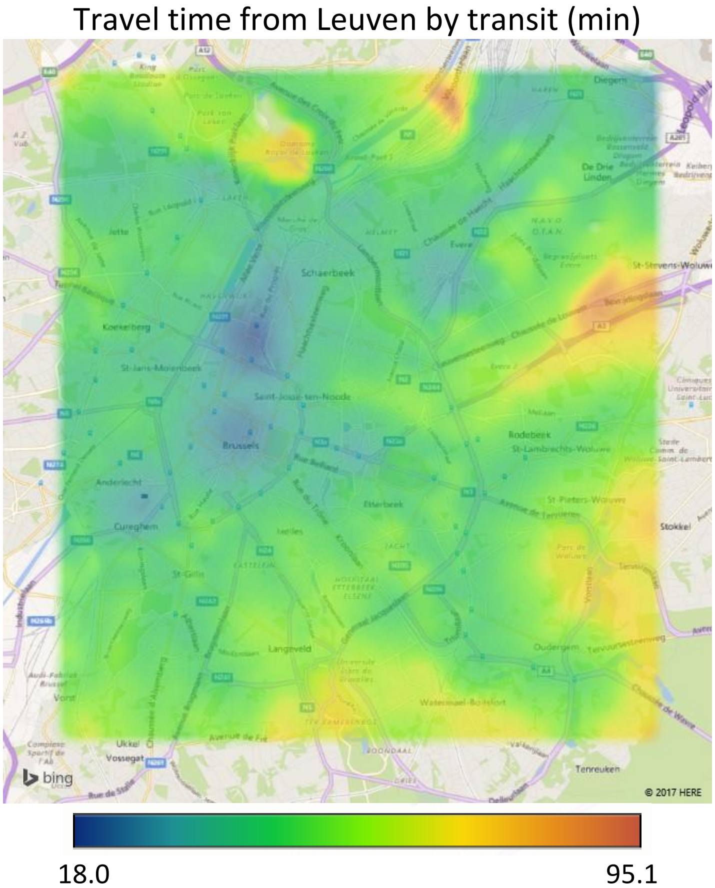


Figure 4-2 Travel time in minutes from Leuven by transit

4.1.1.4 Discussion

Figure 4-2 shows that the lowest transit travel times from Leuven to Brussels are to zones close to the Brussels North and Central railway stations. The South Station area, Schaerbeek and Evere can be reached in a relatively short time as well. Other zones, like the Sint-Stevens-Woluwe business park along the Leuvensesteenweg, are less accessible from Leuven by public transport.

4.1.2 Comparing modes of transport

4.1.2.1 Strategy

To perform a comparison, travel time data was gathered on traveling from Leuven to Brussels using two different modes of transport: transit and car. The input used, is as follows:

Mode	• Transit • Driving
Time	• Departure time • A Thursday morning in May, 8 a.m. (UTC+2)
Origin(s)	• Point close to the Leuven SNCB train station at Martelarenplein. • Coordinates: 50.8813, 4.7155

Destination(s)	• 2500 different points in Brussels, arranged on two interlocking rectangular grids
	• Latitude and longitude ranging in the intervals:
	  • Latitude interval: [50.8054, 50.8934]
	  • Longitude interval: [4.3097, 4.4446]

List 4-2 Overview of the input used

4.1.2.2 *Accessibility definition*

The accessibility definition used, is the same as in the previous section 4.1.1. In the definition of the measure used, travel mode m will now take 2 possible values: transit and driving.

4.1.2.3 *Results*

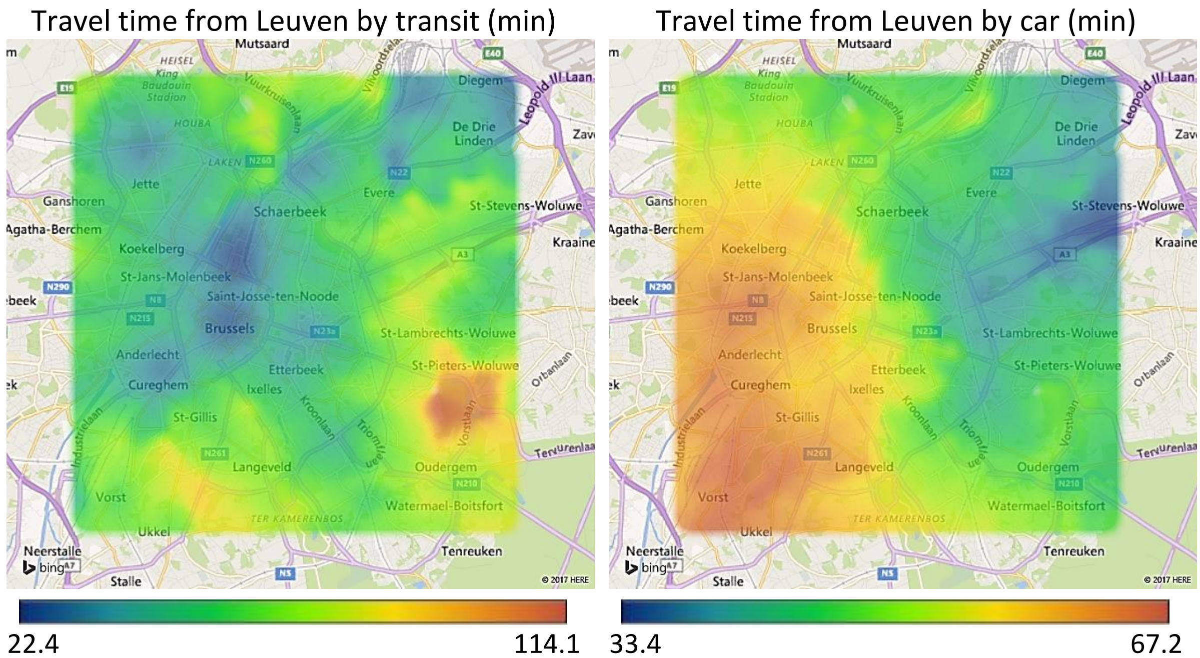


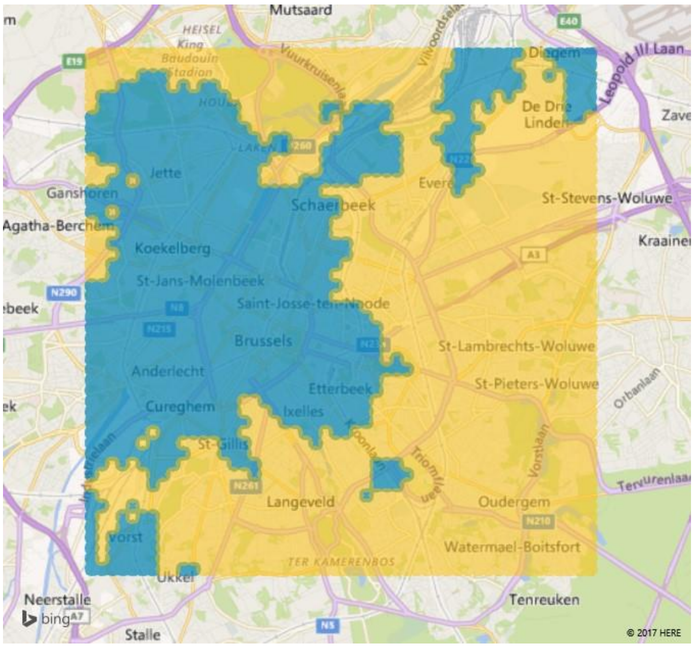
Figure 4-3 Travel time in minutes from Leuven by transit (left) and by car (right)

4.1.2.4 *Discussion*

Travel times by car are displayed in Figure 4-3 on the right. Since Leuven is located east of Brussels, the lowest travel times by car are expected to be obtained at the eastern parts of the investigated area. The map generated from the obtained data illustrates quite well that this expectation has been fulfilled. It is also observed that areas close to major roads have lower travel times by car, which is also in accordance with the expected pattern. It’s clear that the zones that are best accessible by transit do not correspond to the zones best accessible by car.

4.1.2.5 Travel time comparison

To identify the zones better accessible from Leuven by public transport than by car, the sign of the difference in travel time was mapped and displayed in Figure 4-4. The blue coloured area is faster accessible by public transport ($t_{\text{transit}} < t_{\text{car}}$) during the morning peak, while the other locations are faster accessible by car ($t_{\text{transit}} > t_{\text{car}}$) at the same time of day. The places that are faster accessible by transit are located around the train stations. In this comparison, public transportation travel time is probably favoured, due to the chosen origin point Leuven SNCB train station at Martelarenplein. For many other origin points, the car would be the fastest travel mode. On the other hand, the calculated transit and driving travel times are for door-to-door travel routes. The driving travel time doesn’t include the time to find a car parking and park the car. These unquantified issues related to comparing driving and public transport travel times are reasons to proceed with caution when comparing travel times. The optimisation strategy introduced in section 4.2 is not susceptible to these issues, since the travel times for different modes of transport are not subtracted.



Shortest travel times by transit
Shortest travel times by car

Figure 4-4 Zones of Brussels with shorter travel time from Leuven by transit and by car

4.1.3 Alternative indicators

Other studies often use different mobility and accessibility indicators. This section illustrates that these “alternative indicators” for mobility and accessibility by car can also be evaluated using a web scraping approach, provided that the obtained data is transformed to the required form.

4.1.3.1 Strategy

The indicators evaluated here, are the actual driving travel time (traffic delay included), the travel time without traffic delay or free-flow travel time (the ideal case) and some of their derivatives. These derivate indicators can have their use, but exhibit some drawbacks, which is discussed in section 4.1.3.4.

4.1.3.2 *Accessibility definition*

The formulations of the 4 accessibility indicators are:

- $A_{i,\text{driving}} = \sum_j O_j \, f\left(C_{ij,\text{driving}}\right) = \sum_{j \in \{\text{Leuven}\}} \left(1 \, . \, t_{ji,\text{car}}\right) = t_{\text{Leuven},i,\text{driving}}$
- $A_{i,\text{driving,free-flow}} = t_{\text{Leuven},i,\text{driving,free-flow}}$
- $A_{i,\text{driving,delay}} = t_{\text{Leuven},i,\text{driving,peak}} - t_{\text{Leuven},i,\text{driving,free-flow}}$
- $A_{i,\text{driving,index}} = \text{TTI}_{\text{Leuven,i,driving}} = \dfrac{t_{\text{Leuven},i,\text{driving,peak}}}{t_{\text{Leuven},i,\text{driving,free-flow}}}$

4.1.3.3 *Results*

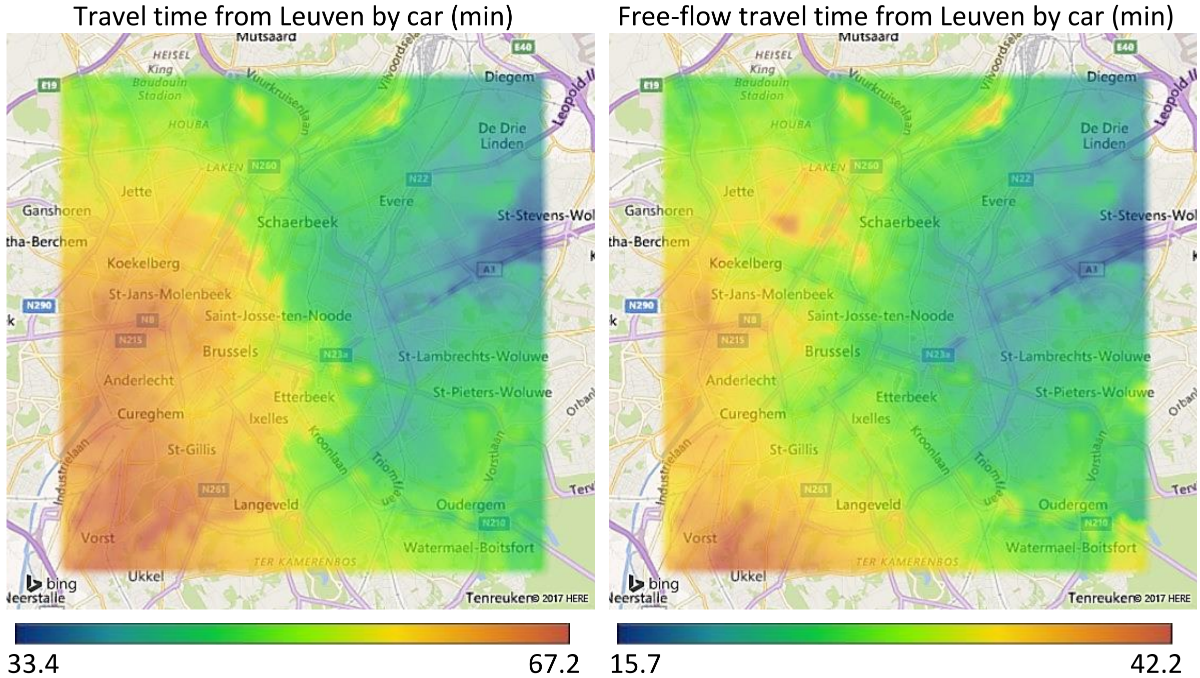


Figure 4-5 Actual travel time (left) and free-flow travel time (right) from Leuven by car in minutes

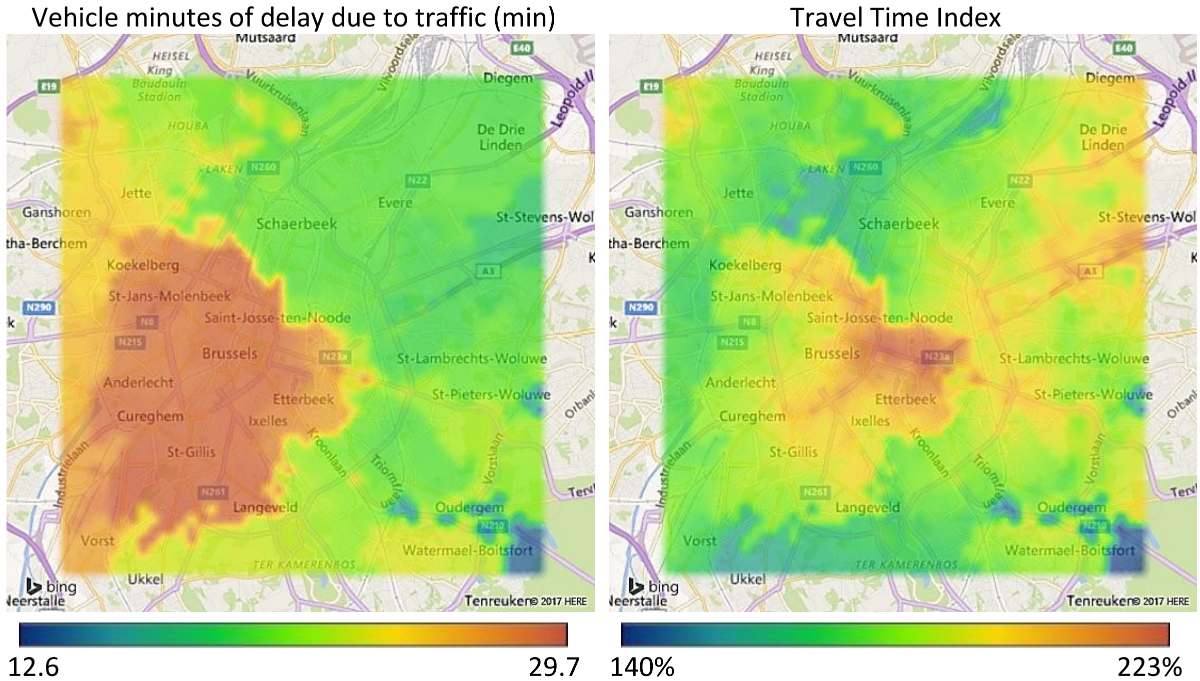


Figure 4-6 Vehicle minutes of delay (left) and TTI (right), evaluated on a route from Leuven to Brussels

4.1.3.4 Discussion

The vehicle time of delay indicator and Travel Time Index are useful in combination with other indicators to help explain some specific mobility or accessibility issues, but on their own, they shouldn't be used for strategic decisions. The Travel Time Index indicator constructed here should certainly be used with care for the intended purpose of this study, since a high value could be explained by both a low free-flow travel time and a high delay time. Low values can be related to a low traffic delay time (which is in favour of the location under investigation) or by a high free-flow travel time, regardless of the traffic conditions (which would indicate bad mobility or accessibility for the investigated location).

4.1.4 Morning peak and evening peak comparison

4.1.4.1 Strategy

To decide at what time of day commuting to Brussels should be studied, 2 possible scenarios are considered and mapped, a first scenario taking place on a normal weekday (Thursday) in the morning and a second scenario taking place in the evening, where people leave work in Brussels to get back home.

Data on commuting from Ghent to Brussels was gathered for both scenarios. The input used, is as follows:

Mode	• Transit • Driving
Time	• Departure time • A Thursday morning in May, 8 a.m. (UTC+2) • A Thursday evening, 5 p.m. (UTC+2)
Origin(s) Destination(s)	• Point close to the SNCB Ghent-Saint-Peter's railway station with coordinates: 51.0364, 3.7110

Destination(s)
Origin(s)
	• 2500 different points in Brussels, arranged on two interlocking rectangular grids
	• Latitude and longitude ranging in the intervals:
	  • Latitude interval: [50.8054, 50.8934]
	  • Longitude interval: [4.3097, 4.4446]

List 4-3 Overview of the input used

4.1.4.2 Accessibility definition

The used indicator is similar to the one from section 4.1.1, only now the Ghent-Saint-Peter's railway station has been used and the origin and destination points have been swapped to correspond to the time of day in the context of commuting to the Brussels-Capital Region.

4.1.4.3 Results

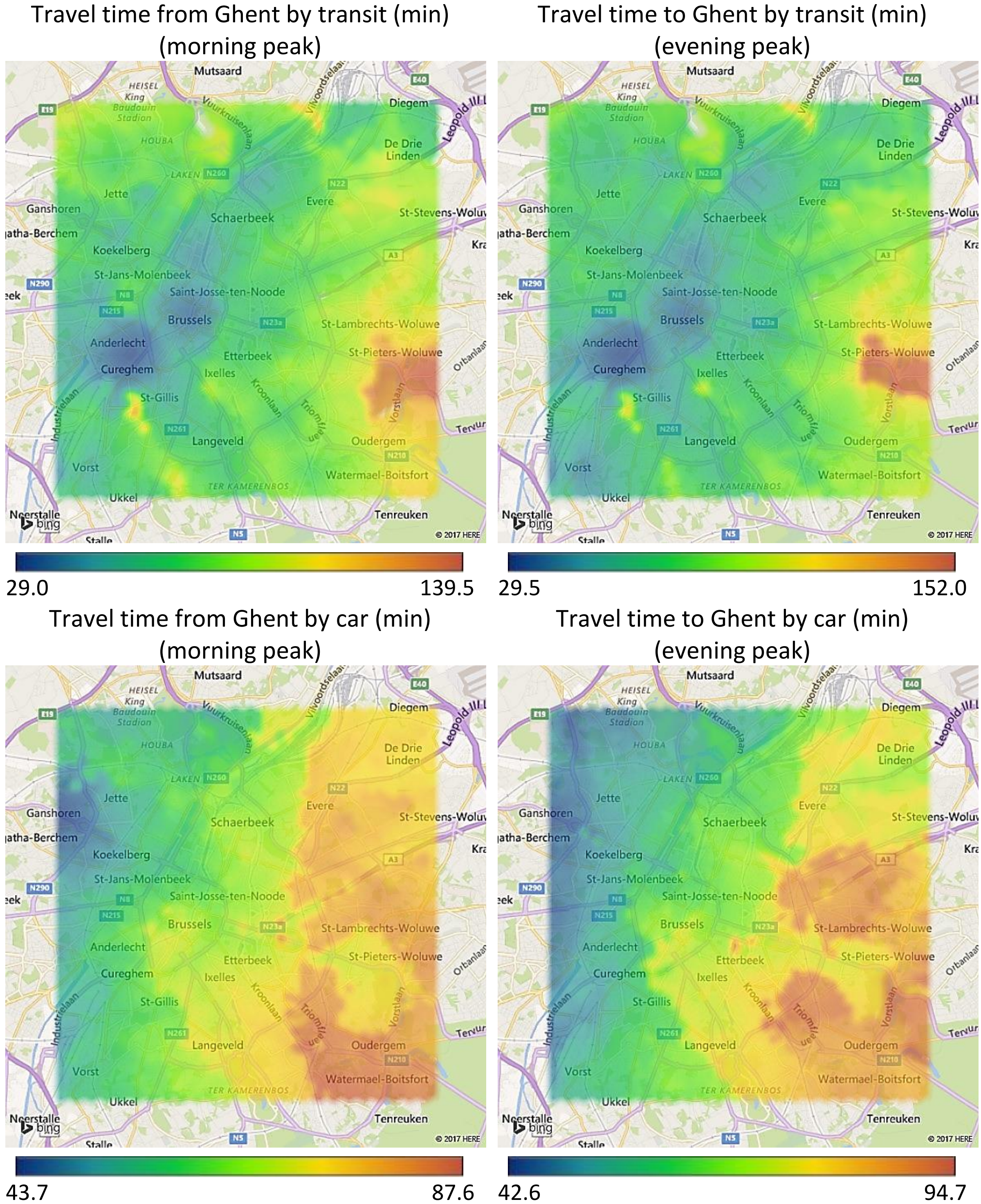


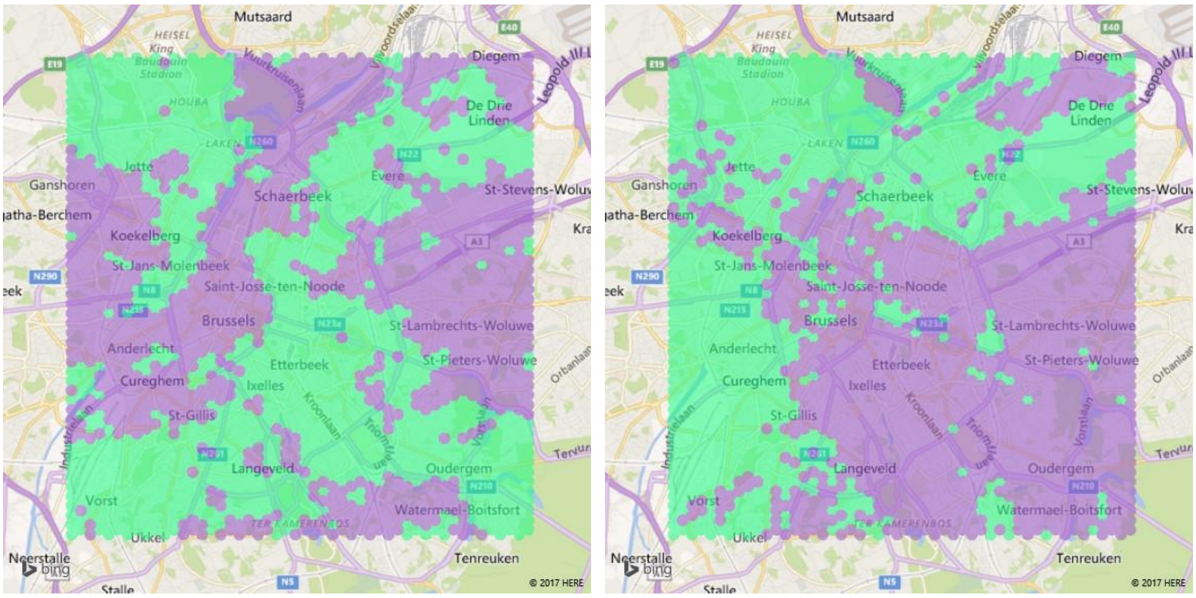
Figure 4-7 Travel time from or to Ghent by transit and car (min), comparison between morning and evening peak

4.1.4.4 Discussion

For both the transit and driving modes the observed patterns in travel times are similar for the morning and evening peak. Since generating both morning and evening peak data during every future stage would double computation times for every study performed during this project, without any evincible increase in the relevance of the results, the choice is made to only calculate morning peak travel times. This choice was based on the observation that most of the time, people talk about commuting travel time from home to work and not vice versa. [11]

4.1.4.5 Travel time comparison

The question whether travel times are longer in the morning or evening peak may arise. In order to investigate if there is any pattern detectable when comparing the morning and evening peak travel time data sets, two additional maps were created and displayed in Figure 4-8 below. The mapped parameter in these maps is the sign of the difference between morning and evening peak travel times. No distinct pattern was observed. The difference in morning and evening peak travel times could not be linked to any geographical location observation nor was it possible to identify a relationship between car and transit travel time differences.



Shortest travel times during the evening peak
Shortest travel times during the morning peak

Figure 4-8 Morning and evening peak travel time comparisons (transit on the left, driving on the right)

4.1.5 Accessibility from different important transit stops

For several purposed, it could be useful to have maps that show the accessibility, measured in terms of travel time from a set of important origin locations. This section presents a set of maps displaying travel times from several important transit stops to other places in and around the Brussels-Capital Region.

4.1.5.1 Strategy

Travel times from several important transit stops in and around the Brussels-Capital Region are mapped. The 4 transit stops deemed most important and relevant have been selected. Data has been collected for accessibility by transit as well as accessibility by car.

[11] No claim is made that this is always or mostly the case, since this statement has not been based on any survey or other results, only on experience. Studying evening peak travel times would produce equally valuable and relevant results.

The input used, is as follows:

Mode
- Transit
- Driving

Time
- Departure time
- A Thursday morning in May, 8 a.m. (UTC+2)

Origin(s)
- Brussels-North railway station
- Brussels Central Station
- Brussels-South railway station
- Brussels Airport

Destination(s)
- Around 5500 points in and around the Brussels-Capital Region, spread equidistantly in a circular area with
  - its midpoint at 50.8526, 4.3740;
  - a diameter of 20 km.

List 4-4 Overview of the input used

4.1.5.2 Accessibility definition
The accessibility definition from section 4.1.1 is used with other origin points.

4.1.5.3 Results
The results can be found in Figure A-1 and Figure A-2 of Appendix A.[12]

4.1.5.4 Discussion
This type of map is very useful when a quantitative assessment of different locations needs to be performed on criteria related to accessibility from important transit stops. A very practically relevant application would be to score different locations on accessibility from the airport by car or by public transport. Internationally or globally oriented organisations, like the European institutions, could consider this as an important criterion in the selection of a location for its offices. Figure A-1 and Figure A-2 contain maps displaying travel times from Brussels Airport to different locations in and around the Brussels-Capital Region by transit and by car. As introduced in section 3.4, the travel time from Brussels Airport has been transformed to a score from 0 to 10 using cut-off values, 10 being the best possible score. This has been illustrated in Figure A-3 and Figure A-4.

[12] The observant reader will notice that the colour scale has been manipulated to provide maps with a better colour variety. Whereas previously the colour scale always stretched from the lowest value presented on the map to the highest value, in the maps created for this section, alternative limit values were sometimes adopted. The choice of the alternative limits was done in favour of the readability of the maps by providing a better division of the values over the adopted colour range. In the rest of this document, both colour scales stretching from lowest to highest value and scales with other limit values have been used.

4.1.6 Accessibility: average for multiple origin locations

4.1.6.1 Strategy

When evaluating possible places to locate a company's office building on accessibility, it makes sense to take multiple origin points into account. On a first attempt to do this, four origin points at province capital cities were considered. The cities chosen for this first study were Ghent (the capital and largest city of the East Flanders province), Hasselt (capital city of the province of Limburg), Liège (capital city of the province of the same name, Liège) and Mons (capital city of the province of Hainaut). Hasselt probably isn't the ideal city to consider for this study because there may be a difference in the proportion of working population commuting to Brussels compared to the other cities. However, at this illustrative stage it is not yet the intention to represent a real-life problem. The cities were chosen based on an equal distribution in each cardinal direction and between Flanders and Wallonia.

Mode
- Transit
- Driving (free-flow conditions)

Time
- Arrival time
- A Thursday morning in May, 9 a.m. (UTC+2)

Origin(s)
- Ghent, point at 51.0364, 3.7110
- Hasselt, coordinates: 50.9309, 5.3271
- Liège, coordinates: 50.6247, 5.5670
- Mons, coordinates: 50.4537, 3.9428

Destination(s)
- Different points in Brussels, arranged in a rectangular grid
- Latitude and longitude ranging in the intervals:
  - Latitude interval: [50.8001, 50.8888]
  - Longitude interval: [4.2943, 4.4437]

List 4-5 Overview of the input used

In this section, the travel times by car are free-flow travel times.

Maps displaying the accessibility by transit and car from all 4 origin points were created, as well as a map with an equally weighted average of the 4 cities.

4.1.6.2 Accessibility definition

The definition of the accessibility measure displayed in the maps with an individual origin point is similar to the one used in section 4.1.1. For the equally weighted average, some additional explanation is provided.

In the case-specific form of the general formulation of the gravity-based measure introduced in section 2.1.6.2, the abstract parameters are concretised:

$$A_{im} = \sum_j O_j \, f(C_{ijm}) = \sum_{j=1}^{4} \left(\frac{1}{4} \, t_{jim} \right) = \frac{1}{4} \left(t_{\text{Ghent},i,m} + t_{\text{Hasselt},i,m} + t_{\text{Liège},i,m} + t_{\text{Mons},i,m} \right)$$

A_{im}	Accessibility measured at point i using mode of transport m, which will take the values “transit” and “driving”
$O_j = \frac{1}{4}$	Equal opportunities for each of the origin points j
$f(C_{ijm}) = t_{jim}$	As cost function, the travel time from point j to point i is used

4.1.6.3 Results

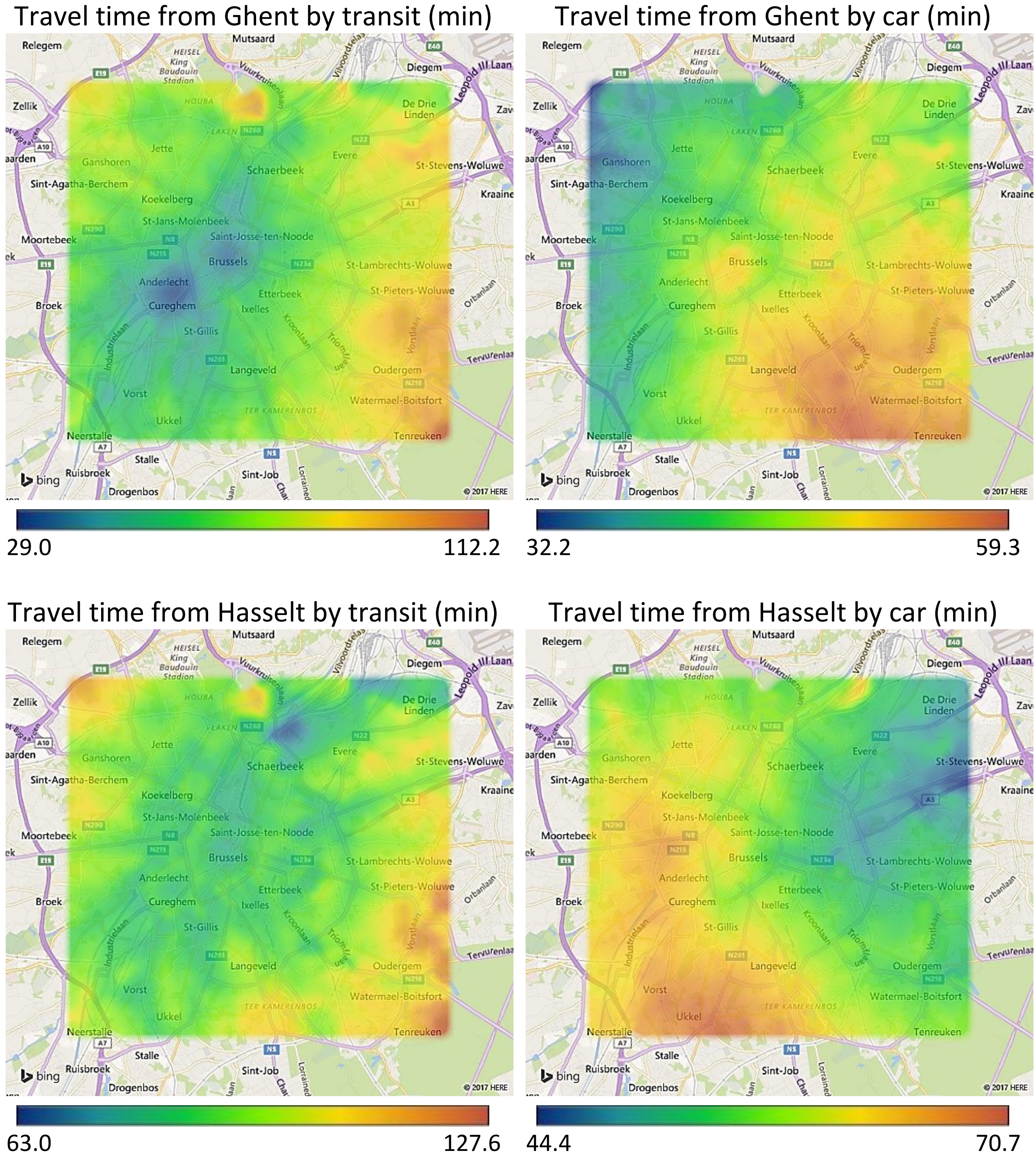


Figure 4-9 Travel time by transit (left) and car (right) from 4 different origin cities to Brussels (1)

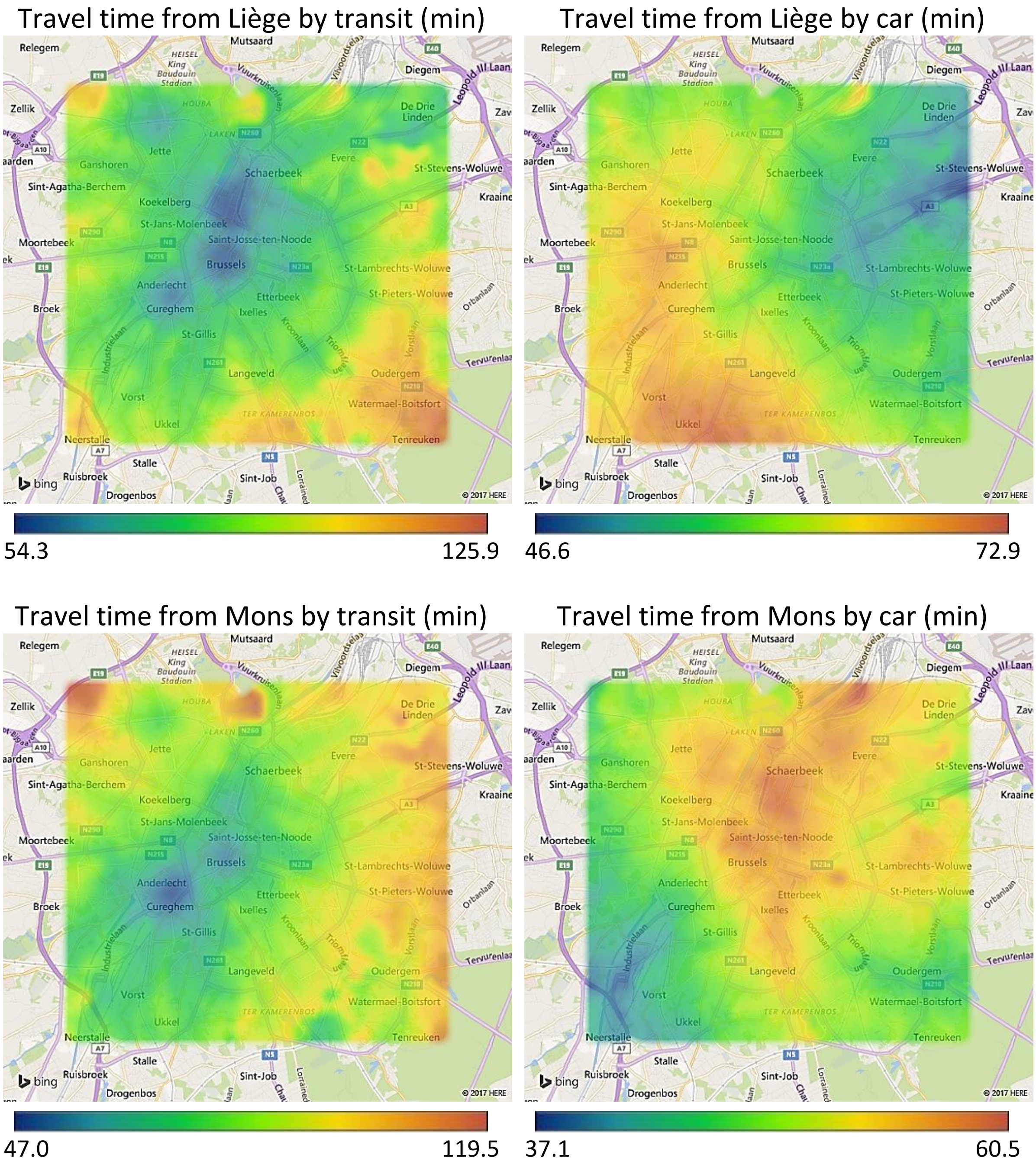


Figure 4-10 Travel time by transit (left) and car (right) from 4 different origin cities to Brussels (2)

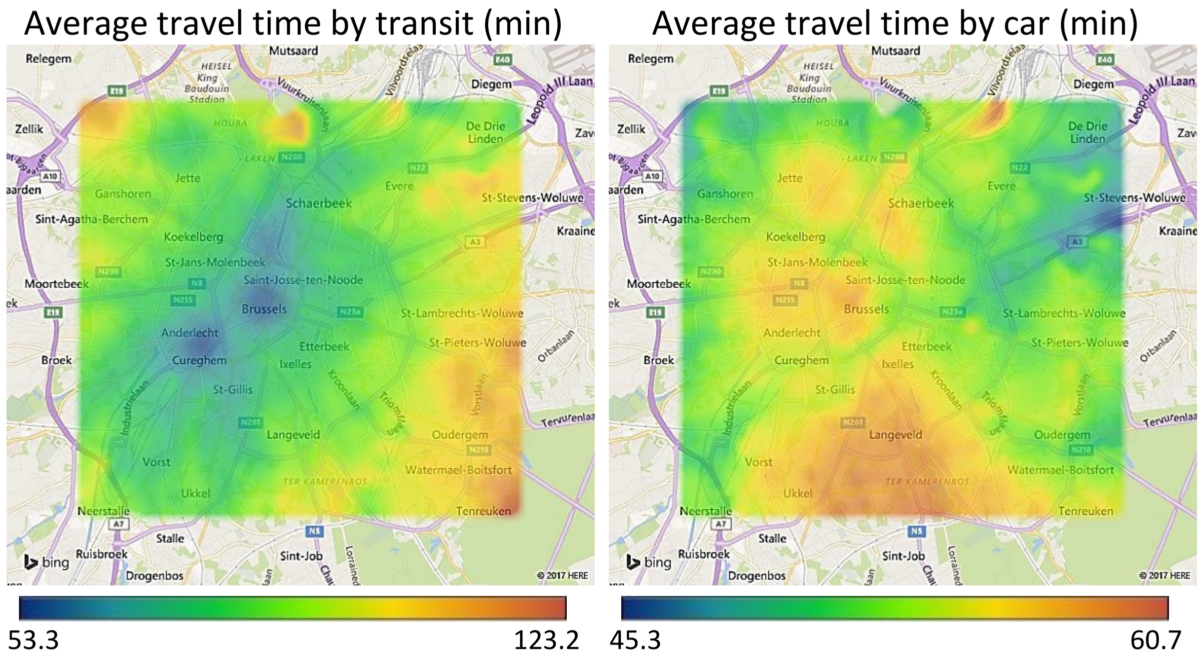


Figure 4-11 Four cities average travel time to Brussels by transit (left) and car (right)

4.1.6.4 Discussion

One can observe that the average travel time maps resemble the pattern shown in the largest numbers of individual origin travel time maps. 2 of the transit travel time maps (the maps with Mons and Ghent as origin points) show a pattern where surroundings of the South and Central railway station are best accessible from the considered origin point. This can be easily explained: the SNCB trains coming from Mons and Ghent both have their first stop in Brussels at the South Station and their second stop at Central Station.

A similar observation can be made for travel times by car: the maps displaying accessibility from Liège and Hasselt show patterns that are very much alike. The explanation here is that whether you come to Brussels by car from Liège or Hasselt, in both cases you will probably take the E40 to enter Brussels, as the E314 one uses when traveling from Hasselt merges on the E40 road.

This illustrates one of the main issues when studying accessibility to Brussels if only a small number of origin cities are taken into consideration. There is a need for additional data. The issue is dealt with in section 4.4, where origin locations are selected based on secondary data regarding commuting to the Brussels-Capital Region, leading to maps that better represent the real commuting pattern.

4.2 INTRODUCTION TO THE MULTI-OBJECTIVE OPTIMISATION METHODOLOGY

4.2.1 Multi-objective optimisation: a first attempt

4.2.1.1 Strategy

In this phase of the study, it was investigated whether the optimisation algorithms discussed in section 2.3 Multi-criteria optimisation on page 12 could be used in the decision-making process to identify optimal locations.

For a first test, an NSGA-II optimisation was performed on both the Liège and Mons travel time based accessibility measures from section 4.1.6. The design variables used, were latitude and longitude of the investigated locations. The design space was limited by imposing upper and lower bounds on the design variables: $50.8001 \leq \text{latitude} \leq 50.8888$ and $4.2943 \leq \text{longiutde} \leq 4.4437$. The NSGA-II algorithm also allows to specify constraints, but this feature was not implemented.

2 objectives were considered, the travel time from the origin city by transit and the travel time by car.

The population size was set to 400 individuals. The cross-over probability was set to 90%, and the mutation probability to 30%.

Since the NSGA-II algorithm identifies the Pareto front by letting a population evolve towards the Pareto optimal set, the result will show the most advantageous locations to locate for example an office building if only the 2 specified criteria are considered.

4.2.1.2 Accessibility definition

The accessibility indicators are the same as in section 4.1.6.

4.2.1.3 Results

In this section, only the initial and the final, converged generations are shown. A full evolution of a random distribution of points in the design space to the converged solution for this optimisation isn't included in this document. Note that the procedure involves letting the population evolve towards the Pareto front, which is always displayed right of the map displaying the locations. The Pareto front contains the Pareto optimal solutions for the problem, in this case the optimal locations based on the objectives accessibility by transit and accessibility by car. Since both objectives are expressed as travel times, in minutes, the objectives need to be minimised by the algorithm. This can be observed graphically: the population evolves to a set of converged solutions as close to the origin as possible.

Origin point in Liège

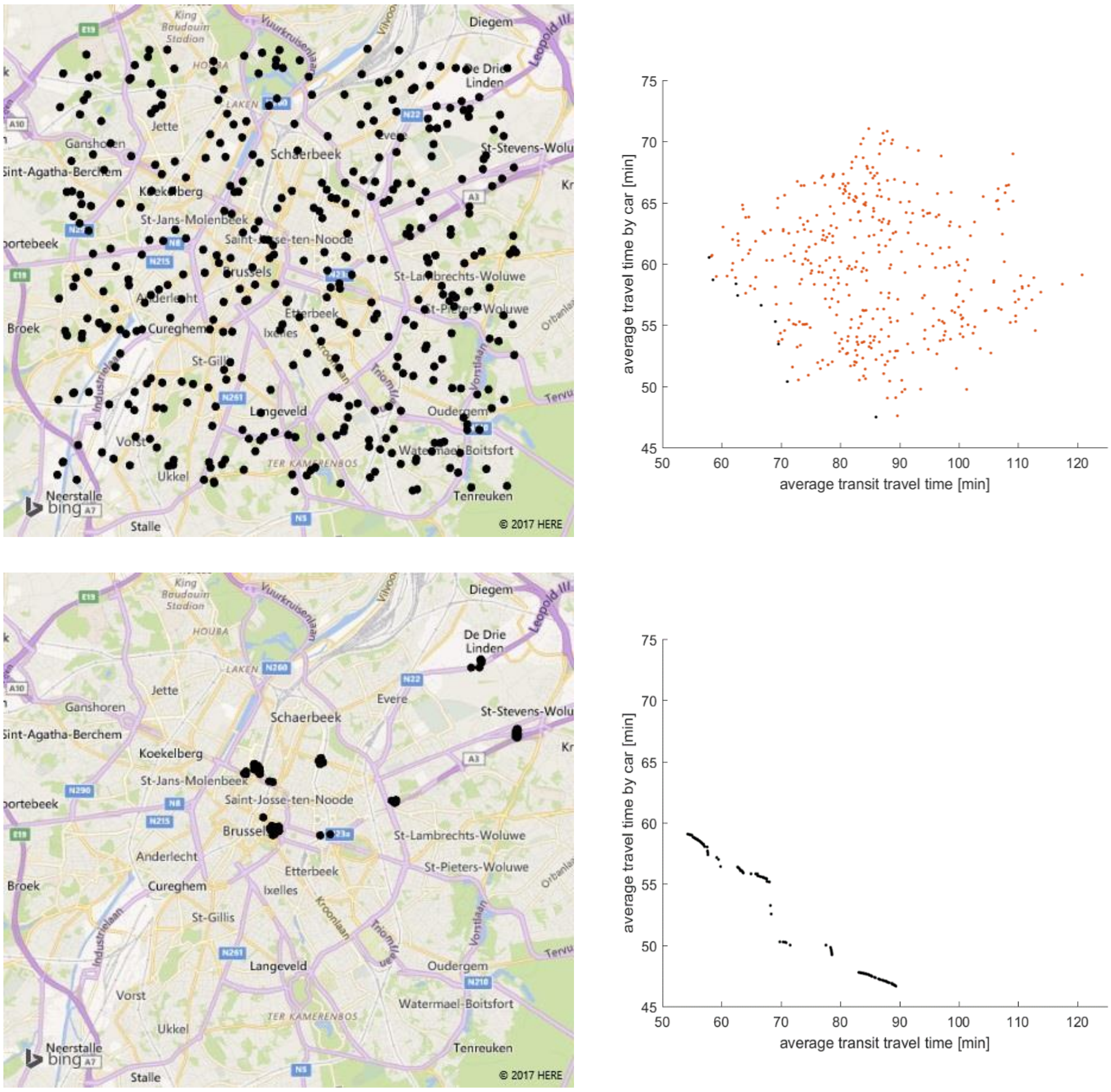


Figure 4-12 NSGA-II optimisation – generation 1 & 15 (one origin point in Liège)

Origin point in Mons

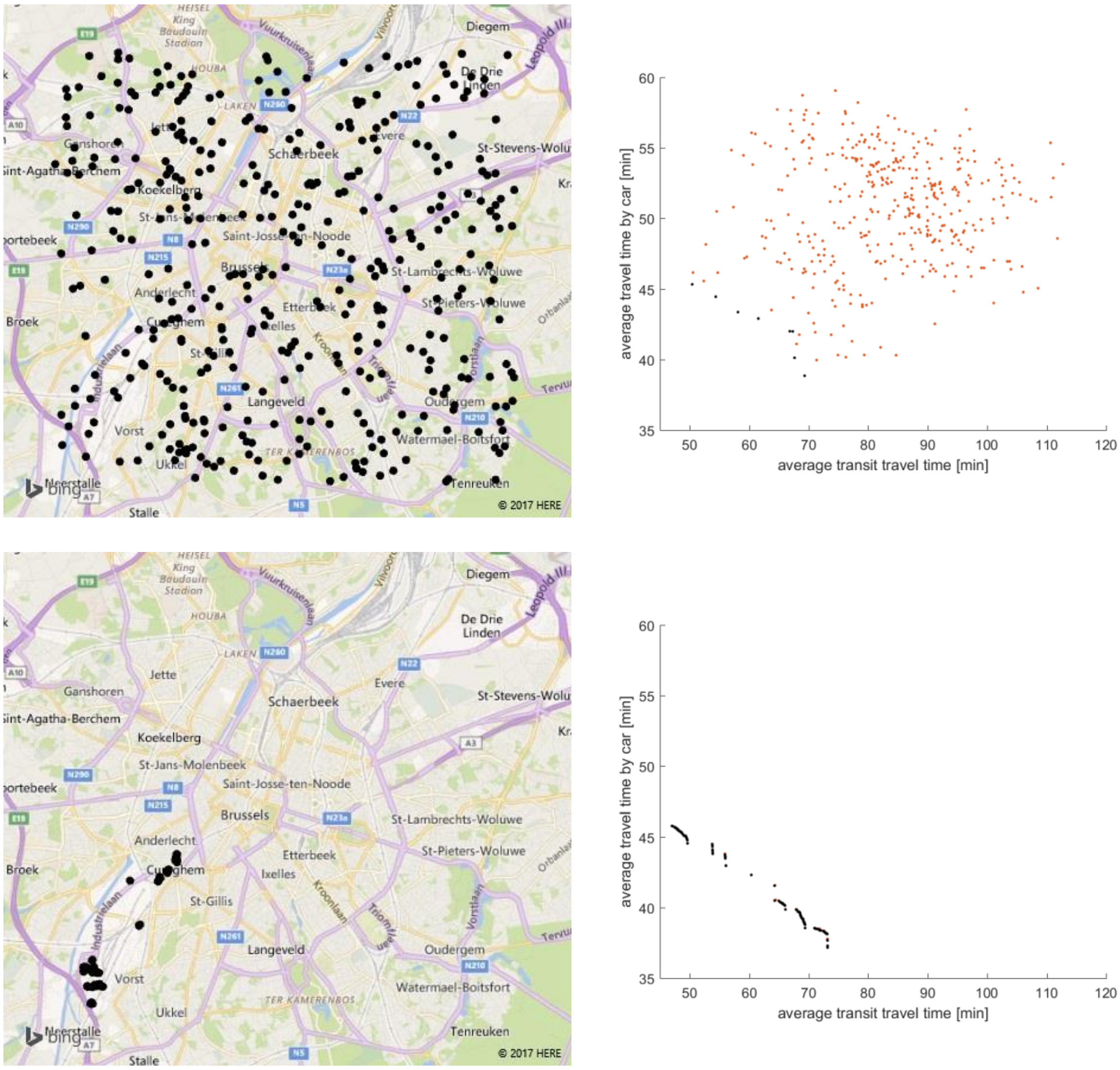


Figure 4-13 NSGA-II optimisation – generation 1 & 15 (one origin point in Mons)

4.2.1.4 Discussion

Origin point in Liège

In the results of the location optimisation on the indicators with Liège as origin points, the initial population has evolved towards the optimal places within the design space to locate for example an office building when only the two location criteria ‘accessibility from Liege by car’ and ‘accessibility from Liege by transit’ are considered. The converged results can be grouped in 8 locations:

- The Boulevard Leopold III, on the road between Brussels National Airport and the centre, close to the Eurocontrol and Bourget transit stations. Located here is a business park in Diegem, where some well-known companies are located: IBM, KPMG, Toyota, Air Liquide, …;
- At the border between Woluwe-Saint-Lambert (Brussels-Capital Region) and Zaventem;
- At the Boulevard Auguste Reyers in Schaerbeek, the east of Brussels, where the A3 starts. This location has a good accessibility by car and by public transport. It’s at this place that the Diamant tram and bus stops are located;
- At the crossing of the Avenue Rogier and the Avenue Paul Deschanel at tram and bus stop Coteaux;

- The Schuman Square. The points are located at Le Berlaymont, Rue de la Loi (European Commission headquarters) and the Charlemagne building (European Commission DG Trade, Ecfin, IAs);
- The Botanique;
- The surroundings of the North station and the Place Rogier;
- Near the Parc de Bruxelles or Warandepark, near the Rue de la Loi or Wetstraat and near the important metro station Arts-Loi, where metro lines 1, 2, 5 and 6 cross.

Origin point in Mons

Here the Pareto optimal locations can also be partitioned into multiple groups:

- The immediate surroundings of the South Station, for example at the Victor Horta Square and the Rue de France;
- At the crossing between the Rue the France and the Rue des Deux Gares;
- At the Rue de la Petite-Ile, Anderlecht. There is a bus stop located here;
- At the Avenue du Pont de Luttre, also close to a bus stop;
- At the Forest-South railway station (located here: Audi car manufacturing site, previously Volkswagen).

General remarks

It needs to be emphasised that this optimisation was just a first try. It makes far more sense to run an optimisation on data gathered for multiple origin points. Even though the optimisation design is far from optimal, the results are useful and show that close attention must be payed when specifying the weights in a multi-criteria selection process, as the optimal location might be different depending on the data scaling and weight allocation methods used.

4.2.2 Multi-objective optimisation: multiple origin locations

4.2.2.1 Strategy

The same procedure as in section 4.2.1 was used on the 4 cities average data from section 4.1.6. This location optimisation is already far more representative for reality, but as mentioned in section 4.1.6, a more complete set of origin points must be considered for the aggregated data to be representative for the real commuting pattern to the Brussels-Capital Region.

4.2.2.2 Accessibility definition

The accessibility measures are the same as in section 4.1.6.

4.2.2.3 Results

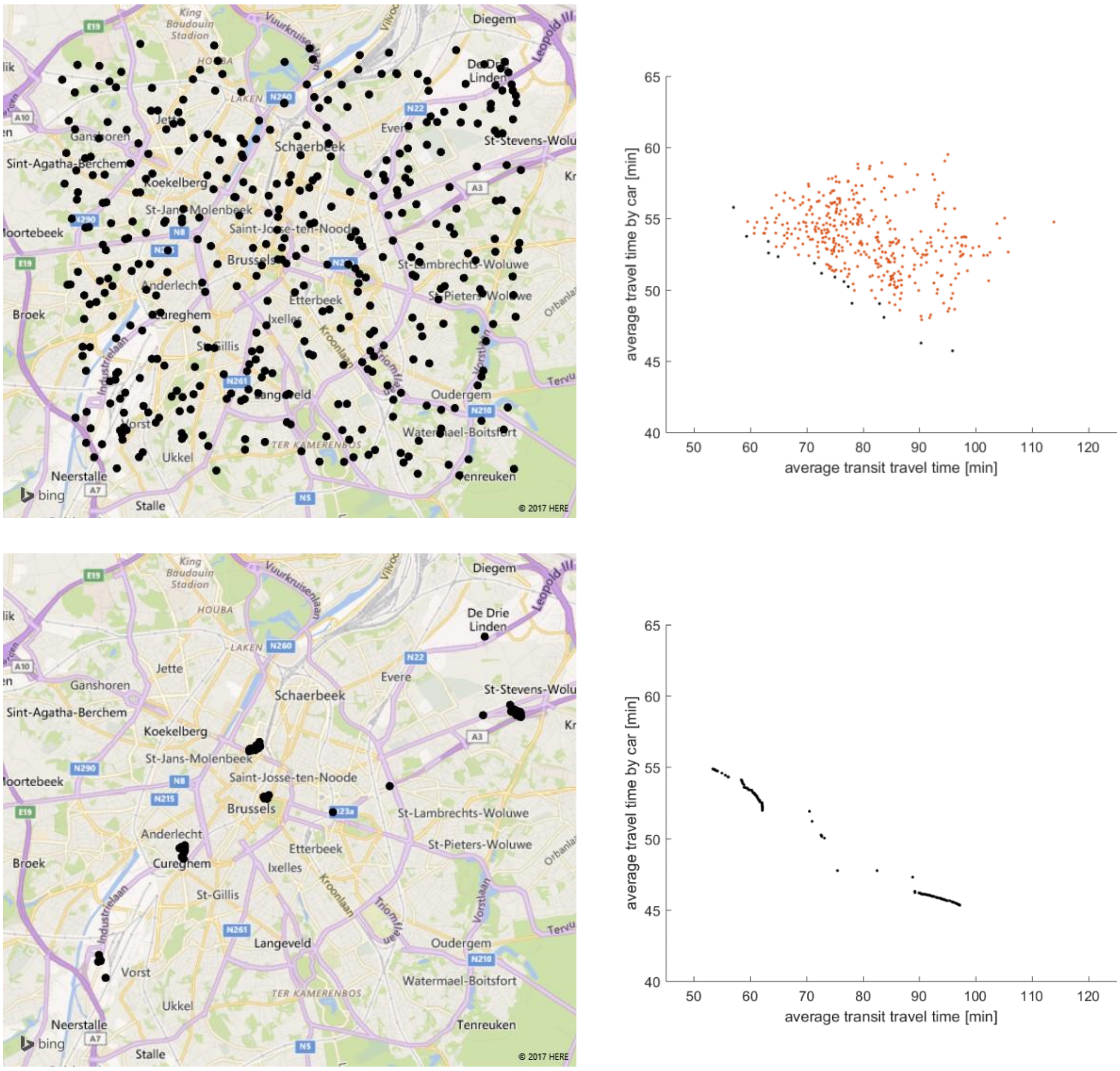


Figure 4-14 NSGA-II optimisation – generation 1 & 15 (origin point in 4 cities, average)

4.2.2.4 Discussion

The converged results show different Pareto optimal locations within the design space. The following locations were identified. Some of these locations were already mentioned in section 4.2.1.

- Business park in Diegem close to the Eurocontrol and Bourget transit stations, where some well-known companies are located: IBM, KPMG, Toyota, Air Liquide, …;
- At the border between Woluwe-Saint-Lambert (Brussels-Capital Region) and Zaventem;
- At the Boulevard Auguste Reyers in Schaerbeek;
- Schuman Square;
- The surroundings of the North station and the Place Rogier;
- In the area between the Parc de Bruxelles or Warandepark and the Brussels Central Station;
- The immediate surroundings of the South Station, for example at the Horta Square and the Rue de France;
- Around the Forest-South railway station.

Both the qualities and importance of these locations can be explained. A relation to accessibility can be made by identifying access to transit stations nearby and/or major roads.

An optimisation like this can thus be useful, provided that the data aggregation is done properly. This requires the use of additional data, as was already discussed in section 2.2.2 Commuting to Brussels: secondary data.

Someone who is not familiar with the concept of multi-criteria optimisation and its applications might comment that the studies executed here don't take any specific modal split into account. These people might suggest working with one specific modal split representing the public sector and another set representing the private sector. The approach used here identifies all Pareto optimal solutions, after which a company – either private or public, where the mobility focus lies either on individual motorised transport or public transport – can make a choice based on its own preferences or the needs of their employees, based on government policy or the company's vision on the future.

4.3 EVALUATING A LOCATION ON MOBILITY

This part of the thesis involves the construction of a mobility indicator and a methodology to automate the process of evaluating the mobility of a location. The approach is similar to the accessibility evaluation approach used in the previous sections. Web scraping is used to collect point-to-point travel time and other data. The technique is then used to evaluate mobility by car and public transport for locations in the Brussels-Capital Region. Like in the previous sections about accessibility evaluation, the results of the evaluation of the mobility measures are shown for both transit and driving travel modes, respectively in subsections 4.3.3 and 4.3.4.

4.3.1 Introduction

Evaluating mobility is different from evaluating accessibility. The difference between mobility and accessibility has been explained in the literature study. Mobility measures the ability to move from one place to another, while accessibility measures the ease of reaching valued destinations rather than focussing on the ease of traveling. For this study, accessibility measures have been composed by considering the places of residence of a company's employees or customers as valued destinations. A mobility indicator should only measure the ease of traveling around, without considering the value of or potential activity at the destination.

Evaluating mobility using a contiguous measure can be done using a quantitative traffic infrastructure density proxy. The approach could be as follows: around the point of interest, a circle is constructed, which is at its turn divided into different cells with the same surface area. A binary value is then assigned to each cell. This binary value represents the extent to which the evaluated cell contains road infrastructure. The measure is evaluated by aggregating the data assigned to each of the cells.

4.3.2 Mobility definition

For this research project, a topological approach to evaluating mobility has been used: around the point of interest, a circle with radius R is constructed, on which N points are chosen, equally distributed on the circle. These points are the N vertices of a regular polygon with the point of interest as centre point. Travel times from each of these N points to the centre point are calculated. The average travel time is used as an indicator for the mobility of the location of interest. This indicator is more valuable for office building location evaluation than infrastructure density, because it is directly related to the ease of travelling, where an infrastructure density measure is more indirectly related to the ease of travelling.

$$M_{im} = \frac{1}{N}\sum_{j=1}^{N} t_{ijm}$$

R has been computed as a distance on the surface of a globally fitting sphere.

Figure 4-15 Illustration of the procedure for a point of interest in Brussels, N = 25 and R = 1 km

4.3.3 Evaluating mobility by transit

4.3.3.1 Strategy and definition

The procedure has already been discussed above. The input used, is listed below.

Mode	• Transit
Time	• Departure time • A Thursday morning in May, 9 a.m. (UTC+2)
Origin(s)	• Different points of interest, spread equidistantly over the Brussels-Capital Region
Destination(s)	• 15 points at a distance R = 10 km from the POI

List 4-6 Overview of the input used

The mobility measure is the one formulated in section 4.3.2:

$$M_{im} = \frac{1}{N}\sum_{j=1}^{N} t_{ijm}$$

The parameters used are $N = 15$, $R = 10\ km$ and the travel mode m is public transport.

4.3.3.2 Results

The map below on the left shows the evaluated mobility indicator values for the Brussels-Capital Region. The corresponding travel distance data was mapped as well (right), as it will be used in the discussion of the computed values.

Travel time as indicator for mobility by transit (min), $R = 10\ km$

Corresponding travel distance (km)

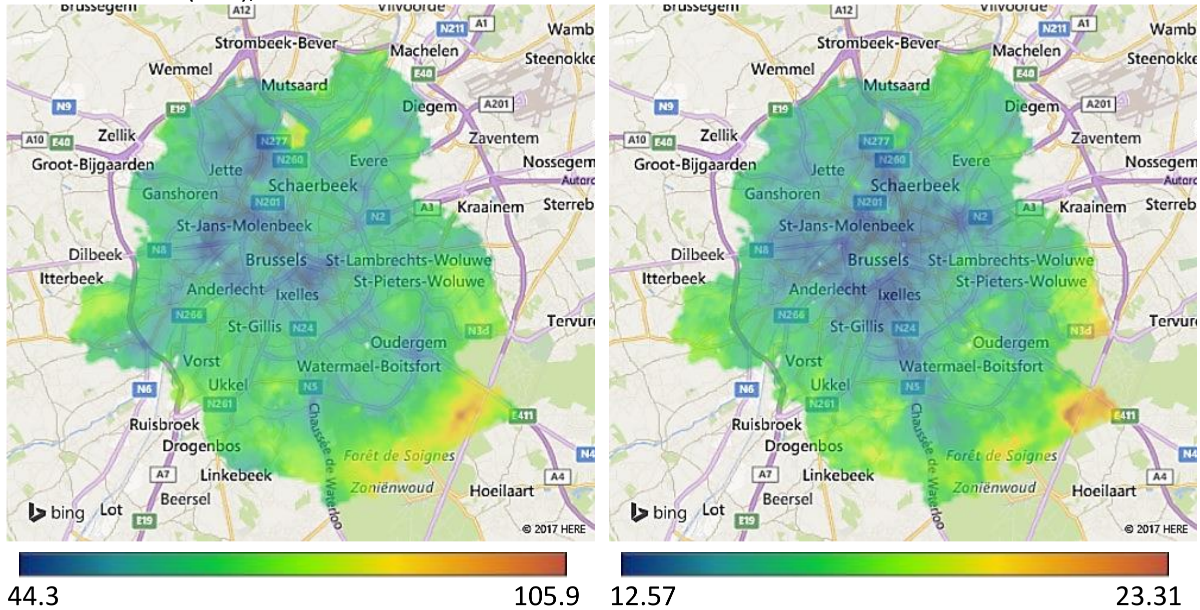


Figure 4-16 Travel time indicator for mobility by transit and the corresponding travel distance

4.3.3.3 Discussion

On first sight, the evaluated indicator for mobility by transit seems to be a valid one. The map showing its values in the Brussels-Capital Region corresponds quite well to the expected pattern for this indicator. The high mobility zones are indicated by a low travel time or blue colour in the presented heatmap on the left of Figure 4-16. The places with the lowest travel time values are located outside the Brussels small ring, in zones where transit service is represented mostly by the STIB tram, metro and bus, but also by train. The chosen radius for the constructed circle or regular polygon will clearly have an influence on the observed pattern and the zones identified as high mobility locations. The transit mode considered is an intermodal way of travelling, which allows to use walking, bus, tram, metro and train. A small radius is expected to result in a higher share of the walking travel time in the total travel time, while a high radius is expected to decrease the relative contribution of the time spent walking and favour locations close to railway stations, as they allow travelling by train. Therefore, the same evaluation has been performed for different values of R in section 4.3.3.4.

4.3.3.4 Recommendation on the radius

As discussed in the paragraph above, this section is devoted to the analysis of the influence of the radius R on the indicator for mobility by transit that was introduced in section 4.3.1. The considered values of R are ranging from $1\ km$ to $25\ km$.

The maps showing the results of the mobility evaluation can be found in Appendix B. As was the case in section 4.3.3.2, next to the travel time based mobility indicator, the travel distance has been mapped as well, as it can be useful to illustrate how the different values of R influence the results.

It's clear that for $R = 1\ km$, the recommended route often doesn't include the use of any transit mode. Reaching the destination by only walking or by using one other single mode of transport will be the fastest. The road density has a high influence on the mobility measure. The values for the distance travelled are very close to one another for most locations.

Increasing the radius R from $1\ km$ to $2.5\ km$, immediately a higher variation in the travelled distance is observed and locations closer to the centre of Brussels start to stand out for their higher mobility by transit. This observation becomes even clearer as the radius R increases further.

As the used radius R passes from $10\ km$ to $15\ km$ and higher, the locations with high mobility start to shift towards the Central and North railway stations. This tipping point can be explained by an increase in the number of routes involving the train as travel mode, complemented with the immediate access to tram, metro and bus at these locations, allowing to travel quite fast in the cardinal directions where trains are not traveling to.

If one wants to evaluate mobility in the Capital region using the approach and measure described in section 4.3 Evaluating a location on mobility, a weighted average of the results of several radii R could be considered in order to let the measure include both short and long distance transit opportunities. This would however even further augment the required amount of data for the evaluation procedure, which was already high for the examples included in this report.

A recommendation to others trying to use this approach on the same or other locations, would be to identify the tipping point, where still both short and long distance transit opportunities influence the results, but a radius below or above this value would start to favour either short or long distance transit usage. The choice can be made to evaluate locations with a focus on either short or long transit routes. However in this study, the aim is to construct an indicator based on a wide variety of route durations and distances. This approach is relevant when evaluating the locations of for example office or retail buildings.

The radius R is best chosen before starting the data collection and aggregation process. A pre-study with a low resolution and low value for N might be helpful to evaluate a chosen radius R and decide whether to change this value or not before proceeding to the final simulations.

4.3.4 Evaluating mobility by car

Section 4.3.3 illustrates how the mobility evaluation procedure can be used for public transportation travel modes. It contains some concepts specific for the considered mode of transport. This section will use the same methodology for the driving travel mode. Concepts and alternative indicators specific to driving, which couldn't be used for transit, can now be evaluated as well.

4.3.4.1 Strategy and definition

The measure formulated before is now concretised to assess mobility by car and other driving modes. The input used in as follows:

Mode	• Driving
Time	• Departure time • A Thursday morning in May, 9 a.m. (UTC+2)
Origin(s)	• Different points of interest, spread equidistantly over the Brussels-Capital Region
Destination(s)	• 15 points at a distance R from the POI

List 4-7 Overview of the input used

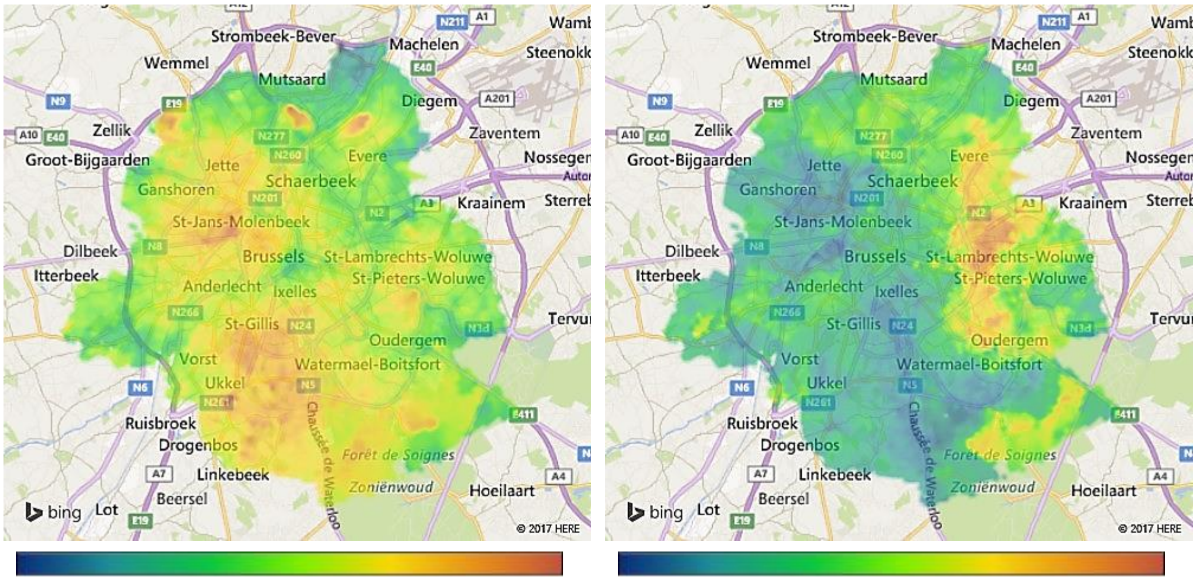
4.3.4.2 Results

The parameters evaluated here are not only travel time and distance. For the driving mode, also the free-flow travel time, the vehicle minutes of delay, Travel Time Index (TTI) and average travel speed were calculated and mapped. These measures were evaluated for radii R in a range from $1\ km$ to $30\ km$. This time, the quantitative time and distance based performance indicator values were represented both as absolute measure and relative to the radius R.

The absolute and relative average travel times and distances are mapped in Figure 4-17 for a radius $R = 10\ km$. Results for different radii and the alternative measures can be found in Appendix C.

Travel time as indicator for mobility by car, $R = 10\ km$

Corresponding travel distance



16.9	[min] 31.1	12.81	[km] 23.01
1.7	[min / km] 3.1	1.28	[-] 2.30

Figure 4-17 Travel time indicator for mobility by car and the corresponding travel distance, absolute and relative values for R = 10 km

4.3.4.3 Discussion

Looking at the visual travel time based indicators (actual and free-flow travel time based indicators), the highest mobility seems to be assigned to locations close to the most major roads (at least for a high enough value of R). Lower mobility is assigned to zones like for example Molenbeek-Saint-Jean and part of the municipality of Uccle. Zooming in on the pentagon, a zone in the east comes forward as a zone with higher mobility by car than the rest of the pentagon. This is the case for small travel distances as well as higher ones. The zone is composed of the surroundings of the part of the small ring between the Avenue de la Toison d'Or or Guldenvlieslaan and the Boulevard Bisschoffsheim or Bisschoffsheimlaan. Traveling from this zone towards the north and the south is thus possible over these roads, while the small ring also provides a way to travel westwards. Also connecting to this zone are the Rue Belliard and Rue de la Loi, providing the connection by car to destinations in the east.

The pattern shown in the map displaying the travel distance measure data is quite different from the travel time based one, illustrating that using a distance based measure instead of a travel time based measure could result in different strategic decisions. The mobility profile of the Brussels-Capital Region based on travel distances suggests that the places with the highest mobility (blue coloured zones in Figure 4-17, right and Figure C-5) are located northwest of the pentagon and in the southern parts of the Region ($R = 10\ km$ and $R = 15\ km$) or northeast, southeast and south of the pentagon, i.a. in Ixelles ($R = 30\ km$). Looking at the map displaying the travel time based indicator, these zones often actually correspond to less mobile locations in terms of travel time (orange to red coloured zones on the maps). It needs to be emphasised that travel distance should only be used to construct a mobility indicator if travel times can't be calculated. The data displayed in this document clearly illustrated that basing a mobility indicator only on travel distance should not be recommended.

Figure C-6 shows the average travel speeds on the routes.[13] These maps are key in illustrating the comment in the previous paragraph and understanding how travel time and travel distance are related. The indicators constructed with $R = 10\ km$ and $R = 15\ km$ illustrate the issue very well. The lowest travel speeds on these maps are found in the zones described earlier, locations with a low travel distance, but a high travel time.[14] Once again, this measure is helpful to get a deeper understanding of the mobility profile, but it's not recommended to base a mobility assessment of a location only on this indicator.

Only the minimum and maximum values can be found in the colour scale of the figures in Appendix C. The average values for the Brussels-Capital Region are displayed in Figure 4-18 and Figure 4-19 (main and alternative travel time based indicators) and in Appendix D (other alternative indicators) for different values of R. Since the evaluated points are spread equidistantly over the Brussels-Capital region, the average over the evaluated points is a valuable value. The average value would be distorted if the concentration of points of interest would not be constant throughout the investigated region and no proper weighting would be introduced to compensate for this issue.

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[13] In previous maps, the lowest indicator values represented lower time or less distance and therefore more appealing locations. In the case of travel speeds, the relation between the measure and the attractiveness of the location is reversed. The blue coloured zones in Figure C-6 are related to less appealing locations, the orange to red coloured zones to higher mobility and thus to more appealing locations. The choice was made to maintain a consistent relation between colour scale and numeric values by continuing assigning the blue colour to low numeric values.

[14] When the values the indicators take for specific locations in the Brussels-Capital Region are referred to qualitatively as either big, small, high or low – as is the case here – one should understand that the comparison has been made to other locations in the Region, rather than to locations further away or even locations in other countries. How the Region compares to other parts of Belgium and to cities in other countries has not been included in the scope of this project yet, as the priority of this study was given to being able to compare different locations in the Brussels-Capital Region.

Both from the visual representations and from the numeric values, it is concluded that the smallest used radii R, $1\ km$ and $2.5\ km$, do not lead to representative measures for mobility by car in the Capital Region. The reason is that distances as small as these are far less likely to be travelled by car than by other modes of transport. Therefore, the indicators based on these relatively small radii R should be investigated with scepticism. When the relative regional average travel distance indicator values are investigated, it is observed that these values are relatively high for these low values of R, compared to the values for higher radii. This is certainly in accordance with expectations, as the distance added to the route due to traveling to the exact origin and destination point, relative to the total distance travelled is higher for the shortest travel routes, rendering the resulting indicators to be less representative. The same can be said for travel times, with the additional remark that another mechanism adds to their sensitivity to the radius R. As travel routes become longer, the chance of them including roads that allow to travel at higher speed – consequently roads with a high maximum speed limit (limited-access roads and highways) – becomes bigger, as well as the share of the distance travelled over these roads in the total distance to travel. This sensitivity to R is reflected quite well in figures Figure 4-18 and Figure 4-19. Figure 4-18 clearly shows that the absolute travel times' second derivatives to R are negative. An increase in R causes an increase in the travel time measures, but the increase itself diminishes with increasing R. This is normal, as one would expect the derivative of the travel time measures' value to R to be constant in the limit. Looking at Figure 4-19 this reasoning can be taken even one step further. The travel time, relative to R, decreases with R (this is related to the absolute travel times' negative second derivatives), but also this effect diminishes with increasing R. This is reflected mathematically in the positive second derivative to R of the relative travel time indicators.

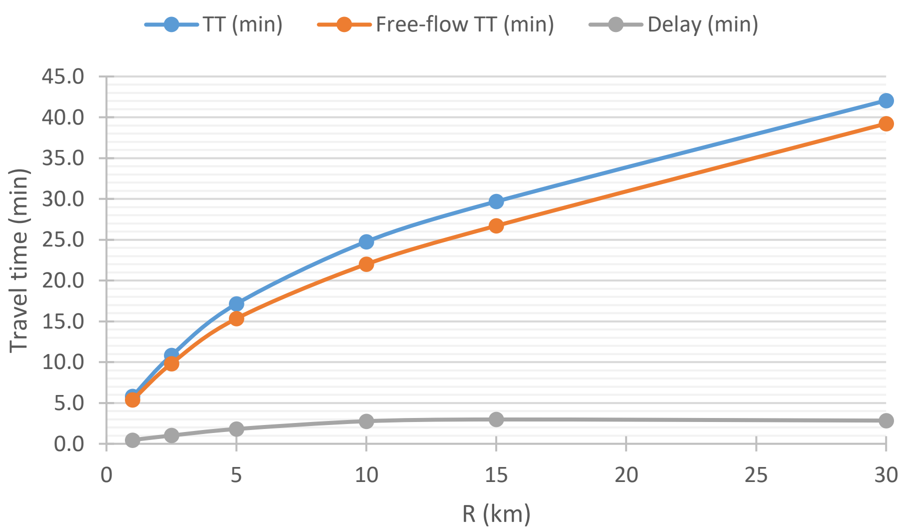

Figure 4-18 Regional average travel time, free-flow travel time and minutes of delay as indicators for mobility, as a function of the adopted radius R – absolute values

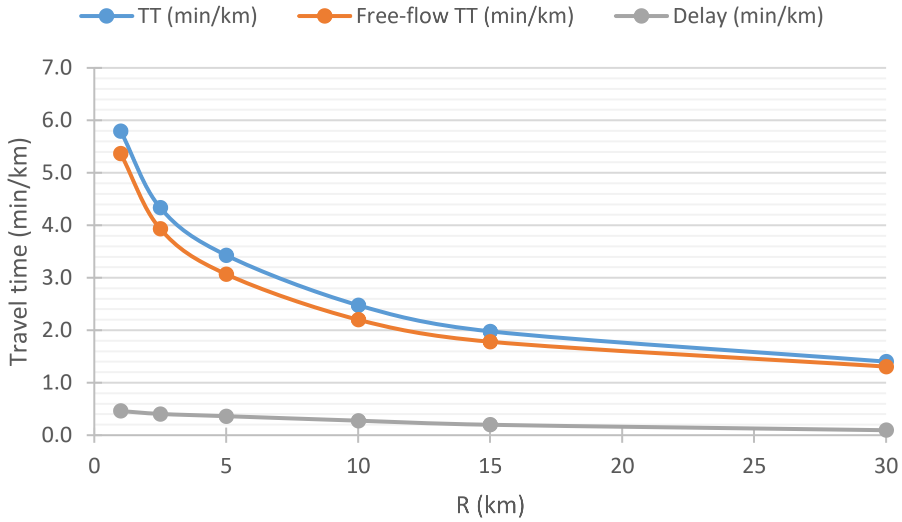

Figure 4-19 Regional average travel time, free-flow travel time and minutes of delay as indicators for mobility, as a function of the adopted radius R – relative values

4.3.4.4 Recommendation on the radius

An explicit recommendation on the radius to adopt in a mobility study in the form of one numeric value for R will not be formulated, as any such recommendation would be flawed or characterised by a weakness somehow. Before making strategic decisions based on an indicator constructed using the described procedure, one should decide whether to evaluate mobility on long or short travel distances or routes. The best recommendation that can be formulated, is to base the choice on data on the (average) distance of displacements made by car, obtained either from a survey or from another reliable source, like for example data collected from navigation devices.

However, when such data can't be obtained or isn't suitable in the context of the study, a substantiated recommendation for high values of R can be formulated. As R increases, the length of the route taken, measured in units of time or as a distance, will increase. A large share of this route will be common for several points of interest. Therefore, the absolute difference between the measure's values at these points of interest might start to become more representative for the immediate surroundings of these points of interest. Some future applications of this methodology might have to be preceeded by a convergence study.

4.4 Final accessibility performance indicators

The research in the sections up to this point has been dedicated to the development of a methodology to evaluate a location's accessibility and mobility. This section introduces an aggregated accessibility performance measure, integrating secondary quantitative commuting information. The methodology includes an aggregation process of a lot of strategically chosen data.

4.4.1 Strategy

The developed methodology to assess the accessibility of a work location from different places of residence from section 4.1.6 requires the choice of the right origin points. For the resulting indicator to be representative for reality, it's key that these origin points are numerous and that the division is a good representation of reality. To fulfil both conditions, the choice of the origin points is based on recent quantitative commuting data, specific for home-work displacements to the Brussels-Capital

Region. An overview of possible sources to consider has already been given in section 2.2.2 Commuting to Brussels: secondary data.

The Diagnostics of workers' commuting movements discussed in section 2.2.2.3 was chosen to be used in this process. The availability of the table containing a full origin-destination matrix on a municipal level of detail on the destination side, with the origin side detailed up to the last digit in the postal code, complete with modal distribution for every origin-destination combination, was decisive in the choice of the secondary data source. The way the modal split is represented in this secondary data source is too detailed to be used in the context of this study, which is why a new division has been conceived: the mode named "public transport" or "transit" aggregates the data that is given on the level of the providers rather than on the level of the sub modes: "train" or "NMBS/SNCB", "De Lijn", "TEC" and "MIVB", while the mode named "driving" aggregates the sub modes "car", "carpooling" and "motorcycle". The latter may also be referred to as "by car".

The quantitative origin-destination matrix from the Diagnostics of workers' commuting movements, obtained from the federal government, serves as secondary data source, providing the weighting for a weighted average aggregation of the primary data generated for this research. For the public transport mode, point-to-point travel times and distances were computed for routes with 1083 different origin points in Belgium to different destinations in the Brussels-Capital Region. The same simulations have been performed for the driving travel mode. For this mode, next to travel time and travel distance measures, also free-flow travel time, minutes of delay, the Travel Time Index and average travel speed have been calculated. As was the case for the mobility indicators evaluated before, these additional or alternative indicators will help with the interpretation of the travel time and distance based indicators and the relation between these indicators.

Mode
- Transit
- Driving

Time
- Departure time
- A Thursday morning in May, 8 a.m. (UTC+2)

Origin(s)
- 1083 different origin points in Belgium

Destination(s)
- 2500 different points in Brussels, arranged on two interlocking rectangular grids
- Latitude and longitude ranging in the intervals:
  - Latitude interval: [50.8045, 50.8934]
  - Longitude interval: [4.3097, 4.4446]

List 4-8 Overview of the input used

4.4.2 Accessibility definition

This subsection has been devoted to the illustration of how the accessibility indicator composed to perform the final office building location accessibility assessment as well as to generate the final accessibility map for the Brussels-Capital Region relates to the gravity-based measure introduced in section 2.1.6.2. The general formula from section 2.1.6.2 is repeated below:

$$A_{im} = \sum_j O_j\, f\left(C_{ijm}\right)$$

In the case-specific form below, the abstract parameters have been concretised:

$$A_{i,\text{transit}} = \sum_j O_j\, f\left(C_{ij,\text{transit}}\right) = \sum_{j=1}^{1083} \frac{n_j}{N} \cdot t_{ji,\text{transit}}$$

$A_{im} = A_{i,\text{transit}}$	Accessibility from home to work by transit, measured at point i
$O_j = \frac{n_j}{N}$	The number of displacements from point j to the Brussels-Capital Region, relative to the total number of displacements to the Brussels-Capital Region. $O_j = n_j$ could be used as well, but the factor $1/N$ is included in the formula to normalise the weight vector.
$f\left(C_{ijm}\right) = t_{ji,\text{transit}}$	As cost function, the travel time by transit from the point of origin j (place of residence of an employee) to the point of interest i is used.

Another way to look at the definition of the accessibility measure used and its relation to the gravity-based measure is by taking the sum over the individual commuting displacements instead of taking the sum over the different places of residence of the commuters:

$$A_{i,\text{transit}} = \sum_j O_j\, f\left(C_{ij,\text{transit}}\right) = \sum_{j=1}^{J} \frac{1}{J} \cdot t_{ji,\text{transit}} = \frac{1}{J} \sum_{j=1}^{J} t_{j,i,\text{transit}}$$

By calculating the sum over all the commuting displacements to the Region (J in number) and by giving each of the individual displacements an equal weight (the time loss of every employee or commuter is equally important), the same aggregated indicator can be composed. Whether the indicator is composed by giving every individual commuter or every individual commuting displacement the same weight or by dividing them into groups and giving every group a weight linear to the number of individuals it is composed of, the resulting measure will take the same form and numeric value.

The summation can also be defined as a summation over all the inhabitants of the country, where the parameter O_j is a binary parameter that only takes a value different from 0 for inhabitants who commute to their location of employment using the considered travel mode. A normalisation is then performed by dividing by the total number of individuals for whom O_j took a value different from 0.

The relation to the 4 components of accessibility introduced in section 2.1.4 can also be illustrated:

The transportation component, land use component and temporal component are all considered in the computation of the point-to-point travel times. It has been mentioned before that the computation of travel times automatically integrates other parameters that are at themselves more difficult to study, which was part of the reason why travel time has been chosen as main source of information in the composition of the developed accessibility and mobility indicators. The individual component of accessibility has been included in the definition of the opportunities O_j as well as in the computation of the travel times, which serves as cost function. For public transport, the availability of the travel mode close to the place of residence of an individual commuter is reflected in the travel time, while the individual needs are reflected in the opportunity O_j, which has been set different to zero only for individuals who need to commute from their place of residence to the Brussels-Capital Region.

The definition and the concretisation of the generic formulation is the same for the driving travel mode.

4.4.3 Transit

4.4.3.1 Results

The results for the public transport or transit mode are mapped in Figure 4-20. One single map shows the spatial accessibility profile of part of the Brussels-Capital Region with an acceptable resolution. The information displayed in one of these maps is the result of the aggregation of around 2.5 million individual point-to-point travel parameter values, as the numeric values displayed in a map is in essence the weighted average of 1083 individual maps with travel data for a single point of origin, like the maps displayed in sections 4.1.1 to 4.1.5.

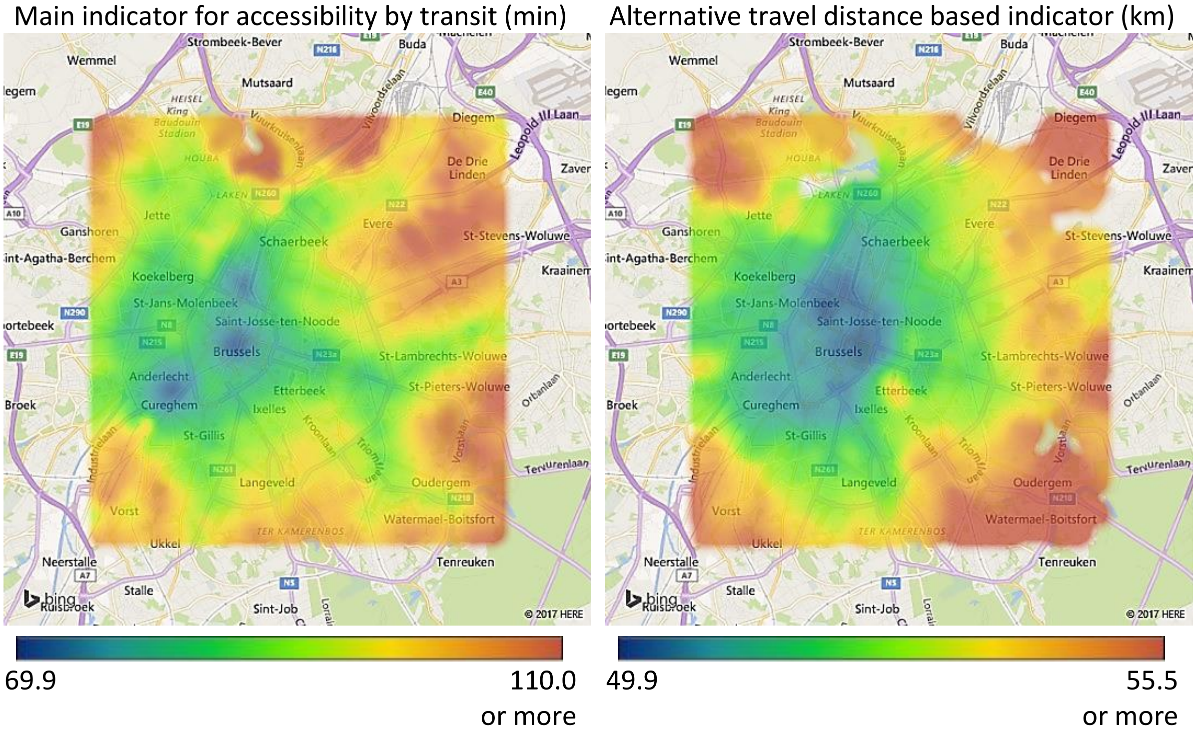

Figure 4-20 Final travel time based indicator for accessibility by public transport and the travel distance based alternative indicator

4.4.3.2 Discussion

Once again, a distinct one-to-one relationship between both the travel time based indicator and the travel distance based alternative does not exist, while it must be said that these maps do show some similarities in the accessibility profile displayed. Due to the complete and all-embracing nature of the adopted travel-time based measure, the developed map can be used to compare different possible office building locations in Brussels in both a qualitative or quantitative way. When 2 or more locations are difficult to compare due to the different nature of transit opportunities in their immediate surroundings, this map can provide a way out of this predicament by giving an answer based on the total time spent by employees all over the country to reach this location, a parameter that can be directly related to the attractiveness of the investigated locations.

The most attractive locations based on the total time spent by possible employees who come to work by public transport are – as could be expected – in the immediate surroundings of the North, Central and South railway stations. These locations do show a relatively low value for the weighted average distance travelled, although the zones with the lowest values do not match fully for both indicators.

Whereas the blue coloured areas on the map displaying the travel time based indicator are located around the most important train stations, the green coloured area seems to be extending from the centre of the city in the same directions as the metro lines have been laid out. The computed indicator results displayed on the map gives the impression that the mapped area was chosen large enough to cover the most attractive locations in terms of accessibility by public transport.

The location with the absolute minimal travel time by public transport is very interesting for a company in search for the best location to be an attractive employer for people working in the Brussels-Capital Region. This location should be the most attractive to the average employee working in Brussels and commuting by transit. Based on the computed travel time based indicator for accessibility by public transport, this absolute minimum in travel time is found at the South Station. This confirms that the buildings occupied by NMBS/SNCB at Frankrijkstraat or Rue de France are indeed very attractive work locations. The same can be said for the Zuidertoren or Tour du Midi, occupied by the Belgian Pensions Administration, as well as for example the Eurostation II office building located at Victor Horta Square 40, currently occupied by the Federal Public Service Health, Food chain safety and Environment and the Federal Public Service Employment, Labour and Social Dialogue, and of course the station itself, the shops located in the station and the signal box at Brussels-South.

4.4.4 Driving

4.4.4.1 Results

The results for the driving mode are displayed in Figure 4-21, Figure 4-22 and Figure 4-23.

Next to the main travel time based indicator, indicators based on free-flow travel time, minutes of delay, Travel Time Index, travel distance and average travel speed have also been evaluated, resulting in a total of 6 maps.

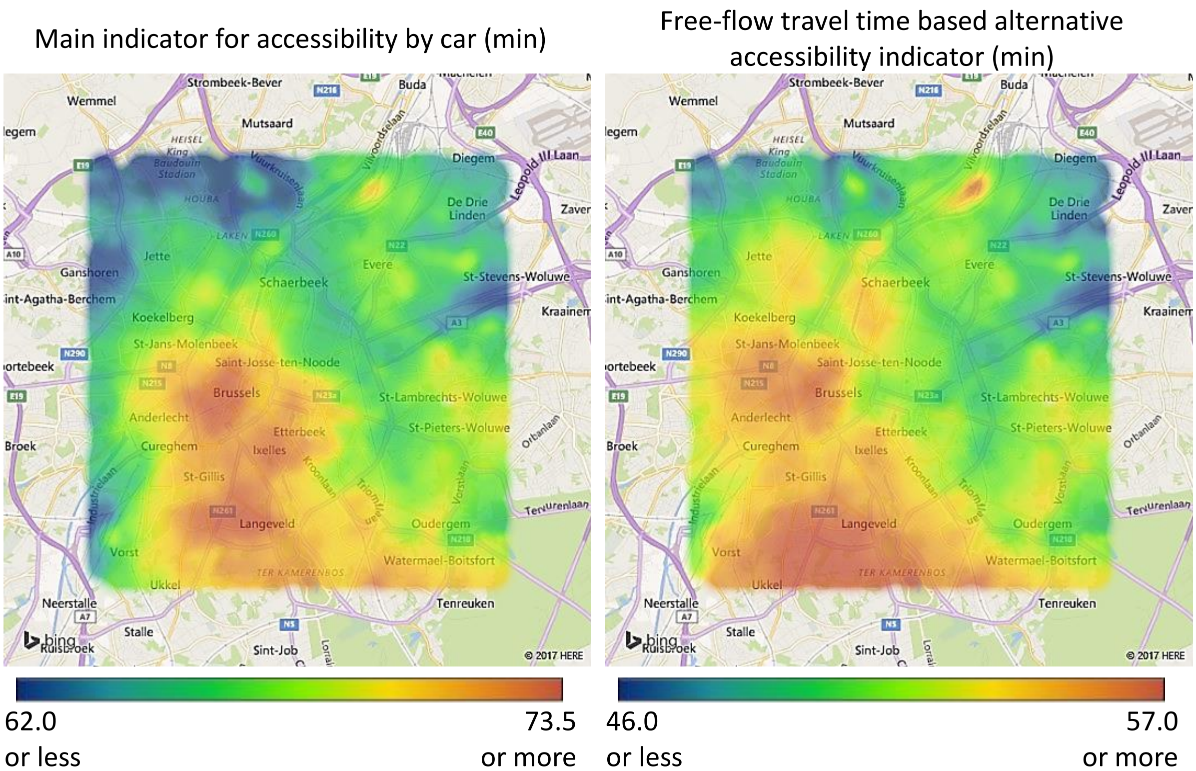

Figure 4-21 Final travel time based and alternative indicators for accessibility by car (1)

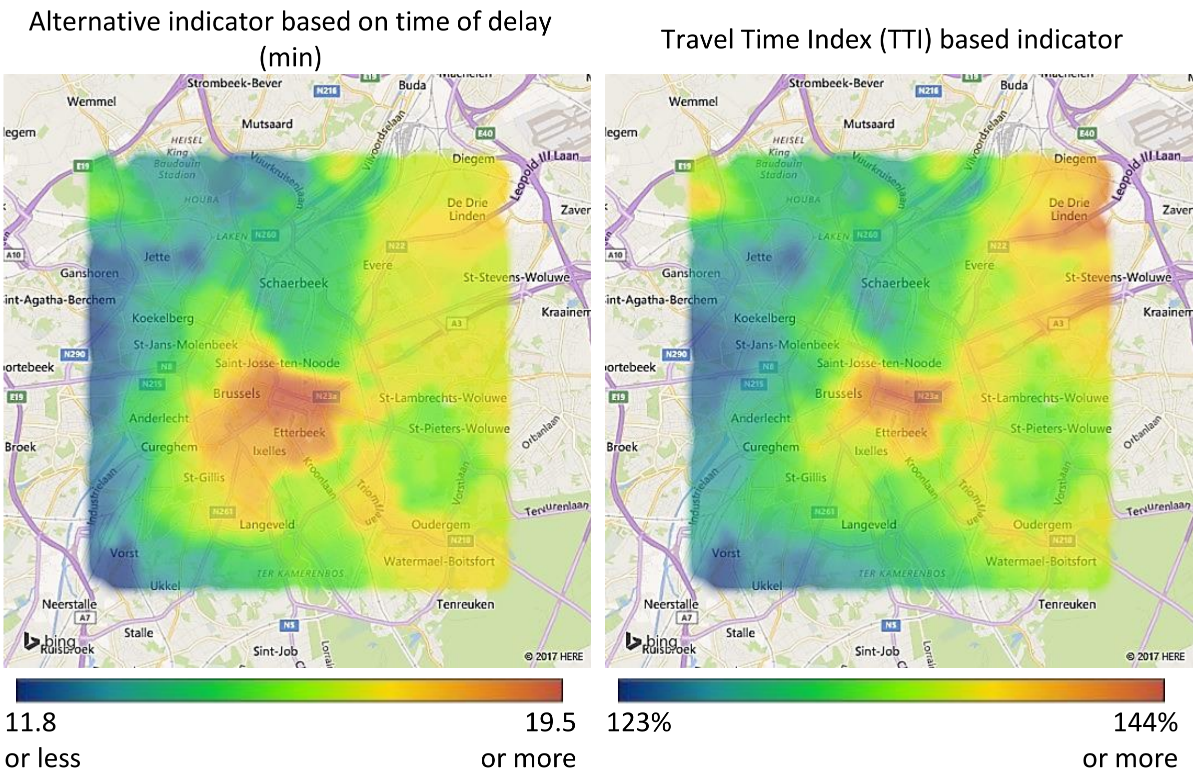

Figure 4-22 Final travel time based and alternative indicators for accessibility by car (2)

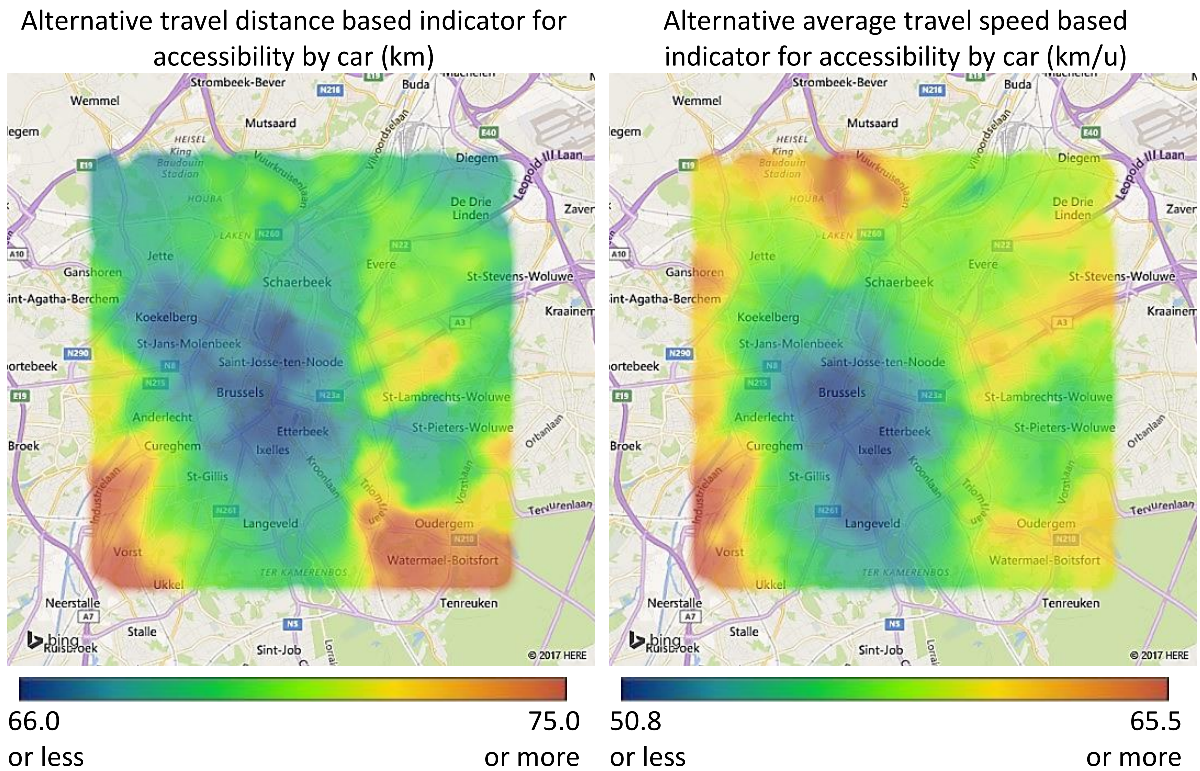

Figure 4-23 Final travel time based and alternative indicators for accessibility by car (3)

4.4.4.2 Discussion

There is clearly a difference between the travel time and travel distance based performance indicators. Whereas both indicators' profiles were somewhat similar on the map in the case of public transport, the maps with the indicators for accessibility by car show completely different patterns for both indicators. The alternative average travel speed based indicator illustrates quite well how the relationship between the two indicators can be explained. Zones with high travel times and low travel distances are located in and around the centre of the Capital Region. One would expect the average travel speed indicator to take low values in these zones, which it does. Locations with a low travel time and high travel distance, which can for example be found in the most southwest part of the mapped area, should correspond to zones with a high average travel speed. Looking at the map on the right of Figure 4-23, they do.

The alternative indicators based on time of delay and Travel Time Index (Figure 4-22) show that congestion is the most problematic when traveling to the western part of the pentagon and just west of the Brussels small ring. It's normal that these indicators show higher values in the centre of a city than at its edges, but it's interesting to observe that the blue zones in the map displaying the travel time based indicator can correspond to either a relatively low TTI (most northwest part of the mapped area) or a relatively high TTI (locations along the A3). These zones have a high accessibility by car thanks to respectively the combination of a relatively low free-flow travel time and a relatively low increase in travel time due to congestion and the combination of a very low free-flow travel time with a significant increase in travel time due to congestion.

Identifying the most attractive places to locate a company's offices should be done based on the travel time based measure. A numeric value that project developers should show interest for, is the location with the absolute minimum travel time by car. This location should represent the work place most attractive to the average employee working in Brussels and commuting by car. Within the considered boundaries this is in the Avenue de Madrid or Madridlaan, close to the Belvédère Castle. Since this location is at the edge of the mapped area, the relevance of extending this area might be significant. The absolute minimum could well be located outside the mapped area. The area was originally chosen to cover at least the locations best accessible by public transport. For accessibility by car, the Brussels Ring, R0, and its surroundings should certainly be included in the search. Therefore, the spatial boundaries will be changed to include a bigger area, as illustrated in Figure 4-24 Extending the mapped area, and additional calculations will be performed to evaluate the developed measures for these additional locations. Keeping the same resolution would result in unacceptable data requirement. The resolution was thus lowered in the added area. The circle considered at this point has a diameter of around 20 km and thus a surface area of around 314 km^2.

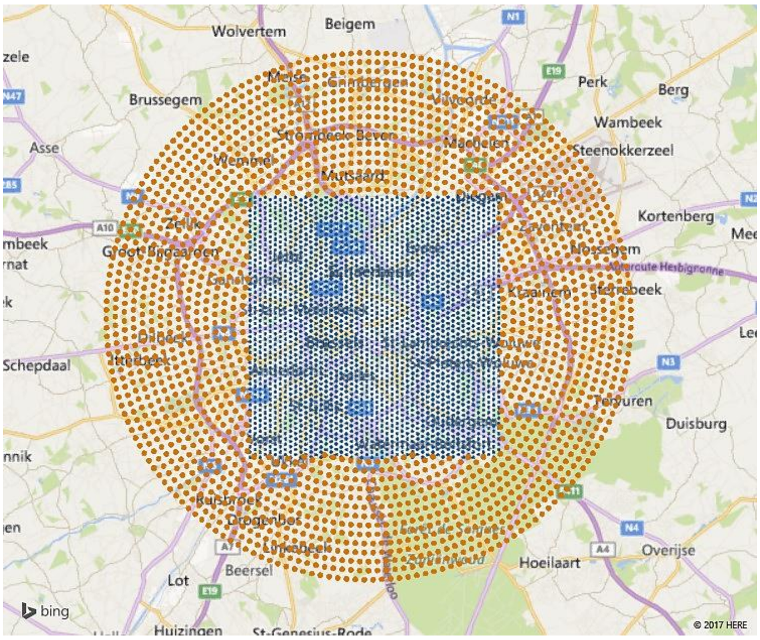

Figure 4-24 Extending the mapped area

4.4.5 Transit, extended area

Although the extension to the mapped area proposed at the end of the previous section was initially not essential when mapping the travel time based indicator for accessibility by public transport, the numeric value of this indicator was computed, as illustrated in Figure 4-25. On the left, the figure shows a map that adopts the same colour scale as used before (Figure 4-20, left), while the map on the right was composed using a colour scale more suitable for the extended data set. 2 zones in Flanders, outside the area defined by the Brussels Ring, are identified as relatively well accessible by public transport: the Brussels National Airport and Vilvoorde. Both these locations' accessibility is mainly thanks to their train station. The two locations are served by multiple bus lines as well.

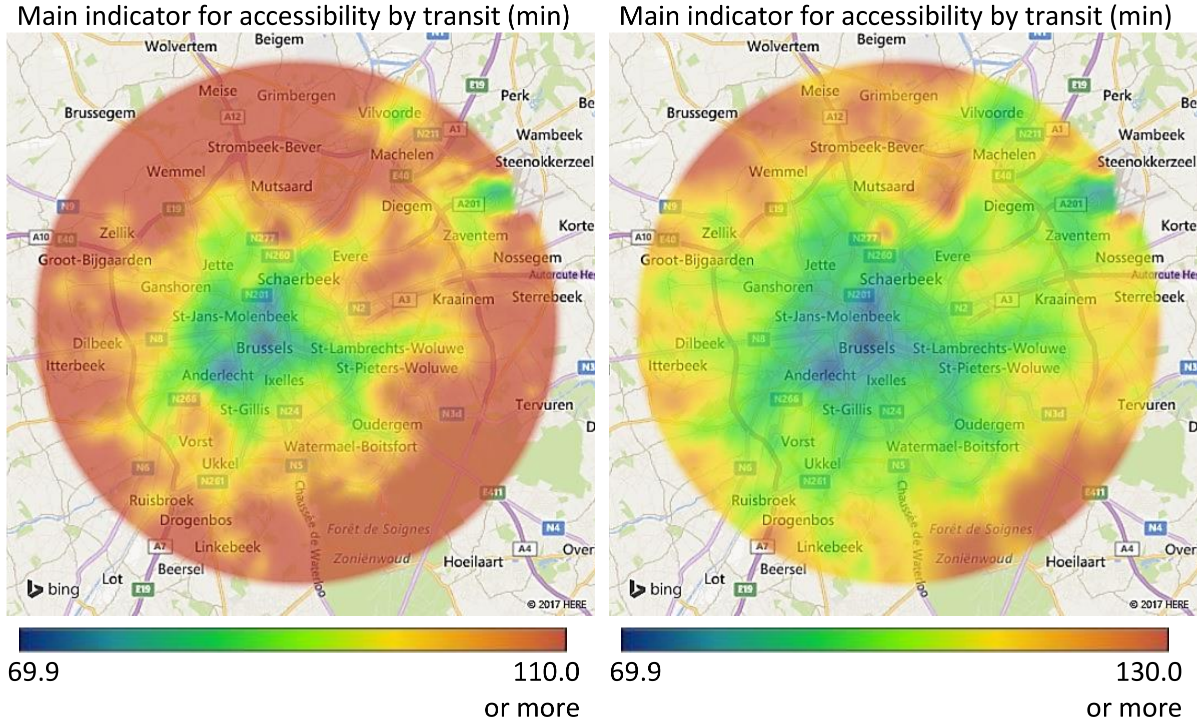

Figure 4-25 Final travel time based indicator for accessibility by public transport, extended area

4.4.6 Driving, extended area

The figures below display the numeric values of the main and alternative measures for accessibility by car. Based on the developed model and indicator, another location with the same absolute minimal average travel time is identified at the exit of the E19 in Dilbeek, a municipality in the province of Flemish Brabant. The difference in average travel time with the location at the Avenue de Madrid or Madridlaan is negligible. Also, the difference in travel time with the other blue coloured zones is very small.

As expected, mostly locations along the Brussels Ring show excellent accessibility. Additional places that come forward as well accessible are located near the interchange Groot-Bijgaarden and the Strombeek-Bever interchange. Some known industrial sites and business sites can be identified here, like Researchpark Zellik (Asse), Industrial Zone 3 Doornveld (Asse), the new Business Park West Gate (Groot-Bijgaarden) and Business Site Strombeek-Bever West.

A pattern that couldn't be identified as clearly before extending the mapped area, is now very prominent in Figure 4-27, Figure 4-28 and Figure 4-29. The developed indicators suggest that the share of the morning peak commuting travel time that's due to traffic delay or congestion on the Brussels Ring is more problematic on the part between Machelen and Leonard (east of the Capital Region) than on the part between Stombeek-Bever and Halle (west of the Region). To illustrate the parts of the Brussels Ring discussed, Figure 4-26, which has been obtained from the Flemish Traffic Centre, is included in this document. It shows the Brussels Ring as a set of motorway sections connecting 7 important nodes. [30] All 6 indicators serve their part in illustrating this observation. The travel time based indicator shows shorter travel times to destinations along the part between Strombeek-Bever and Halle, while the free-flow travel time based indicator shows that when delays would not be taken into consideration, there would be no significant difference. The time of delay and TTI show that both the absolute and relative delay times are larger for destinations along the part connecting Machelen and Leonard. The travel distances do not differ significantly. Average route travel speeds are higher for a destination on the part connecting Stombeek-Bever and Halle. This observation confirms the value of the alternative accessibility measures, as they can serve as part of the answer to certain questions.

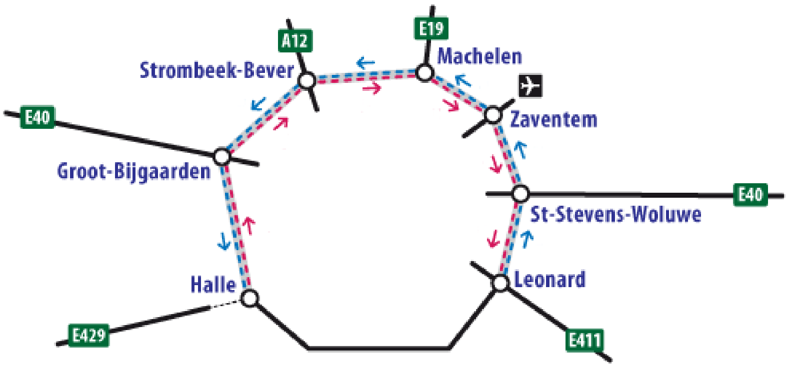

Figure 4-26 The Brussels Ring, source: Flemish Traffic Centre [30]

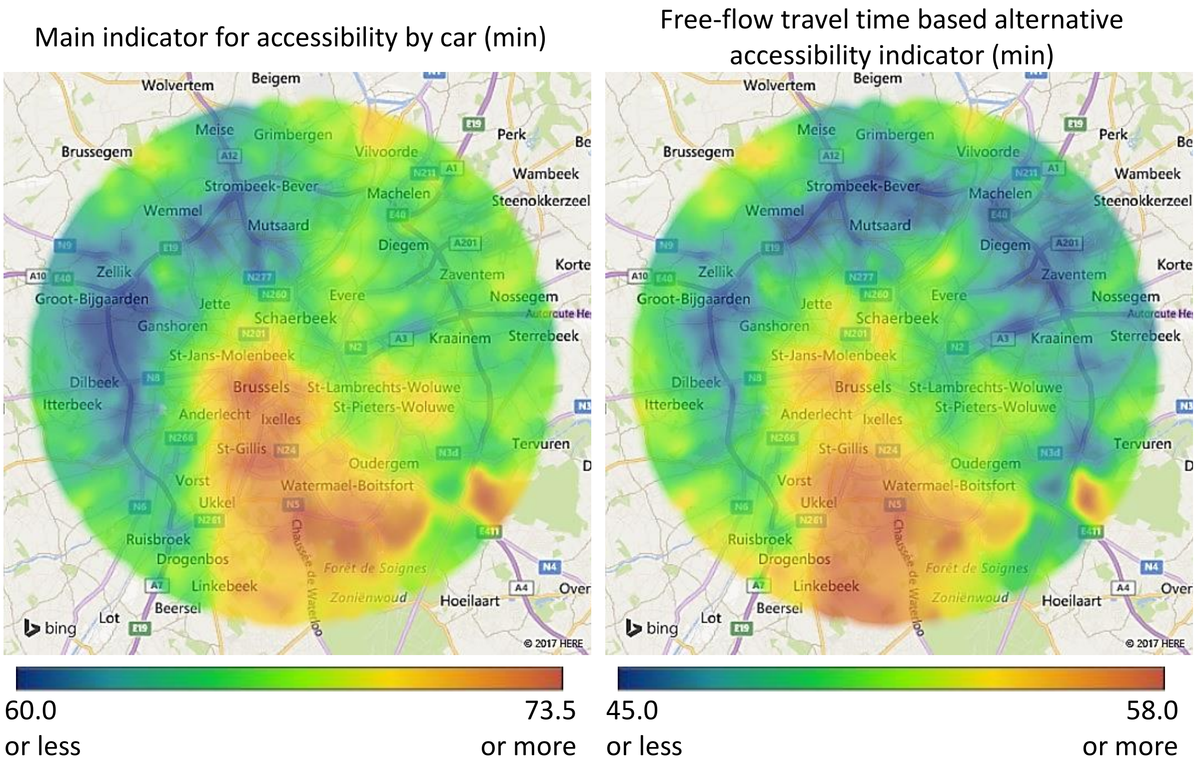

Figure 4-27 Final travel time based and alternative indicators for accessibility by car, extended area (1)

Alternative indicator based on time of delay (min)

Travel Time Index (TTI) based indicator

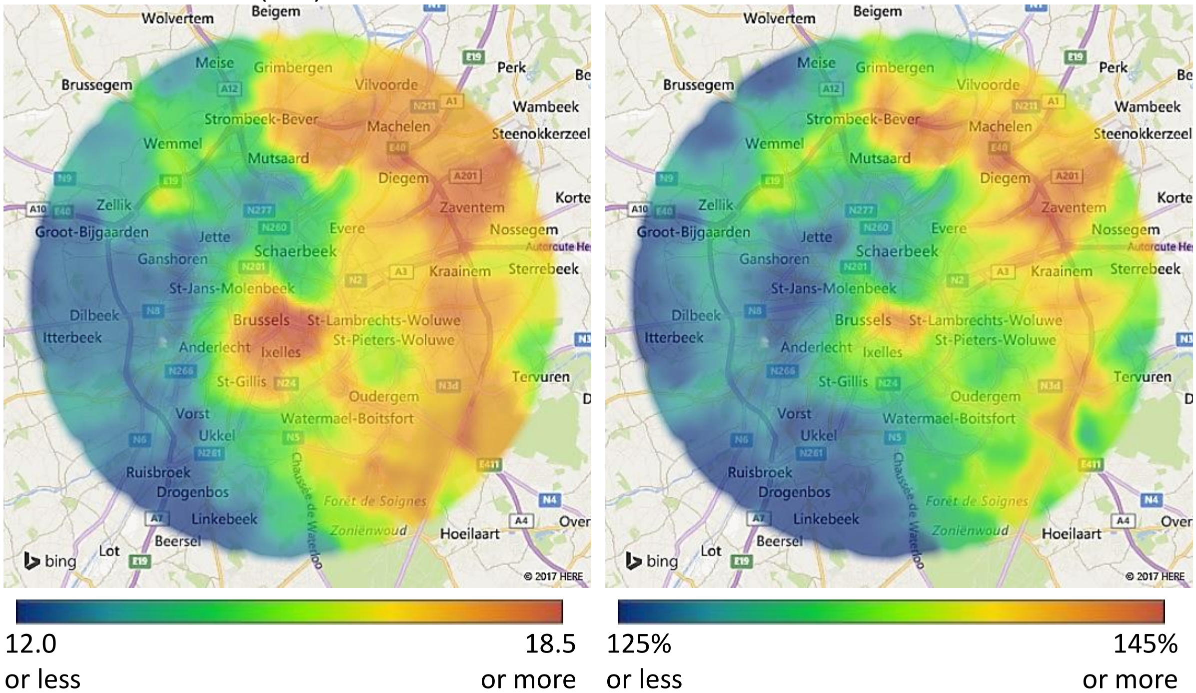

Figure 4-28 Final travel time based and alternative indicators for accessibility by car, extended area (2)

Alternative travel distance based indicator for accessibility by car (km)

Alternative average travel speed based indicator for accessibility by car (km/u)

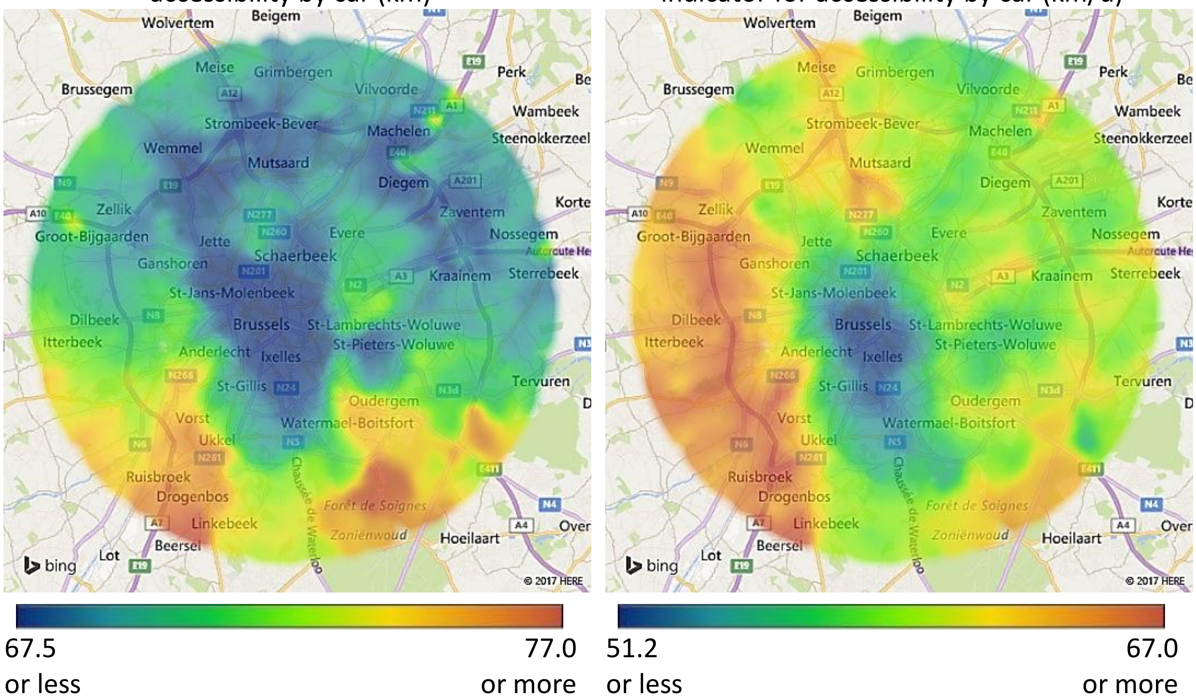

Figure 4-29 Final travel time based and alternative indicators for accessibility by car, extended area (3)

4.4.7 Limitations of the model

Even though a lot of effort was put into making the developed indicators as representative for reality as possible, as with any model, there are still some things that could improve the results. For example: a significant number of people commuting to work by public transport carry part of their journey out by car or by bicycle. These people make use of transit parking lots or Park and Ride lots and bicycle parking. This practice wasn't incorporated in the model, as the secondary data from the Diagnostics of workers' commuting movements used to perform the aggregation of the individual travel times only provides the main commuting mode used. The practice of carrying out part of the trip by car will probably lead to an overestimation in the average travel time by transit. The overestimation will however be roughly the same for every point of interest. Besides, in most applications, the difference in average transit travel time between certain points of interest will be used to make decisions and not the absolute value of transit travel time.

A second limitation is that the set of commuting displacements used to compose the weight vector for the aggregation of the individual travel times only includes commuting displacements from places of residence in Belgium. While most of the commuting displacements will be covered this way, some people working in the Brussels-Capital Region don't live in Belgium. For the public transport mode, taking these additional international train journeys into account would probably increase the absolute average transit travel time a little. Since international train journeys arrive at the South Station, locations around this station would gain some attractiveness.

Finally, one could consider taking displacements from Brussels Airport and Brussels South Charleroi Airport to the Brussels-Capital Region into account. Most of these displacements don't occur on a daily basis, which is why their weighting should be chosen carefully.

4.4.8 Simulating a variation in the employees' places of residence

The goal of this section is to study if the developed accessibility indicators are sensitive to changes in the commuting pattern of the Belgian employees used for the data aggregation. The effect of a change in the employees' places of residence will be studied based on a fictitious, randomly generated staff turnover. When basing strategic decision on the developed accessibility indicator, one would like the accessibility profile of the Brussels-Capital Region to be as insensitive as possible to changes in the company's work force.

A 30% staff turnover was randomly generated, with a turnover chance that's higher for the commuters with a place of residence further away from Brussels. The change in the numeric values of the developed accessibility indicators was observed. The observation was made that, while the absolute values of the accessibility indicators did change significantly due to the elimination of the longest travel times, the general profile for the Brussels Capital Region remained almost unaffected. It has already been mentioned that for most decision-making application, the absolute values are not that important, since mainly differences between the accessibility of multiple locations will be studied. Appendix E contains a visual comparison between the original spatial accessibility profile of the Region and the accessibility profile after the introduction of 30% turnover. Only a very subtle colour difference can be observed. Introducing a 30% turnover for an indicator generated for a specific company might result in a more visible change in the accessibility profile.

4.4.9 Possible applications of the accessibility maps

The graphical representation of the numeric values of the final accessibility indicators in section 4.4 is an accessibility map that can serve as an aid in strategic location decisions. The two maps that were created, display the numeric values of the final travel time based indicators for accessibility by public transport and accessibility by car. These maps provide a partial answer to the demand for an accessibility map formulated in the IRIS 2 mobility plan.

The maps can be used to evaluate the relevance of the location of existing and new projects to the destination or intended use of the project in terms of accessibility, providing a way to easily compare the accessibility of several locations.

Next to strategic location decisions, the maps can be useful for future government policy and spatial planning processes. The maps can for example help in the process of defining ambitious, but realistic objectives for the desired modal distribution in specific zones. The measure for accessibility by public transport can be used to identify locations suitable for transit-oriented development.

It's important to realise that the numeric values of the accessibility indicators are not constant over time. Performing the same simulations in a few years would be very useful. Due to road infrastructure works, changes in public transport services like the introduction of new tram lines and possible changes in commuting preferences, the results might change over time. Since the execution of the procedure has been automated, it would not even be that much work to make a new evaluation in a few years. The next edition of the federal Diagnostics of workers' commuting movements is planned to start on 1 July 2017, so a new origin-destination matrix providing the actual commuting displacements to Brussels will be available soon.

The procedure that was used to obtain the accessibility profile for the Capital Region can easily be adapted to fit the needs of an individual company. Based on the places of residence of the employees and their preferred mode of transport, a map can be generated showing the average or total commuting time of these employees for different possible work locations, identifying the best places for the company to be located at in order to minimise the total commuting time of its employees.

4.5 FINAL MULTI-OBJECTIVE OPTIMISATION

4.5.1 Strategy

The strategy described in section 4.2 was adapted to serve the purpose of identifying the Pareto optimal locations based on the final travel time based indicators for accessibility by public transport and by car described in section 4.4.

The design variables used here were not any longer latitude and longitude of the investigated locations, but the distance r from a point at 50°51'09.4"N 4°22'26.6"E and the angle θ to a fixed horizontal base. A circular design space was defined by imposing upper and lower bounds on the design variables: $0\ km \leq r \leq 10\ km$ and $0° \leq \theta \leq 360°$.

2 objectives were considered, the developed weighted average transit travel time and the weighted average driving travel time indicators. Both objectives are to be minimised.

The population size was set to 400 individuals. The cross-over probability was set to 90%, and the mutation probability to 30%.

The NSGA-II algorithm identifies the Pareto front by letting a population evolve towards the Pareto optimal set. The result will show the most attractive places to locate an office building if only the 2 specified criteria are considered.

4.5.2 Results

Only the initial and the final converged generation are shown in Figure 4-30. A more complete evolution of a random distribution of points in the design space to the converged solution was included in this document as Appendix F.

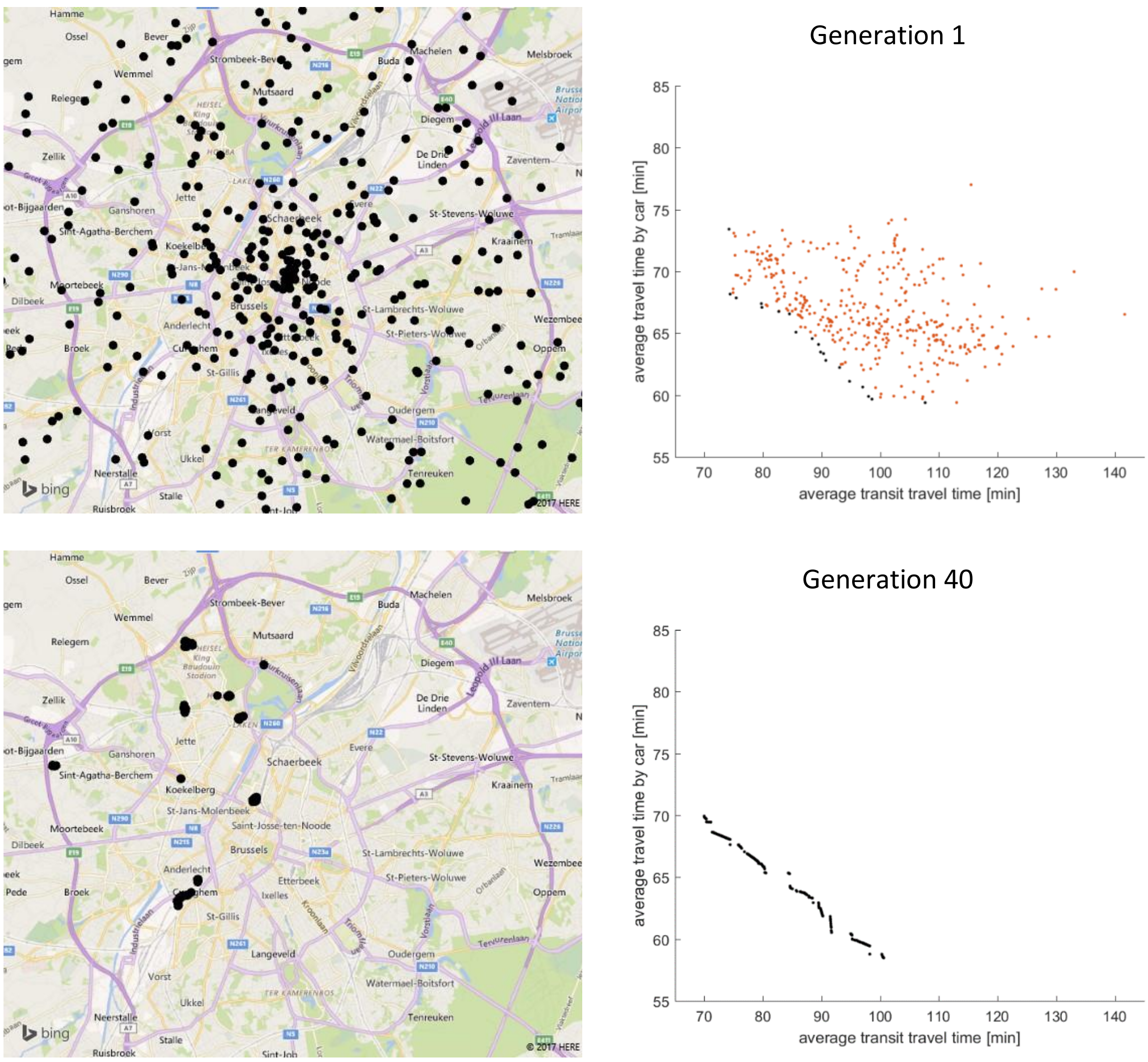

Figure 4-30 NSGA-II optimisation using the final travel time based indicators – generation 1 & 40

4.5.3 Discussion

The identified Pareto optimal locations are the following:

- Locations near the interchange Groot-Bijgaarden;
- Area surrounding the Koning Boudewijn transit stations;
- Area near the transit station De Wand;
- Locations around the Jette Train Station;
- Area near Stuyvenberg;
- Area near the Bockstael transit stops;
- Area near the Simonis transit stop;
- Area between the North Station and Rogier;
- Locations in the immediate surroundings of the South Station, for example at the Horta Square and the Rue de France;
- Locations along the Tweestationsstraat or Rue des Deux Gares, where for example Philips and Infrabel's I-ICT are located.

The obtained results are quite realistic. Qualitative arguments for the performance of this locations of accessibility can always be found.

These are the best possible locations in Brussels based on the 2 evaluated indicators. A certain deviation on the exact location displayed should be allowed. It is however important to emphasise that other (location) criteria should also be considered when making strategic decisions. A third objective, like for example the perceived reputation of an area, crime rate, the quality of the public spaces or the land or real estate prices could be included in the optimisation process, which could then reveal additional Pareto optimal locations. For more internationally or globally oriented companies, travel time from the airport could also be considered, either as a separate criterion or by incorporating this in the form of additional displacements in the aggregation process of the travel time based accessibility indicators. When someone wants to integrate an additional objective in the optimisation process, the availability of a well composed measure for this objective should be considered, as well as the quality and detail of the geospatial data one wants to use for the optimisation. The data should be available on a level that’s detailed enough for the intended purpose.

This multi-objective optimisation procedure is a way to take the variation on modal split for different sectors or companies into account. As was already mentioned in the literature study in section 2.3, a posteriori methods first produce all the Pareto optimal solutions, after which the decision to select one of these Pareto optimal solutions can be made, based on personal preference or additional criteria. When using an optimisation procedure, the identification of the Pareto optimal locations should thus be followed by the selection of one or a few of the produced solutions, where – in the case of location optimisation – a certain deviation should be allowed since a practical and available location within the budget will most likely not correspond exactly to the computed optimal location.

4.6 ADDITIONAL CASE STUDIES

Next to the construction, computation and evaluation of mobility and accessibility indicators for office building location selection in the Brussels-Capital Region, the developed procedure should also be applicable to other practical cases within the same context and within a wider scope. Appendix G provides a list of possible case studies that could be performed using travel time data. These case studies have been chosen, based on personal research interests and questions asked by people in the industry. One of the additional case studies, regarding commuting from Brussels to Paris, was performed during this study. The context, used strategy, results and conclusion of this case study can be found in the same appendix.

5 CONCLUSION

The objective of this thesis was to provide a methodology for a quantitative mobility and accessibility location assessment in the context of the selection of an office building for a company.

The literature study provided an overview of the possible definitions for accessibility and mobility, as well as some generic formulations for possible indicators. Since the geographical scope of this thesis was the Brussels-Capital Region, part of the literature study was also devoted to the IRIS 2 mobility plan and the exploration of existing quantitative data on commuting to the Brussels-Capital Region.

Chapter 3 introduced how the developed accessibility and mobility indicators can be evaluated using a web scaping approach, involving the computation of a large set of point-to-point travel times.

Chapter 4 illustrated how the developed accessibility measure evolved from a measure considering displacements to the Brussels-Capital Region from a single point of origin to a more complex measure and finally to a measure developed using secondary data from the federal government's Diagnostics of workers' commuting movements in its aggregation process. Figure 5-1 illustrates how the final accessibility indicator was composed, combining the primary data obtained in this research with secondary data from the federal government to accomplish the goal of this thesis. Chapter 4 also discussed the development of a methodology to evaluate locations on mobility.

Figure 5-1 Illustration of the development of the final accessibility performance indicator

Based on the developed model, the location in the Brussels-Capital Region with the best accessibility by public transport is found at the South Station. The model also indicates that the locations with high accessibility by car are mainly found around the western part of the Brussels Ring, between Stombeek-Bever and Halle.

The developed travel time based performance indicators for location assessment on the criteria mobility and accessibility provide an answer to the central research question, which was to look for a good way to use accurate travel time estimations to evaluate the location criteria mobility and accessibility quantitatively. Using a web scraping approach, the process of evaluating these performance measures could be automated, providing an answer to the first sub-question.
For this study, Google has been used as travel time data provider, as it is indisputably a company with the assets, capabilities and reputation to be considered among the leading experts in travel time estimation. However, future research and application should not necessarily adopt Google as a provider. It's certainly necessary to consider exploring and comparing other travel time data providers' services.

Another important part of the research was to look at the possibility to compose an accessibility map for the Brussels-Capital Region. The demand for an accessibility map had been formulated in the IRIS 2 mobility plan. [2] A recent study on metropolitan transportation plans mentioned that such a map

was still not developed five years after the publication of the IRIS 2 mobility plan. [12]
Based on the developed travel time based accessibility indicators, two accessibility maps were created, one for accessibility by public transport and one for accessibility by car. These maps provide a partial answer to the demand for an accessibility map formulated in the IRIS 2 mobility plan. The maps can be used to evaluate the relevance of the location of existing and new projects to the destination or intended use of the projects in terms of accessibility. The maps provide a way to easily compare the accessibility of several locations within the Brussels-Capital Region.
Next to strategic location decisions by firms, the maps can be useful for future government policy and spatial planning processes. They can for example help in the process of defining ambitious, but realistic objectives for the desired modal shift in specific zones. The measure for accessibility by public transport can be used to identify locations suitable for transit-oriented development.

A multi-objective optimisation has been carried out, identifying the Pareto optimal places for a company to locate its offices in the Brussels-Capital Region, based on two criteria: accessibility by public transport and accessibility by car. Realistic results were obtained from this optimisation.

The methodology of this study can easily be adapted to create a company specific indicator for accessibility by public transport and by car if the addresses and preferred commuting modes of the employees are known. An accessibility map can be composed and an optimisation can be performed, identifying the Pareto optimal places to locate an office building for this specific company.

Suggestions for additional case studies that can be solved using an approach similar to the methodology demonstrated in this thesis were provided in Appendix G.

Future research in the same domain might be targeted at accounting for people commuting to work mainly by public transport, carrying part of their journey out by car or by bicycle. It would also be useful to perform the same simulations again in the future to study how stable the obtained accessibility profile is over time, since a new origin-destination matrix will be available and the road and transit infrastructure will have changed. Applying the methodology to other cities or at a larger scale would certainly lead to interesting results, as well as creating company specific accessibility maps based on the address list of the existing employees.

Part of the objective of this thesis was to promote future individual and publicly or privately funded studies based on travel time data, which is collected in an automated and properly targeted way. People should develop the reflex to resort to the methods that are most efficient and result in accurate and meaningful data with a low risk of misinterpretation. Research methods should limit as much as possible the possibility to be steered in a predetermined direction. Mainly thanks to the possibility of automatic data gathering and by expressing the developed performance indicators in units of time, which can be interpreted by anyone, the developed travel time based evaluation method lends itself well to meet these requirements.

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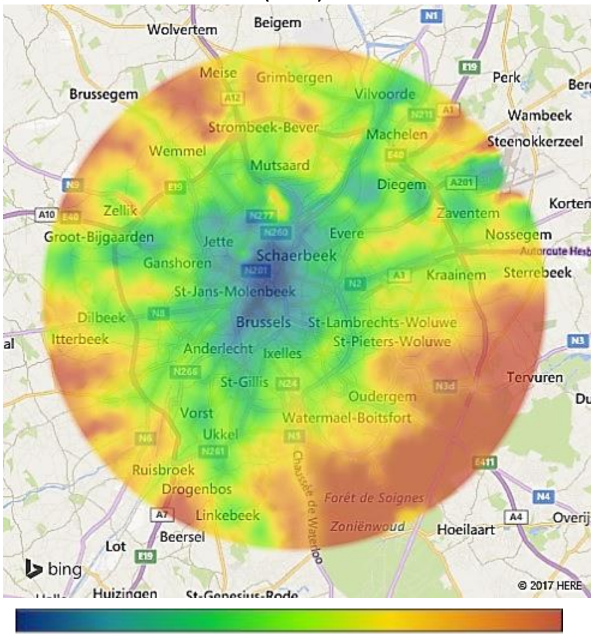
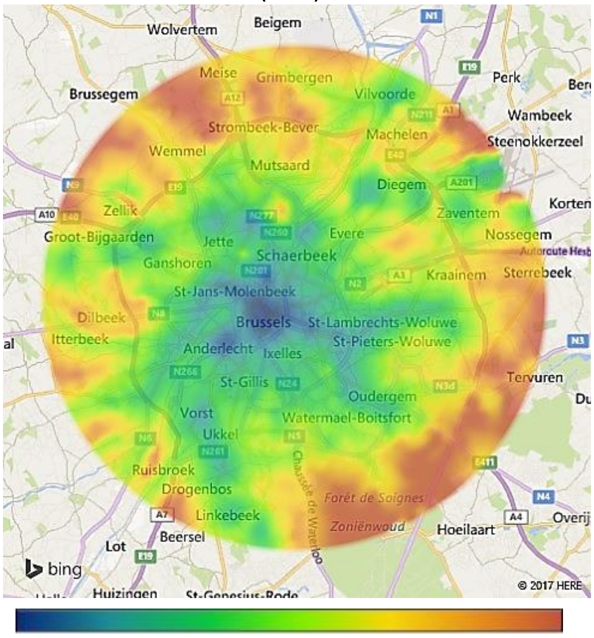
Appendix A ACCESSIBILITY FROM DIFFERENT IMPORTANT TRANSIT STOPS

Transit travel time from the North Station (min)



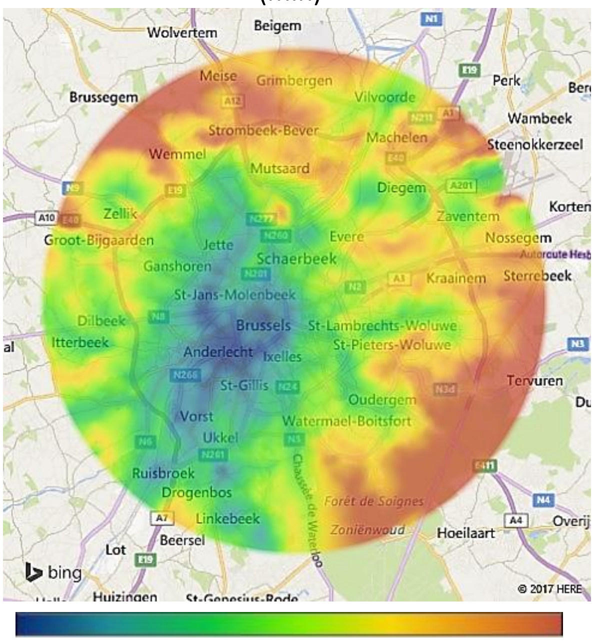
5.0 or less — 60.0 or more

Transit travel time from the Central Station (min)



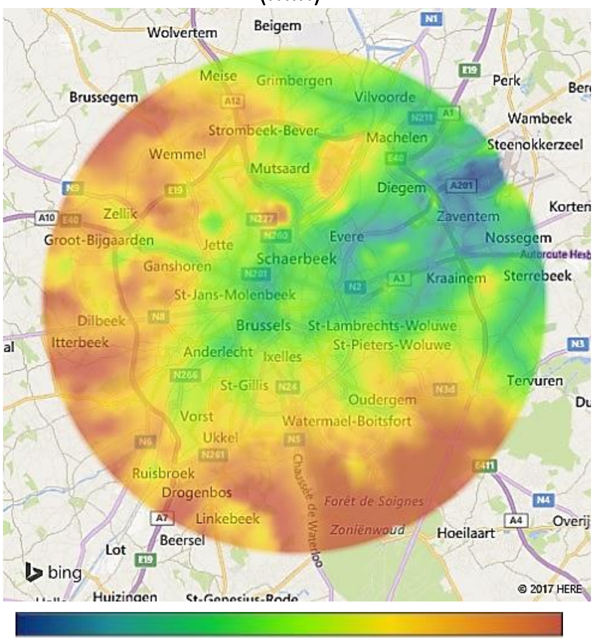
5.0 or less — 60.0 or more

Transit travel time from the South Station (min)



5.0 or less — 60.0 or more

Transit travel time from Brussels Airport (min)



5.0 or less — 80.0 or more

Figure A-1 Transit travel time from different important transit stops

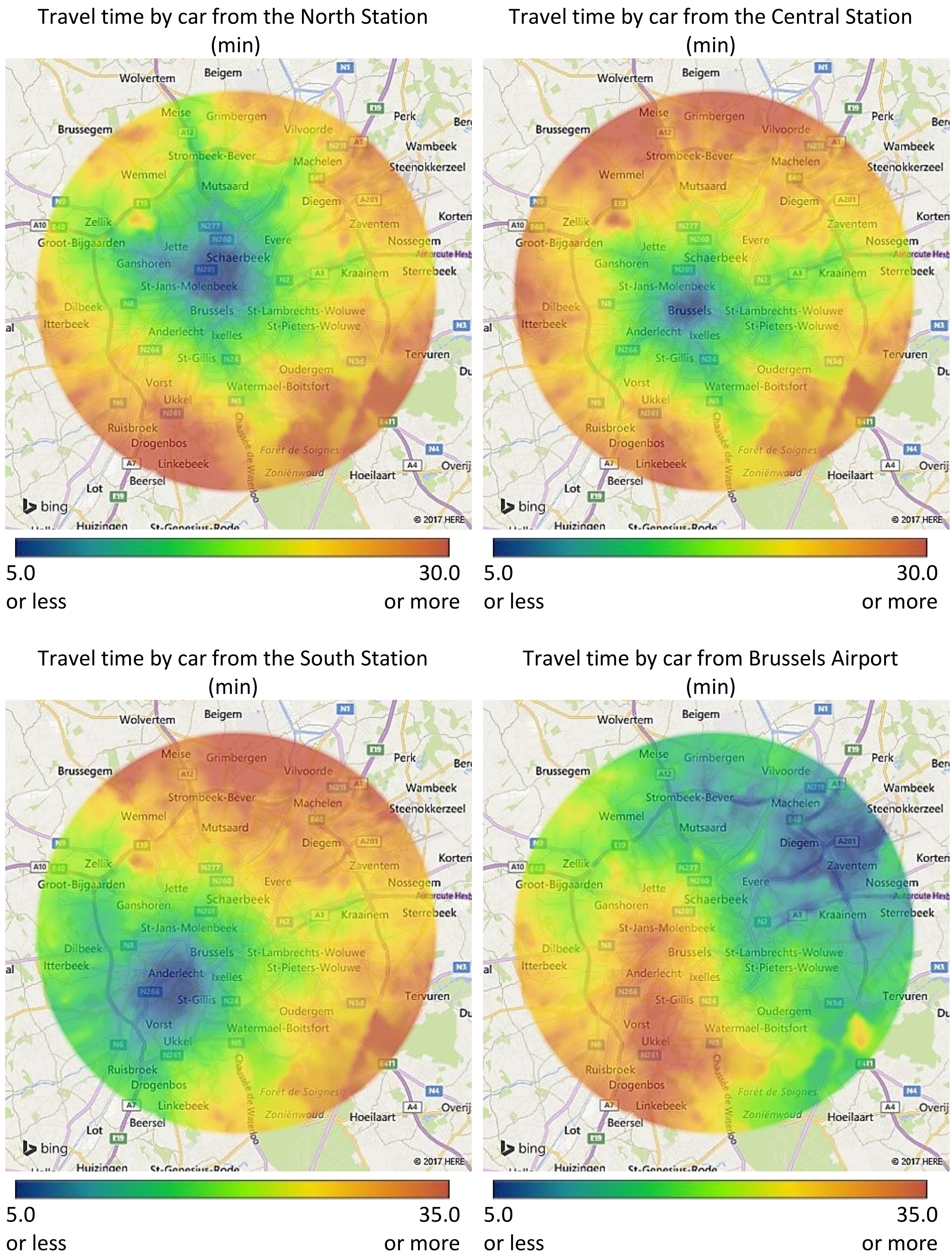


Figure A-2 Travel time by car from different important transit stops

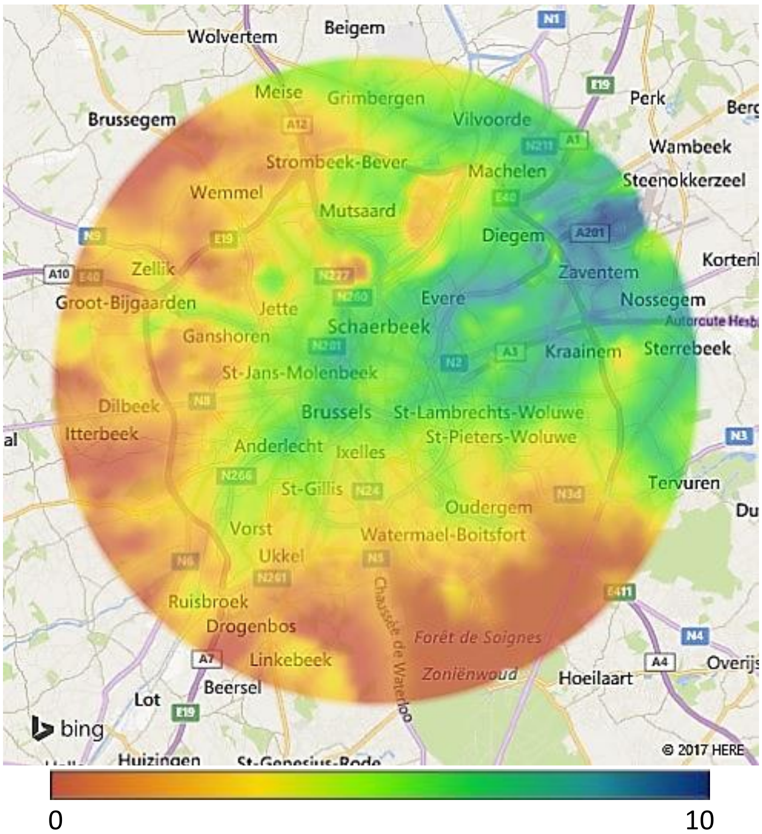


Figure A-3 Accessibility from Brussels Airport by public transport - scoring between 0 and 10

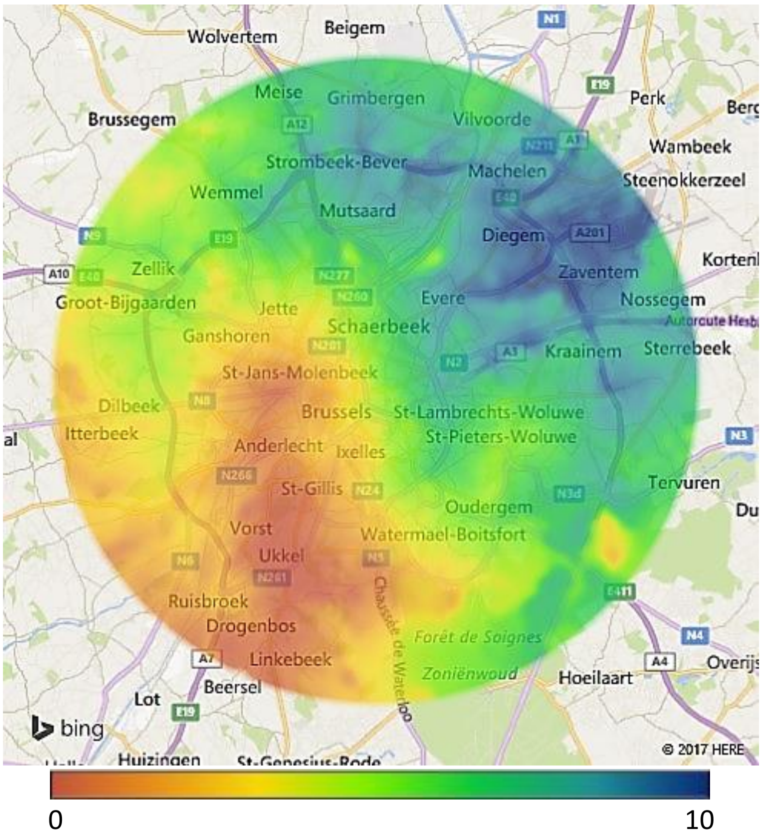


Figure A-4 Accessibility from Brussels Airport by car - scoring between 0 and 10

Appendix B MOBILITY BY TRANSIT INDICATOR VALUES FOR DIFFERENT RADII R

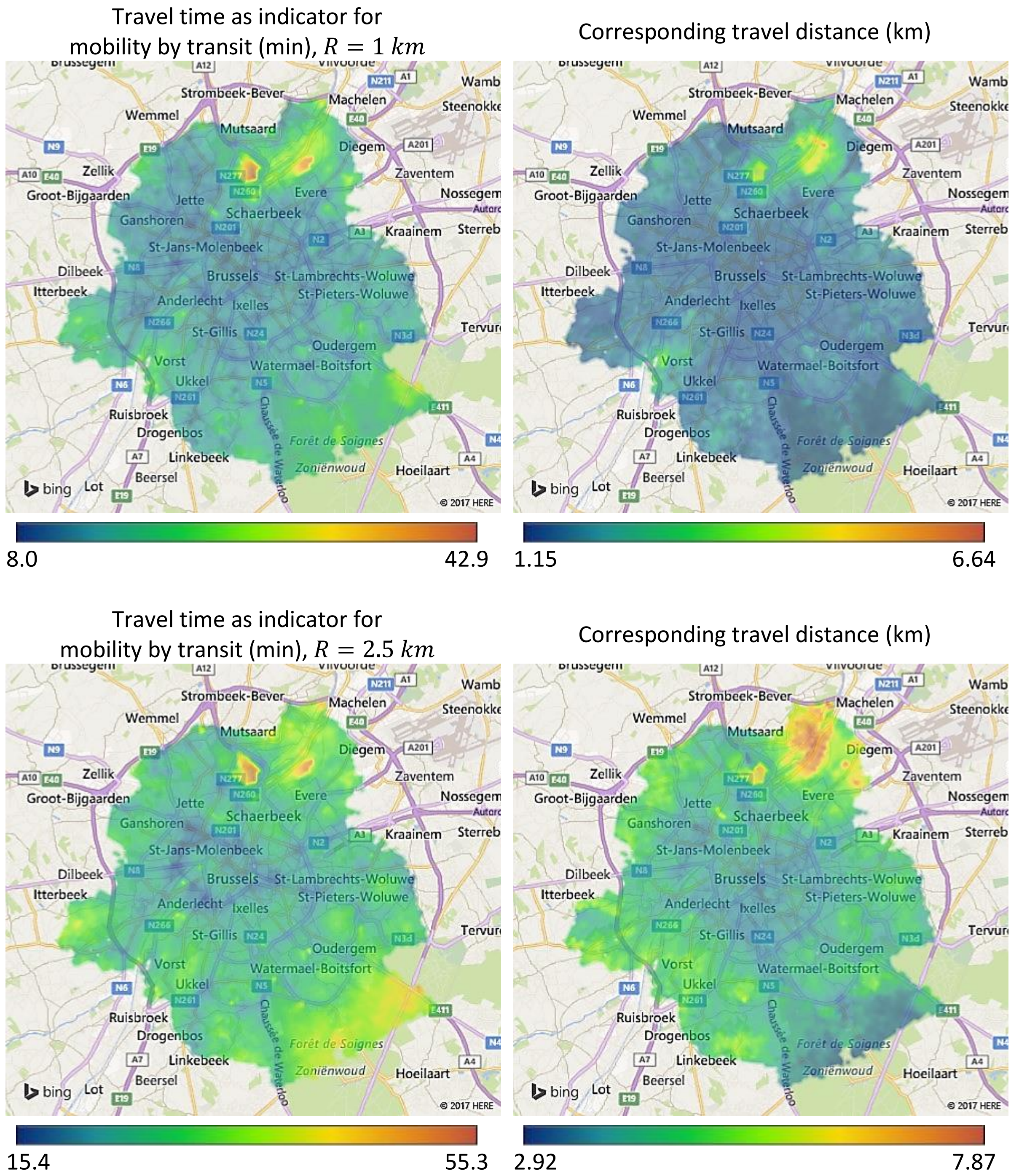


Figure B-1 Travel time indicator for mobility by transit and the corresponding travel distance for R ranging from 1 to 25 km (1)

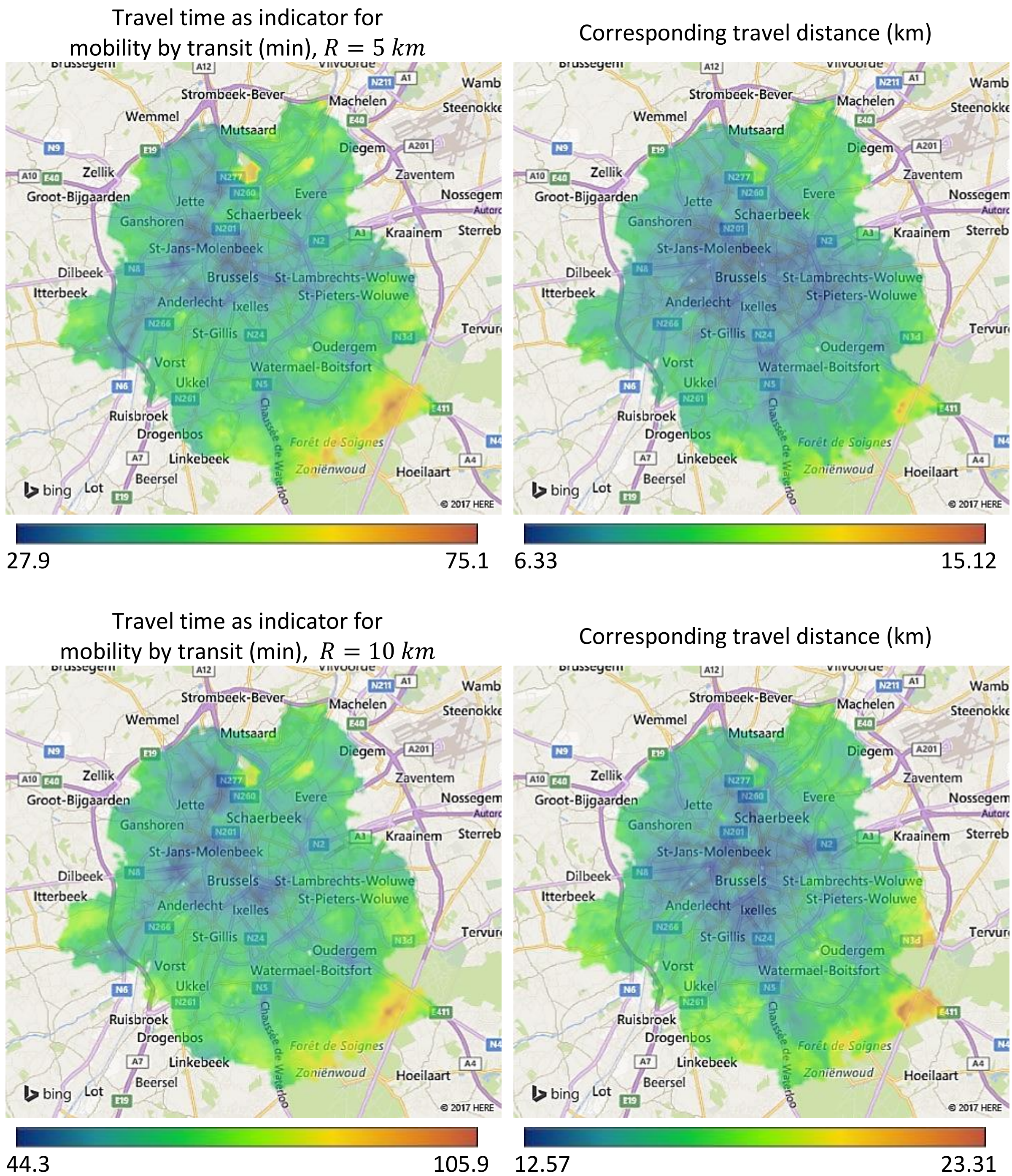
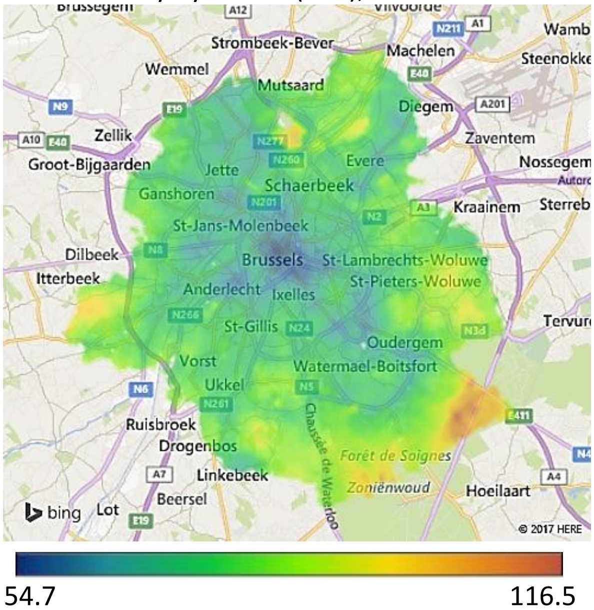
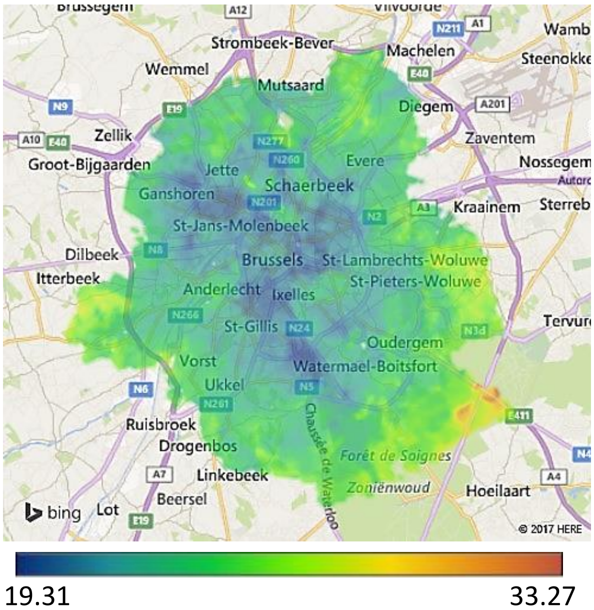


Figure B-2 Travel time indicator for mobility by transit and the corresponding travel distance for R ranging from 1 to 25 km (2)

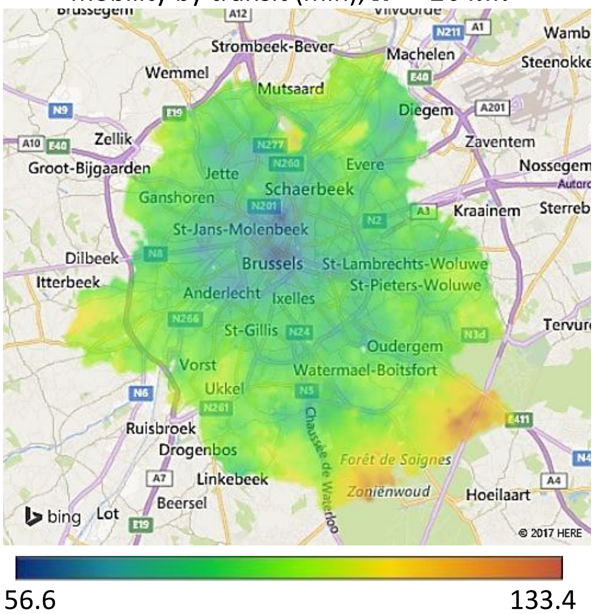
Travel time as indicator for mobility by transit (min), $R = 15\ km$



Corresponding travel distance (km)



Travel time as indicator for mobility by transit (min), $R = 20\ km$



Corresponding travel distance (km)

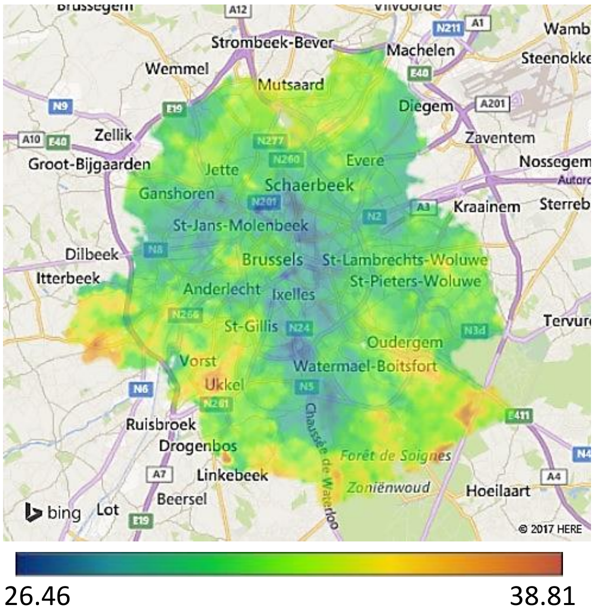


Figure B-3 Travel time indicator for mobility by transit and the corresponding travel distance for R ranging from 1 to 25 km (3)

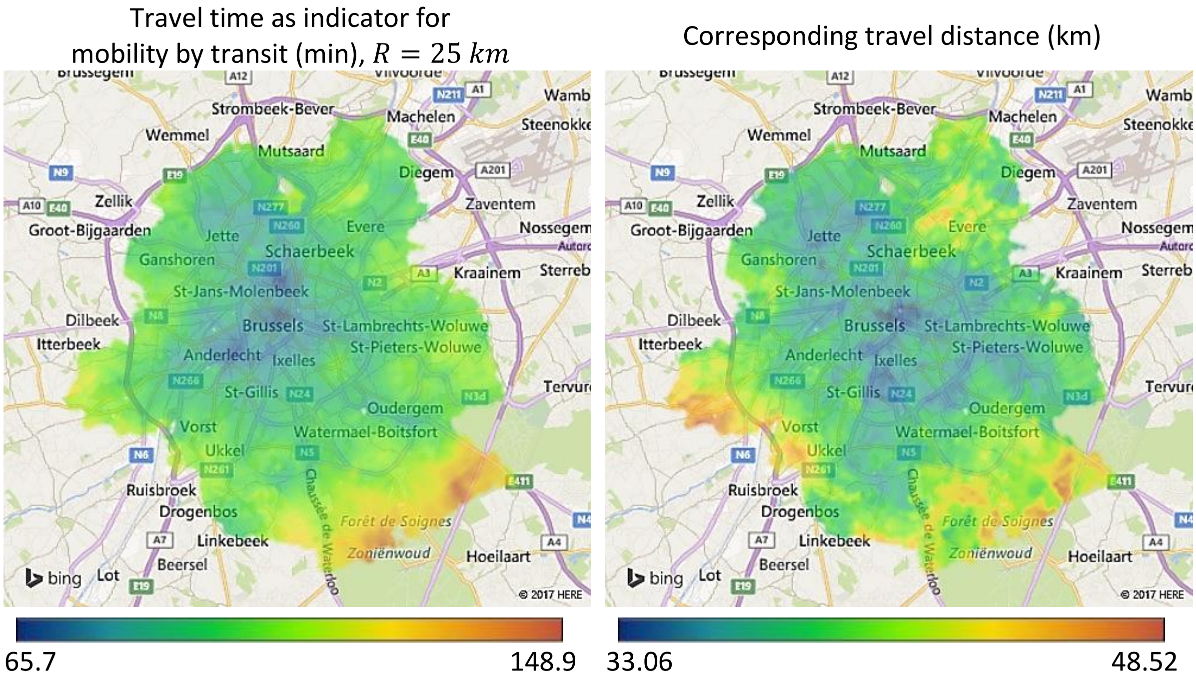


Figure B-4 Travel time indicator for mobility by transit and the corresponding travel distance for R ranging from 1 to 25 km (4)

Appendix C MOBILITY BY CAR INDICATOR VALUES FOR DIFFERENT RADII R

There were 6 different indicators mapped, for 6 values of R. The choice was made to arrange the maps by type of indicator. This way the absolute and relative values of the measures can be compared easily for different values of the radius R, as they are on the same page.

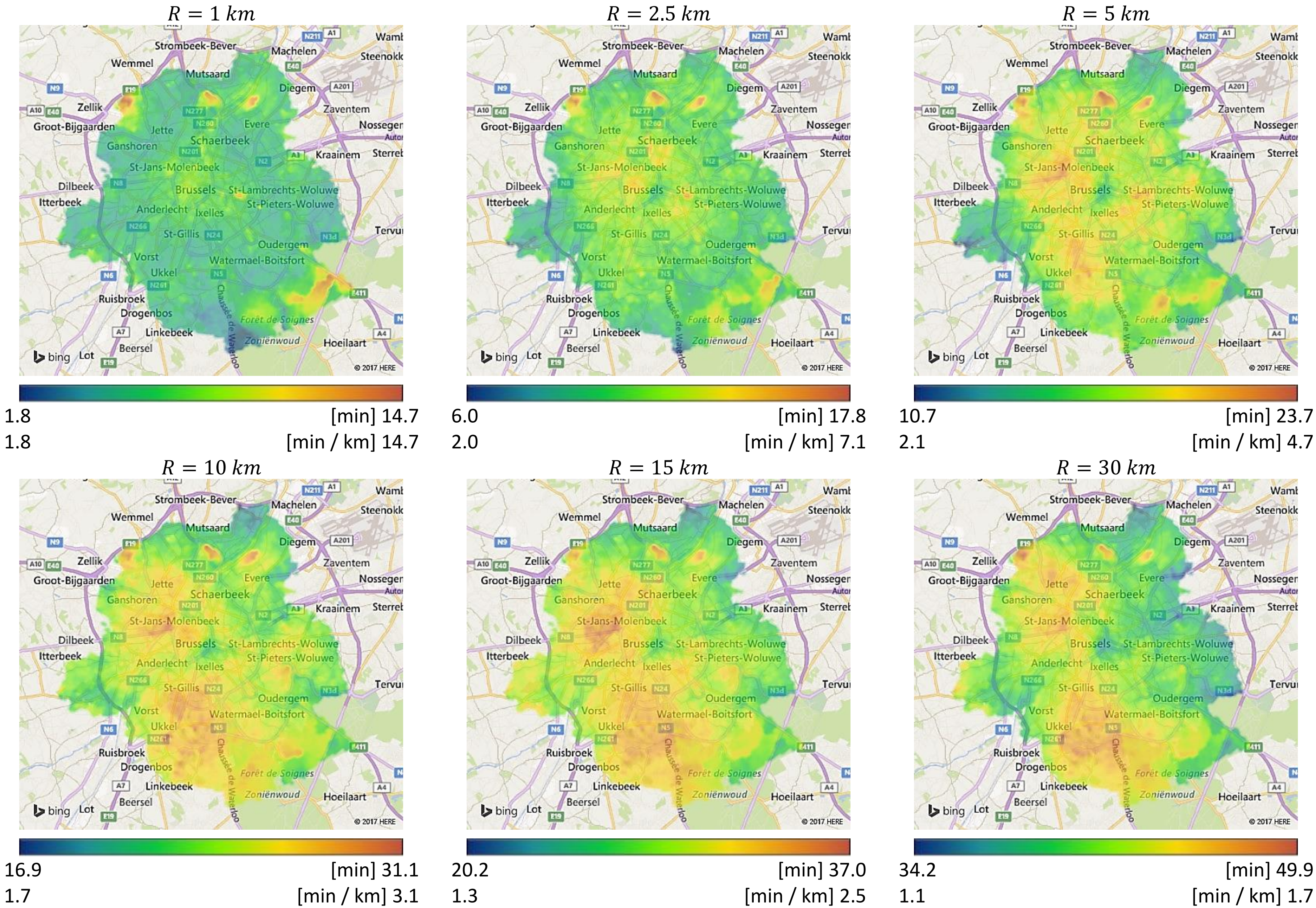


Figure C-1 Average travel time indicator for mobility by car for radius R ranging from 1 to 30 km, absolute and relative values

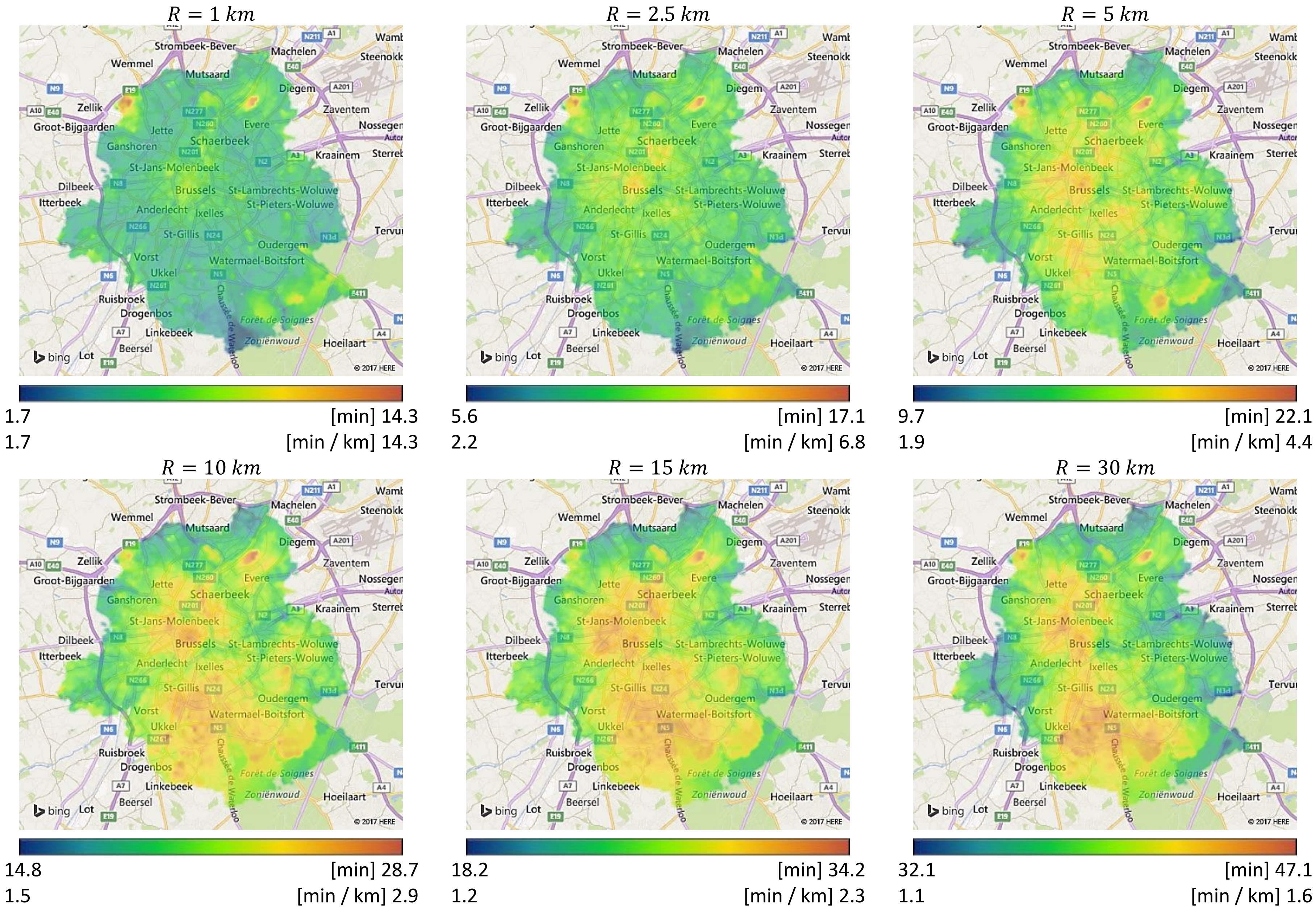


Figure C-2 Average free-flow travel time indicator for mobility by car for radius R ranging from 1 to 30 km, absolute and relative values

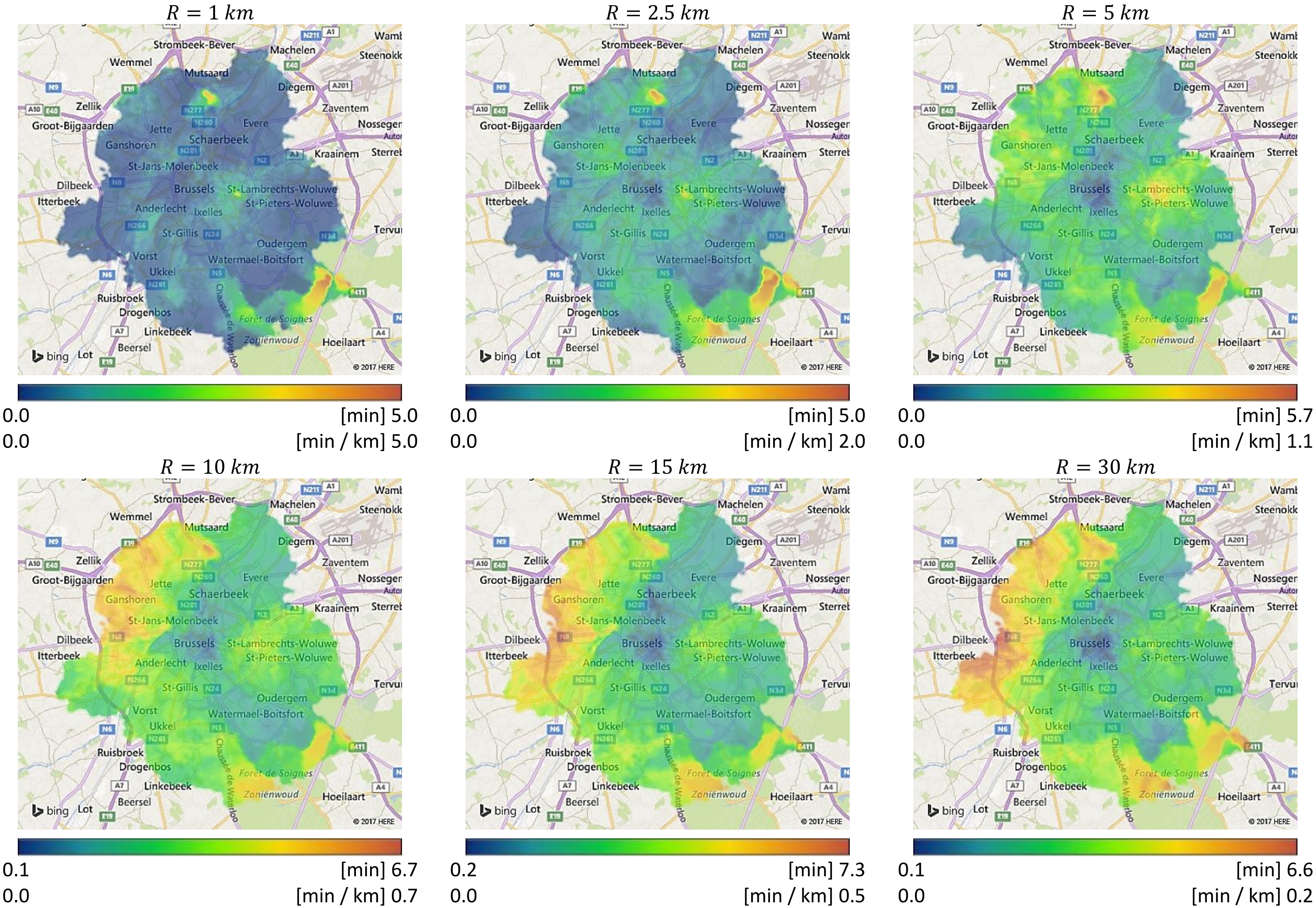


Figure C-3 Average minutes of delay indicator for mobility by car for radius R ranging from 1 to 30 km, absolute and relative values

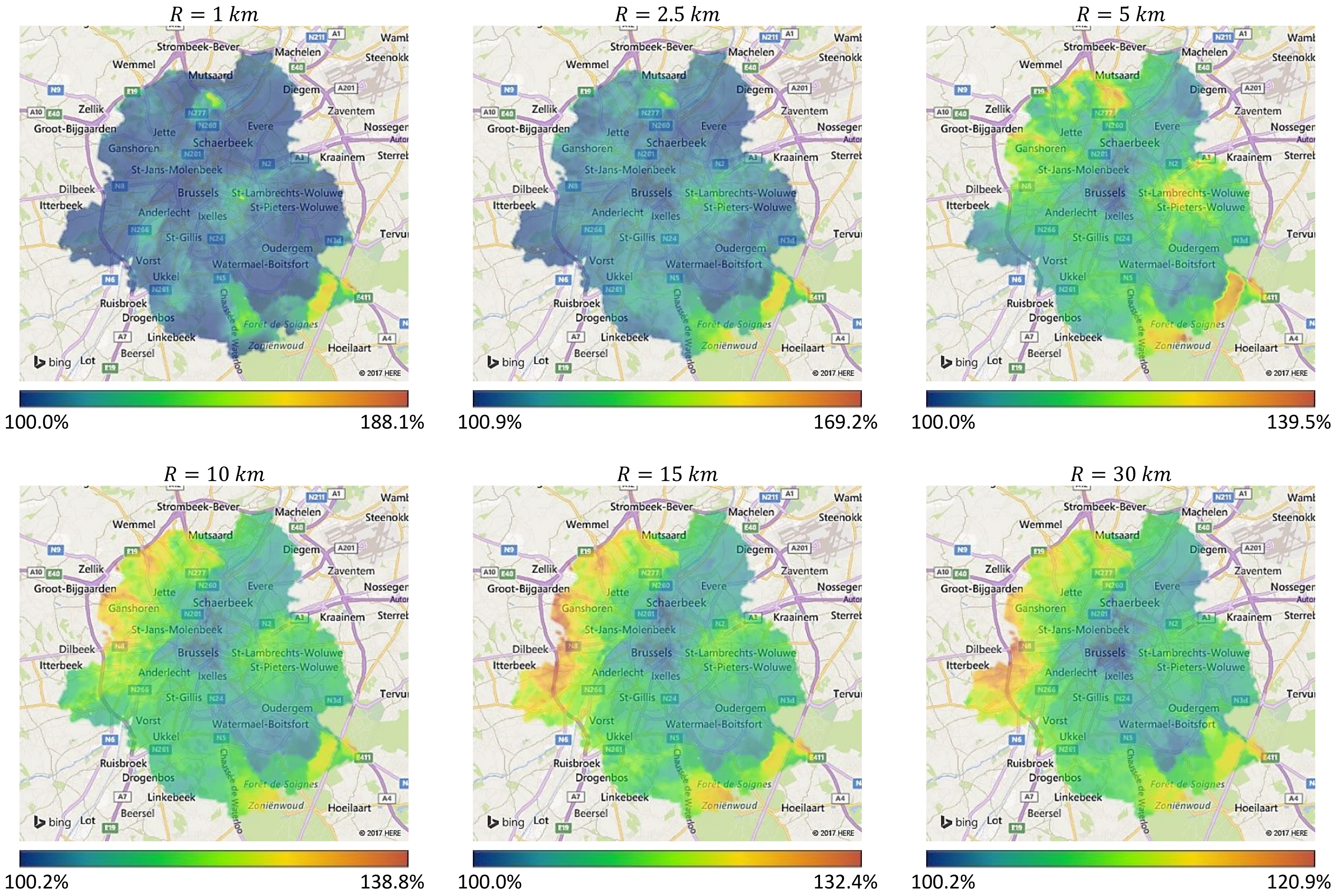


Figure C-4 Average Travel Time Index (TTI) indicator for mobility by car for radius R ranging from 1 to 30 km, absolute values only

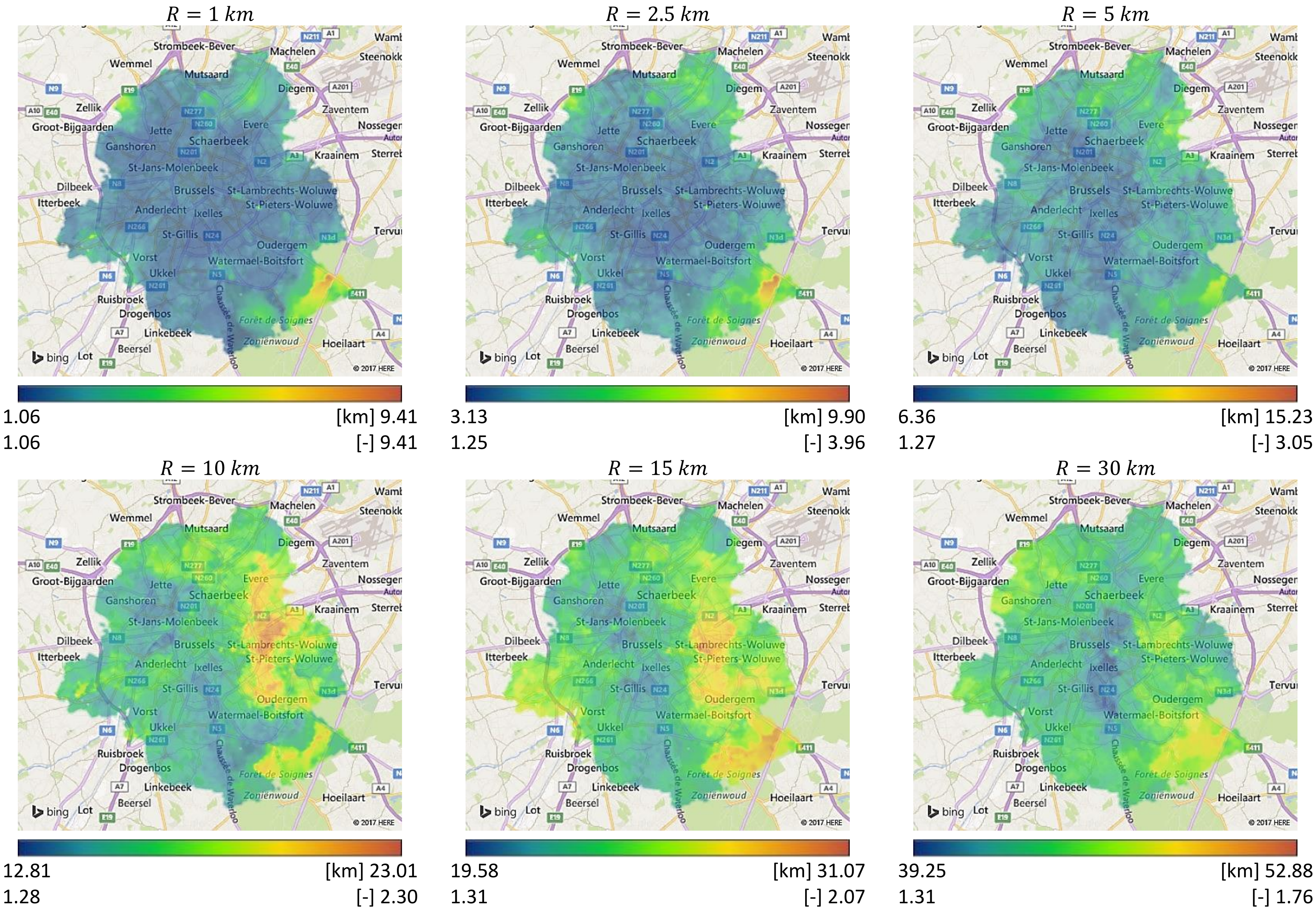


Figure C-5 Average travel distance indicator for mobility by car for radius R ranging from 1 to 30 km, absolute and relative values

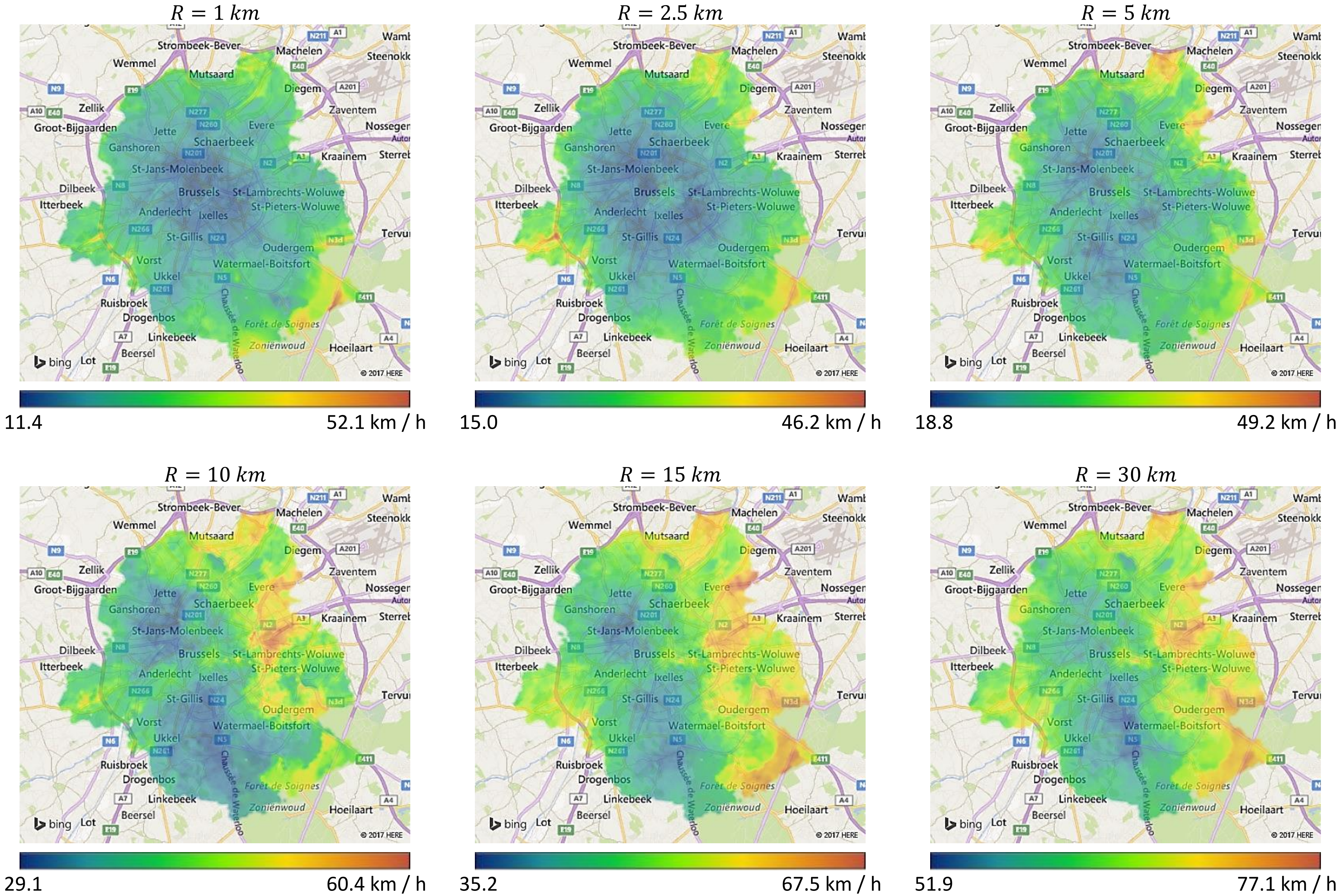


Figure C-6 Average travel speed indicator for mobility by car for radius R ranging from 1 to 30 km, absolute values only

Appendix D REGIONAL AVERAGE ALTERNATIVE INDICATOR VALUES AS A FUNCTION OF R

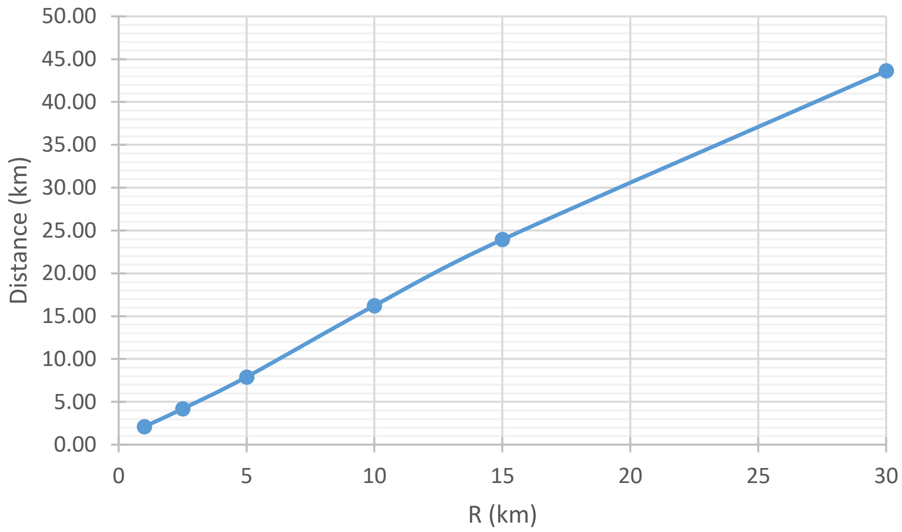


Figure D-1 Regional average travel distance as an indicator for mobility, as a function of the adopted radius R – absolute values

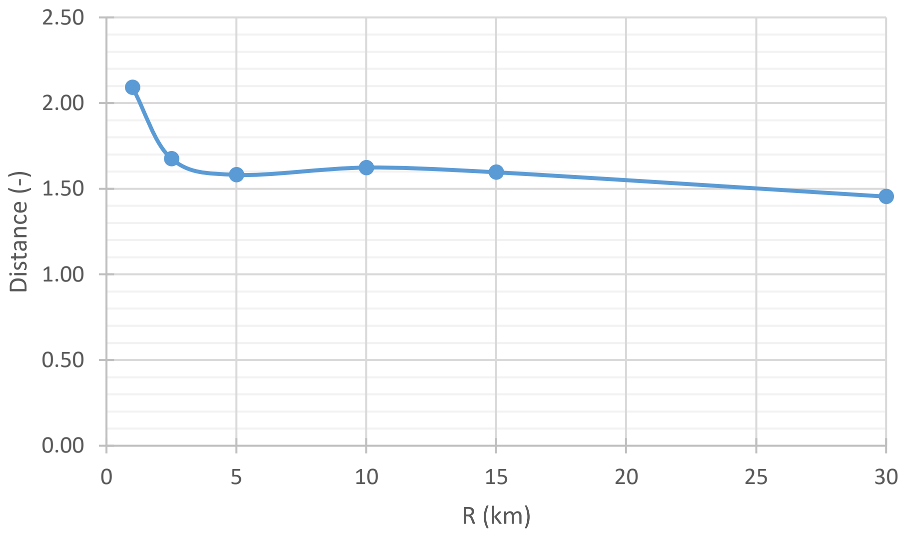


Figure D-2 Regional average travel distance as an indicator for mobility, as a function of the adopted radius R – relative values

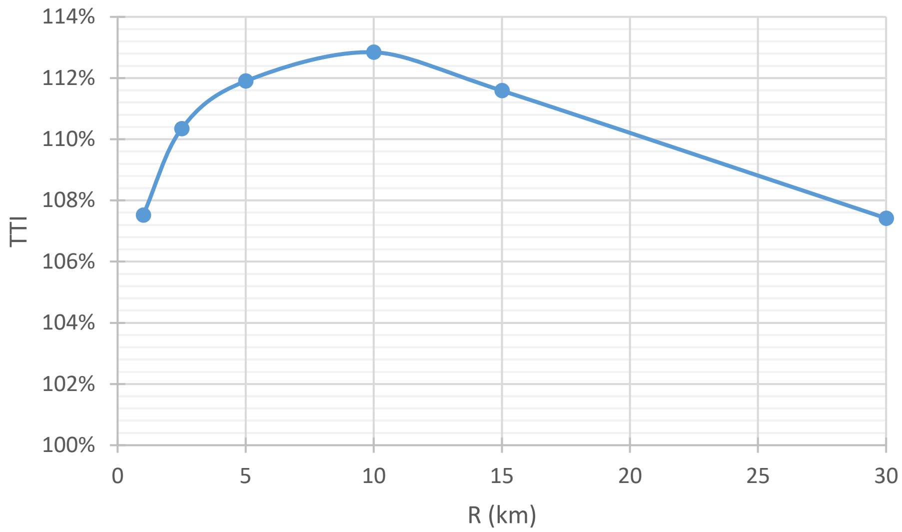


Figure D-3 Regional average Travel Time Index as an indicator for mobility, as a function of the adopted radius R

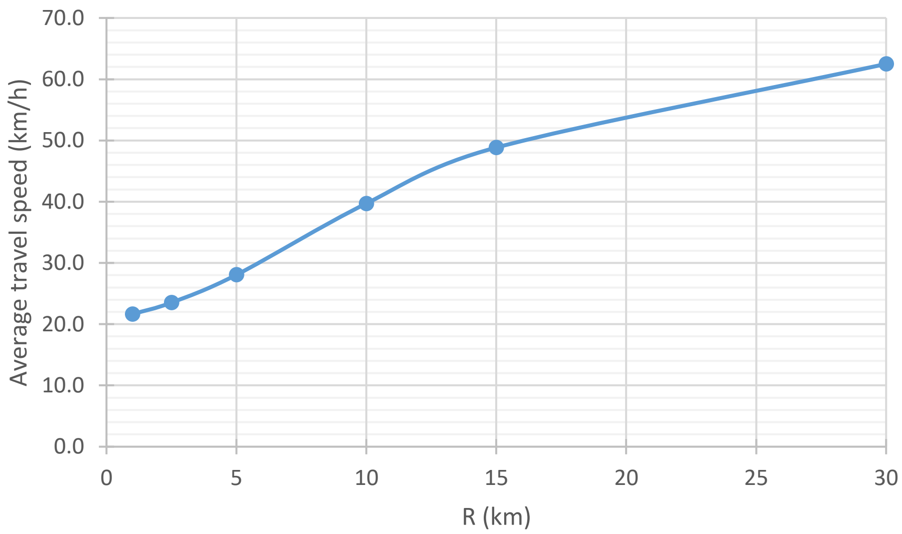


Figure D-4 Regional average of the average travel speed along the route as an indicator for mobility, as a function of the adopted radius R

Appendix E SIMULATING A VARIATION IN THE COMMUTING DISPLACEMENTS

Original indicator for accessibility by public transport (min)

Indicator for accessibility by public transport after the introduction of a 30% turnover (min)

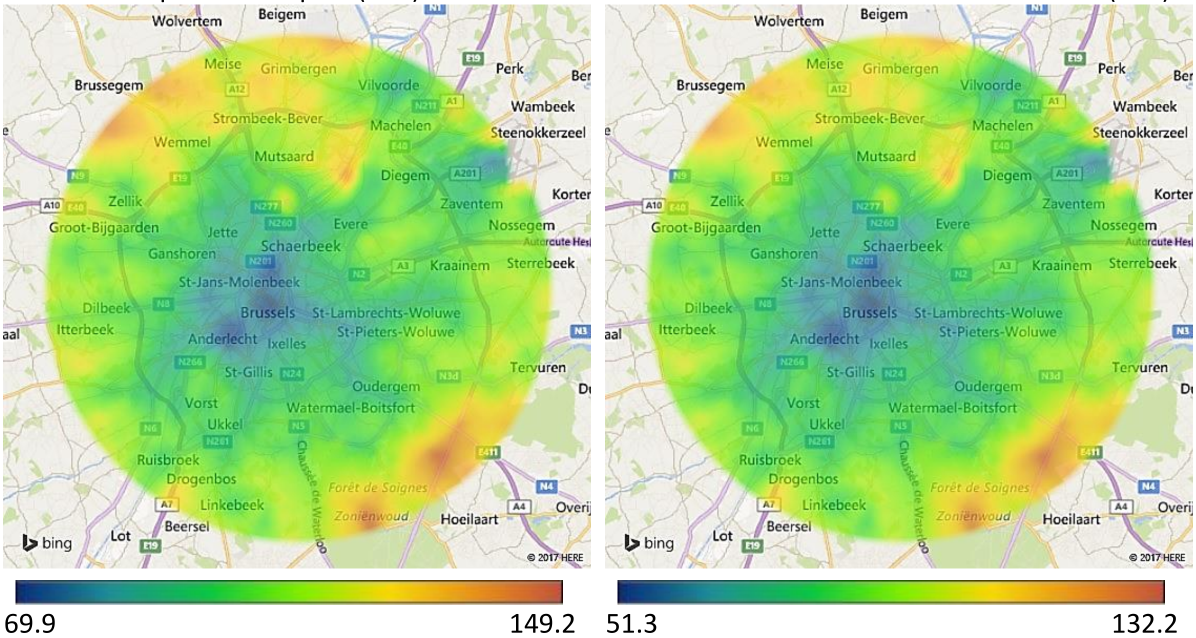


Figure E-1 Original indicator for accessibility by public transport and indicator after turnover

Original indicator for accessibility by car (min)

Indicator for accessibility by car after the introduction of a 30% turnover (min)

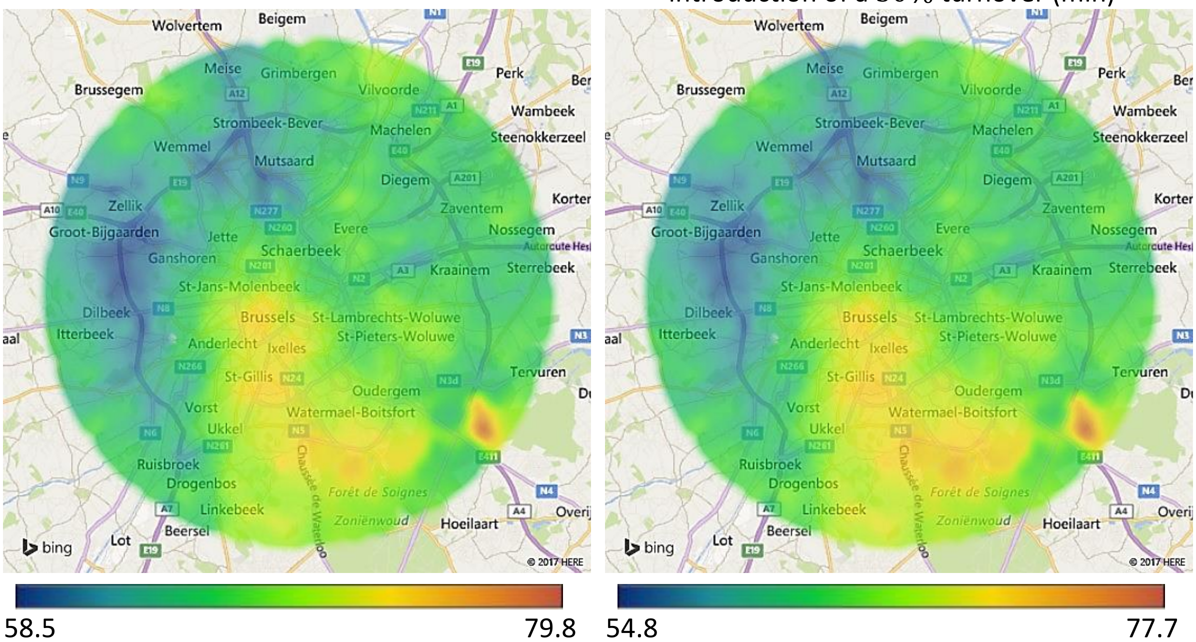


Figure E-2 Original indicator for accessibility by car and indicator after turnover

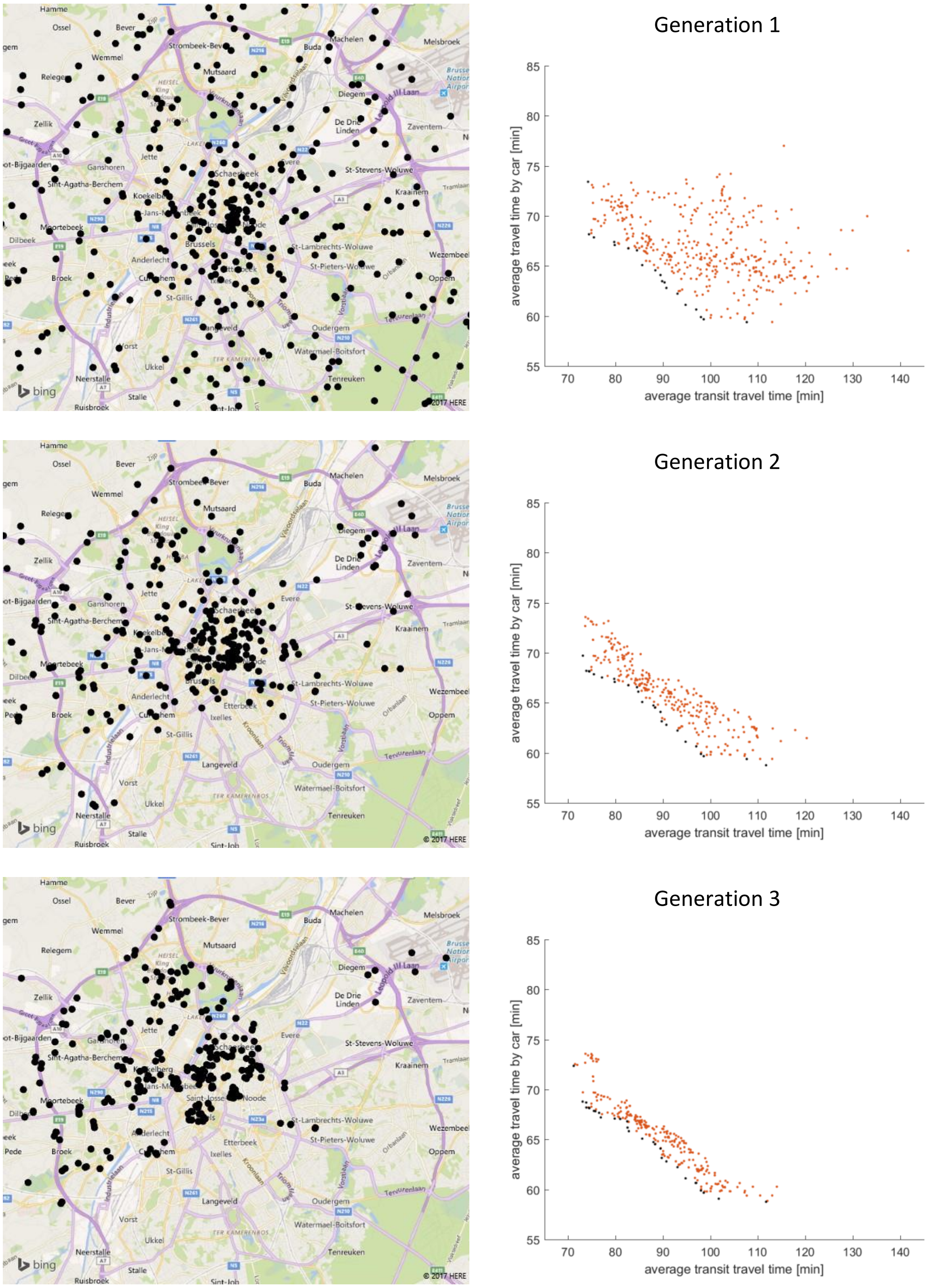


Figure F-1 NSGA-II optimisation to locate an office building – generations 1-40 (1)

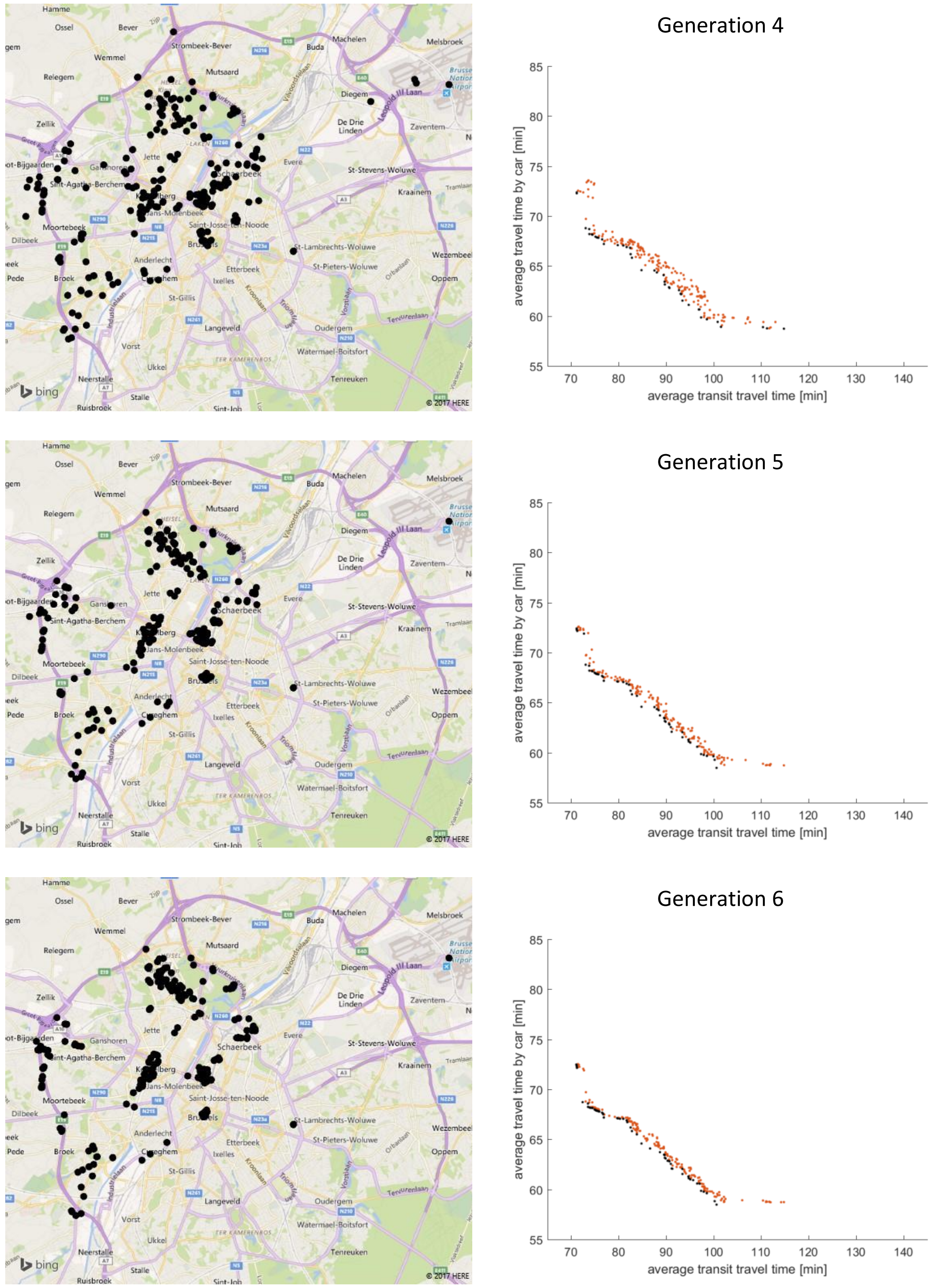


Figure F-2 NSGA-II optimisation to locate an office building – generations 1-40 (2)

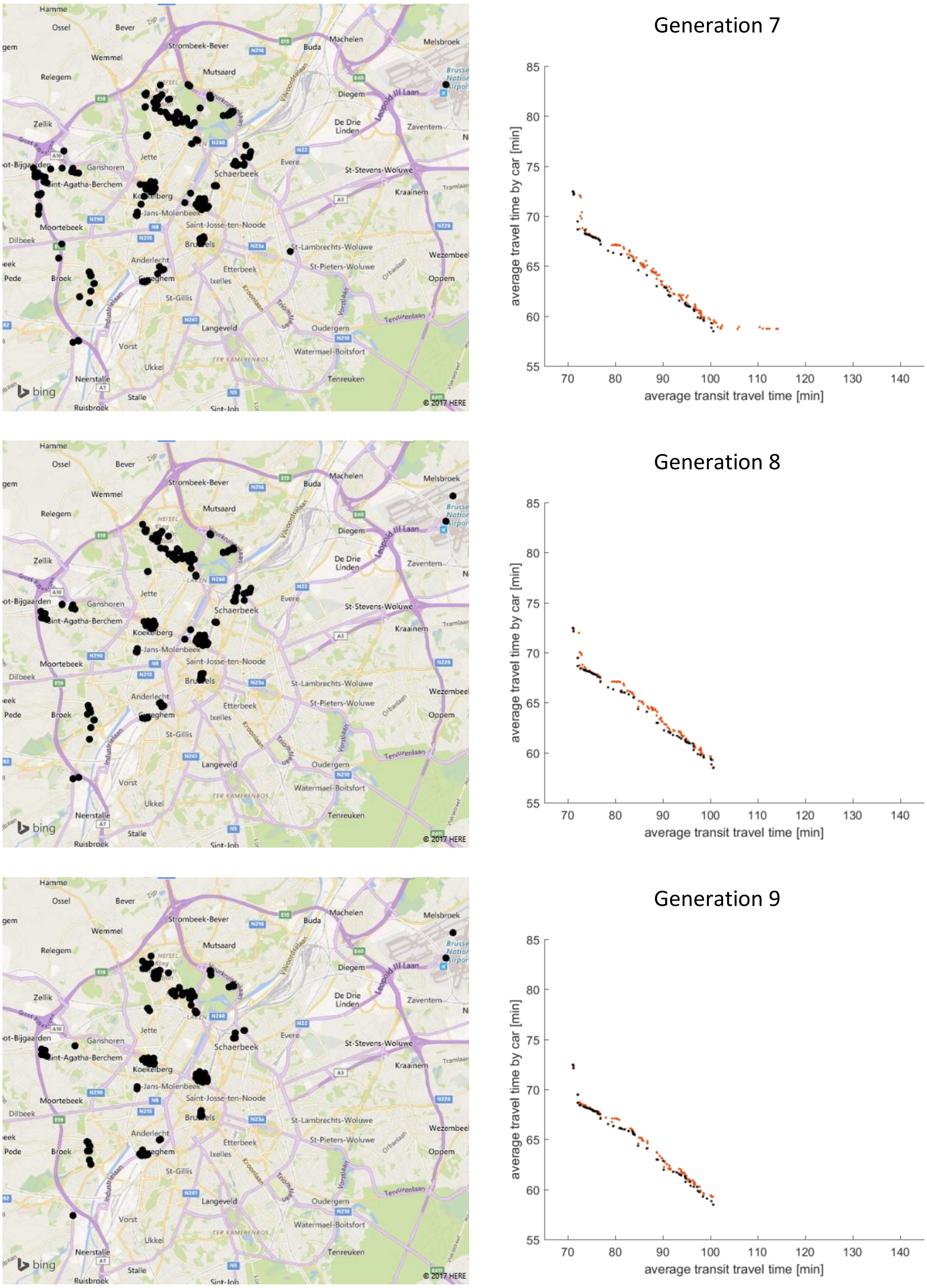


Figure F-3 NSGA-II optimisation to locate an office building – generations 1-40 (3)

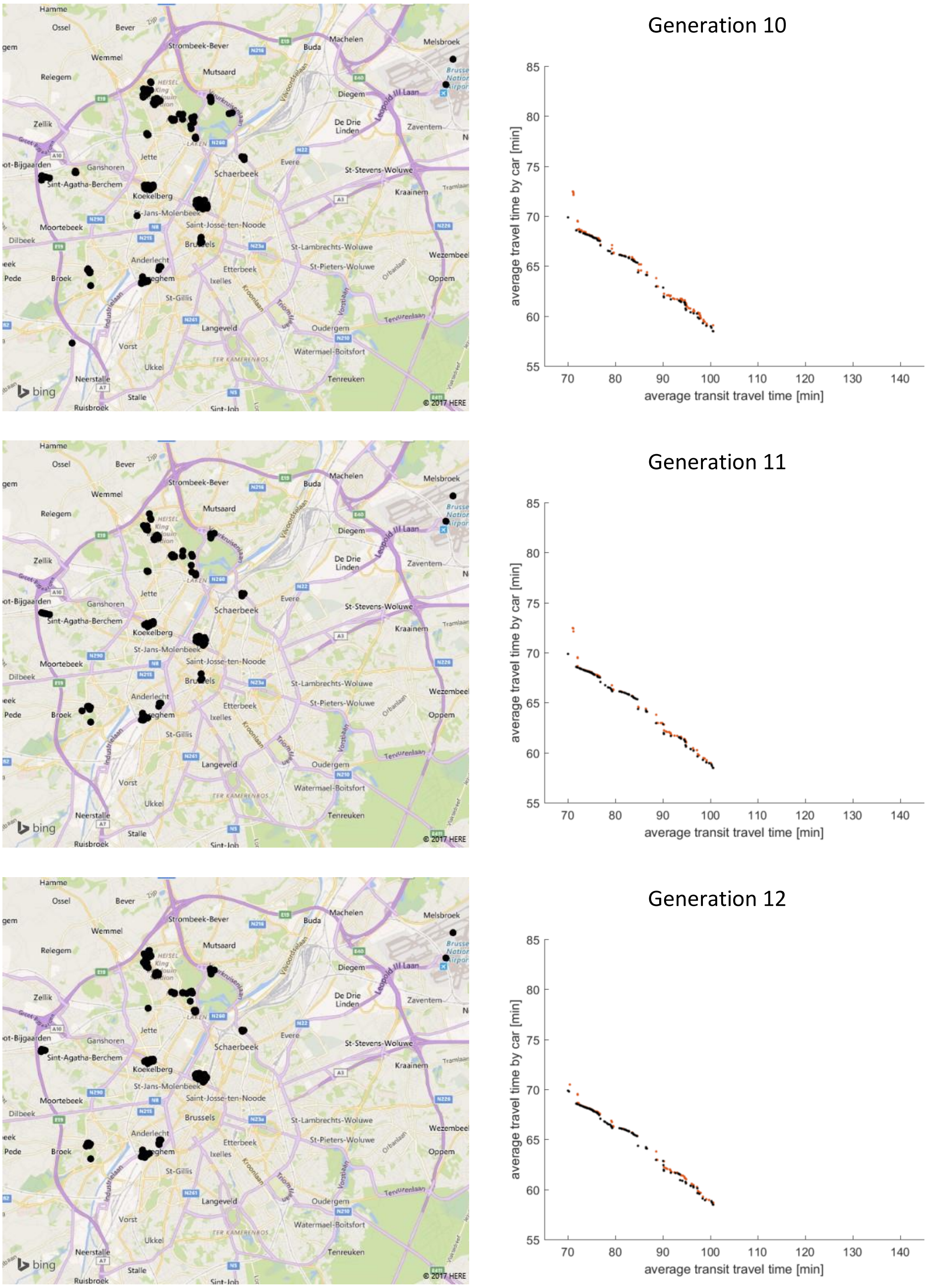


Figure F-4 NSGA-II optimisation to locate an office building – generations 1-40 (4)

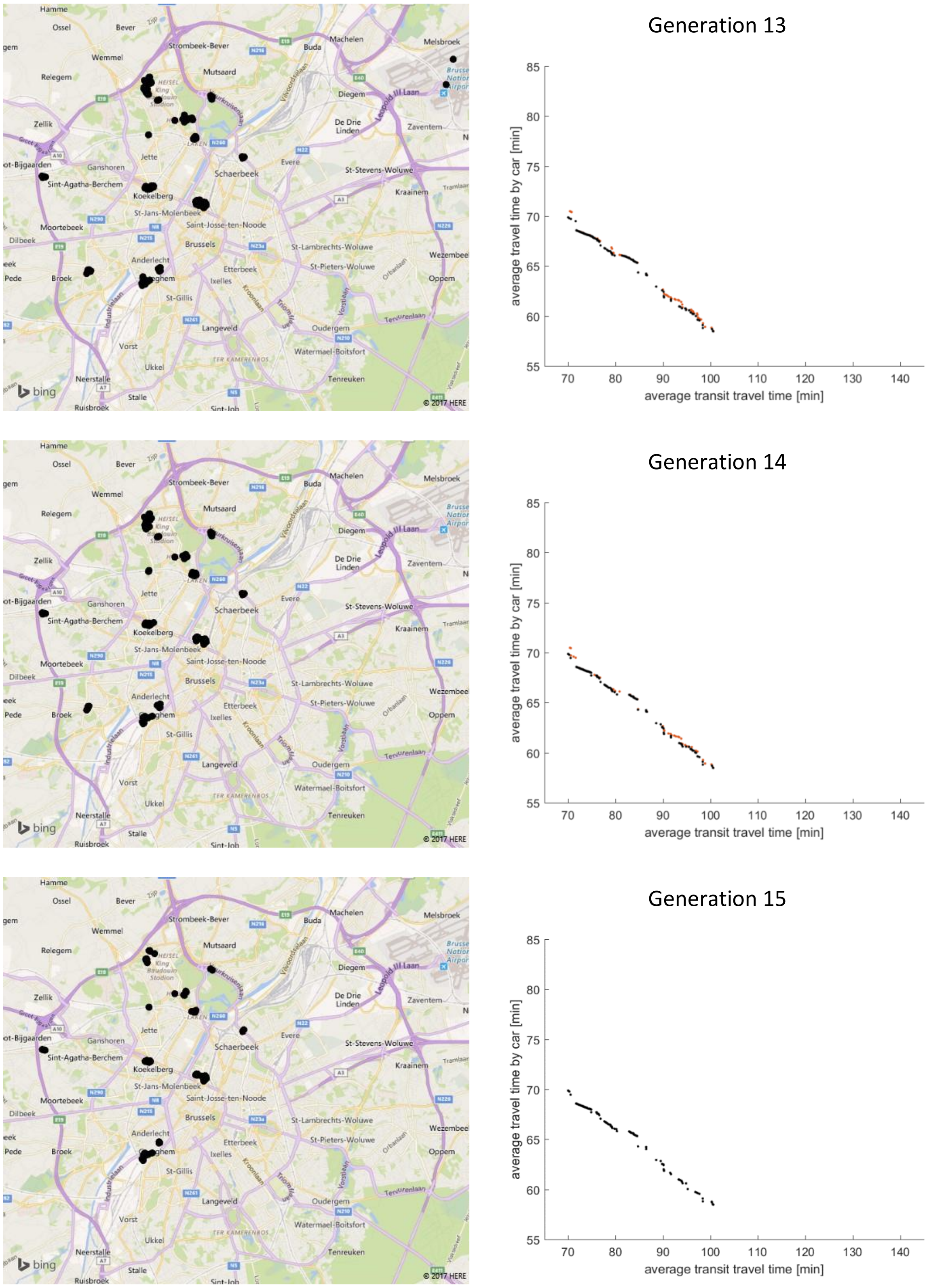


Figure F-5 NSGA-II optimisation to locate an office building – generations 1-40 (5)

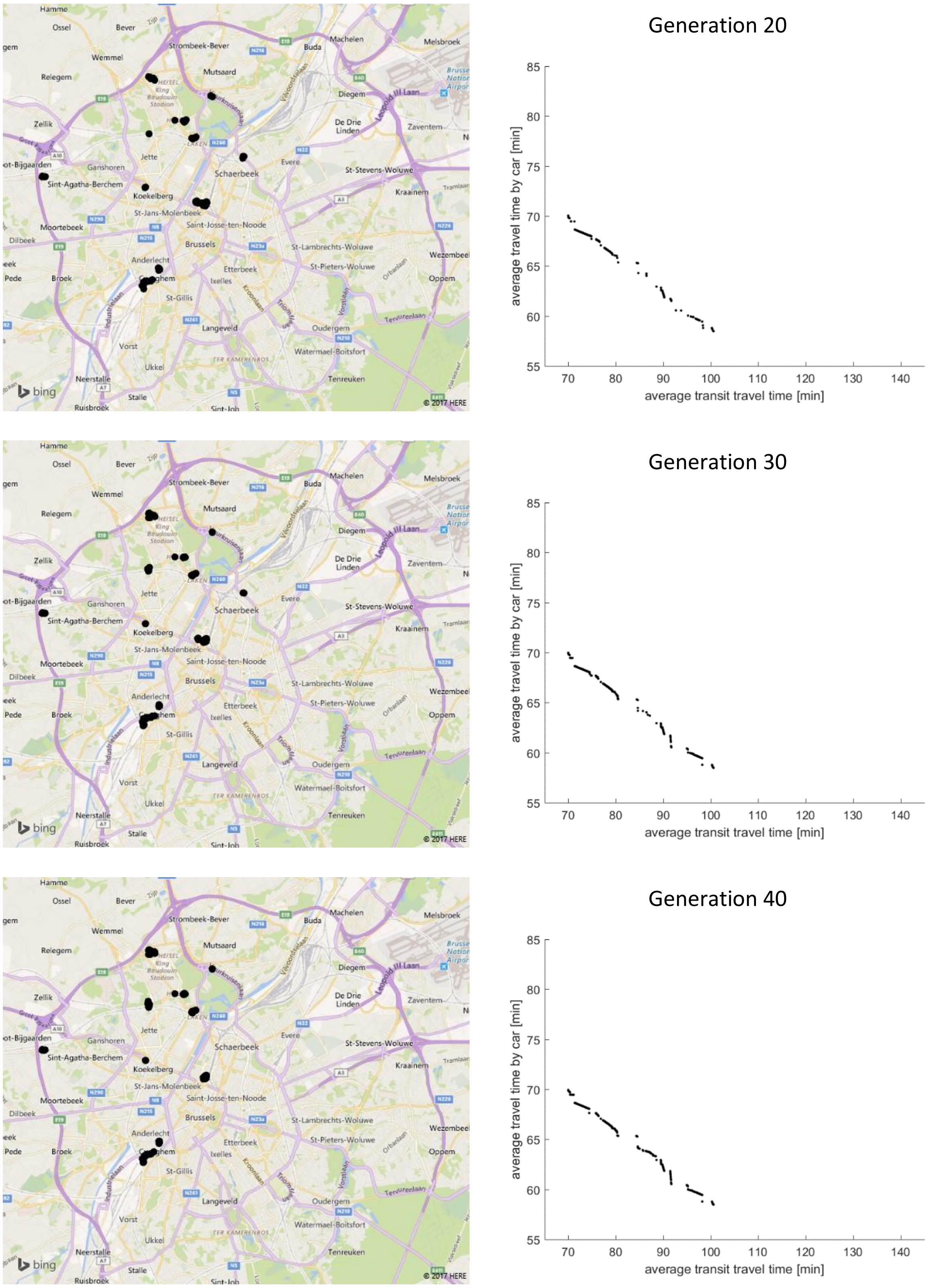


Figure F-6 NSGA-II optimisation to locate an office building – generations 1-40 (6)

Appendix G ADDITIONAL CASE STUDIES

This appendix presents a set of additional case studies that could be performed using travel times. First, a case regarding commuting from Brussels to Paris is presented, along with the used strategy and the obtained results. For the rest of the possible case studies, the context has been provided in section G.2.

G.1 ADDITIONAL CASE STUDY: COMMUTING FROM BRUSSELS TO PARIS

This section presents an additional case study that was performed using a variation on the developed approach.

G.1.1 Problem statement

Research questions:

- Would it be possible to have a scenario in which employees live in the surroundings of Brussels, Belgium and commute to work in Paris, France by high-speed train (Thalys), resulting in a lower total travel time than when these employees would live in the surroundings of Paris?
- What would be the absolute minimum distance from the Paris North railway station at which an employee working near the Paris North station would already be living in order to consider moving to Belgium and commuting by Thalys every day?

G.1.2 Strategy

According to the Thalys website, traveling from the Brussels-South railway station to the Paris North train station by Thalys takes at least 1 hour 22 minutes. In practice, 90 minutes is a more realistic time. The composed scenario will not take traveling from a place of residence in Belgium to the South Station into account, nor any reserve in order not to miss the train.

The scenario takes an office building into account in the immediate surroundings of the Paris North station, where the Thalys arrives. Since the aim is to study whether commuting from Brussels can be faster than commuting from the surroundings of Paris, travel times by public transport and by car from different points, widely spread around the station, to the station itself are calculated. The input used, is as follows:

Mode	• Transit • Driving
Time	• Departure time • A Thursday morning in May, 7:30 a.m. (UTC+2)

Origin(s)	• Different points around the Paris North station, spread equidistantly in a circular area with
	  • its midpoint at the Paris North station;
	  • a diameter of 110 km (transit) or 160 km (driving).

Destination(s)	• The Paris North train station

List G-1 Overview of the input used

G.1.3 Results

A filter has been applied on the results to show only the locations that are within a travel time of less than 90 minutes from the Paris North station. The results are mapped in Figure G-1 and Figure G-2. The continuous colour scale has been chosen to display all locations with a travel time of 30 minutes or less in the deepest blue, while green correspond to a time of 60 minutes. Note that the edge of the mapped area is the isochrone line of exactly 90 minutes travel time. Locations on this isochrone are coloured in the deepest red.

G.1.4 Discussion

The coloured locations on the created maps are locations with a travel time of less than 90 minutes to Paris North. On the map displaying transit travel times, the different railway lines are can clearly be identified. People living in the non-coloured area that are employed by a firm could decide to come and live in Brussels when hired by a firm located in the immediate surrounding of the Paris North station, resulting in a lower total travel time than when these employees would remain at their current place of residence. For people that would travel by car, the corresponding minimum travel distance to Paris North would be $30.3\ km$, at a geographical distance of $24.2\ km$. For people that would otherwise travel by public transport, these values are a travel distance of $16.5\ km$ and a geographical distance of $13.2\ km$. When people living at these locations are hired by a firm located in the immediate surroundings of the Paris North station or when a firm would move to the surroundings of Paris North, the firm could suggest moving to Brussels and Commuting to Paris.

Moving to another country is a profound change in the life of an employee, so the employee (and his family) must be open for this change and should have a strong, long term commitment to the firm. Of course, the firm could also suggest moving somewhere close to Paris North. People commuting from Brussels to Paris could have their breakfast and evening meal on the train and can already start working on their laptop, since there is internet connection possibility. This could justify a slightly longer travel time. The firm could probably negotiate a reduced subscription rate when several people commute daily by Thalys.

Travit travel times to Paris North (min)

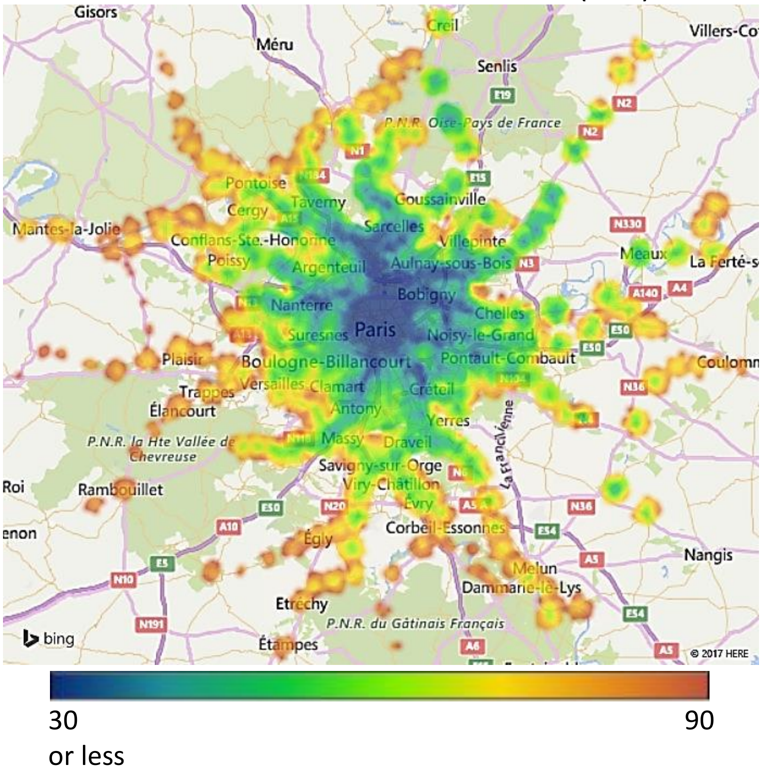


Figure G-1 Transit travel times to Paris North smaller than 90 minutes

Driving travel times to Paris North (min)

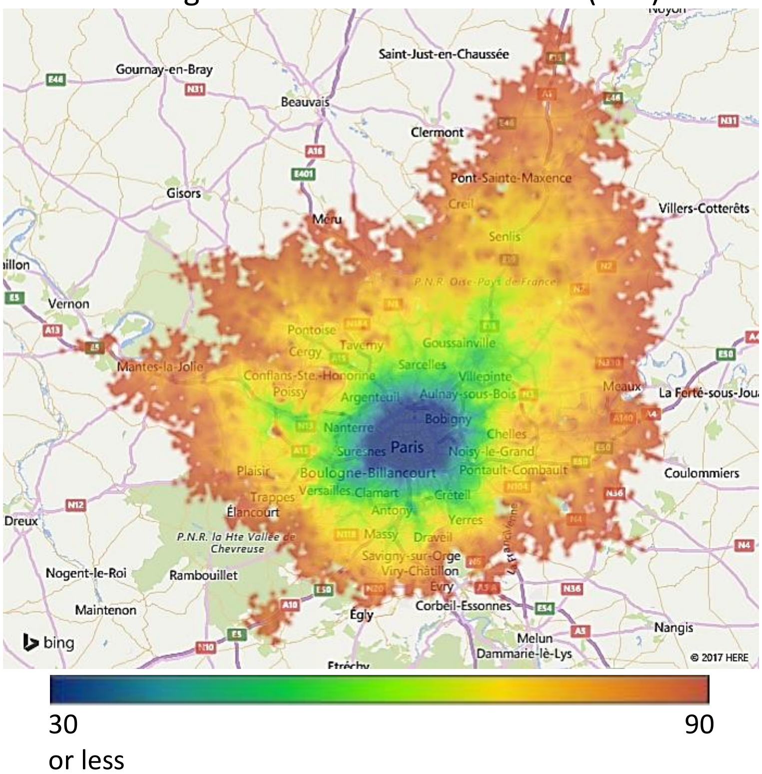


Figure G-2 Driving travel times to Paris North smaller than 90 minutes

G.2 SUGGESTIONS FOR ADDITIONAL CASE STUDIES

G.2.1 Identifying the best work schedule

A study of the different departure times for employees commuting to work by car. Since a company could implement multiple possible work schedules, what are the different gains in terms of travel time or additional time due to congestion that can be realised? In order to be able to answer this question, other sub-questions should be answered:

- Which increase in travel time in traffic does one get when travelling during the morning and evening peak, compared to more quiet moments of the day?
- For different routes, are the magnitudes of morning and evening peaks and the difference between the two in accordance with people's expectations?
- Which gain in travel time or time in traffic can be realised by which shift in work schedule? Within a realistic range of possible shifts in work schedule, which one should be implemented and why? What is the exact decrease in morning, evening and total travel time?
- What added value can flexible schedules, compressed work weeks, staggered shifts and teleworking provide with respect to this issue?
  Which added value can be realised by combining for example staggered shifts and a compressed work week?

G.2.2 Improving the composite indicator used for assigning schools

In the Belgian French speaking community, enrolment in the first year of secondary education encompasses a complex procedure. Since places per school are limited, the allocation of places in the most coveted schools is carried out based on a series of criteria, some of which are geographical. The criteria are aggregated to calculate a composite index, which is used to allocate the available places. Contrary to earlier systems, the date of inscription is not among the considered criteria. Some of the criteria incorporate distances, like for example home-school distances. These distances are considered as distances "as the crow flies", also called "in a beeline" distances. From a mobility or accessibility perspective, it would make sense to consider using travel distances or even (rush hour) travel times instead. [31]
The aim of the decree is to realise a situation where each child is assigned with priority to a school as close as possible to his or her place of residence. In order not to put children living far from amenities in a disadvantaged position, only the proximity order of different schools is used in the calculation of the composite index, not the absolute value of the distance between place of residence and school. [32] [33] The question may arise whether this is a smart decision. Encouraging people to live close to amenities is essential in a sustainable planning vision. Using the absolute proximity instead of the proximity order in the process of assigning schools could therefore be justified. However, providing equal opportunities for education is also regarded as very important.

This case study would consist of formulating recommendations on how to integrate travel distances or travel times in the computation of the composite index. Next to this, the exercise can be made to construct a quick-evaluation travel distance or travel time map based on the considered indicator for a given school in the French speaking community. This case study would be a way to illustrate the extendibility of the research conducted in context of office building evaluation to other fields of practice.

In the same context, a study can be performed providing an answer to the question if the decree leads to shorter travel times to in its current form. This study could be performed by sampling transit, driving, bicycling and walking travel times for routes from several locations to different secondary schools and evaluating the relative number of cases where a decision based on travel time alone contradicts the decision that is made, based on a as the crow flies distance.

G.2.3 Occupying a single or multiple office buildings

Quantifying the reduction in a company's employees' travel time when changing from occupying a single office building to occupying multiple office buildings at different locations, assuming an employee will be allowed to work in the building located closest to his place of residence.

Sub-questions or quantitative sensitivity analysis:

- What is the best place to locate an additional office building and is it possible to quantify the effect the new location has on the average or total travel time of the existing employees?
- In case one office site must be closed to cut costs, which building should be chosen to close to reduce the average or total travel time of the employees as little as possible?

G.2.4 Individual commuting travel time map

This case study involves providing an answer to a simple question. Where should someone who works at a specified place buy his house?

Based on the work location of an individual working at a certain company, a map can be made showing commuting travel times for possible locations to be housed. This map can then be used by this individual to obtain the commuting travel time from different possible places of residence to the company at a glance, allowing easy comparison of several locations.

G.2.5 European institutions

An evaluation of the buildings occupied by the European Commission in Brussels on mobility or accessibility in order to identify the buildings with the most advantageous or most attractive location.

The accessibility study can be performed with a focus on accessibility from various valued transit stops during peak hours. The transit stops presented in the accessibility sheets for European Commission buildings in Brussels could be considered. [34]

G.2.6 Average commuting travel time to the European institutions

While performing the literature study, two recent sources for the modal split of commuter traffic to the European institutions located in Brussels were found.
The most recent survey report on the Brussels Diagnostics of workers' commuting movements (section 2.2.2.3), dating from 2016 and using data from 2014, contains a table showing the modal split for people working at the European Commission. The table can be found on page 23 of the report. [18]
The full report on the 2014 Company mobility plans (section 2.2.2.4), issued in December 2016, contains a table on page 94 showing the modal distribution of commuting traffic to the European institutions. The table on page 93 of the same document contains information on the places of residence of the people working at the European institutions. The average distance between place of residence and work place is provided as well. [20]

By combining modal split and places of residence of people working at the European institutions, an estimation of the average commuting travel time to the buildings occupied by the European institutions, most of which are located in Schuman district, can be made.

G.2.7 Post-Brexit relocation of employees stationed in London

In context of Post-Brexit relocation of employees stationed in London, an evaluate the quality of Brussels as a possible location to station these workers could be performed. By developing a well-constructed, globally applicable mobility indicator, a comparison to other important European cities can be made.