A Quantitative Analysis of the Sensitivity of the Axial and Road Centreline Space Syntax Mapping Techniques

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Abstract

Good modelling practice requires the modeller to provide an evaluation of the confidence or uncertainty in their model. Up until now the uncertainty in a Space Syntax model has not been expressed in any way. In order to improve the application and legitimacy of Space Syntax modelling and to make informed design decision based on a Space Syntax model the uncertainty in the syntactic measures should be known. This thesis conducted an experimental study to quantify the sensitivity of the angular configurational measures of the axial map and road centreline map of the city of Groningen in order to develop a function that would allow for the error in the data collection process to be distributed and error bounds on the configurational measures to be determined. Thus allowing the confidence in the model to be expressed. Further, this thesis aimed to compare the sensitivities of the angular configurational measures of the axial map and the road centreline map in order to determine which of these was more robust. This would further improve the application of Space Syntax.

Strong linear relationships were found between the change in input, measured in terms of total length of segments added or removed, and the change in output, measured in terms of each configurational measure, for both the axial map and the road centreline map. Therefore, tentative formulae were developed to quantify the uncertainty for each configurational measure of both the axial map and the road centreline map. Based on these formulae, it was shown that the measure of angular choice was significantly more robust than angular integration. Additionally, it was shown that the road centreline map and the axial map were equally sensitive for the measure of angular integration. Finally, for the measure of angular choice, the road centreline map was more sensitive at the local scale and the axial map was more sensitive at the global scale.

Key words: Angular segment analysis, sensitivity, road centreline map, axial map

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1 Introduction

1.1 Space Syntax: an overview

Space Syntax is an overarching paradigm, a set of specific theories and a set of analytical models and tools proposed to elucidate the relationship between society and space (Karimi, 2012). It was developed by a research group lead by Bill Hillier and Julienne Hanson at University College London in the late 1970's and early 1980's (see Hillier & Hanson (1984)) and has been built on by various other academic researchers with 9 dedicated symposia being held since. It is based on two fundamental propositions. Firstly, space and society are intrinsically linked (Hillier B. , 1996b). Secondly, space is fundamentally a configurational entity, which means that all spaces in a spatial system are related to each other in a unique way (Karimi, 2012). Considering these two propositions, Space Syntax attempts to quantify the configuration of space in order to determine the effects of configuration on various social or cultural variables, such as movement patterns, land uses or crime patterns (Bafna, 2003).

Understanding the effects of configuration on social variables allows Space Syntax to build more rigour into studying the components of a city in the design process (Karimi, 2012). It does this by providing the tools to analyse an existing situation, which allows for the testing of the effects of desired situations on social variables such as movement or crime patterns. In doing this, it allows the designer to gather more information than can be gathered intuitively (Karimi, 2012). This greater understanding of cities and plans for cities can contribute to producing more sustainable designs and interventions (Hillier B. , 1996b).

Space Syntax proposes various analytical methods to quantify configuration. One group of methods extracts space as a map, transforms this map to a graph and then analyses are performed on this graph. The axial map was the first line-based method proposed as a technique for representing space in Space Syntax. It abstracts space as the least number of axial lines covering all convex spaces. An axial line is the longest straight line of sight or movement within a convex space possible to follow on foot and is therefore a representation of the city that captures the human cognitive interpretation of the city (Klarqvist, 1993). The axial map is therefore a representation of accessibility and visibility that the built environment allows through its structure (Dhanani, Vaughan, Ellul, & Griffiths, 2012).

An axial map is transformed into a graph in order to quantify the configuration of the network. In this transformation the axial lines of the map comprise the nodes of the graph and the intersections of the axial lines are the edges of the graph, which represent the relations of access between the axial lines (Hillier B. , 1996a). The first configurational measures developed in Space Syntax were integration and choice. Integration is calculated for each axial line by justifying the graph which places the line in question as the root of the graph and the remaining nodes are aligned above this node according to the number of edges to be crossed to reach the root node (Osman & Suliman, 1994). The integration value of this line is then the average distance, or depth, of each axial line from every other axial line. It has been shown that this measure correlates well with the degree of utilisation of a space (Hillier B. , 1996b). Additionally, there is the measure of choice which is a measure of the flow through a space. It is calculated by constructing shortest path routes between all possible origin and destination pairs. The choice value is then the summation of the all the paths through that space.

The method of abstracting space as an axial map however has several drawbacks, both practically and technically. Practically, the map has to be hand drawn, which is a time consuming process and it is also prone to human error such as the use of differing scales of mapping and varying levels of detail that the observer maps (Dhanani, Vaughan, Ellul, & Griffiths, 2012). Technically, several inconsistencies have been pointed out by Ratti (2004), but mainly he has shown the discontinuous nature of axial map transformation where two different axial maps are possible for the same grid layout. The practical challenges of producing axial maps has reduced its commercial adoption and penetration into urban analysis and the technical flaws has attracted severe criticism and threatened its academic legitimacy.

Alasdair Turner proposed angular analysis as an alternative to Space Syntax for the quantification of space (Turner, 2000). The method was later refined as an extension of the axial analysis (Turner, 2001). It is based on the idea that a person will attempt to turn as little as possible when travelling from an origin to a destination (Turner, 2000). Therefore, it proposes to calculate 'angular integration' using an angular weighted graph where the edges of the justified graph are weighted according to the angle of connection of the axial lines. Additionally, it proposes to calculate 'angular choice' but the shortest path is defined as the path with the least sum of angular turns.

Turner (2007) proposed using angular analysis of a segment map based on road centrelines as a solution to the practical and technical challenges of the axial map and analysis. As the name suggests, road centreline data represents the street network as a series of lines that follow the centreline of the road (Dhanani, Vaughan, Ellul, & Griffiths, 2012). Road centreline registries are held by many national road agencies and therefore do not have to be hand drawn and because they follow the centre of the road they are not discontinuous under transformation.

The angular segment analysis of road centreline maps calculates further refined versions of angular integration and angular choice. The measures are calculated by using a length weighted normalisation procedure (Turner, 2007). It was shown that the angular segment analysis of a road centreline map correlates better with movement patterns than an angular segment analysis of an axial map, with the measure of angular choice producing the highest correlation with actual movement patterns. Therefore, it was concluded that the efficiency of producing the road centreline map was complemented by higher level of accuracy when predicting movement patterns (Turner, 2007).

1.2 Problem definition

The quality of a Space Syntax model, and any model in fact, is dependent on the quality of the data on which it is based. Therefore, if there is any uncertainty or error in the input data this same error will propagate in the output of the model and the output may not be sufficiently reliable for correct conclusions to be drawn from it (Heuvelink, 1999). Space Syntax models produced and used until now have not included any acknowledgement of error in the input data and therefore the accuracy of the models has been not expressed. This has occurred because traditional axial analysis discards all metric information therefore only binary errors can occur in the analysis meaning that an axial line is either missing when it should be present or present when it should be missing. Therefore, acknowledging these errors would require the modeller to concede that the axial map they produced was not completely accurate.

The introduction of the angular segment analysis of road centreline maps by Turner (2007) introduced the weighting of the nodes of the graph by the angle of connection between segments and the weighting of the configurational measures by the length of the line. This means that there can either be an error in the angle of this connection or in the length of the line. Errors occur either as a result of measurement errors, spatial and temporal variation or mistakes in data entry (Heuvelink, 1999). Good modelling practice requires that an evaluation of the confidence in the model is provided in terms of the uncertainties associated with the output of the model as a result of errors in the input of the model (Crosetto, Tarantola, & Saltelli , 1999).

Uncertainties in the output can be determined by performing a sensitivity analysis. Investigating the sensitivity of a model will reveal the relationships between input and output variables which will allow for the most important variables influencing the analysis to be revealed (Campolongo, et al., 2008). Further, a sensitivity analysis can provide an understanding of how a model depends upon the information fed into it and hence to establish requirements for the quality of the data required in future model production (Crosetto, Tarantola, & Saltelli , 1999). Finally, understanding the sensitivity of the model is important in order to assess the validity of the network. This is particularly true when we study large networks, where the data is likely to be missing or hidden such as in a city-wide Space Syntax model (Borgatti, Carley, & Krackhardt, 2006).

1.3 Research goal

This thesis aims to perform a sensitivity and comparative analysis of the angular configurational measures of the axial map and the road centreline map. This sensitivity analysis will determine the influence of errors in the input data of the model on the angular configurational measures of the axial and road centreline maps. This will then be used to develop a function that will allow for the quantification of confidence intervals around each measure. Additionally, this sensitivity analysis will allow for a comparison to be made to determine which of the angular measures and which mapping technique is more sensitive, which will further add to the research performed by Turner (2007). Ultimately, this will improve the application of the modelling techniques of Space Syntax.

Although not a key research goal, the generation of axial and road centreline maps of the modelled city as original maps in the sensitivity analysis will allow for the quantification of configuration of the street network. This can be used by future urban planners and designers and enable them to better understand the grid in order make better informed design decisions.

1.4 Academic and societal relevance

The sensitivity analysis proposed in this research will allow for the construction of formulae that will enable the quantification of confidence intervals around the angular configurational measures of the axial and road centreline maps. This will improve the legitimacy of Space Syntax as the quantification of errors in the technique will allow an assessment of the validity of the model to be made (Borgatti, Carley, & Krackhardt, 2006). Additionally, expressing the uncertainty in the model will allow for more informed design decisions to be made if these decisions are based on the model. Further, the quantification and identification of sources of error will enable future modellers to minimise the error in their models. Finally, the sensitivity analysis will allow for data quality requirements to be known, which in commercial applications of Space Syntax will allow for cost-benefit analyses to be performed to determine whether a Space Syntax analysis should be performed or which modelling technique and measure should be selected.

The confidence interval formulae developed in this thesis will allow a comparison of the angular configurational measures and the axial and road centreline mapping techniques to be performed. This will provide future modellers with insight into the best configurational measure or mapping technique to use. This will improve the application of Space Syntax and can further enable it to contribute to the design process and achieve its proposed goals of producing environments that enhance mobility, economic activity, safety and positive social interaction (Space Syntax Ltd, 2015).

1.5 Research questions

This thesis aims to perform a sensitivity and comparative analysis of angular configurational measures of the axial map and the road centreline map. This therefore leads to the following research question:

1. What is the sensitivity (numerical error delta) of the angular segment measures of configuration of the axial and road centreline map?

In order to investigate this research questions, it has been divide into the following sub questions:

   a. What is the effect of error in segment length on the sensitivity of the angular configurational measures?
   b. What is the effect of error in angle of connection between segments on the sensitivity of the angular configurational measures?

The answers to these research questions will then allow for the following research questions to be investigated:

2. What is the difference in sensitivity between the axial map and the road centreline map?
3. What is the difference in sensitivity between the different measures of configuration?

1.6 Research plan

An experimental study of the axial and road centreline maps of the city of Groningen, in the Netherlands, has been performed in order to produce data to answer the above research questions. The city of Groningen has been selected for the experimental study because it is of a manageable size and the city centre has the form of a traditional deformed organic grid. Therefore, it will be comparable to the many other cities in world that have similar grid patterns.

Groningen is a town in the north of the Netherlands, shown in Figure 1, with a population of approximately 200,000 inhabitants making it the seventh biggest city in the country. It is a monocentric city, with the city centre bound by canals. The street network of Groningen does not follow one consistent typology. There are varying grid typologies throughout the city, with the three most prevalent being the layout of the suburb of Beijum Figure 2 (a), the city centre Figure 2 (b) and an orthogonal grid Figure 2 (c).

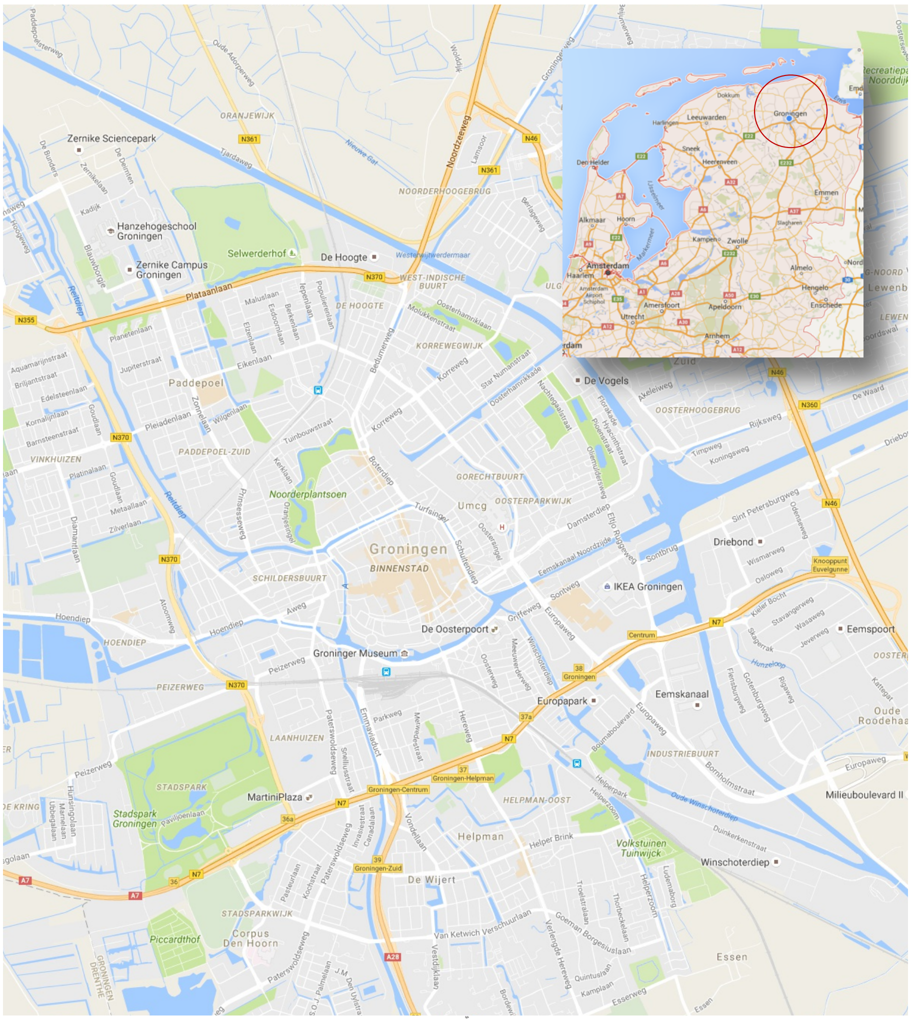
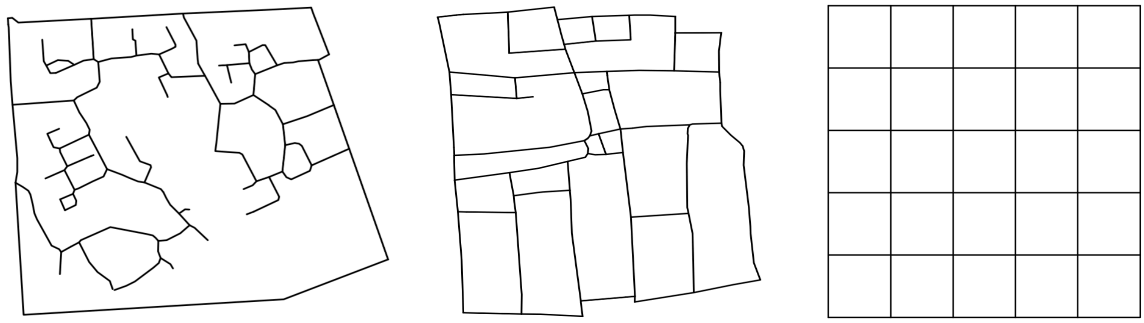


Figure 1: Groningen, the Netherlands, circled in red (Google, 2016)



(a) (b) (c)

Figure 2: Grid typologies in Groningen (a) Beijum grid (b) city centre grid (c) orthogonal grid

In 1977 the political executive in Groningen introduced the *verkeerscirculatieplan* with the intention of preventing all through-traffic through the city centre (Tsubohara , 2007). This was meant to give priority to pedestrians, public transport and cyclists. Further, because almost 40% of the population of the city is made up of students the levels of car ownership are low and bicycle ownership is extremely high with the city containing more bicycles than residents. The result of these facts is a modal split that is vastly in favour of non-motorised forms of transport.

This experimental study was carried out according to the flow chart in Figure 3 below. This involved first sourcing and generating original axial and road centreline maps of the non-motorised transport network of the city. Secondly, angular segment analyses of the original axial and road centreline maps were performed. Then, updates were made to these maps by adding and deleting street segments according to the three grid patterns above. Angular segment analyses were then performed on these updated models and the measures of configuration were compared with the original values. This comparison allowed for error deltas to be calculated and the sensitivity of each measure in the axial map and the road centreline map to be determined. These values were then compared with each other in order to determine which mapping technique was more sensitive than the other.

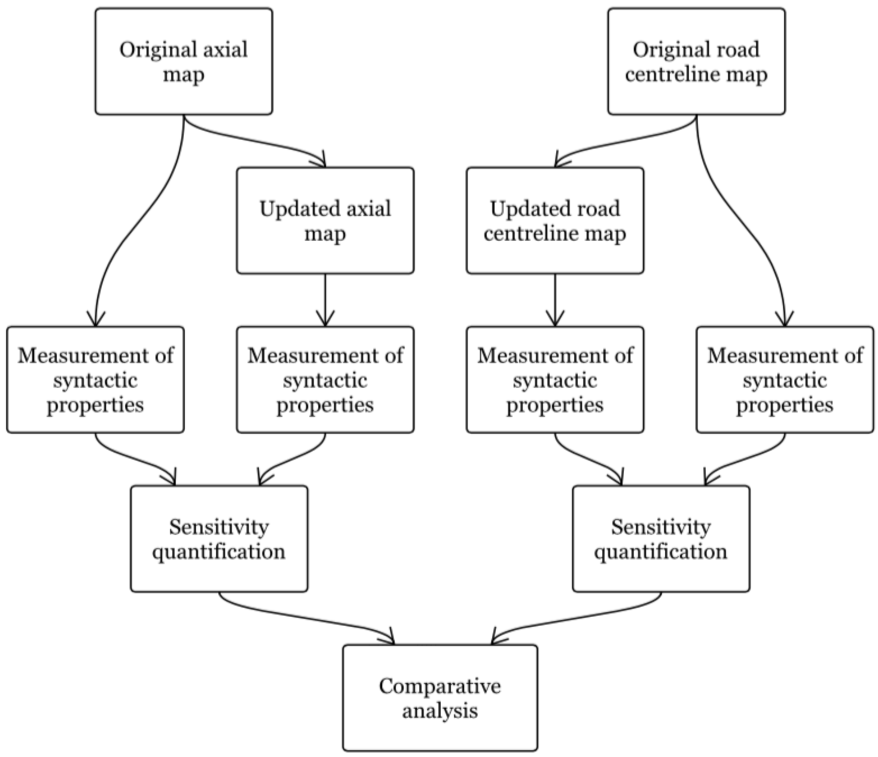


Figure 3: Flow chart of processes for data collection to investigate research questions 1, 1a, 1b and 1c

1.7 Scope and limitations

The focus of this thesis is on the axial and road centreline representations of space analysed using angular segment analysis of Space Syntax. Therefore, formulae for the confidence intervals will be specific to each measure within each mapping technique. Additionally, the empirical component of this study will model only the city of Groningen and this will therefore limit the generality of the conclusions drawn. These limits are due to the fact that Groningen is located in Western Europe and therefore it followed a specific pattern of development. This pattern of development may not be the same for cities developed in different parts of the world. Therefore, the results may be limited to cities of similar developmental patterns. Additionally, in the experimental component of this study, the maps have been produced at a level of detail that only includes pedestrian and bicycle movements as this is the dominant mode of transport in the city. Therefore, the results may not be applicable to models produced at higher or lower levels of detail.

The research will also be limited by the quality of the data used for producing the maps. The road centreline data has been sourced from the website: http://www.geofabrik.de. This data is derived from the Open Street Map (OSM) project, which is described as volunteered geographic information (Dhanani, Vaughan, Ellul, & Griffiths, 2012). This means that members of the public have devoted their time to creating freely available geo-located information. The creation and compilation of this data is done in several ways including on-foot data collection, aerial imagery digitisation and local knowledge (Dhanani, Vaughan, Ellul, & Griffiths, 2012). The fact that this data is compiled completely voluntarily and is not controlled by a regulatory body means that it may be incomplete or inaccurate and the quality of the data varies depending on the country and the region. Therefore, the use of OSM data may limit the accuracy of the results as the accuracy of this data is not known. However, it has been found that data surrounding urban areas is more accurate and therefore the data is assumed to be of reasonable accuracy (Dhanani, Vaughan, Ellul, & Griffiths, 2012).

1.8 Structure of thesis

This following section will provide a review of the literature on the theories, definitions and applications of the axial and road centreline mapping techniques. Additionally, a theoretical description of the sensitivity analysis employed during this research is provided. This, together with the Space Syntax overview, provide a theoretical framework for the research as a whole. This theoretical framework is summarised and illustrated in conceptual model, where the factors influencing the sensitivity of the model have been identified. Following this, the methodology of the research is described as well as the experimental methods used to collect data. The results of the experiments are then presented in the form of tables and graphs to provide an objective overview of the data. This data is then analysed in terms of the conceptual model presented earlier in order to determine the effects of each variable in the conceptual model on the sensitivity of the angular configurational measures of the road centreline map and the axial map. This will allow for the quantification of the sensitivity of the angular configurational measures of the road centreline map and the axial map. The sensitivity of the axial map and the road centreline map is then compared and conclusions are drawn based on this comparison. Finally, some improvements to this thesis and directions for future research are proposed.

2 Theoretical framework

This theoretical framework is comprised of a review of international literature which includes an introduction to the theoretical underpinnings and method of an axial analysis, this is followed by a discussion of the criticisms and limitations of this method. The angular segment analysis of a road centreline map is then presented as an alternative to overcome these criticisms.

To analyse the axial and road centreline maps the method of calculating the angular configurational measures of integration and choice is provided. This forms the backbone of the Space Syntax analysis performed in the experimental component of the thesis. Additionally, it allows for the identification of the key variables that influence the configurational measures. These key variables are the sources of sensitivity and were the focus of the sensitivity analysis.

This theoretical framework is summarised and illustrated in a conceptual model, which is provided at the end of the chapter. This model provided structure to the research of the sensitivity of angular configurational measures of each mapping technique and the differences between the two.

2.1 Space Syntax: Analytical methods

Section 1 provides a brief introduction to the overarching logic of Space Syntax as well as the analytical methods of the axial map and analysis and the angular segment analysis. The purpose here is to expand on these introductions.

2.1.1 Analytical methods of Space Syntax

The primary object of analysis within Space Syntax is the configured building or urban space. For a traditional Space Syntax analysis this space is represented in an abstract format, as an axial map and then as a graph, which focuses on its topology and reveals the patterns of relationships between spaces (Karimi, 2012). The logic behind abstracting the topological configuration of space as a graph is that the sociologically relevant aspects of the configured space are internalised at the topological level (Hillier B. , 1999). This process of abstraction disregards small, circumstantial and generally socially irrelevant geometrical differences between configured spaces and captures only socially relevant information (Bafna, 2003).

The axial map

Within Space Syntax there are a number of methods of representing space. This research focuses on the traditional line representations of space, namely the axial line. An axial line is the longest straight line of sight or movement within a convex space possible to follow on foot (Klarqvist, 1993). Individual units of space in a model are represented by one of these lines and the representation of the entire network as the least number of axial lines forms the axial map. The axial map reveals the most likely selected path within a space by revealing the most efficient path of movement across a convex space (Behbahani, Gu, & Ostwald, 2014). In the construction of the axial map all metric information is discarded. In theory each axial line represents a change in direction from another line. Therefore, constructing an axial map to model movement patterns is based on the assumption that the number of turns a person has to make is more important than the metric distance covered.

Graph construction

An axial map is transformed into a graph in order to quantify the configuration of the network. In this graph the axial lines comprise the nodes and the edges are the intersections of the axial lines, which represent the relations of access between the axial lines (Hillier B. , 1996a). In order to calculate the configurational properties of an axial line it is required to justify the graph to this line. This means that a graph is drawn with this line as the root or base and the remaining nodes are aligned above this node according to the number of nodes to be crossed to reach the root node (Osman & Suliman, 1994). This process is illustrated for an architectural space represented as convex spaces in Figure 4 (a) – (d) below where the graph is justified to the outside space. The process is the same for an axial map except each convex space is represented as an axial line. The key discovery of configuration here is that when the graph is justified to each different space it has a different shape (Dalton N. , 2001).

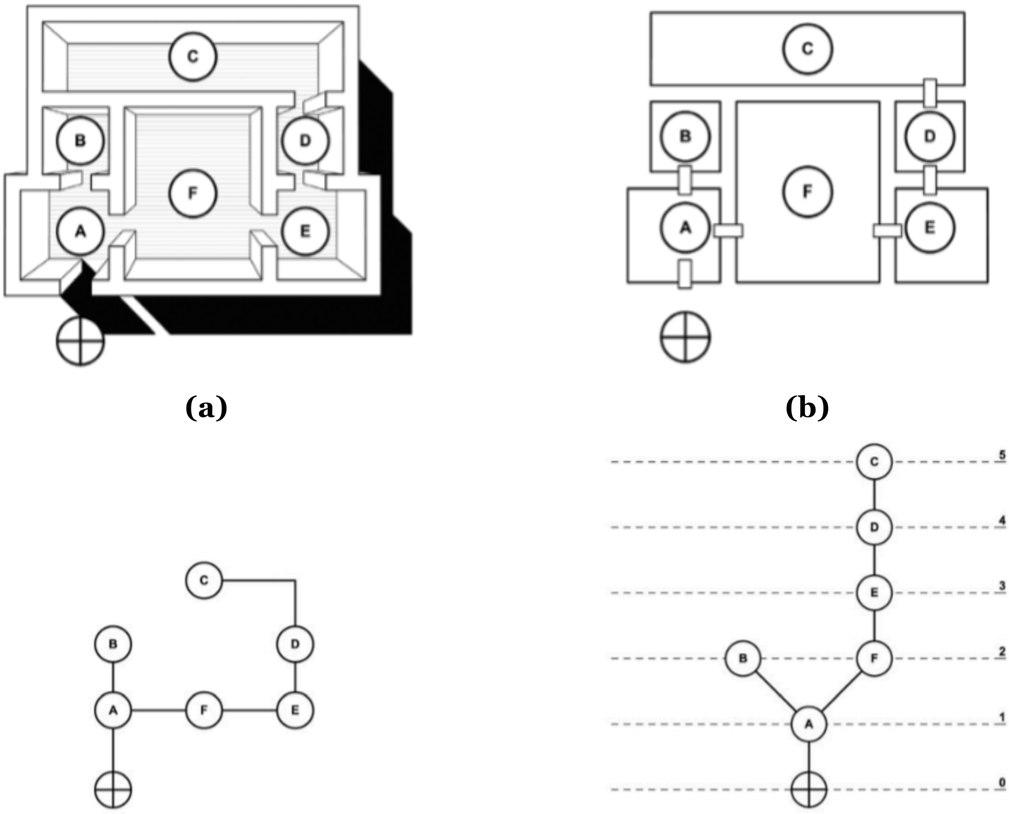


Figure 4: Process of producing a justified graph. (a) architectural space (b) convex plan (c) plan graph (d) justified graph (Osman & Suliman, 1994)

Axial integration

Axial integration is one of the measures of configuration of a network. In order to calculate the integration value of an axial line a measure called depth is required. An axial line may either be many (deep) or few (shallow) changes in direction from the root line. Each line in a map is assigned a number according to how many changes in direction separate it from the root line and can be conceived as a topological distance (Ratti, 2004). Total depth is an extension of the depth concept and is determined by building a j-graph for a node and calculating the total depth from all other nodes. Mean depth is then calculated by dividing this value by the total number of nodes (Hillier, Hanson, & Graham , 1987). This value can be considered as the total distance to move from the root line to all other lines (Ratti, 2004). This value is then used to determine integration.

Integration is a measure that describes the average depth of a space relative to all other spaces in the system, therefore, having a focus on destinations. This measure describes how easily accessible a space is within a given network of other spaces. This allows the spaces in the system to be ranked to determine the most integrated and the most segregated spaces (Klarqvist, 1993). This measure tends to correlate with the degree of utilization of a space, which can be an indication of economic centres for high integration or areas with high crime for low integration (Hillier B. , 1996b). The full equation for calculating axial integration can be seen in equation 11 in Appendix A.

Axial choice

Choice or through movement describes the amount of flow through a space. It is calculated by constructing shortest path routes between possible origin – destination pairs. Whenever a node is passed through on one of these paths, its value is incremented (Turner, 2007). Spaces with high through movement values are located on the highest number of shortest paths between all origins and all destinations (Varoudis, Law, Karimi, Hillier, & Penn, 2013). This leads to frequently used nodes having higher values and therefore higher accessibility.

2.1.2 Criticisms and limitations of the axial map

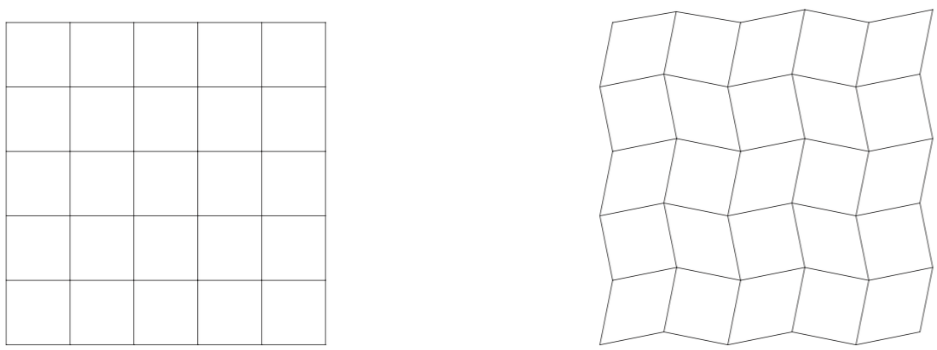
Despite showing high correlations with actual movement patterns the axial map has received much criticism. This criticism has been directed at the theoretical underpinnings of the axial map and the practical difficulties in producing an axial map.

Theoretical limitations

The theoretical criticisms of Space Syntax mainly question the claim that Space Syntax models pedestrian choice making (Ratti, 2004). This stems largely from the fact that the line-based representation of a city as an axial map disregards valuable geometric information and focuses only on topology (Ratti, 2004). This two dimensional simplification of space results in a number of issues. Firstly, it doesn't take into account the dimensional property of streets but only the way they connect to each other. This means that long straight lines are treated the same as shorter straight lines and in reality they are significantly different. Secondly, axial maps disregard all 3D information (Ratti, 2004). Thereby removing the influence of, for example, building heights on movement patterns.

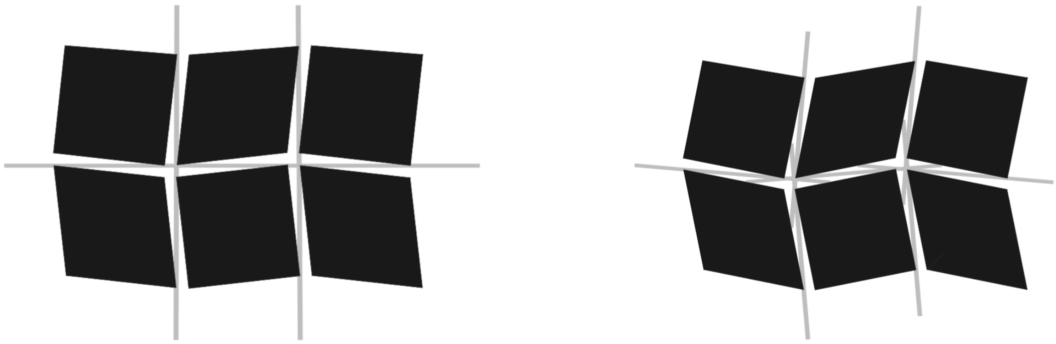
Modelling very long and straight streets with axial lines is problematic. Dalton (2001) describes these lines as 'ultra-long' lines and explains that axial measures calculate one value per space and this limits the ability to represent changing conditions along the length of a road segment (Dalton, Peponis, & Conroy-Dalton, 2003). Therefore, when an axial line is extremely long it will have varying cognitive interpretations and varying movement patterns along its length, but the morphological properties and axial measure will be the same for the whole length. This is however not an accurate representation of the cognitive interpretation of a street because the visual field observed and drawn in the axial line differs from the visual field observed from the other end of the line and any other point along the line. Therefore, it is not logical to assign the same morphological properties to an axial line as is done in a traditional Space Syntax analysis (Jiang & Claramunt, 2002).

The two dimensional simplification of space as an axial map is discontinuous in nature when transformed (Ratti, 2004). A hypothetical orthogonal grid, shown in Figure 5 below, was gradually deformed by increasing its skew so that it gradually approach (b). The corresponding axial map would initially remain unchanged, as in Figure 6 (a). After some critical point it would abruptly deform to produce the axial seen in Figure 6 (b). At this critical angle there are therefore two different axial maps possible for the same geometrical arrangement. This result leads to an inconsistency in the correlation of Space Syntax measures with movement patterns and the social logic of space because human behaviour does not change in quantum leaps as happens in the hypothetical situation described above (Ratti, 2004).



(a) **(b)**

Figure 5: Hypothetical (a) orthogonal axial map, (b) deformed axial map (Ratti, Urban texture and space syntax: some inconsistencies, 2004)



(a) **(b)**

Figure 6: Corresponding axial maps for Figure 1 (a) and (b) (Ratti, Urban texture and space syntax: some inconsistencies, 2004)

Constructing the graph of an axial map and analysing it uses a system which expresses the presence or absence of a link between axial lines in a binary fashion (Osman & Suliman, 1994). This means that the all turns in a street network are weighted equally regardless of the angle of connection. This is in contrast to cognitive findings that suggest that the angle of the turn has a large influence on the way humans perceive the world (Turner, 2007). Therefore, the analytical procedures can result in misleading interpretations since they do not calculate values that reflect the actual urban fabric (Osman & Suliman, 1994).

In the transformation of an axial map to a graph in traditional Space Syntax analysis streets are not viewed as locations and therefore the relations between two streets can never be uniquely embedded in Euclidian space (Batty, 2004). This results in the analysis of the topological relations being entirely abstract because it forces the representation of distance between two streets to be distance in the graph-theoretic rather than the Euclidean sense. Therefore, the relational graph is removed from the physical space in which it is initially defined (Batty, 2004).

The results of a Space Syntax analysis are influenced by the extent of the city chosen to be modelled (Ratti, 2004). Configurational measures like integration depend on having an adequate buffer of nodes and connections to produce accurate results. Edge effects result from graphs that do not have an adequate buffer zone, producing artificially lower results. This is because the network model does not take into account components of the network that exist beyond the network boundary (Gil, 2015). Therefore, the accuracy of integration measures decreases the closer to the axial line is to the edge of the system.

Practical limitations

The axial map has been also criticized in terms of its practical application. The precise definition of the axial line is still contested and the process of deriving an axial map appears to be arbitrary and time consuming (Jiang & Claramunt, 2002). The hand drawing process begins with the identification of the longest axial line continuing to the shortest axial line resulting in a map of the least number of axial lines. Based on human judgement it is possible to complete an axial map of an urban system, but the process becomes time consuming in larger urban systems (Jiang & Claramunt, 2002). Further, there is no way of guaranteeing that two axial maps produced by different people will be precisely the same and situations are possible where two different axial maps are produced from the same original map (Dalton, Peponis, & Conroy-Dalton, 2003). Finally, there is no way to ensure that it is constructed out of the fewest number of axial lines (Jiang & Claramunt, 2002). These practical difficulties have resulted in Dalton (2001) describing the process of constructing an axial map as a “Black art”.

2.1.3 Road centreline mapping

The criticisms of the axial map necessitated an alternative to overcome the theoretical and practical limitations. Turner (2007) proposed an angular segment analysis of road centrelines in order to do this. As the name suggests, road centreline data represents the street network as a series of lines that follow the centreline of the road (Dhanani, Vaughan, Ellul, & Griffiths, 2012). Historically, this has been the traditional method of representing street networks and therefore large databases exist in many countries. In addition to these large databases there are computational methods for producing maps of this kind. Therefore, resulting in very few practical limitations. In order to uncover how the road centreline deals with the theoretical criticisms of the axial map it is necessary to explain the angular segment analysis proposed by Turner (2007).

Angular segment analysis of road centreline map

Road centreline maps do not perform well using traditional Space Syntax analysis because the mapping technique breaks streets into segments causing what has been called "the segment problem" (Turner, 2007). This means that their analysis by traditional methods makes them appear excessively deep making the analysis cluster near the centre of gravity of the area rather than highlighting the global spatial structure (Dhanani, Vaughan, Ellul, & Griffiths, 2012). Angular segment analysis of road centrelines has therefore been proposed as an alternative to the traditional Space Syntax analysis.

Turner (2007) showed that the values of integration and choice for the angular segment analysis of a road centreline map correlated better with actual movement patterns than the axial map of the same area. Additionally, it was shown that angular choice was a better model of movement than angular integration.

Angular analysis is based on the traditional methods of analysis of Space Syntax however, it uses an angular weighted graph, rather than the unweighted graph of the axial map (Turner, 2001). This stemmed from work by Dalton (2001) who suggested that depth can be calculated according to fractional rather than unit changes. In angular segment analysis this is done by assigning nodes a fractional values based on the angle of connection between the axial lines.

The logic of weighting the graph according the angle of the connections is that turns are interpreted differently by humans depending on the angle of the turn (Turner, 2001). Additionally, doing this overcomes the binary simplification of turns in the axial map and provides a more accurate representation of the urban fabric. Further, the weighting of nodes in the graph according to the angle of connection means that the segment problem for the road centreline map is overcome because there is no angular turn to a segment that leads straight on therefore there is no artificial 'cost' that is added (Turner, 2007).

2.1.4 Angular segment integration

The measure of depth in angular segment analysis is calculated as the sum of the angular weighted edges between points two points rather than only the sum of the number of edges as in the axial map. Figure 7 below illustrates this where the depth from segment A to segment B is 0.5 corresponding to a turn of 45^o and the depth to segment C is 1.33 corresponding to a turn of 45^o followed by a turn of 60^o (Turner, 2007).

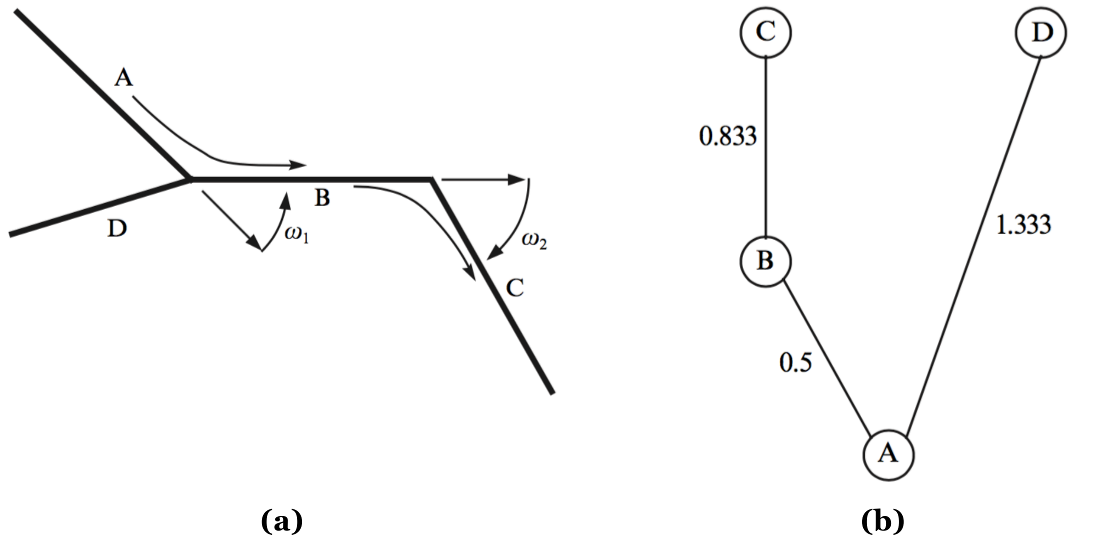


Figure 7: (a) path through a network (b) the corresponding angular weighted j-graph of the path (Turner, 2007)

The measure of angular integration is calculated for each segment using this angular depth according to the same method as axial integration. However, for the analysis of road centrelines the calculation is weighted by the length of the segment. This is because it is expected that longer segments are associated with a higher percentage of origins and destinations of journeys than shorter segments (Turner, 2007). The formula for calculating angular integration appears as formula 13 in Appendix A. The breaking of the street network into segments at junctions and changes in direction means that the problem of ultra-long streets is not experienced and changing conditions can be expressed along the length of the street.

2.1.5 Angular segment choice

The measure of angular segment choice is calculated according to a method similar to axial choice, however a different definition of shortest path is adopted. For this measure the shortest path is defined as the path with the least sum of angular turns. For road centrelines the calculation is weighted by multiplying the length of the origin segment by the length of the destination segment and this weight is assigned to each segment on the shortest path (Turner, 2007). The origin and destination of the path is given half this weight. The assumption being that one would start and conclude a journey at the middle of each segment (Turner, 2007). The formula for calculating angular choice appears as formula 15 in Appendix A.

2.1.6 Criticisms of the road centreline map

Despite the fact that the angular analysis of the road centreline map correlated better with actual movement patterns than the axial map of the same area there are some criticisms of the method. In producing the road centreline map there is a risk the endpoints of two segments that are supposed to meet at a node are offset by a very small amount. This means that visually it would not be apparent and this would lead to the failure of the angular segment algorithm (Dalton, Peponis, & Conroy-Dalton, 2003). Further, there can be measurement errors in the data collection process, which is explained in section 2.4.

2.2 Resolution of Space Syntax analysis

A Space Syntax analysis can be conducted at varying radii. The radius defines the number of steps or distance away from each space that is included for syntactic analysis (Turner, 2007). It can be thought of as an isolation of certain levels or distances (Ostwald, 2011). Radii measures are categorized into local and global measures. Global measures examine the space as a whole whereas, smaller, local, radii measures examine the relationships of all points to their neighbours within a given number of steps or metric distance away. Generally, an analysis at a local radius corresponds to small-scale, local human activity and radius n corresponding to large-scale, long distance, global activity. These measures are useful for looking at different scales of a spatial system (Karimi, 2012).

2.2.1 Global analysis

Global analysis uses a radius n and examines the spatial graph as a whole thereby taking into account every spatial relationship in the system (Karimi, 2012). Therefore, this reveals large scale configurational properties of a spatial system. This is useful for examining large-scale movement throughout a spatial system. In general, it correlates with long distance journeys and behaviour of outsider groups. Often it relates strongly to vehicular movements, which is less dependent on local-configuration (Space Syntax Ltd, 2004).

2.2.2 Local analysis

Local analysis involves using defined units for the scale of the analysis either measured in topological steps for axial analysis or metric distance for angular segment analysis. Local analyses allow small scale configurational relationships to be measured. These measures correlate strongly with local pedestrian movement meaning short trips to local destinations. In general, it correlates with the movements of locals rather than visitors (Hillier B. , 1996a).

For the axial analysis the smallest useful topological radius is radius 3. This includes the root node and two levels of depth beyond that. For angular segment analysis of road centreline maps, Turner (2007) proposes using metric radii for local analyses. The logic behind this being that traditional local radius calculations suffer under different representations as the number of segments away from a particular location depends on the number of segments that the cartographer used to represent the system. Additionally, this deals with the problem of ultra-long lines and only considers a metric radius within the boundary of the modelled area (Turner, 2007).

2.3 Correlations of measures

Once the configurational properties of a space have been calculated, according to either of the methods described above, the measures can be statistically correlated with observed social or spatial variables by performing a linear regression. The measures can be correlated with social variables because it is assumed that there is a direct relationship between spatial configurations and urban functions (Karimi, 2012). The correlations with spatial variables are performed in order to gain a higher understanding of the way in which a spatial system operates (Space Syntax Ltd, 2004).

2.4 Errors in Space Syntax modelling

Any deviation from the input data in a space syntax model and reality can be considered error (Heuvelink, 1999). Errors in Space Syntax modelling can be introduced as a result of errors in the mapping techniques. In the case of the road centerline map errors can be introduced as a result of measurement errors, spatial and temporal variations or from mistakes in the data entry (Heuvelink, 1999). Additionally, the axial map is constructed by hand by drawing axial lines this process itself is prone to errors particularly when the size of the system increases. This means that lines are imprecise and can vary depending on the cartographer.

Traditionally, the axial analysis discards all metric information and therefore the accuracy of drawing the axial lines was not relevant. However, the introduction of the angular segment analysis and the subsequent angular weighted graph and length weighted normalization has resulted in the problem of errors propagating or even being amplified.

2.5 Sensitivity analysis

2.5.1 Overview

A sensitivity analysis, according to Campolongo *et al* (2008), is a study of how uncertainty in the output of a model can be apportioned to different sources of uncertainty in the input. This should then be followed by an uncertainty analysis which quantifies the uncertainty in the model output (Campolongo, et al., 2008). The information provided by a sensitivity analysis can help significantly with building confidence into a Space Syntax analysis for decision making. If the model is robust then there is confidence in implementing recommendations based on it (Pannell, 1997).

Sensitivity analyses have a number of uses in modelling. Table 1 below shows the uses of a sensitivity analysis and how it can contribute to Space Syntax modelling. In the case of the Space Syntax sensitivity analysis the attempt will be to improve decision making, communication, increasing understand or quantification of the system and model development. These will all contribute to the understanding of the Space Syntax model under scrutiny, which will in turn improve the interpretation of the model.

Table 1: Uses of a sensitivity analysis (Pannell, 1997)

Area of model improvement	Function
Decision making or recommendation development	Testing robustness Identifying critical or sensitive values
Communication	Making recommendations more credible
Increasing understanding or quantification of the system	Determining and understanding relationships between input and output variables
Model development	Testing accuracy or validity of a model Searching for errors in a model Simplifying a model Coping with poor or missing data

2.5.2 Conducting a sensitivity analysis

There has been one study performed to quantify the sensitivity of Space Syntax models to changes in inputs, but these changes in inputs were to investigate the effect of boundary selection on configurational measures. Therefore, no changes were made within the system, but only the size of the system was increased. Research has however been conducted on the sensitivity of centrality measures in network data, which is comparable to Space Syntax, by Borgatti, Carley and Krackhardt (2006) and Herland, Pastran & Zhu (2013).

Borgatti, Carley and Krackhardt (2006) conducted research investigating the sensitivity of centrality measures under conditions of imperfect data in graphs. This study determined the robustness of a large sample of random graphs in order to determine the validity of the network under research. Their method began with a known network then centrality of this original network was measured known, as “true centrality”. An observed network was then created by distorting the known network and centrality was re-measured as “observed centrality” (Borgatti, Carley, & Krackhardt, 2006).

In order to construct the observed network one of four types of errors was introduced: node removal, node addition, edge removal and edge addition. Node removal was performed by extracting a random portion of existing nodes. Conversely, node addition involved adding a node randomly and adding edges randomly connecting this node to other nodes in the network. Edge removal and edge addition involved removing or adding random edges respectively. The centrality measures of the observed network were then compared with those of the known network. It was found that the accuracy of the model declines with increasing error and this decline was smooth and predictable and therefore it was possible to construct confidence intervals around each measurement provided the error in input was known (Borgatti, Carley, & Krackhardt, 2006).

Quantifying sensitivity

Quantifying sensitivity involves uncovering and quantifying a relationship between input and output variables. This means that input variables must be quantified and output variables must be quantified. Herland, Pastran & Zhu (2013) conducted an empirical study investigating the sensitivity of network centrality scores in various network conditions. Nodes and edges were added and removed as percentages of the total number of nodes and edges of the true network in order to quantify the change in input to the model.

Gil (2015) measured the sensitivity of spatial network centrality analysis to boundary conditions. The sensitivity of the measures was quantified by performing Pearson and Spearman correlations to measure the differences between true and observed values and then applied a simple regression model. Sensitivity is then measured by the coefficient of determination (R2). If the scenarios are identical then R2 has a value of 1 and the smaller the R2 value, the greater the sensitivity of the model (Gil, 2015). It is argued that the simple regression model is appropriate because identical measures are compared that would be perfectly correlate under normal conditions.

2.6 Conceptual model

2.6.1 Overview

The theoretical framework presented above allows for the identification of sources of sensitivity in a Space Syntax analysis and a conceptual model to be made based on this. The conceptual model is shown in Figure 8 below and illustrates the sensitivity of the angular segment configurational measures of the axial and road centreline maps.

There are two main categories of variables that influence the sensitivity of the angular configurational measures of a Space Syntax model. These categories are the variables relating to the properties of the original model and variables relating to the properties of the update made to the model. The magnitude of these two classes of variables are not dependant on each other, but the sensitivity of the model is dependent on these and the interaction between these.

The effect of the original Syntactic properties of the model will not be investigated in this thesis as only one city has been modelled. It is therefore only possible to have one model with its original properties and therefore investigating different original properties is beyond the scope of this thesis. The number of nodes and edges in the original model is however important to be noted as it may have effect on the sensitivity of the model, but in this thesis it is held constant. Therefore, these variables have been omitted from the conceptual model as they are not researched in this thesis.

2.6.2 Explanation

The model in Figure 8 below shows the sensitivity of the angular configurational models of an axial and road centreline map in pink, the variables in the map influencing this sensitivity in green and the subsequent variable in reality that influences these variables. The solid lines represent the process of measuring the angular configurational measures and the dotted lines represent the process of mapping the street network.

The sensitivity of the configurational measures is dependent on: the change in number of segments, the change in total length of segments and the change in angle of connections between segments. These variables influencing the sensitivity of the configurational measures are chosen because an angular segments analysis measures the configuration of a network based on a graph where nodes are angle weighted with each node being representative of a segment in the system. Further, the configurational measures of the angular segment analysis are length weighted. Therefore, the sensitivity of the configurational measure will change when either of these variables is changed.

The changes in these variables is dependent on the typology of the grid in reality. The typology of the grid captures these geometric and topological properties of the streets that influence the sensitivity of the model and is therefore represented in this conceptual model. This conceptual model was applied in this research to quantify the sensitivity of the angular configurational measures of the axial map and the road centreline.

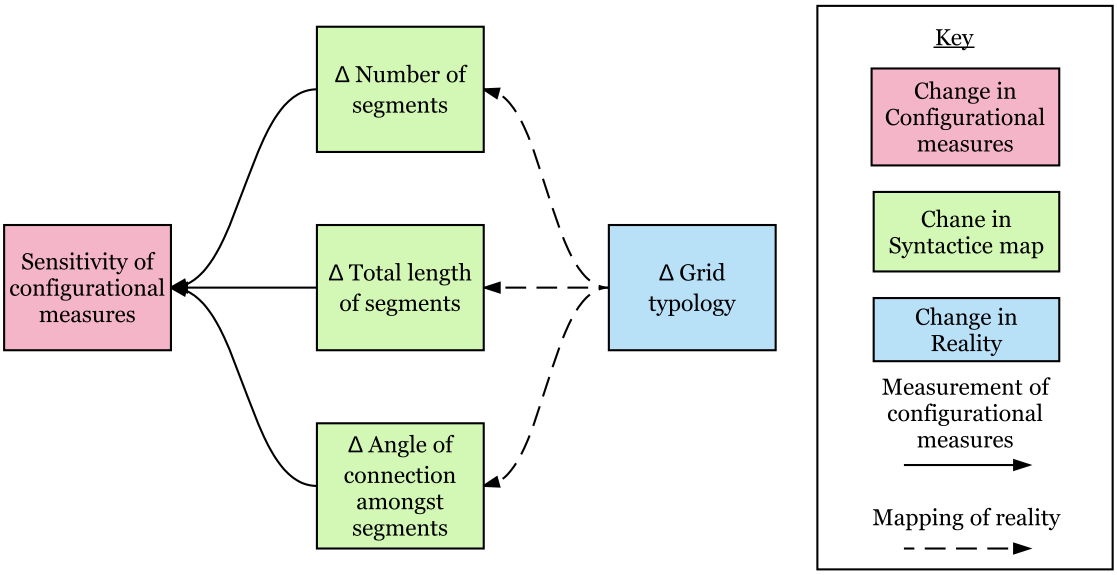


Figure 8: Conceptual model

3 Methodological Design

3.1 Methodology

This thesis aims to quantify the sensitivity of the angular syntactic measures of the axial map and the road centreline map. This involves investigating the relationship between changes in input in a model and the changes in output. What is meant by input is the variables on which the model is based and what is meant by output are the measures of configuration. Therefore, this study aims to investigate the relationships between the input variables and the output measures. This is best achieved by performing an experimental study because an experimental study records quantitative observations made by defined and recorded operations and in defined conditions followed by examination of the data, by appropriate statistical and mathematical rules, for the existence of significant relations (Nesselroade and Cattell, 2013 in (Cash, Stanković, & Štorga, 2016)).

The research aims and the corresponding data and method of collecting data required to achieve these aims is summarised in Table 2. The quantitative data will be collected by performing experimental studies of an axial map and road centreline map of the city of Groningen. These methods will be further explained below.

Table 2: Research aims, required data and methods

Research aim	Data type required	Methods
Determine the sensitivity of the angular segment measure of configuration for the road centreline and axial maps.	Quantitative data	• Experiment 1 & 2 • Linear regression
Determine the effect of error in segment length on the sensitivity of the angular configurational measures	Quantitative data	• Experiment 1 & 2 • Linear regression
Determine the effect of error in angle of connection between segments on the sensitivity of the angular configurational measures	Quantitative data	• Experiment 1 & 2 • Linear regression
Determine the difference in sensitivity between the axial map and the road centreline map	Quantitative data	• Experiment 1 & 2 • Linear regression
Determine the difference in sensitivity between the different measures of configuration	Quantitative data	• Experiment 1 & 2 • Linear regression

3.2 Research design

3.2.1 Introduction

Quantitative data was collected in order to answer the proposed research questions. Quantitative data was collected according to the research strategy shown in Figure 3 in the introduction. An experimental study of an axial map and a road centreline map of the city of Groningen was performed to quantify the sensitivity of the angular syntactic properties of each map. For this experimental study, the sensitivity of the axial map and road centreline map was determined by developing true, or original, maps and updated maps and comparing the syntactic properties of these maps in order to determine the numerical error delta between true and updated maps.

A true axial map and road centreline map were sourced and constructed respectively and updated maps were then produced by conceiving possible development scenarios and updating these true maps to include these developments. The syntactic measures of the true maps and updated maps were then calculated by performing an angular segment analysis using the *depthmap X* software package developed by Tasos Varoudis (2012). The syntactic measures of the original map and the updated map were then compared and the differences calculated. These differences were then correlated with the independent variable to investigate the effect of this on the differences between original and updated model. The method of data collection is based on the research performed by Costenbader and Valente (2003), Borgatti, Carley and Krackhardt (2006), Herland, Pastran & Zhu (2013) and Gil (2015).

3.2.2 True maps

An axial map and a road centreline map of Groningen were sourced from Akkelies van Nes (TUDelft) and the website http://www.geofabrik.de/ respectively. The road centreline data is based on open street map data and was cleaned using the *AutoCAD* software package in order to fix disconnected elements and to remove the numerous unnecessary elements and the vehicle only segments. These maps will address bicycle and pedestrian movement modes only and vehicular through movement has been excluded. This is done as Groningen has a modal split that is vastly in favour of non-motorised forms and has the largest density of bicycles in Europe.

The unprocessed true axial map and road centreline map of Groningen can be seen below in Figure 9 (a) and (b) respectively. An angular segment analysis was performed on the true maps using the *Deptmap X* software package and this formed the basis for the sensitivity and comparative analyses. The updated maps were produced in the experimental study, which is explained below.

Study area and boundary selection

The study area, shown in Figure 10 below, consists of the city centre of Groningen, labelled with a pink boundary, a so-called inner city area, labelled with a green boundary and an outer city area labelled with a blue boundary. The study area is divided into an inner city and outer city area in order to determine the sensitivity of each model to changes made in the inner city, the outer city and a combination of both. The city was dividing according to this scheme for both the axial and road centreline maps.

The inner city area is physically bounded by the ring road around Groningen which consists of the N370 to the north, N46 to the east, N7 to the south and the N370 to the west. The outer city area, labelled with a blue boundary, was chosen to minimise edge effects on the reference area of the system under study. As a result, a number of suburbs and areas outside of the municipal boundary of Groningen were included, including the Zernike university campus and the neighbouring villages of Beijum, Lewenborg, Helpman, Helpmaar and Zuidwolde.

(a) (b)

Figure 9: Unprocessed (a) road centreline map and (b) axial map of Groningen

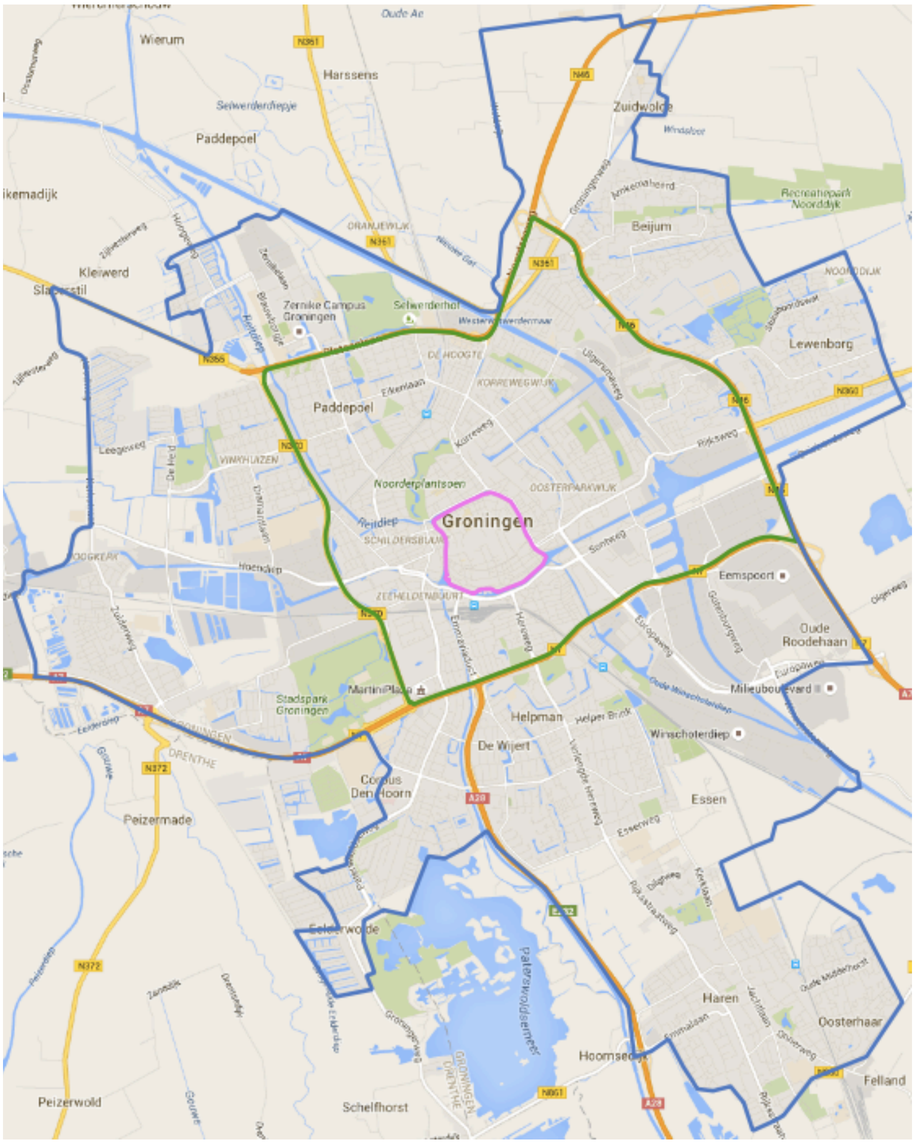


Figure 10: Study area and model boundary

Reference area

The sensitivity of the model has been determined by taking a reference area for the analysis. This means that syntactic measures were calculated for the entire model, but when calculating the sensitivity of the model only changes to this reference area were considered and the rest of the model was not analysed. This was done mainly to make the quantity of data more manageable. Additionally, in scenarios where lines were deleted taking a reference area ensured that all of the lines existed in all of the scenarios as no changes were made to the reference area itself.

The city centre, bound by the canals and marked in pink in Figure 10 above, was chosen as the reference area. The axial map and road centreline map of this area can be seen overlayed in Figure 11 below. This area was chosen as the city centre is the core of the system. This means that the edge effect experienced on the various measures is reduced to a minimum as the city centre has the largest buffer zone in the model. Further, because Groningen is a monocentric city the centre is the most important component of the city and therefore the most relevant component of the city to measure the sensitivity of. All of the changes made in the experiments have therefore been made relative to this centre in terms of distances.

Figure 11: Axial map in red overlayed on road centreline map in blue

Simplifications

Traffic management features were left in the models for both the axial map and the road centreline map. Additionally, extraneous lines were not removed for the analysis meaning that axial stubs remained in the model.

3.3 Updated maps

The true axial maps and road centreline maps were updated in the experimental study by generating scenarios where either undeveloped regions of the city are developed or undeveloped regions of the city are expanded. For the scenarios where undeveloped regions are developed street segments were added to the map. This was done at various locations and using various typologies of streets. The addition of street segments will result in the addition of nodes and edges to the graph of the original street network. For scenarios where the undeveloped regions are expanded street segments were removed from the map. This was done at varying locations in the map. It should be noted that for scenarios where streets are deleted then the typology of the change cannot be investigated because streets cannot be deleted according to a particular typology. The deletion of streets will result in the deletion of nodes and edges from the graph of the original street network.

The changes in input were made to each map by mapping the same changes in reality using the axial mapping technique and the road centreline mapping technique. These mapping techniques abstract space differently and therefore the same change in reality will have a different quantifiable change in input in the axial map and the road centreline. Changes are made to the maps in this way and not randomly because this research aims to provide a comparison of sensitivity between the axial map and the road centreline map. Therefore, the same changes have to be made to each and adding random errors would not allow for a comparison of the behaviour of each as the changes made would be different.

Location changes

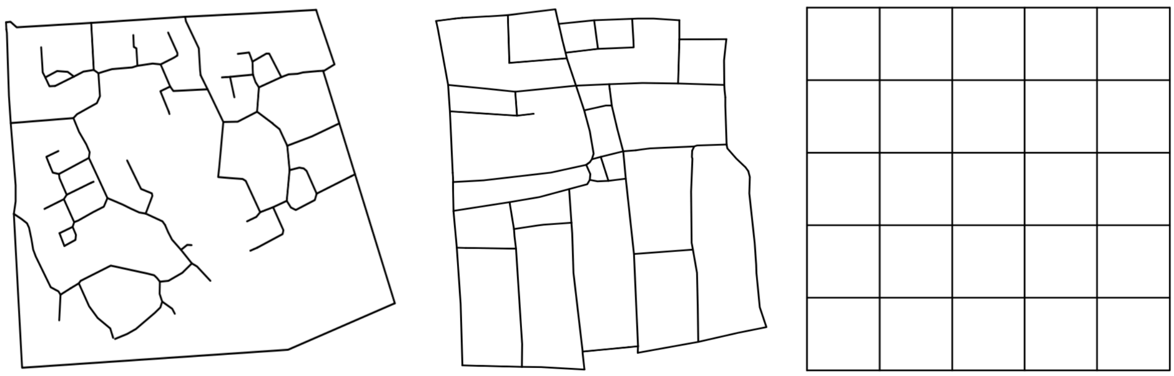
Changes were introduced to the models at varying locations. The locations of the changes are divided into three areas, namely inner-city, outer-city and a combination of both inner and outer-city. The division of the maps and locations of developments can be seen in Figure 13 below. These locations were selected at areas in the map where there was little or no development in order to realistically represent a possible future change to the system. The locations of the change were varied in order to provide a larger sample size. Further, because the model properties would be different at each location it would allow for the effect of the original model properties on the sensitivity to be investigated.

Table 3: Locations for developments

Area	Sub-area
Inner city	east
Outer city	south
Combination	Inner east + Outer south

Typology changes

Three different typologies of changes were investigated. These are shown in Figure 12 below. These were selected because they were the most common grid layouts in the city and they resulted in different abstractions in the axial map and the road centreline map. The inner city grid had the longest total segment length, the Beijum grid the second most and the orthogonal grid the least. Additionally, the angles of connections between streets varied through the typologies. Therefore, the effect of the total length of the streets added or removed on sensitivity and the angle of connection of the streets added or removed on sensitivity could be investigated. The width selected for each road segment in the axial map was 15m as this was found to be a consistent distance between buildings in the existing model. This width of 15m was applied consistently through the updated layout resulting in no street hierarchy.



(a) (b) (c)

Figure 12: Grid typologies in Groningen (a) Beijum grid (b) city centre grid (c) orthogonal grid

Quantifying the development

The changes made to the models were quantified in order to quantify the sensitivity of the model. The different typologies of changes were quantified by determining the total length of streets added. This is an appropriate quantification of the input because in the angular segment analysis the configurational measures are calculated by weighting each line by its length.

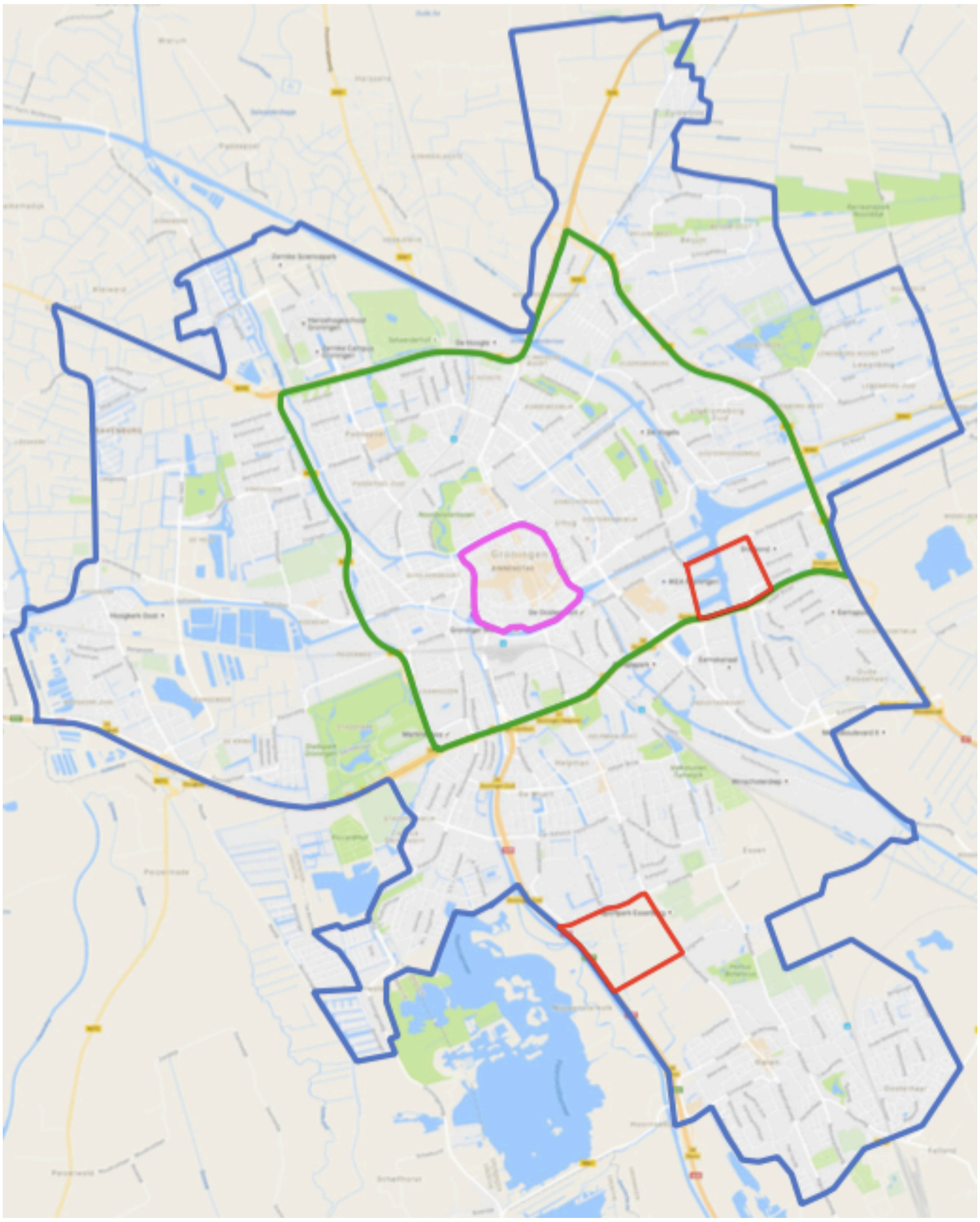


Figure 13: Inner city and outer city developments

3.3.1 Data collection

Experiment 1 – addition of segments

This experiment involved adding three different typologies of grids at two different locations in the map and a combination of these locations resulting in nine total scenarios for both the axial map and the road centreline map. The locations and combinations of these changes can be seen in Table 4 below. The axial and road centreline maps of each addition can be seen in Appendix B.

Aim

The purpose of this experiment was to determine the effect of the angle of connections and the total length of segments in the change on the sensitivity of the angular segment measures of each map. This aims to allow for the development of formulae to quantify the sensitivity of each angular measure of both mapping techniques to the addition of street segments. This will further allow for a comparison of the mapping techniques and the angular configurational measures to determine which is less or more sensitive.

Hypothesis

This lead to the hypothesis that the magnitude of change of the angular segment measures will be proportional to the number of segments added and the angle of connection between segments will have a minimal effect.

Table 4: Experiment 2 scenarios

Reference	Area	Sub-area	Typology
IE B	Inner city	East	Beijum
IE IC	Inner city	East	Inner city
IE O	Inner city	East	Orthogonal
OS B	Outer city	South	Beijum
OS IC	Outer city	South	Inner city
OS O	Outer city	South	Orthogonal
IE+OS B	Combination	East + South	Beijum
IE+OS IC	Combination	East + South	Inner city
IE+OS O	Combination	East + South	Orthogonal

Independent variable

The independent variables, those which were varied in the experiments, for the axial and road centreline map were:

1. The typology of streets

Maps of the street typologies can be seen in Appendix B.

Dependent variables

The dependant variables, those which were measured in the experiments, for the axial map and road centreline map were:

1. Global length weighted angular integration
2. Global length weighted angular choice
3. Local length weighted angular integration
4. Local length weighted angular choice

Measurement

These variables were measured by performing an angular segment analyses using a length weighted normalisation for each of the scenarios for the axial and road centreline maps using the *Depthmap X* software package. The choice measures were normalised by using a log(choice+2) normalisation. Local measures were calculated at 40% of the model size. This was done to ensure that the reference area fell within the local radius.

Experiment 2 – deletion of segments

This experiment involved deleting nodes at approximately the same locations as experiment 1. It was not possible for the exact same locations to be achieved as experiment 1 because streets are deleted and therefore the area will change in shape and increase in size. The locations of the deletion of streets can be seen in This lead to the hypothesis that the magnitude of change of the angular segment measures will be proportional to the number of segments added and the angle of connection between segments will have a minimal effect.

Table 5 below. It should be noted that streets cannot be deleted according to a specific typology and therefore streets were deleted by randomly expanding the areas.

Aim

The purpose of this experiment was to determine the effect of the angle of connections and the total length of segments in the change on the sensitivity of the angular segment measures of each map. This aims to allow for the development of formulae to quantify the sensitivity of each angular measure of both mapping techniques to the deletion of street segments. This will further allow for a comparison of the mapping techniques and the angular configurational measures to determine which is less or more sensitive.

Hypothesis

This lead to the hypothesis that the magnitude of change of the angular segment measures will be proportional to the number of segments added and the angle of connection between segments will have a minimal effect.

Table 5: Experiment 3 scenarios

Reference	Area	Sub-area
D - C IE+OS	Inner city	East
D - IE	Outer city	South
D - OS	Combination	East + South

Independent variables

The independent variable for the axial and road centreline map were:

1. The length of streets

Dependent variables

The dependant variables for the axial and road centreline map were:

1. Global length weighted angular integration
2. Global length weighted angular choice
3. Local length weighted angular integration
4. Local length weighted angular choice

Measurement

These variables were measured by performing an angular segment analyses using a length weighted normalisation for each of the scenarios for the axial and road centreline maps using the *Depthmap X* software package. The choice measures were normalised by using a log(choice+2) normalisation. Local measures were calculated at 40% of the model size. This was done to ensure that the reference area fell within the local radius.

3.3.2 Data analysis

To quantify the sensitivity of the angular configurational measures for the axial map and the road centreline map the magnitude of the change in input was correlated with the magnitude of the change in output. This was done by performing a linear correlation between the input and the output using the *SPSS* software package. If there is a statistically significant correlation between the two variables, then a formula can be developed to determine confidence intervals for each measure provided the error in the input data is known.

4 Results - Space Syntax maps

Presented below are the results of the angular segment analysis of the original road centreline map in Figure 15 and Figure 16 and the road centreline map of the scenario where the inner city grid was added at both the inner city east and outer city south locations (C IE+OS IC) in Figure 17 and Figure 18. This scenario was selected to be shown here because it resulted in the largest change in input to the system measured in the total length of segments added. The maps of the remaining scenarios and the original axial map can be found in Appendix C.

The purpose of this chapter is to examine the configurational structure of the street network in Groningen and to provide an illustration of how the changes were made to the maps in the experimental work. Additionally, the visual changes to the configurational measures as a result of the added segments will be discussed here. The entire Space Syntax maps of each measure are shown below, but the focus will be on the city centre bound by the canals i.e. the reference area.

The maps below show the configurational measures where the lines in the map are shaded on a spectrum from blue through cyan, green, yellow until red. The blue colours represent the lowest values in the system and the red colours the highest values, this spectrum is shown in Figure 14 below.

Figure 14: Space Syntax colour spectrum (Orellana, 2012)

4.1 Original road centreline map

The road centreline map has been selected to analyse the configurational structure of Groningen because Turner (2007) showed that the road centreline map correlated better with actual movement patterns than the axial map. The difference between the configurational structure shown by the axial map and the road centreline map is minimal and difficult to identify visually. Additionally, the aim in this thesis is not to compare the differences between the configurational structure that each map shows, but rather to identify the difference in sensitivity between the two mapping techniques which is performed in sections 5, 6 and 7 below.

4.1.1 Global analysis

The global analysis is a system-wide analysis where every node is considered in the analysis. This helps visualise the connectivity structure of the street network (Czerkauer-Yamu & Voigt, 2011). This usually correlates with motor vehicle movement however the motor vehicle-only through roads were not included in the map therefore this only shows the potential for motor vehicular movement within the city.

Angular integration

The original global angular integration map is shown in Figure 15 (a) below. The city centre is highlighted as the most spatially integrated area of the city. The streets of highest integration are Folkingestraat, Brugstraat and Gedempte Zuiderdiep. The streets of lowest angular integration are Martinikerkhof and Museumstraat.

It should be noted that Turner (2007) showed that the measure of angular integration did not correlate well with actual movement patterns, however it did pick out the central area of the analysis zone. It was shown that angular choice was a far better predictor of traffic flow. Therefore, angular choice will be used here as the indicator of movement potential in the system.

Angular choice

The original global angular choice map is shown in Figure 15 (b) below. The choice measures clearly show a foreground and a background network. The foreground is comprised of a network of linked centres that sits within a globally segregated background residential network (Hillier B. , 1996a). Further, a faint “deformed wheel” structure emerges, however because the ring road was removed from this analysis this deformed wheel is not very pronounced. The deformed wheel is a configuration pattern shown in many organically grown European cities (Czerkauer-Yamu & Voigt, 2011).

The streets of highest angular choice are the same as those of highest angular integration. Namely, the Folkingestraat, the Brugstraat and the Gedempte Zuiderdiep. The streets of lowest angular choice are the Jonkerstraat and the Hoogstraatje.

4.1.2 Local analysis

The local analysis is performed at a defined metric radius and only considers points within that radius from each street. The local analysis was performed at 40% of the system size at a radius of approximately 4000m. The local analysis reveals the potential in the grid particularly for bicycle and pedestrian movement. This is because the radius of analysis was approximately 4000m which indicates a journey of approximately 15 minutes by bicycle.

Angular integration

The original local angular integration map is shown in Figure 16 (a) below. The integration core shifts slightly to the south in the local analysis. The local angular integration does not reveal multiple centres in the system and confirms the monocentric nature of the city. However, because the radius of the analysis selected was too large to accurately model pedestrian movement the presence of local centres cannot be ruled out.

The same three streets are shown as the most integrated streets, namely Folkingestraat, Brugstraat and Gedempte Zuiderdiep. The streets of lowest integration are Martinikerkhof and Popkenstraat.

Angular choice

The original local angular choice map is shown in Figure 16 (b) below. The background and foreground network emerges more clearly in the local angular choice analysis. Additionally, the “deformed wheel” structure is again visible (Czerkauer-Yamu & Voigt, 2011).

The streets of highest angular choice are the same as those of highest angular integration. Namely, the Folkingestraat, the Brugstraat and the Gedempte Zuiderdiep. The streets of lowest angular choice are the Jonkerstraat and the Hoogstraatje.

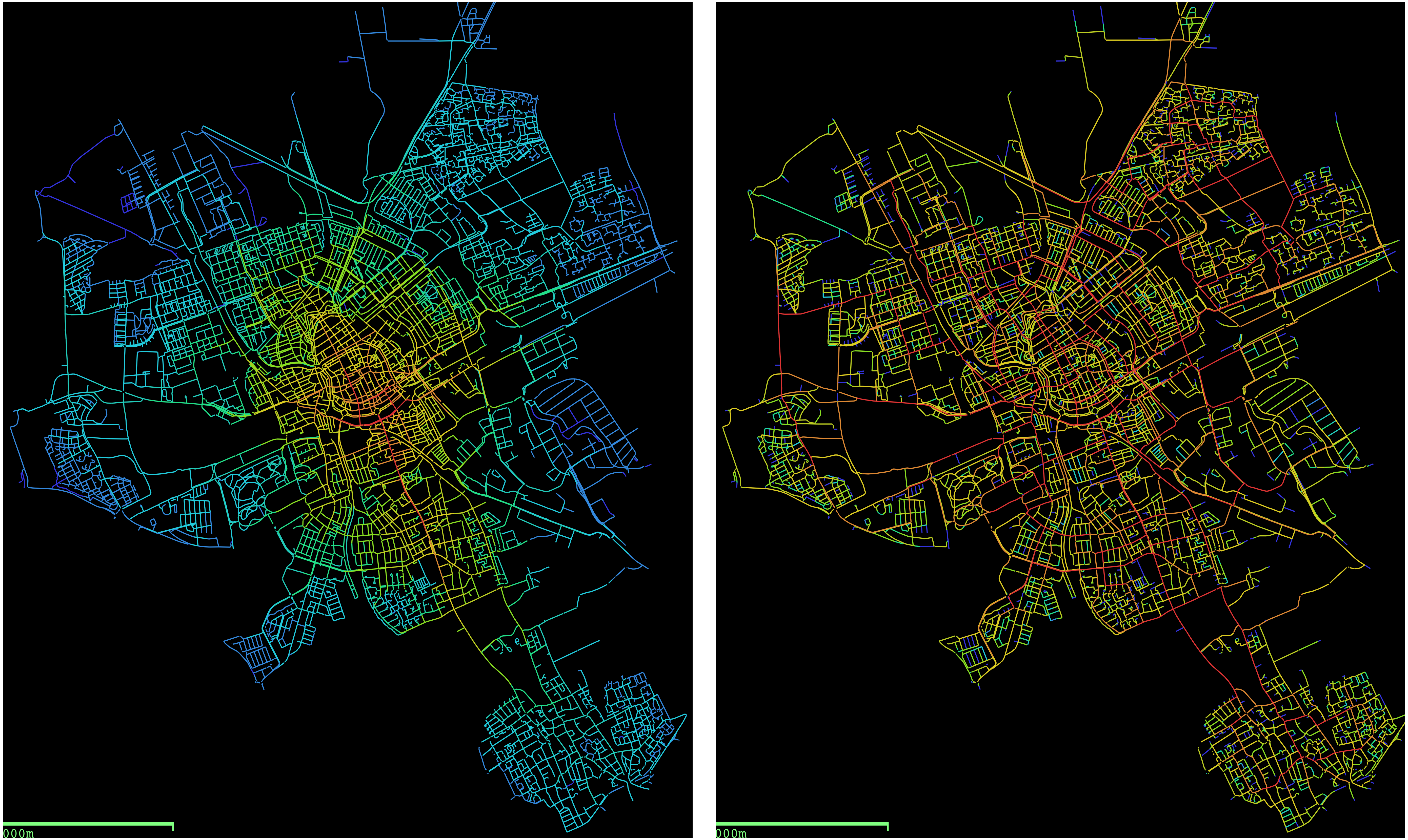
4.2 Updated map

The maps of the configurational measures of the C IE+OS inner city scenario can be seen in Figure 17 and Figure 18 below. The added segments are circled in white in Figure 17 (a). These segments were added to the model according to the city centre grid layout in the original map.

Examining and comparing the maps in Figure 17 and Figure 18 with those of the original maps in Figure 15 and Figure 16 reveal little visible change in output. The magnitude of the change made in input was an additional 3% length of street segments. This means that the change was relatively small and caused no large scale shifts in the configurational structure of the city. Therefore, in order to determine the effects of the change a finer detail, quantitative analysis is required. This is performed in sections 5, 6 and 7 below.

(a) (b)

Figure 15: Original road centreline map global angular (a) integration and (b) choice

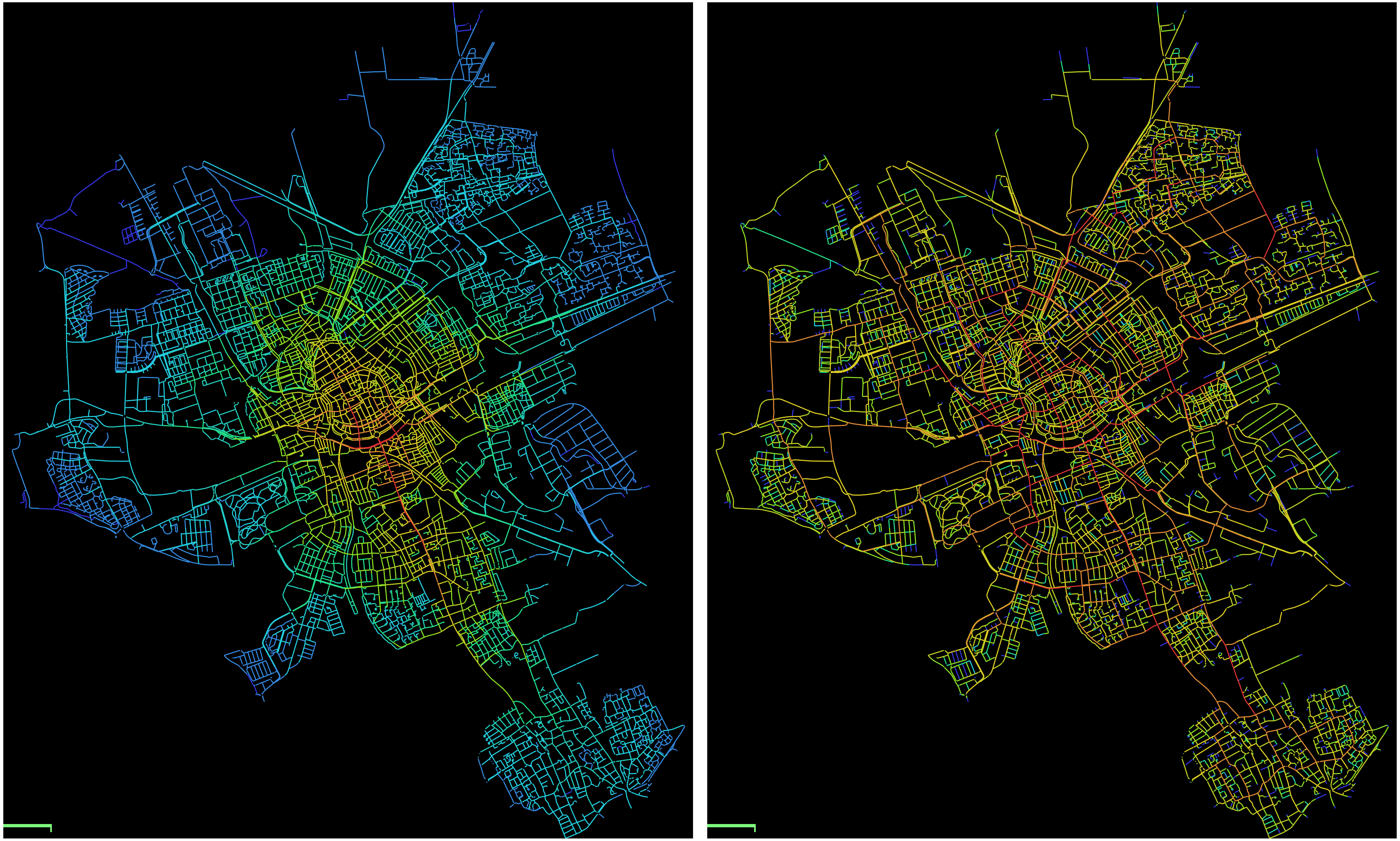


(a) (b)

Figure 16: Original road centreline map local angular (a) integration and (b) choice

(a) (b)

Figure 17: Road centreline map C IE+OS IC global angular (a) integration and (b) choice



(a) (b)

Figure 18: Road centreline map C IE+OS IC local angular (a) integration and (b) choice

5 Results – Experiments

5.1 Experiment 1

The results of the experiments were calculated by only analysing the reference area in the model, but the syntactic measures were calculated by considering the entire model. The change in each measure for each scenario was calculated by subtracting the value of configurational measure in the original map from the updated map. This difference was then expressed as a percentage of the value in the original map. An average of these values for the whole area was then calculated to determine the change for the reference area as a whole.

5.1.1 Road centreline map

Global and local integration

Table 6: Road centreline changes in global and local integration

Reference	Change in AGI	Change in ALI	Length added (m)
C IE+OS B	3.22%	1.48%	17060.34
C IE+OS IC	3.62%	3.17%	21616.62
C IE+OS O	1.24%	0.90%	13957.16
IE B	1.53%	2.09%	8183.46
IE IC	1.95%	3.06%	11030.46
IE O	0.52%	0.95%	6987.14
OS B	1.94%	0.18%	8876.89
OS IC	1.73%	0.26%	10586.16
OS O	0.92%	0.19%	6970.02

Global and local choice

Table 7: Road centreline changes in global and local choice

Reference	Change in AGC	Change in ALC	Length added (m)
C IE+OS B	0.19%	0.25%	17060.34
C IE+OS IC	0.19%	0.28%	21616.62
C IE+OS O	0.04%	0.07%	13957.16
IE B	0.10%	0.25%	8183.46
IE IC	0.12%	0.26%	11030.46
IE O	0.03%	0.06%	6987.14
OS B	0.08%	0.01%	8876.89
OS IC	0.09%	0.03%	10586.16
OS O	0.01%	0.00%	6970.02

5.1.2 Axial map

Global and local integration

Table 8: Axial map change in global and local integration

Reference	Change in AGI	Change in ALI	Length added (m)
C IE+OS B	3.48%	3.02%	18,691.45
C IE+OS IC	5.18%	4.79%	23,683.18
C IE+OS O	1.41%	1.41%	12,064.37
IE B	1.49%	1.93%	8,913.21
IE IC	2.41%	3.30%	11,763.52
IE O	0.71%	0.99%	6,059.99
OS B	2.00%	1.08%	9,778.24
OS IC	2.77%	1.49%	11,919.66
OS O	0.65%	0.35%	6,004.37

Global and local choice

Table 9: Axial map change in global and local choice

Reference	Change in AGC	Change in ALC	Length added (m)
C IE+OS B	0.16%	0.14%	18,691.45
C IE+OS IC	0.22%	0.19%	23,683.18
C IE+OS O	0.05%	0.05%	12,064.37
IE B	0.07%	0.10%	8,913.21
IE IC	0.11%	0.15%	11,763.52
IE O	0.03%	0.03%	6,059.99
OS B	0.09%	0.04%	9,778.24
OS IC	0.12%	0.05%	11,919.66
OS O	0.02%	0.01%	6,004.37

5.3 Experiment 2

The changes in the maps were calculated according to the same method as experiment 1.

5.3.1 Road centreline map

Global and local integration

Table 10: Road centreline changes in global and local integration

Reference	Change in AGI	Change in ALI	Length removed (m)
D - C IE+OS	-4.98%	-6.97%	-31072.62
D - IE	-2.14%	-4.00%	-11675.52
D - OS	-2.84%	-2.60%	-19888.12

Global and local choice

Table 11: Road centreline changes in global and local choice

Reference	Change in AGC	Change in ALC	Length removed (m)
C IE+OS	-0.06%	-0.65%	-31072.62
D - IE	0.19%	-0.23%	-11675.52
D - OS	-0.12%	-0.25%	-19888.12

5.3.2 Axial map

Global and local integration

Table 12: Axial map changes in global and local integration

Reference	Change in AGI	Change in ALI	Length removed (m)
D - C IE+OS	-5.36%	-6.01%	-37,308.22
D - IE	-2.56%	-3.23%	-14,791.45
D - OS	-2.84%	-2.74%	-23,485.20

Global and local choice

Table 13: Axial map changes in global and local integration

Reference	Change in AGC	Change in ALC	Length removed (m)
D - C IE+OS	-0.12%	-0.25%	-37,308.22
D - IE	-0.02%	-0.12%	-14,791.45
D - OS	-0.10%	-0.13%	-23,485.20

6 Analysis

This analysis aims to develop formulae that will allow for the quantification of the sensitivity of the angular measures of each mapping technique. In order to determine whether sensitivity formulae could be devised for each measure of configuration the relationship between the change in input and the change in output was investigated. The results of experiment 1 and 2 were combined for this analysis because the deletions in experiment 1 were made at the same locations as in experiment 2 and further it is theorised that the length of the change has the largest influence on the sensitivity of each measure. Therefore, the differing angles of connection within the change were not relevant. This relationship between input and out was investigated by performing a Pearson correlation between the magnitude of the change in terms of the total length of segments added and the magnitude of the change in configurational measure. The results of these correlations are shown in Table 14 below.

Table 14: Road centreline correlations between number of segments and change

	Road centreline map	Axial map
Global integration	0.99**	0.98**
Local integration	0.93**	0.97**
Global choice	0.65**	0.94**
Local choice	0.94**	0.95**

** indicates a statistically significant correlation

From the correlation performed in Table 14 it can be seen that the change in values of global and local angular integration and choice both positively correlated with the total length of segments added or deleted and this correlation was statistically significant. This correlation indicates a consistent relationship between the change in input and the change in output. Based on these positive correlations and the fact that the measures behaved the same when segments were added and deleted it is possible to calculate tentative sensitivities for each measure, which is performed below. These sensitivities can then be used to calculate confidence intervals for each measures provided the error in the data collection process is known.

6.1 Sensitivities

The sensitivities of global and local angular integration and angular choice were calculated for the axial map and the road centreline map by expressing the change in output of the model per unit of change in input to the model. The change in output was determined by calculating the change in syntactic measure as a percentage of the original measure for each line in the reference area, an average of this value was then taken to determine the average change for the whole area. The change in input was calculated by determining the total length of the segments added. These values were then plotted on a graph and a trend line was added. The equation of this trend line can then be used to calculate error bounds provided the error in the input is known. The R^2 value presented in the graph is an indication of the accuracy of the trend line.

6.1.1 Road centreline map

Global integration

From Figure 19 the equation of the trend line is:

$$y=2\times10^{-6}x-8\times10^{-5} \quad (1)$$

where,

y is the magnitude of the error in the measure in %, and

x is the magnitude of the error in the data in m

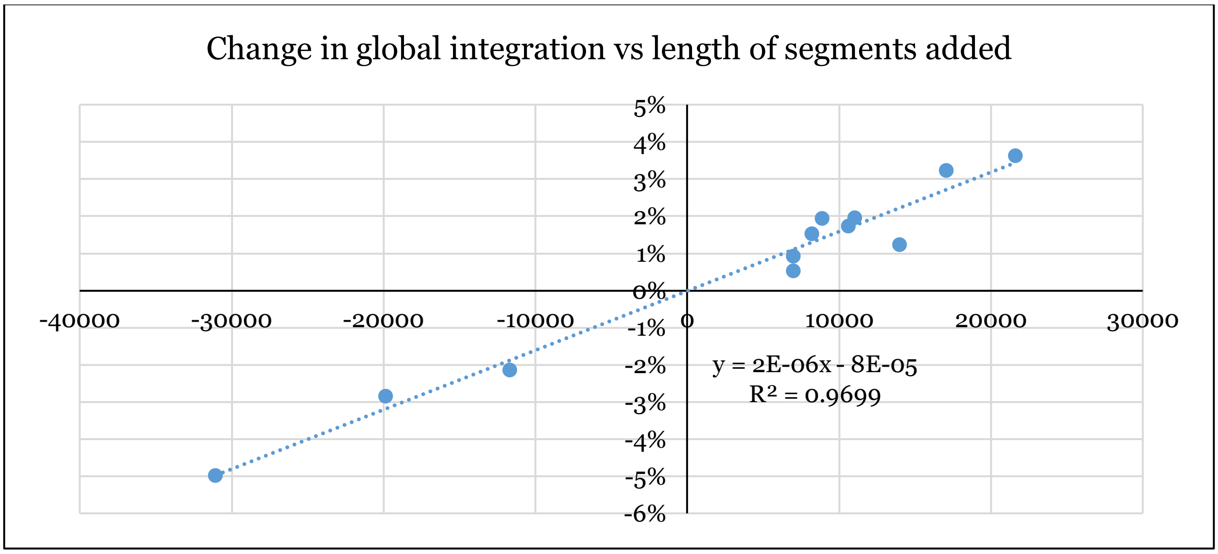


Figure 19: Road centreline change in global integration vs length of segments added

Local integration

From Figure 20 the equation of the trend line is:

$$y=2\times10^{-6}x-0.0073 \quad (2)$$

where,

y is the magnitude of the error in the measure in %, and

x is the magnitude of the error in the data in m

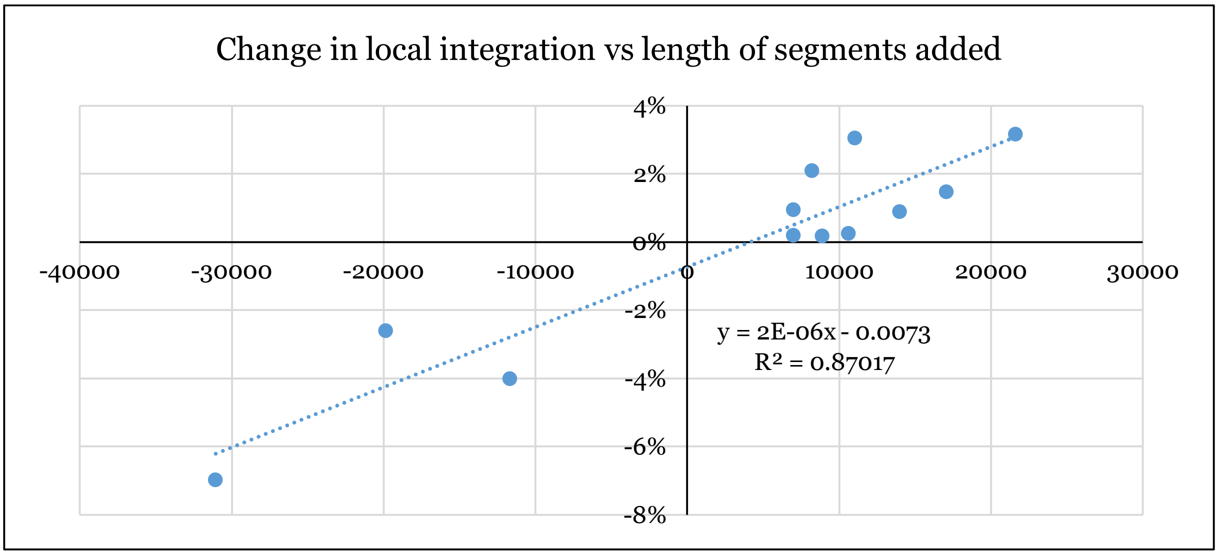


Figure 20:Road centreline change in local integration vs length of segments added

Global choice

From Figure 21 the equation of the trend line is:

$$y=4\times10^{-8}x+0.0006 \quad (3)$$

where,

y is the magnitude of the error in the measure in %, and

x is the magnitude of the error in the data in m

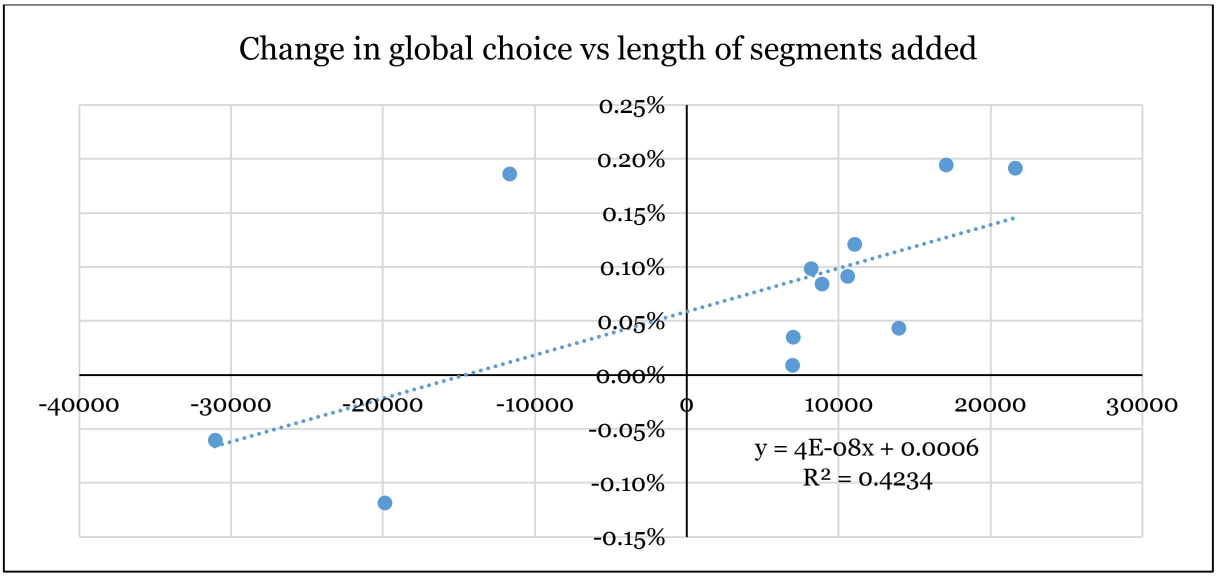


Figure 21: Road centreline change in global choice vs length of segments added

Local choice

From Figure 22 the equation of the trend line is:

$$y=2\times10^{-7}x-0.0005 \quad (4)$$

where,

y is the magnitude of the error in the measure in %, and

x is the magnitude of the error in the data in m

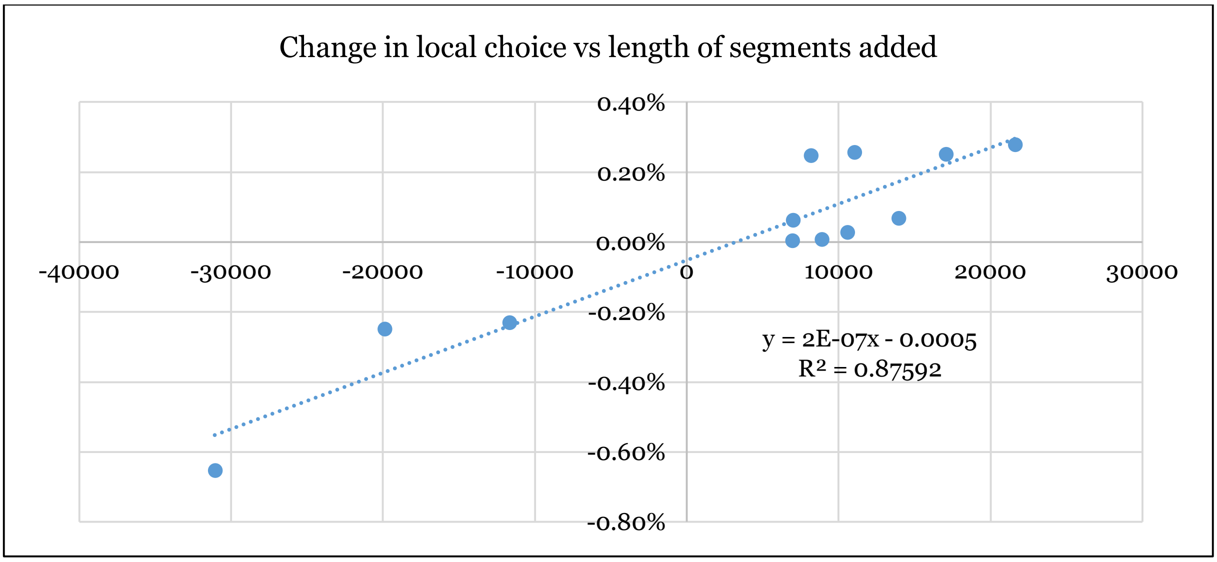


Figure 22: Road centreline change in local choice vs length of segments added

6.1.2 Axial map

Global integration

From Figure 23 the equation of the trend line is:

$$y=2\times10^{-6}x+0.0033 \quad (5)$$

Where,

y is the magnitude of the error in the measure in %, and

x is the magnitude of the error in the data in m

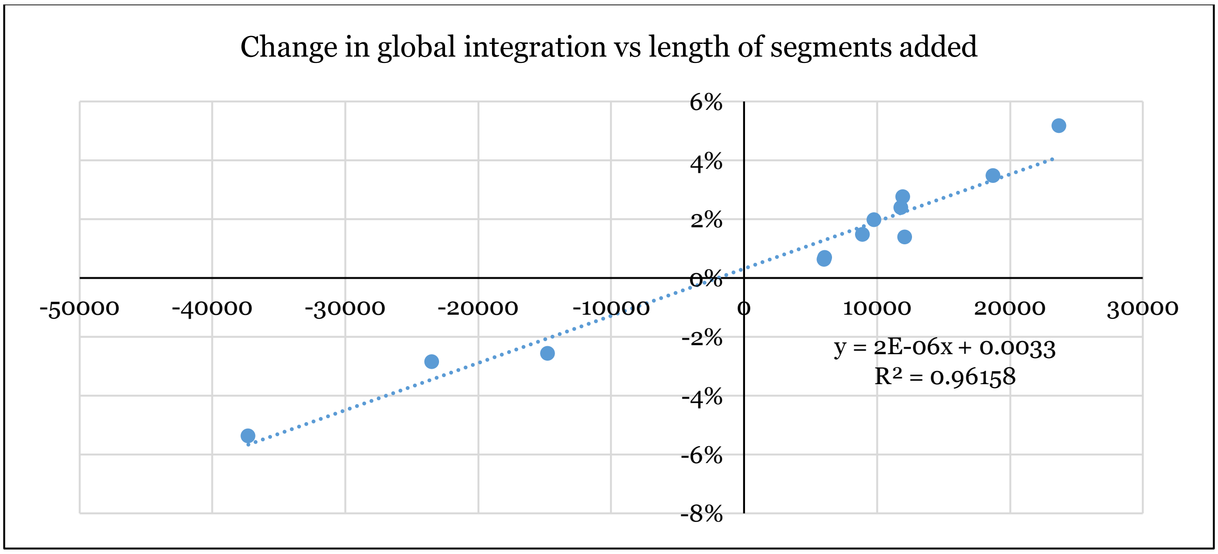


Figure 23: Axial map change in global integration vs length of segments added

Local integration

From Figure 24 the equation of the trend line is:

$$y=2\times10^{-6}x+0.0008 \quad (6)$$

where,

y is the magnitude of the error in the measure in %, and

x is the magnitude of the error in the data in m

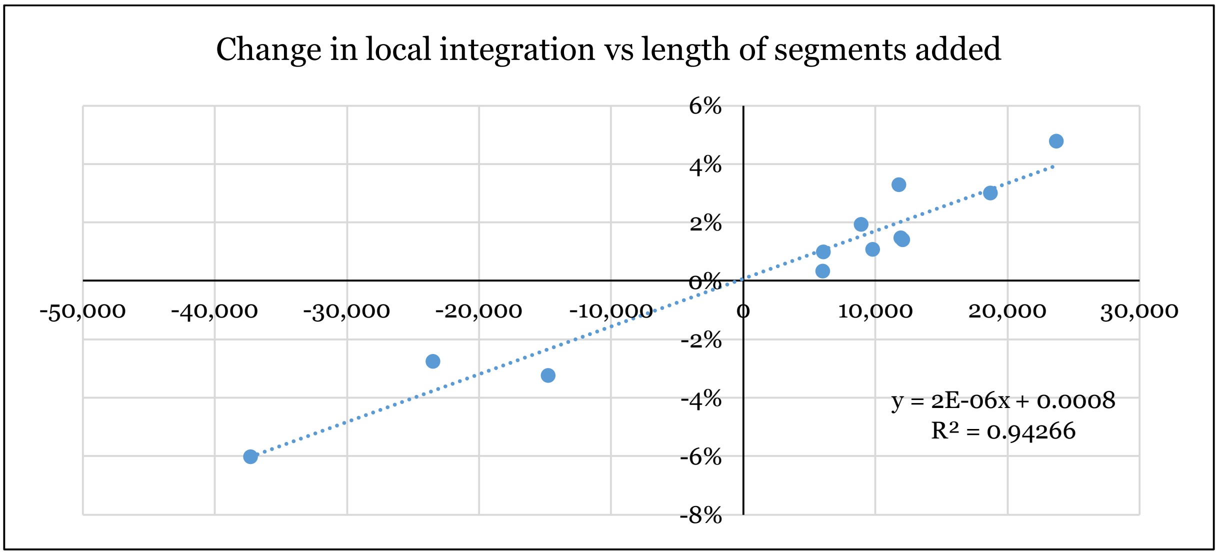


Figure 24: Axial map change in local integration vs length of segments added

Global choice

From Figure 25 the equation of the trend line is:

$$y=5\times10^{-8}x+0.0004 \tag{7}$$

where,

y is the magnitude of the error in the measure in %, and

x is the magnitude of the error in the data in m

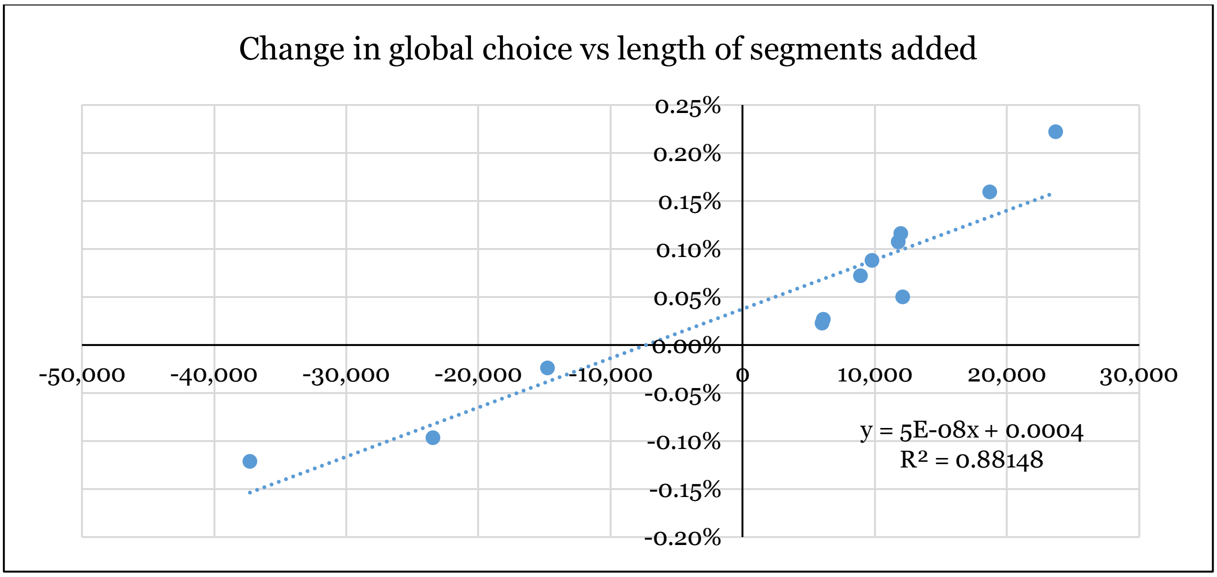


Figure 25: Axial map change in global choice vs length of segments added

Local choice

From Figure 26 the equation of the trend line is:

$$y=7\times10^{-8}x+5\times10^{-5} \tag{8}$$

where,

y is the magnitude of the error in the measure in %, and

x is the magnitude of the error in the data in m

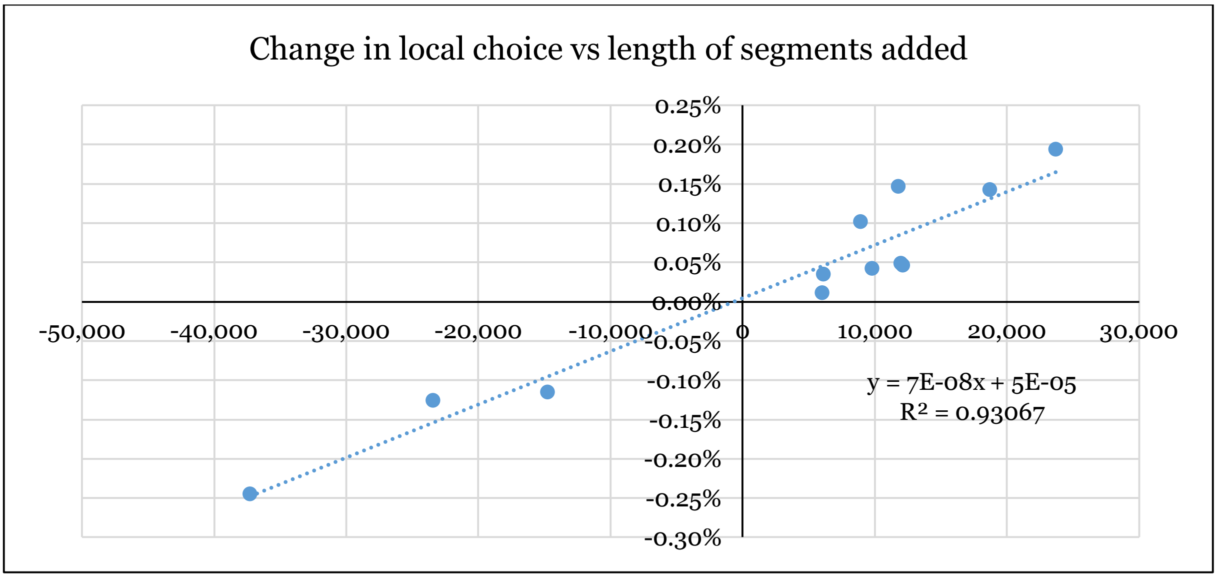


Figure 26: Axial map change in local choice vs length of segments added

7 Discussion

This chapter discusses the results and analysis of the research. The analysis of the original road centreline maps is covered first and then the research questions are addressed individually. Finally, a critique of the experimental work is provided.

7.1 Space Syntax maps

The analysis of the configuration of the original road centreline map shows the streets in the city with the highest and lowest levels of accessibility. This has highlighted the areas in the city of potential and areas that are lacking in efficiency. For example, it appears as though there is potential to extend the Folkingestraat which would improve the connection between the area south of the central station and the city centre. Further, inefficiencies have been shown around the Martini Church area.

The presence of the foreground network and the background network have a few implications. The foreground network is responsible for the guiding of movement and attraction of movement seeking land uses (Hillier B. , 1996a). Groningen can therefore be conceptualised to some extent as a movement economy. This means that the structuring of movement by the grid leads, through multiplier effects, to dense patterns of mixed use encounters, which themselves are influenced by the relationship between movement and space, which gives the city its characteristic structure (Hillier B. , 1996b). The foreground network in this characteristic structure suggests the presence of commercial zones whereas the background network is comprised more of residential zones (Mirincheva, 2012). This is consistent with the “deformed wheel” that has been observed where the spokes of the wheel are the foreground network and the background network makes up the space in between the spokes.

It should be noted that the formulae for quantifying the uncertainty in a space syntax models developed in this thesis cannot be applied to these model that examined the configurational structure of Groningen because the error in the input data that the models are based on is not known. This means that design decisions should not be based on these models, but rather they should be used as an indication of potential in the system. If design decisions are to be based on a Space Syntax model, then the uncertainty in the model should be known.

7.2 What is the effect of error in the segment length and the angle of connection between segments on the sensitivity of the angular configurational measures?

The typology of the change resulted in a number of differences in the input. The inner city grid had the largest total length of segments added, the Beijum grid the second most and the orthogonal grid the least. Additionally, each grid typology varied in the angle of the connections between streets. It was not possible to quantify the input in terms of the angle of connection of the segments in the change because the angle weighting of the graph differs for each justified graph. Additionally, the relevance of investigating this is questioned as errors in the spatial data collection that a Space Syntax model is based on is defined in terms of metric distance and not angular error therefore formulating an equation for sensitivity based on the angular error would not be valuable.

The correlations performed show that there is a strong linear relationship between the length of segments added and the change in the measure. Further, this relationship was consistent for each typology. This therefore confirms the hypothesis of each experiment. This shows that despite the fact that the angular segment analysis weights each node in the graph by the angle of its connection, and each typology contained different angles of connection, the length of the segments added has a larger influence on the accuracy of the model because each line is weighted by its length. Therefore, the formulae were defined in terms of the length of segment added.

7.3 What is the sensitivity (numerical error delta) of the angular segment measures of configuration of the axial and road centreline map?

The relationship between change in input and change in output is shown in Figure 19 – 25 above. From the data collected it was possible to calculate formulae for the sensitivity of each configurational measure for each modelling technique and these are shown in equations (1) – (8). These formulae will allow for the confidence in the model to be expressed provided the error in the data collection process is known.

These formulae all contain the same terms:

y is the magnitude of the error in the measure in %, and

x is the magnitude of the error in the data in m

Road centreline map:

Angular global integration:

$$y=2\times10^{-6}x-8\times10^{-5} \tag{1}$$

Angular local integration

$$y=2\times10^{-6}x-0.0073 \tag{2}$$

Angular global choice

$$y=4\times10^{-8}x+0.0006 \tag{3}$$

Angular local choice

$$y=2\times10^{-7}x-0.0005 \tag{4}$$

Axial map:

Angular global integration:

$$y=2\times10^{-6}x+0.0033 \tag{5}$$

Angular local integration

$$y=2\times10^{-6}x+0.0008 \tag{6}$$

Angular global choice

$$y=5\times10^{-8}x+0.0004 \tag{7}$$

Angular local choice

$$y=7\times10^{-8}x+5\times10^{-5} \tag{8}$$

It should however be noted that these equations are not entirely accurate as Table 15 below which shows the R^2 value for each of the formulae. The closer the R^2 value is to 1 the more reliable the trend line is. For the global choice measure in the road centreline map the R^2 value is below 0.7 which indicates that the trendline does not accurately predict the relationship between the length of segments added and the change in the measure. This is therefore an indication that the formula is not accurate. Further, all of the R^2 values are below 1 and thereby indicating some level of inaccuracy in each.

Table 15: R^2 values for the sensitivity formulae for each measure of the road centreline and axial maps

	Road centreline map	Axial map
Global integration	0.97	0.96
Local integration	0.87	0.94
Global choice	0.42	0.88
Local choice	0.86	0.93

7.4 What is the difference in sensitivity between the axial map and the road centreline map?

From the graphs in Figures 16-25 and the corresponding formulae it can be seen that for global and local integration measures the sensitivity of the axial map and the road centreline are virtually identical. The gradient of the graphs is the same and the slight difference in sensitivity occurs as a result of the added constant in the formulae. However, the presence of this constant indicates that the data collected is not entirely accurate because the graph should intersect with the origin as if a change of magnitude 0 is made there is no change in the output. The presence of these errors in the formulae is addressed later in the chapter.

A comparison of the global choice sensitivities of the two mapping techniques shows that the road centreline map is less sensitive than the axial map. In contrast to this, the measure of local choice was less sensitive for the axial map than the road centreline map. However, these result found here should not be taken as completely accurate because of the low accuracy of the sensitivity function developed for global choice for the road centreline map. This low accuracy occurred because of errors in the data collection process which is addressed later in this chapter.

7.5 What is the difference in sensitivity between the different measures of configuration?

From the graphs in Figure 16-25 and the corresponding formulae it can be seen that the measure of angular choice is far more robust than the measure of angular integration. The changes across all scenarios were in the order of magnitude of 10 less for angular choice than angular integration.

The local measures were more sensitive than their global counterparts only when changes were made at smaller distances. This is because in the local analysis only a defined radius is considered and when the change is at a smaller distance it will make up a larger portion of the analysis area. Therefore, the magnitude of the change in input is larger in the local measures at smaller distances than local measures at larger distances. This is illustrated in Figure 27 below where the reference area is shown in red, the change in green and the area of analysis in black (a) shows a local analysis with changes made at a small distance and (b) shows a local analysis with changes made at a larger distance. This observation is an indication of the relational effect of the changes made in the experimental work, which means that each line experiences changes differently (Gil, 2015). These relational effects are an indication of the errors in the experimental work which is addressed later in this chapter.

Figure 27: (a) local measure where change is made at a smaller distance (b) local measure where change is made at a larger distance

7.6 Assessment of formulae and experimental work

The formulae for calculating the confidence intervals on the angular configurational measures proposed above should however not be taken as absolutely correct. This is based on the fact that the R^2 values do not have a value of one and it can be seen that none of the trendlines pass through the origin of the graph. These trendlines should pass through the origin because if a change of 0 magnitude is made in the input there should be a change of 0 magnitude in the output. These inaccuracies are an indication of errors that were made in the experimental component of this study.

The experimental work was conducted by mapping the same changes in reality using both mapping techniques. This resulted in different quantifiable changes in each map. The data was collected in this way because one of the research aims was to compare the two mapping techniques. Therefore, the same changes in reality had to be made to both otherwise an accurate comparison would not have been possible. However, this experimental design was not appropriate for determining formulae for calculating the confidence intervals of the angular configurational measures.

These errors in the experimental design stem largely from the fact that changes were made to the models at very specific locations. The effect of this is that the changes in the output are relational meaning that every line experiences the change differently (Gil, 2015). This is shown in Figure 28 below where the spatial distribution of the change in (a) global integration and (b) choice is shown for one of the scenarios. The lines are shaded on a spectrum from green indicating low levels of change to red indicating high levels of change. This shows that lines closer to the change experienced higher levels of change than lines that were further away. Therefore, the data may not be appropriate to develop general system wide sensitivity formulae for errors that occur in data collection. This is because the errors in data collection are generally distributed far more evenly through the system than in this experimental work. Therefore, the experimental design was not appropriate for quantifying confidence intervals as a result of errors in the data collection and model generation process.

The formulae calculated for the configurational measures of the axial map could contain further inaccuracies because the axial stubs were not removed in the analysis. This means that the skeletal network of the system was not represented accurately (Turner, 2007). Additionally, Table 16 and Table 17 below show the length of the lines added and removed as a percentage of the total length of lines added and removed. From these tables it can be seen that only errors less than a magnitude of 5% were introduced. Therefore, the behaviour of the mapping techniques to large errors in data is not known.

Based on the above criticisms and errors in the data collection process it is proposed that the experimental component of this study be re-performed in order to gather data that is specifically more appropriate for quantifying the sensitivity of each configurational measure. Therefore, an improved experimental design is provided in the recommendations chapter

(a) (b)

Figure 28: Inner city east global (a) integration (b) choice

Table 16: Road centreline map lines added and removed as a percentage of the total lines in the map

Total length of change	L% of total
17060.34	1.90%
21616.62	2.41%
13957.16	1.55%
8183.46	0.91%
11030.46	1.23%
6987.14	0.78%
8876.89	0.99%
10586.16	1.18%
6970.02	0.78%
-31072.62	-3.46%
-11675.52	-1.30%
-19888.12	-2.22%

Table 17: Axial map lines added and removed as a percentage of the total lines in the map

Total length of change	L% of total
18,691.45	2.03%
23,683.18	2.58%
12,064.37	1.31%
8,913.21	0.97%

11,763.52	1.28%
6,059.99	0.66%
9,778.24	1.06%
11,919.66	1.30%
6,004.37	0.65%
-37,308.22	-4.06%
-14,791.45	-1.61%
-23,485.20	-2.56%

8 Conclusions

This thesis aimed to quantify the sensitivity of the configurational measures of angular integration and angular choice of the axial map and the road centreline map. This was done to improve the application of Space Syntax by providing a formula to determine the confidence interval of each configurational measure. This would provide more legitimacy to a Space Syntax model as the accuracy of the model could be expressed. Further, the aim was to contribute to the study performed by Turner (2007) to determine which mapping technique and which measure of configuration was more robust to error. Data was collected by performing an experimental study of the axial and road centreline maps of the city of Groningen. In addition to the research aims, this allowed for the configurational structure of the city of Groningen to be analysed. The data collected was analysed allowing for tentative formulae to be developed to quantify the uncertainty in each angular configurational measure. Additionally, a comparative analysis of the mapping techniques and measures was performed. The implications of these findings are discussed below.

8.1 Original Space Syntax model

Although not one of the main research goals, the generation of the road centreline map of the city of Groningen as original maps in the sensitivity analysis has allowed for the quantification of configuration of the street network. Areas of high potential and areas of low spatial efficiency have been highlighted and this can be used by future urban planners and designers and enable them to better understand the grid in order make better informed design decisions (Czerkauer-Yamu & Voigt, 2011). Further, the models could be used to identify the factors of success that have resulted in the high use of non-motorised transport in the city in particular the high bicycle density. It should be noted that the uncertainty in these models is not known as the error in the input data is not known. Therefore, design decisions should not be based on the models. They should only be used as preliminary indications of potential.

8.2 Sensitivity analysis

This thesis has managed to achieve its aim to some extent by providing tentative formulae for the quantification of confidence intervals of angular configurational measures of the axial map and the road centreline map. This means that future modellers can express the confidence in their model, provided the error in the input data is known, which is an important part of good modelling practice (Crosetto, Tarantola, & Saltelli , 1999). Knowledge of this confidence interval allows for an assessment of the accuracy of the model to be made which will allow for more informed design decisions to be made based on the model (Pannell, 1997). This means that the application of Space Syntax can be improved enabling it to further contribute to the design process.

8.3 Comparative analysis

8.3.1 Road centreline map vs axial map

The comparison of the road centreline map and the axial map showed that the sensitivities of the global and local measure of integration are virtually the same. Therefore because Turner (2007) showed that the road centreline map correlated better with actual movement patterns the road centreline map is presented here as the favoured mapping technique for the measures of global and local angular integration. This means that in scenarios where angular integration will be used as the key determinant of movement then the road centreline mapping technique should be used, which will minimise the effects of error in the input data on the accuracy of the model.

The measures of global and local choice were however less consistent. For global measures the road centreline map was less sensitive and for local measures the axial map was less sensitive. This means that in scenarios where the measure of angular choice will be the key determinant of movement then the scale of movement patterns desired to be modelled can be a criterion for the selection of the mapping technique. This is explained by considering that global measures generally correlate better with larger scale movement such as vehicular movement and local measures generally correlate better with smaller scale or pedestrian movements (Hillier B. , 1996a). Therefore, for models that aim to predict vehicular movements the road centreline map is more appropriate because it has lower data quality requirements and therefore will be more economical (Crosetto, Tarantola, & Saltelli , 1999). Conversely, local measures correlate better with pedestrian and bicycle movement patterns and therefore for models that aim to predict the pedestrian and vehicle movements the axial map is more appropriate because it has lower data quality requirements (Crosetto, Tarantola, & Saltelli , 1999).

It should be noted that the sensitivity of the mapping technique should not be the only criterion for determining which mapping technique to select. Turner (2007) showed that the angular measures of a road centreline map correlated better with actual movement patterns than an axial map and Ratti (2004) showed the theoretical and practical limitations of the axial map. Additionally, the sensitivities of the measure of local angular choice shown in this experimental work indicate only a minor difference in sensitivity between the road centreline map and the axial map, with the road centreline map still showing significant robustness. Therefore, despite the argument in favour of the selection of the axial map for modelling movement patterns if local angular choice is the key determinant of movement, the higher correlations with actual movement patterns and the widespread presence of road centreline data combined with the limitations of the axial map and the robustness shown here by the road centreline map make the road centreline map a more favourable mapping technique.

8.3.2 Angular choice vs angular integration

From the experimental data in this thesis it has been shown that the measure of angular choice is significantly more robust than the measure of angular integration with the sensitivity of angular choice being in the order of 10 times less than angular integration. This conclusion complements the findings of Turner (2007) who showed that the measure of angular choice was a better predictor of movement patterns than angular integration. Therefore, further evidence has been provided in favour of the measure of angular choice as a predictor of human movement.

This higher robustness of angular choice values means that errors made when producing a model will have less of an effect on the accuracy of the model. Additionally, this means that the data quality requirements are lower for developing a Space Syntax model to measure angular choice. However, this robustness may also negatively influence the ability of choice measures to predict the effect of systematic changes made to the model such as when desired scenarios are added to a model. A Space Syntax model should be robust to small errors, but should be flexible to large or systematic changes (Gil, 2015). However, this thesis has only collected data where small changes were made to the model simulating small errors therefore it cannot be concluded that the measure of angular choice is not flexible to large of systematic changes. This should be covered in future research and is addressed in the recommendations chapter below.

8.4 Moving forward

There are some clear indications that the formulae developed in this thesis are not completely accurate. This could either be as a result of inaccurate data collection or because there exists no consistent relationship between the change in input data and the change in output data. The results here do however indicate the presence of a relationship between input change and output change and errors in the data collection process have been highlighted above. Therefore, it is proposed that the experimental component of this thesis be re-preformed in order to more accurately determine a function that will allow for the construction of confidence intervals around the measures of angular configuration and to further improve the comparative analysis of the angular configurational measures of the axial and road centreline maps.

9 Reflection and recommendations

9.1 Improved experimental design

In order to improve the data and draw more reliable conclusions an improved experimental component of this thesis is proposed. This improved experimental component involves selecting a different city for modelling and introducing different changes to the model that better simulate errors that can occur in modelling. Additionally, a larger data set is proposed which involves adding and removing segments over a larger range of changes and at more clearly defined intervals.

9.1.1 City selection

The selection of a reference area for analysis initially appeared to be a good idea in order to make the analysis of data more manageable. However, it was realised late in the data analysis process that the selection of the city centre may have limited the effectiveness of the study. This is because the city centre is surrounded by canals and therefore its connectivity to the rest of the city is limited to 14 bridges. This differs from an area not bound by canals where there would be many more street segments connecting the city centre to the rest of the system. Therefore, the selection of Groningen as a case study city was perhaps not a good decision as the results are not universally applicable. Therefore, it is recommended that a similar study be performed and a reference area be selected that is not bound by canals, but is consistently connected to the rest of the network.

9.1.2 Changes to model

The changes made to the model in this experimental work were limited in that they did not accurately simulate errors that could occur when models are produced. Additionally, only small errors were introduced to the model and therefore, the flexibility to large or systematic change of each measure is not known. The experimental component was performed in the way it was because it was argued that a comparison in sensitivity between the axial map and the road centreline map would not be possible unless the same grids were added or deleted from each map. However, this data was not of a sufficient quality to calculate accurate formulae for confidence intervals for the angular configurational measures of the road centreline map and the axial map. Therefore, in order to collect data to determine more accurate formulae for the sensitivity of the angular configurational measures for each mapping technique the following changes to the experimental work are proposed:

1. Distribute the changes over a larger spatial area,
2. Introduce errors randomly,
3. Introduce errors in defined portions of the original model and up to a larger portion of the original model, for example 0, 1, 5, 10, 25 and 50% of the original model size, and
4. Increase the sample size.

The distribution of errors over a larger spatial area and the introduction of errors randomly will better simulate the errors that occur in the data collection process. Errors introduced in defined portions of the model will allow for more accurate formulae to be developed to distribute the uncertainty in the data collection process as a more accurate relationship between the change in input variables and the change in output variables can be determined. Introducing errors up to a larger portion of the original model will allow for the investigation of the sensitivity of each measure to large scale and systematic change. Finally, increasing the sample size will allow for more confidence in the formulae developed.

9.2 Directions for future research

In addition to the improvements to the experimental work performed in this thesis some directions for future research are proposed here. The width of the street has an influence on the number of segments in the axial map, but not in the road centreline map. Therefore, investigating the effect of road width on the sensitivity of the axial map is proposed for future research. This will refine the sensitivity formula calculated for the axial map in this thesis and add a width component to it as the formula in this thesis is only a function of length.

This research shows the behaviour of configurational measures under conditions of changing input data. This is potentially a first step towards Space Syntax incorporating time into its analysis, which would possibly allow Space Syntax to model changes in human movement patterns. The logic behind this being that if the configuration of the grid is the key determinant of movement in the grid, then the way the configuration changes when the grid is changed should also reflect the way movement patterns change. This research shows that there is a strong positive linear relationship between the length of segments added and the magnitude of the change in the configurational measures. Therefore, the human movement patterns should change in the same way. This claim can however not be confirmed without the measuring of human movement patterns and it leads to the question do human movement patterns in a network change in a linear pattern when more street segments are added or removed from the network?

References

Bafna, S. (2003, January). SPACE SYNTAX A Brief Introduction to Its Logic and Analytical Techniques. *Environment and Behavior, 35*(1), 17-29.

Batty, M. (2004, February 23). A New Theory of Space Syntax. *CASA Working Paper Series*, 1-36.

Behbahani, P. A., Gu, N., & Ostwald, M. J. (2014). Comparing the Properties of Different Space Syntax Techniques for Analysisng Interiors. *Architectural Research through to Practice: 48th International Conference of the Architectural Science Association* (pp. 683-684). Genova: The Architectural Science Association & Genova University Press.

Borgatti, S. P., Carley, K. M., & Krackhardt, D. (2006). On the robustness of centrality measures under conditions of imperfect data. *Social Networks*, 124-136.

Campolongo, F., Gatelli, D., Saisana, M., Ratto, M., Saltelli, A., Andres, T., . . . Tarantola, S. (2008). *Global Sensitivity Analysis*. Chichester, England: John Wiley & Sons Ltd.

Cash, P., Stanković, T., & Štorga, M. (2016). An Introduction to Experimental Design Research. In P. Cash, T. Stanković, & M. Štorga, *Experimental Design Research* (pp. 3-13). Springer International Publishing Switzerland.

Costenbader, E., & Valente, T. (2003). The stability of centrality measures when networks are sampled. *Social Networks*, 283-307.

Crosetto, M., Tarantola, S., & Saltelli , A. (1999). Sensitivity and uncertainty analysis in spatial modelling based on GIS. *Agriculture, Ecosystems and Environment*, 71-79.

Czerkauer-Yamu, C., & Voigt, A. (2011). Strategic Planning and Design with Space Syntax. *City Modelling - eCAADe 29* , (pp. 125 - 133).

Dalton, N. (2001). Fractional Configurational Analysis And a solution to the Manhattan problem. *Proceedings. 3rd International Space Syntax Symposium* , (pp. 26.1-26.13). Atlanta.

Dalton, N. S., Peponis, J., & Conroy-Dalton, R. (2003). To tame a TIGER one has to know its nature: Extending weighted angular integration analysis to the description of GIS road-centerline data for large scale urban analysis. *Proceedings . 4th International Space Syntax Symposium*, (pp. 65.1-65.10). London.

Dhanani, A., Vaughan, L., Ellul, C., & Griffiths, S. (2012). FROM THE AXIAL LINE TO THE WALKED LINE: evaluating the utility of commercial and user-generated street network datasets in space syntax analysis. *Proceedings: Eighth International Space Syntax Symposium*.

Gil, J. (2015). Examining 'edge effects': Snesitivity of spatial network centrality analysis to boundary conditions. *Proceedings of the 10th International Space Syntax Symposium* (pp. 147:1-147:16). London: Space Syntax Laboratory, The Bartlett School of Architecture, University College London.

Google. (2016). *Maps*. Retrieved April 15, 2016, from Google: https://www.google.nl/maps/place/Netherlands/@52.7691335,5.6043148,8.13z/data=!4m2!3m1!1s0x47c609c3db87e4bb:0xb3a175ceffbd0a9f

Herland, M., Pastran, P., & Zhu, X. (2013). An Empirical Study of Robustness of Network Centrality Scores in Various Networks and Conditions. *IEEE 25th International Conference on Tools with Artificial Intelligence*, 221-228.

Heuvelink, G. (1999). Propagation of error in spatial modelling with GIS. *Geographical information systems*, 207-217.

Hillier, B. (1996a). *Space is the machine*. Cambridge: University of Cambridge.

Hillier, B. (1996b). Cities as movement economies. *URBAN DESIGN International, 1*(1), 41-60.

Hillier, B. (1999). The hidden geometry of deformed grids: or, why space syntax works, when it looks as though it shouldn't. *Environment and Planning B: Planning and Design, 26*, 169-191.

Hillier, B., & Hanson, J. (1984). *The social logic of space*. Cambridge : Cambridge: Press syndicate of the University of Cambridge.

Hillier, B., & Penn, A. (2004). Rejoinder to Carlo Ratti. *Environment and Planning B: Planning and Design, 31*, 501-511.

Hillier, B., Burdett, R., Peponis, J., & Penn, A. (1987). Creating life: Or, does architecture determine anything? *Architecture et Comportement/Architecture and Behaviour 3.3, 3*(3), 233-250.

Hillier, B., Hanson, J., & Graham , H. (1987). Ideas are in things: an application of the space syntax method to discovering house genotypes. *Environment and Planning B: Planning and Design, 14*, 363-385.

Jiang, B., & Claramunt, C. (2002). Integration of Space Syntax into GIS: New Perspectives for Urban Morphology. *Transactions in GIS* , 295-309.

Karimi, K. (2012). A configurational approach to analytical urban design: 'Space syntax' methodology. *URBAN DESIGN International*, 297-318.

Klarqvist, B. (1993). A Space Syntax Glossary. *Nordisk Arkitekturforskning, 2*, 11-12.

Mirincheva, V. (2012, September). THE CENTRAL BUSINESS DISTRICT OF DOHA: AN INVESTIGATION INTO THE CHALLENGES OF CREATING A SPATIAL CENTRALITY AND SOCIO-ECONOMIC VIABILITY. *Master's Dissertation*.

O'Leary, Z. (2010). *The Essential Guide to Doing your Research Project*. London: Sage.

Orellana, N. (2012, September). ON SPATIAL WAYFINDING: AGENT AND HUMAN NAVIGATION PATTERNS IN VIRTUAL AND REAL WORLDS.

Osman, K. M., & Suliman, M. (1994). The Space Syntax Methodology: Fits and Misfits. *Architecture and Behaviour, 10*(2), 189-204.

Ostwald, M. J. (2011). The Mathematics of Spatial Configuration: Revisiting, Revising and Critiquing Justified Plan Graph Theory. *Nexus Network Journal* , 445-470.

Pannell, D. J. (1997). Sensitivity Analysis of Normative Economic Models: Theoretical Framework and Practical Strategies. *Agricultural Economics*, 139-152.

Ratti, C. (2004). Urban texture and space syntax: some inconsistencies. *Environment and Planning B: Planning and Design, 31*, 1-12.

Ratti, C. (2005). Suggestions for developments in space syntax. *5th International Space Syntax Symposiom Proceedings* , (pp. 83-95).

Space Syntax Ltd. (2004). *D3.1 Technology Platform Report*. AGORA Cities for People.

Space Syntax Ltd. (2015). *Service Offer*. Retrieved November 17, 2015, from Space Syntax: http://www.spacesyntax.com/service-offer/methodology/our-unique-methodology/

Tsubohara , S. (2007). *The effect and modification of the Traffic Circulation Plan (VCP)* . Urban and Regional Studies Institute.

Turner, A. (2000). Angular Analysis: A Method for the Quantification of Space. 1-22.

Turner, A. (2001). Angular Analysis. *Proceedings 3rd International Space Syntax Symposium Atlanta*, (pp. 30.1-30.11).

Turner, A. (2007). From axial to road-centre lines: a new representation for space syntax and a new model of route choice for transport network analysis. *Environment and Planning B: Planning and Design, 34*(3), 539-555.

Varoudis, T., Law, S., Karimi, K., Hillier, B., & Penn, A. (2013). SPACE SYNTAX ANGULAR BETWEENNESS CENTRALITY REVISITED. *Proceedings of the Ninth International Space Syntax Symposium*, (pp. 057:1-057:16).

Appendix A – Glossary and formulae

9.3 Representations of Space

Space can be abstracted in a number of ways; these include: the convex map, axial map, isovist map and angular segment map. These different abstractions are described in detail below.

9.3.1 Convex map

A convex space is a space where no line between any two points within the space crosses the perimeter (Klarqvist, 1993). An urban space can be transformed into a convex map by representing it in terms of the least number of convex spaces that fully cover its layout and the connections between them (Klarqvist, 1993).

The convex spaces on the map are translated into nodes of a graph while their connections are represented as the edges of the graph (Behbahani, Gu, & Ostwald, 2014). The connections are defined as a property of both adjacency and permeability between two spaces (Behbahani, Gu, & Ostwald, 2014). Convex map graphs are normally used to investigate the configurational relationship between open urban spaces rather than narrow streets (Behbahani, Gu, & Ostwald, 2014). Convex maps generally reveal the hierarchy and permeability of spaces (Behbahani, Gu, & Ostwald, 2014).

9.3.2 Axial map

An axial map is a representation of space abstracted as the least number of axial lines covering all convex spaces. An axial line is the longest straight line of sight within a convex space possible to follow on foot (Klarqvist, 1993). This line must pass through at least one permeable threshold between two convex spaces. An urban space can be transformed into an axial map by depicting the least number of axial lines covering all of the convex spaces and connections of the layout and the axial map is complete when all permeable thresholds have been crossed (Bafna, 2003).

9.4 Syntactic measures

Graphs are used to quantify the syntactic properties of a space. This process begins by determining the syntactic step for each node. A syntactic step is the direct connection or permeable relation between a space and its immediate neighbours or between overlapping isovists (Klarqvist, 1993). In addition to this Turner (2001) has proposed that in axial maps the syntactic step may be understood as the change of direction from one line to another. The depth of a point in space is calculated by summing the least number of syntactic steps in a graph to another point (Klarqvist, 1993).

A justified graph is a graph where a point of interest is placed at the bottom as the “root space”. The graph is then constructed by placing all spaces one syntactic step away on the first level, spaces two steps away on the second level etc. This provides a visual representation of the depth of a layout seen from one of its points (Klarqvist, 1993).

9.4.1 Numeric measures

The main numeric measures concern the number of elements in a spatial system. Such as the number of lines in an axial map, number of convex spaces or size of isovist analysis. The number of elements is used as base-line comparison to quantify system size (Space Syntax Ltd, 2004).

9.4.2 Metric measures

These are often traditional geometric measurements such as length, width and area. This could represent the lengths of axial lines, area covered by convex space or perimeter length of an isovist. These measures are useful to describe physical properties of space. However, these measures relate less directly to syntactic measurements and social behaviour (Space Syntax Ltd, 2004).

9.4.3 Configurational measures

Once a space has been represented as a graph a mathematical analysis of the relational properties of a space it is possible. The aim of this being to deepen the description of a space by revealing the complex relational properties of spaces and the relational system. Individual spaces are considered in terms of their relation to the whole system or local system depending on whether global or local resolutions are selected (Space Syntax Ltd, 2004). This analysis measures four syntactic properties, namely: connectivity, depth, integration and choice (Klarqvist, 1993).

Depth

An axial line may either be many (deep) or few (shallow) changes in direction from the root line. Each line in a map is assigned a number according to how many changes in direction separate it from the root line and can be conceived as a kind of distance (Ratti, Urban texture and space syntax: some inconsistencies, 2004). Total depth is an extension of the depth concept and is determined by building a j-graph for a node and calculating the total depth from all other nodes. Mean depth is then calculated by dividing this value by the total number of nodes (Hillier, Hanson, & Graham , 1987). This value can be conceived as the total distance to move from the root line to all other lines (Ratti, Urban texture and space syntax: some inconsistencies, 2004). This value is then used to determine relative asymmetry.

Relative asymmetry

Relative asymmetry (RA) provides a normalisation of the mean depth between the deepest a node can be (at the end of a sequence) and the shallowest (when all nodes are directly connected to it). This measure gives a value between 0 and 1. A low value indicates a space from which the system is shallow, which tends to integrate the system, and a high value indicates a space that is segregated from the system (Space Syntax Ltd, 2004). This value is then used to determine real relative asymmetry.

$$RA = \frac{2\,(MD - 1)}{k - 2} \tag{9}$$

Where,

RA – relative asymmetry

MD – mean depth

k – number of spaces in system

Real relative asymmetry

Real relative asymmetry (RRA) provides a relativisation of RA to allow for comparisons of depth between spatial systems of different sizes (Space Syntax Ltd, 2004). This value is then used to determine integration.

$$RRA = \frac{RA}{Dk} \tag{10}$$

Where,

RRA – real relative asymmetry

Dk – Diamond k value

Integration

Integration is a global measure that describes the average depth of a space relative to all other spaces in the system. This measure describes how easily accessible a space is within a given network of other spaces. This allows the spaces in the system to be ranked to determine the most integrated and the most segregated spaces (Klarqvist, 1993). This measure tends to correlate with the degree of utilization of a space (Space Syntax Ltd, 2004).

$$I = \frac{1}{RRA} \tag{11}$$

Where,

I – integration

RRA – real relative asymmetry

9.4.4 Angular analysis syntactic measures

Angular integration

Angular integration is analogous to integration described above. It can be calculated according to the following formula (Turner, 2001):

$$C_\theta(x)=\frac{n}{\sum_{i=1}^{n} D_\theta(x,i)} \quad (12)$$

Where,

$C_\theta(x)$ is the measure of angular integration for segment x,

n is the number of nodes in the graph, and

D(x,l) is the weighted mean depth of the segment

For the calculation of angular integration using a road centreline map the measure of angular closeness is length weighted and can be calculated according to the following formula (Turner, 2007):

$$C_\theta^1(x)=\frac{\sum_{i=1}^{n} l(i)}{\sum_{i=1}^{n} D(x,i)l(i)} \quad (13)$$

Where,

$C_\theta^1(x)$ is the measure of angular integration for segment x,

l(i) is the length of the segment, and

D(x,l) is the weighted mean depth of the segment

Angular choice

Angular choice is analogous to choice described above. It can be calculated according to the following formula (Turner, 2001):

$$B_\theta^1(x)=\frac{\sum_{i=1}^{n}\sum_{j=1}^{n} \sigma^l(i,x,j)}{(n-1)(n-2)/2} \text{ such that } i\neq x\neq j \quad (14)$$

Where,

$B_\theta^1(x)$ is the measure of angular choice for segment x,

$\sigma^l(i,x,j)$ =1 if the shortest path from i to j passes through x, and 0 otherwise,

n is the number of segments in the graph

For the calculation of angular choice using a road centreline map the measure of angular choice is length weighted and can be calculated according to the following formula (Turner, 2007):

$$B_\theta^1(x)=\sum_{i=1}^{n}\sum_{j=1}^{n} \sigma^l(i,x,j) \text{ such that } i\neq j \quad (15)$$

Where,

$B_\theta^1(x)$ is the measure of angular choice for segment x,

$\sigma^l(i,x,j)$ = l(i) x l(j) if the shortest path from i to j passes through x,

$\sigma^l(i,x,j)$ = (l(i) x l(j))/2, or

$\sigma^l(i,x,j)$ = 0 otherwise

Appendix B - Scenario Maps

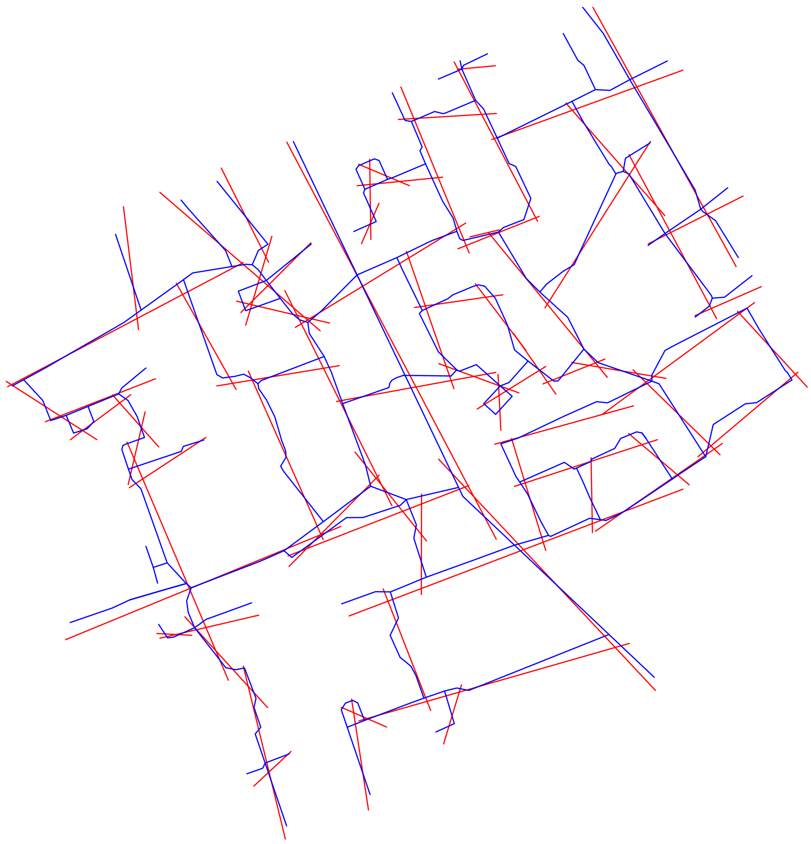


Figure 29: Inner city east Beijum grid, axial map in red and road centreline map in blue

Figure 30: Inner city east inner city grid, axial map in red and road centreline map in blue

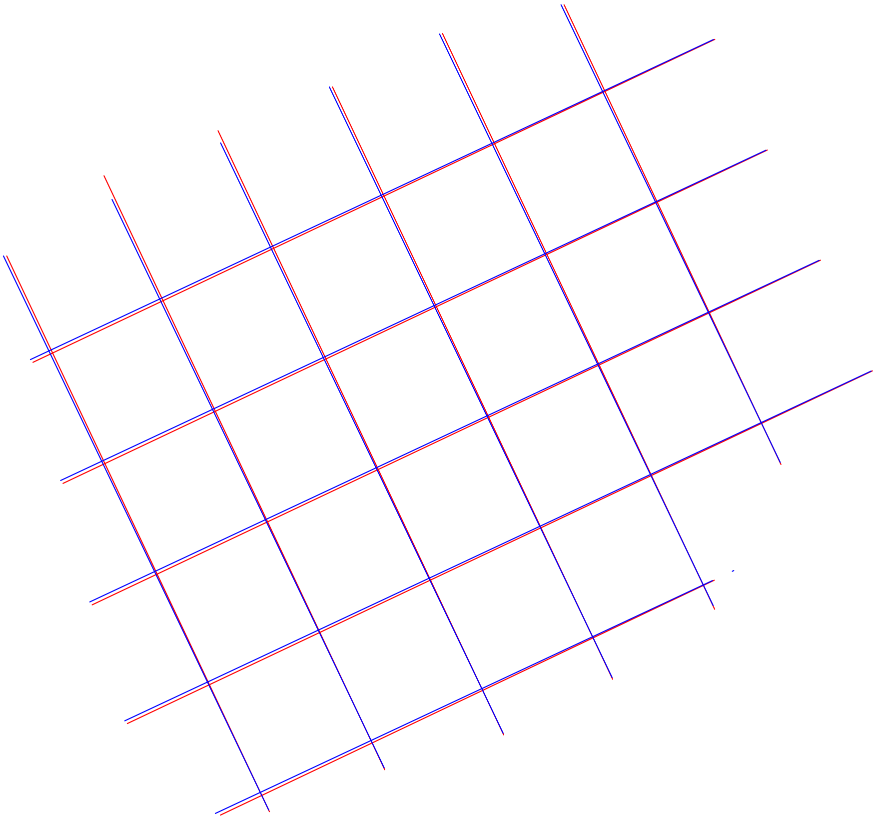


Figure 31: Inner city east orthogonal grid, axial map in red and road centreline map in blue

Figure 32: Outer city south Beijum grid, axial map in red and road centreline map in blue

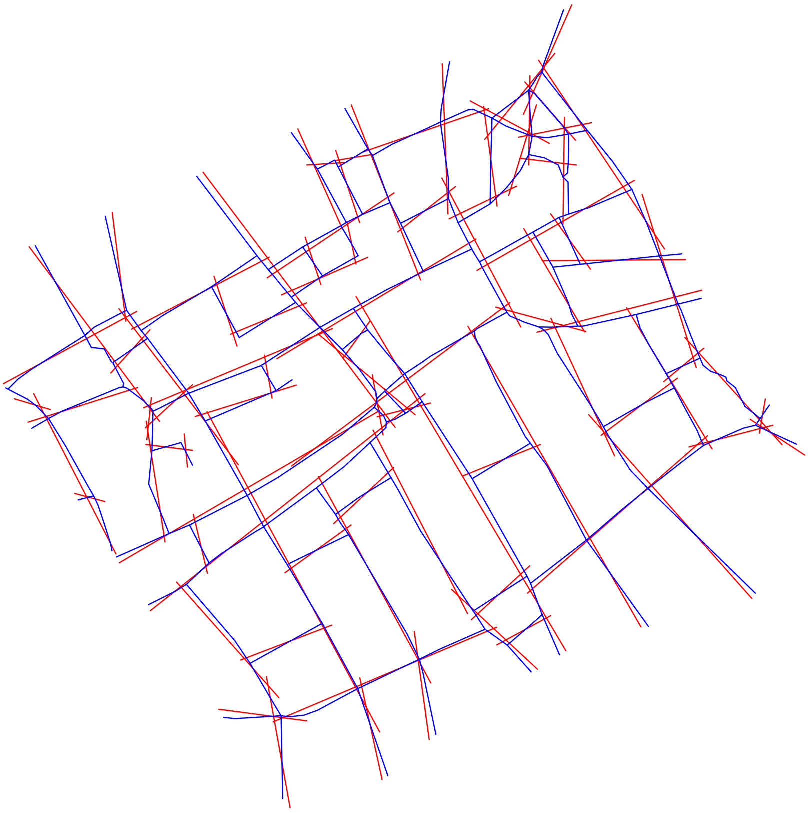


Figure 33: Outer city south inner city grid, axial map in red and road centreline map in blue

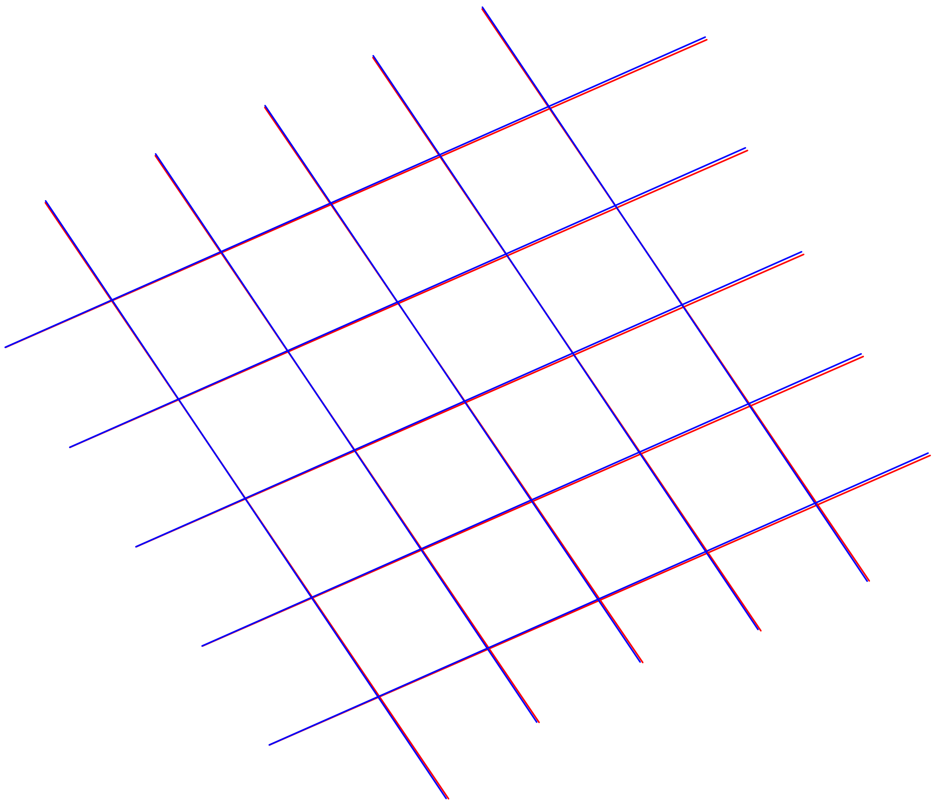


Figure 34: Outer city south orthogonal grid, axial map in red and road centreline map in blue

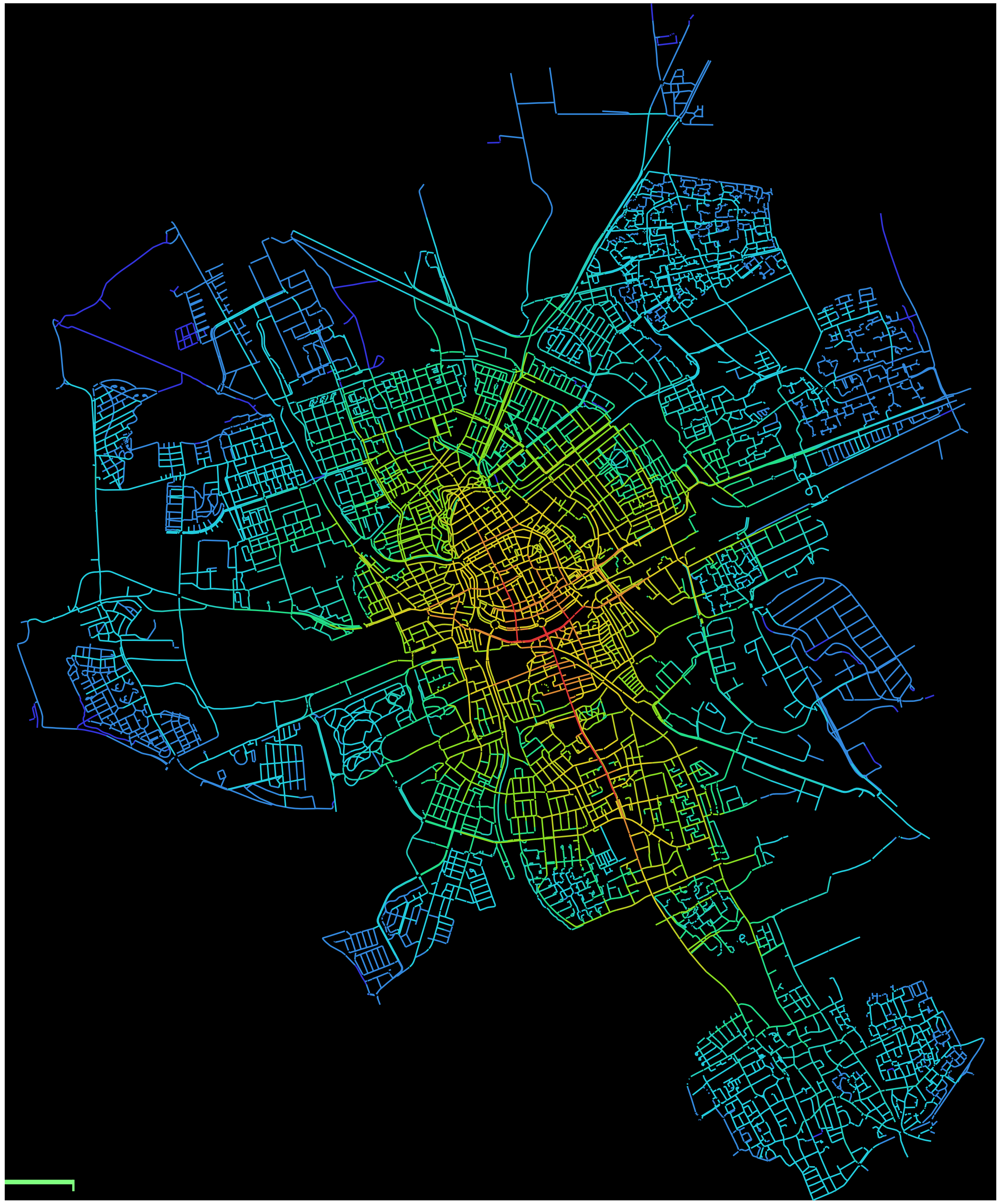
10 Appendix C – Space Syntax maps

10.1 Road centreline map

10.1.1 Experiment 1

(a) (b)

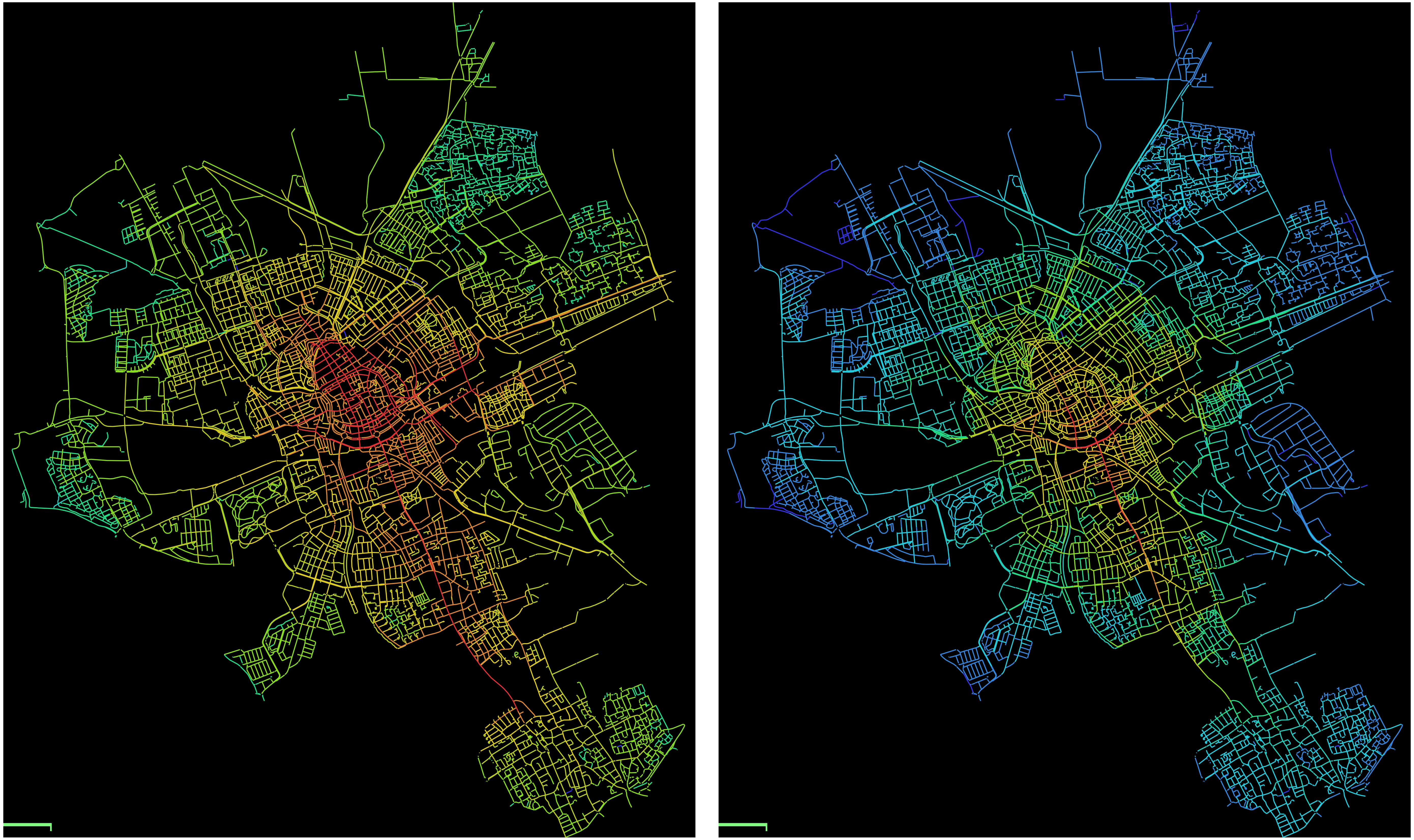
Figure 35: Road centreline map C IE+OS B global angular (a) integration and (b) choice



(a)

(b)

Figure 36: C IE+OS B choice (a) global and (b) local



(a) **(b)**

Figure 37: C IE+OS IC integration (a) global and (b) local

(a) (b)

Figure 38: C IE+OS IC choice (a) global and (b) local

(a) (b)

Figure 39: C IE+OS O integration (a) global and (b) local

(a) (b)

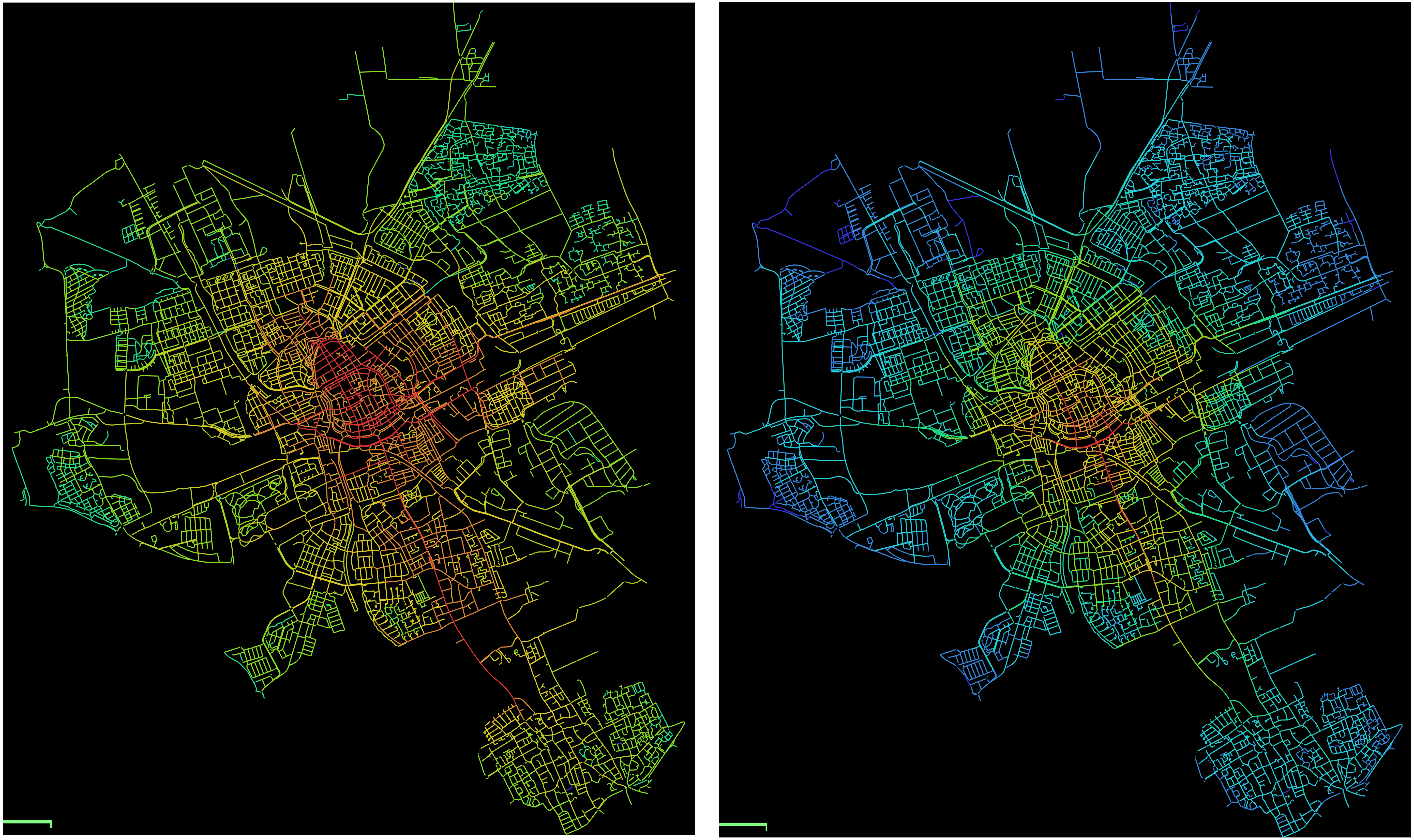
Figure 40: C IE+OS O choice (a) global and (b) local

(a) (b)

Figure 41: IE B integration (a) global and (b) local

(a) (b)

Figure 42: IE B choice (a) global and (b) local



(a)

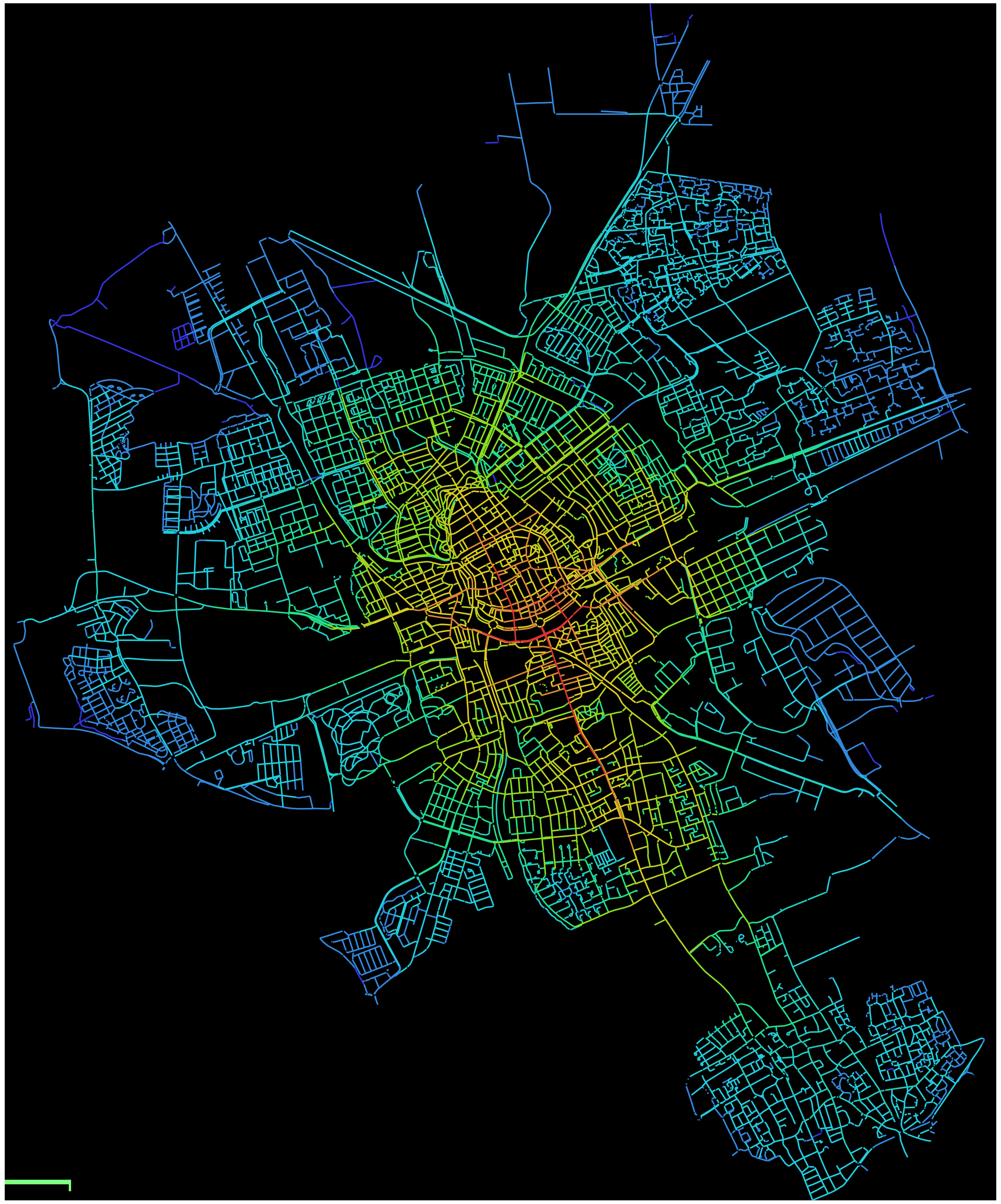
(b)

Figure 43: IE IC integration (a) global and (b) local

(a) (b)

Figure 44: IE IC choice (a) global and (b) local

(a)



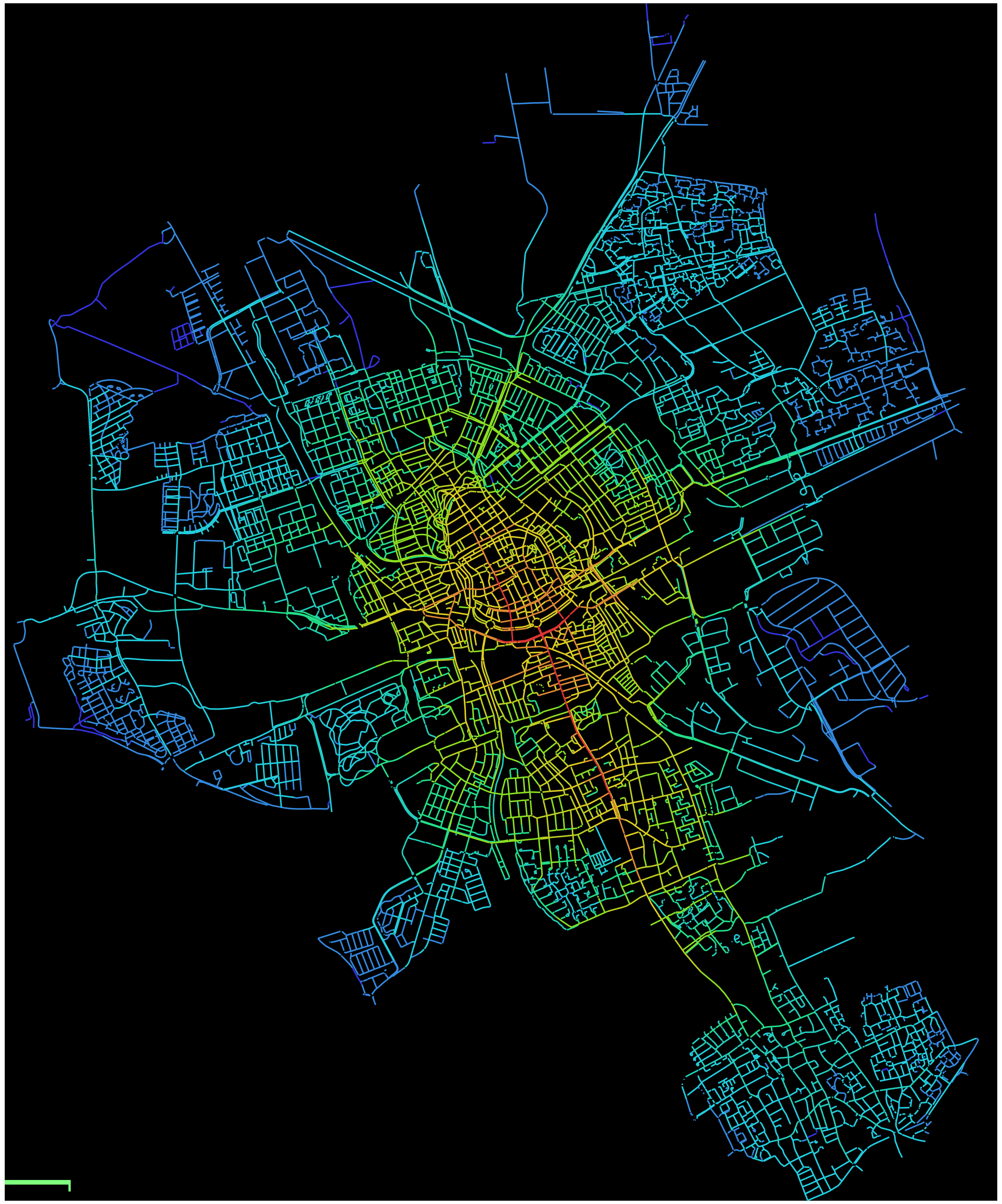
(b)

Figure 45: IE O integration (a) global and (b) local

(a) (b)

Figure 46: IE O choice (a) global and (b) local

(a)

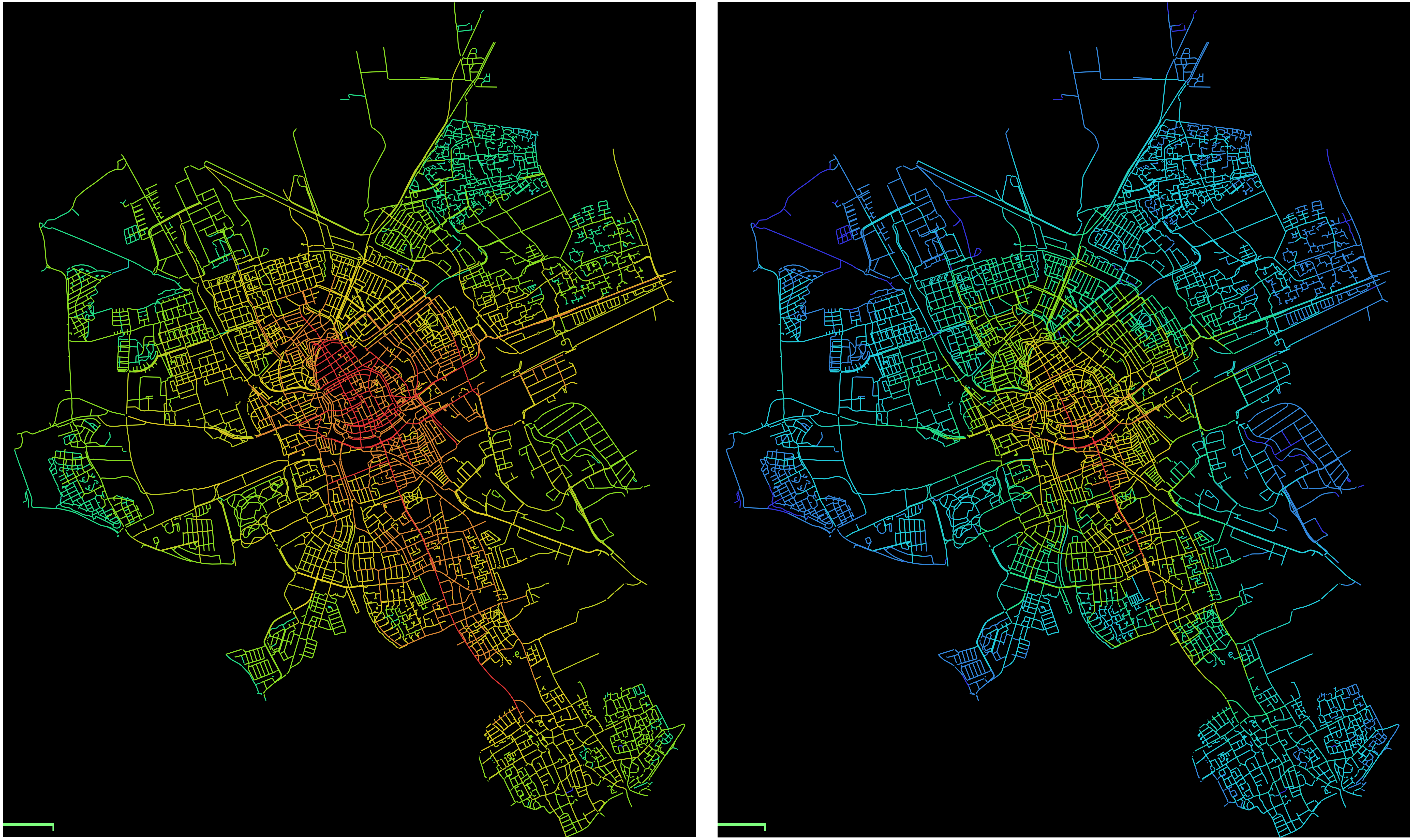


(b)

Figure 47: OS B integration (a) global and (b) local

(a) (b)

Figure 48: OS B choice (a) global and (b) local



(a) (b)

ure 49: OS IC integration (a) global and (b) local

(a) **(b)**

Figure 50: OS IC choice (a) global and (b) local

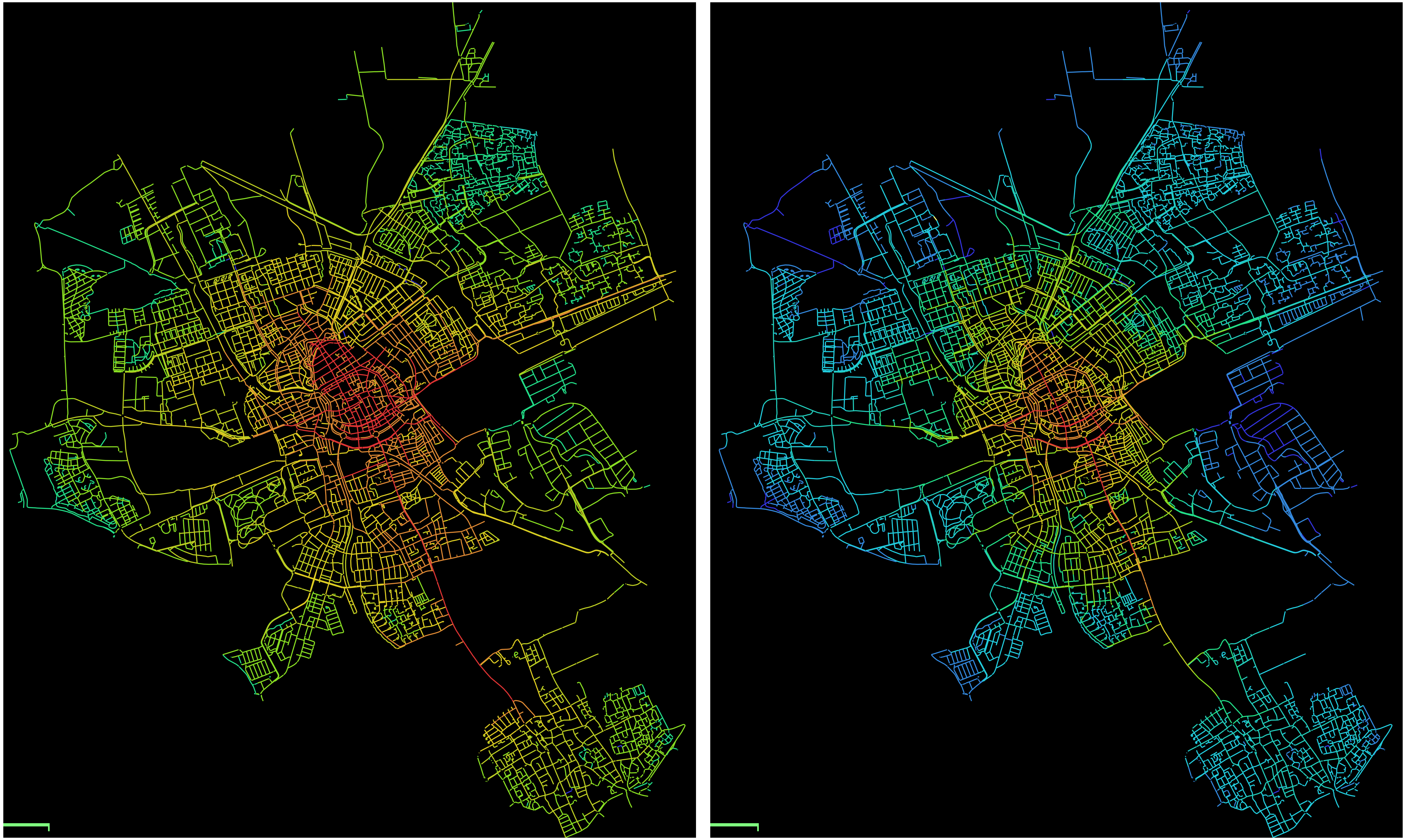
(a) (b)

Figure 51: OS O integration (a) global and (b) local

(a) (b)

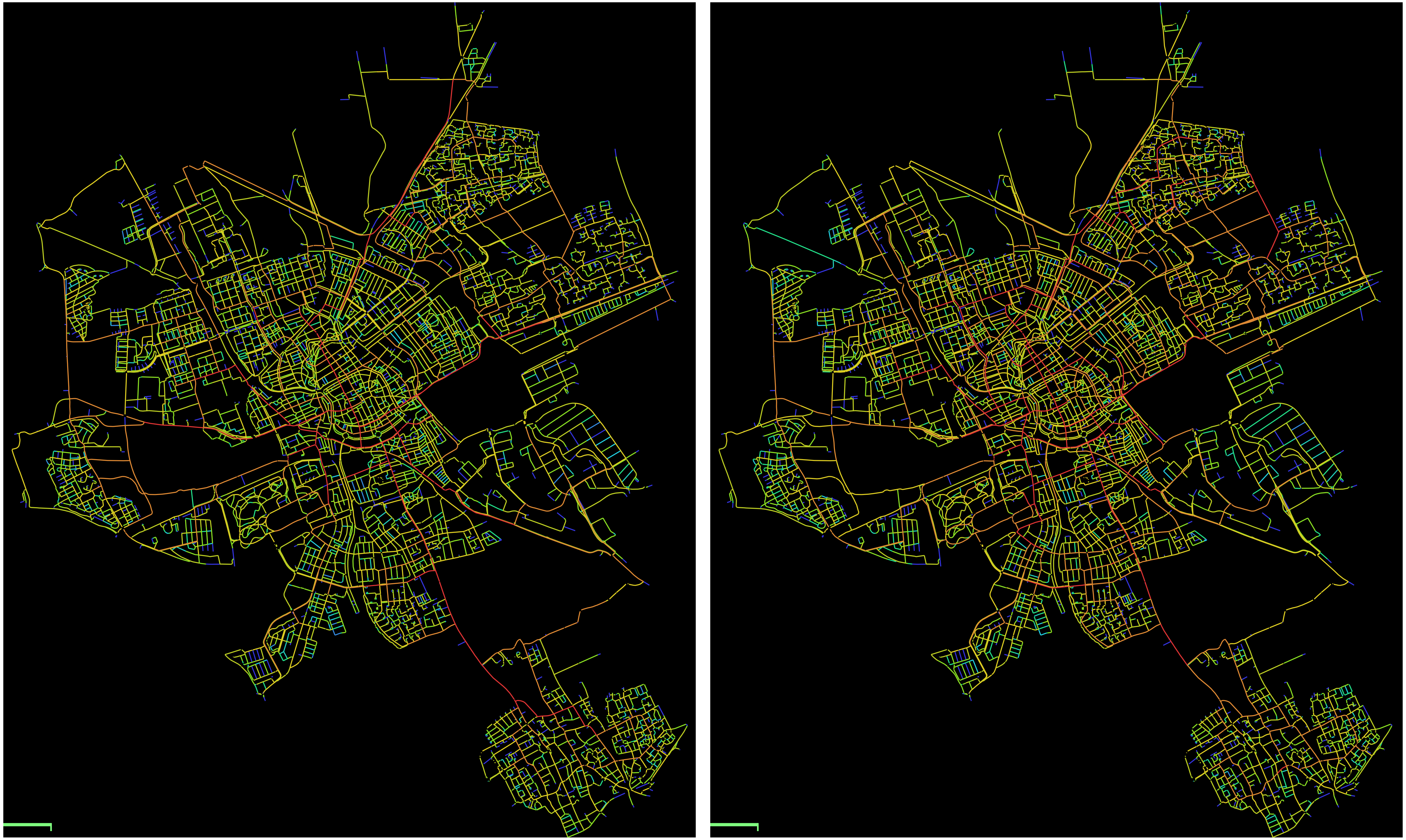
Figure 52: OS O choice (a) global and (b) local

10.1.2 Experiment 2



(a) **(b)**

Figure 53: C IE+OS integration (a) global and (b) local

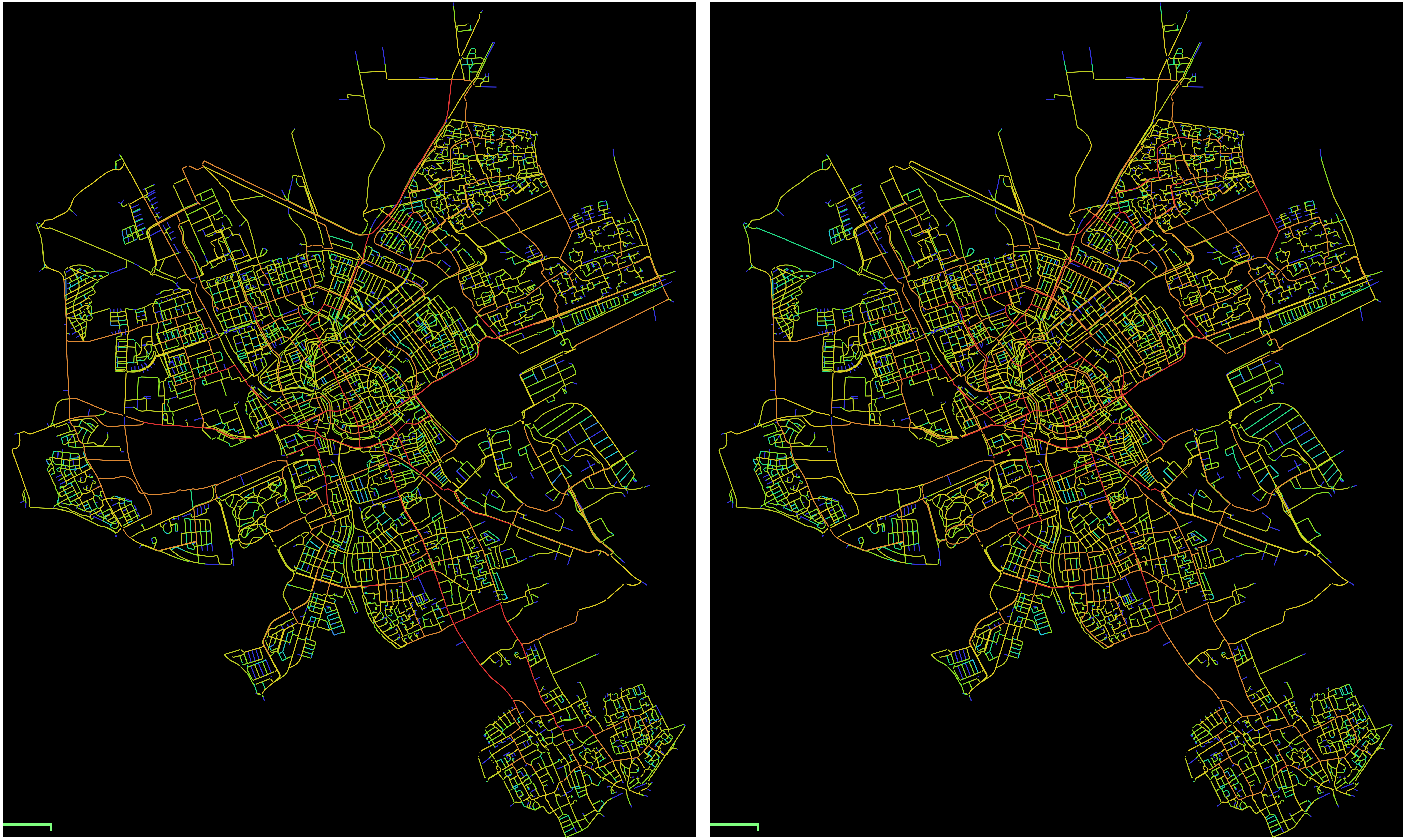


(a) (b)

Figure 54: C IE+OS choice (a) global and (b) local

(a) (b)

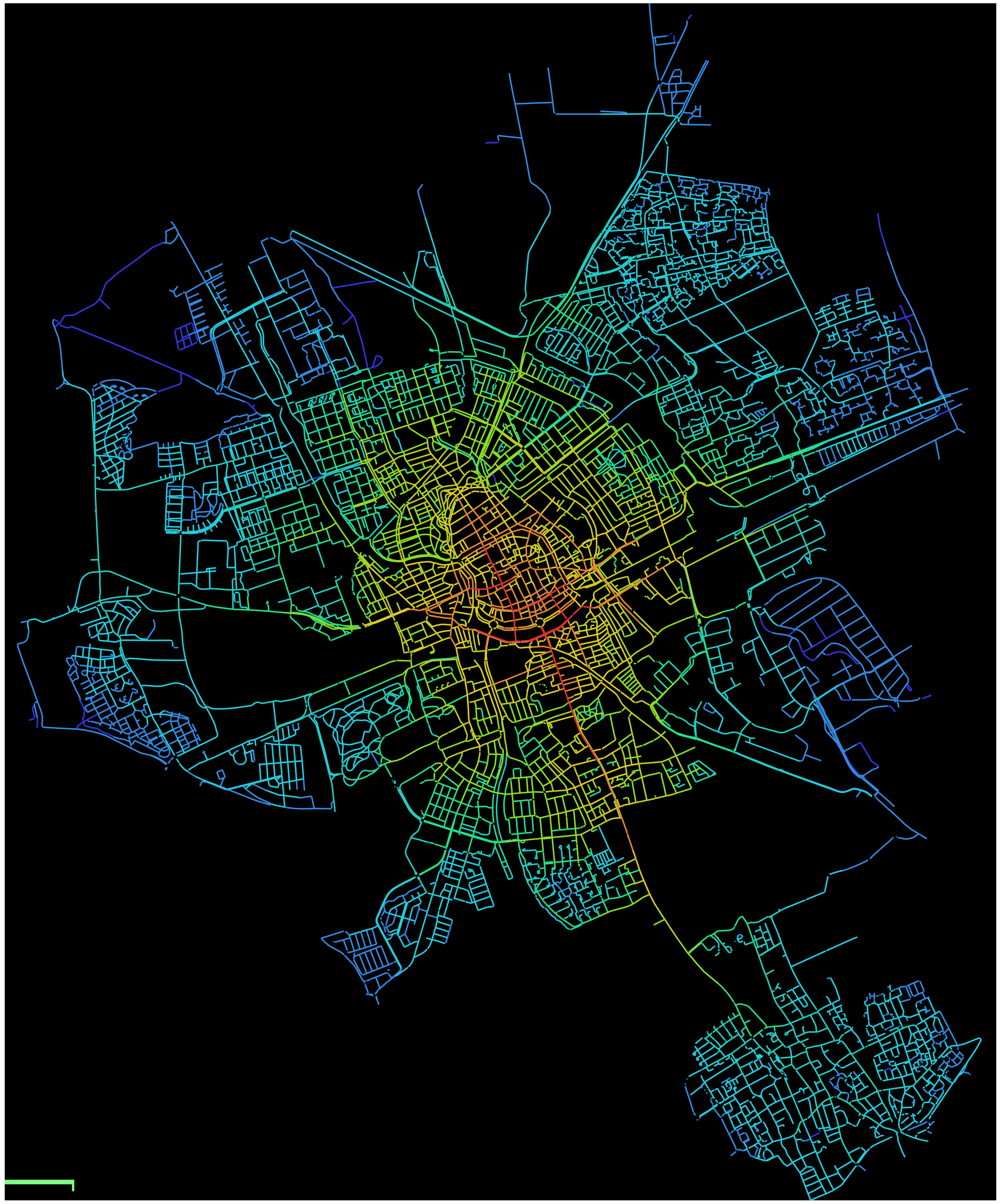
Figure 55: IE integration (a) global and (b) local



(a) (b)

Figure 56: IE choice (a) global and (b) local

(a)



(b)

Figure 57: OS integration (a) global and (b) local

(a) (b)

Figure 58: OS choice (a) global and (b) local

10.2 Axial map

10.2.1 Original

(a) (b)

Figure 59: Original axial map integration (a) global and (b) local

(a)

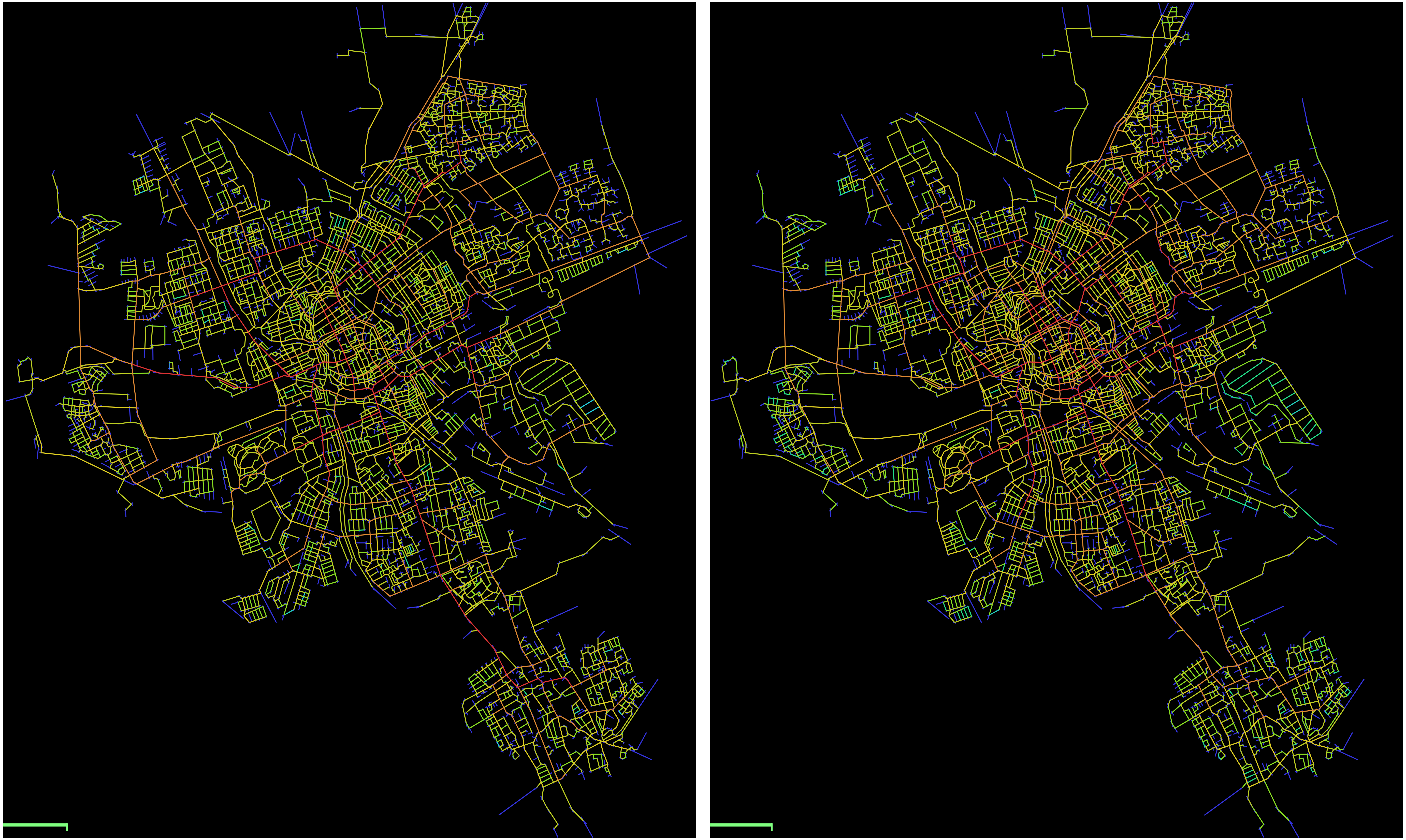
(b)

Figure 60: Original axial map choice (a) global and (b) local

10.2.2 Experiment 1

(a) (b)

Figure 61: C IE+OS B integration (a) global and (b) local

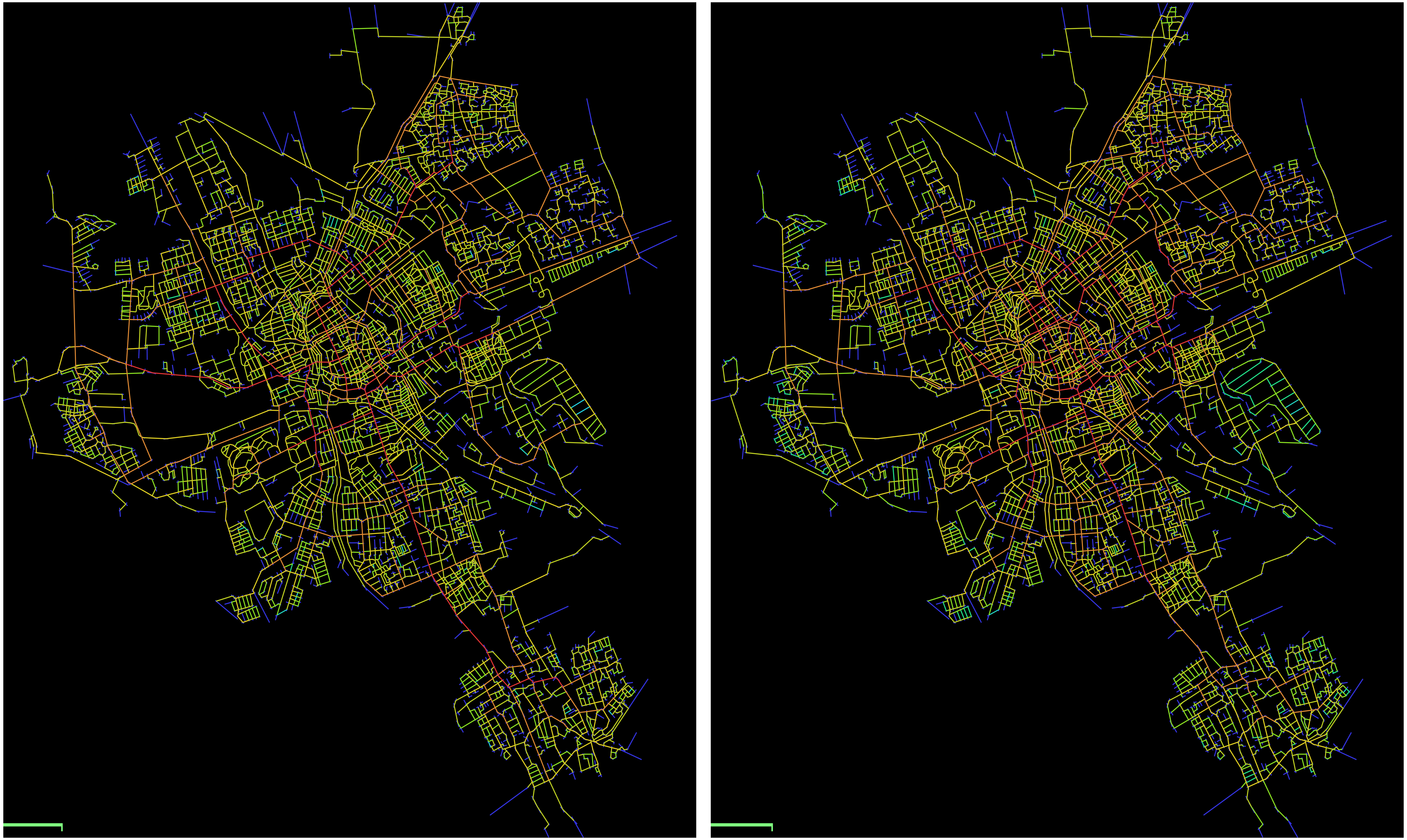


(a) (b)

Figure 62: C IE+OS B choice (a) global and (b) local

(a) (b)

Figure 63: C IE+OS IC integration (a) global and (b) local



(a) **(b)**

Figure 64: C IE+OS IC choice (a) global and (b) local

(a) (b)

Figure 65: C IE+OS O integration (a) global and (b) local

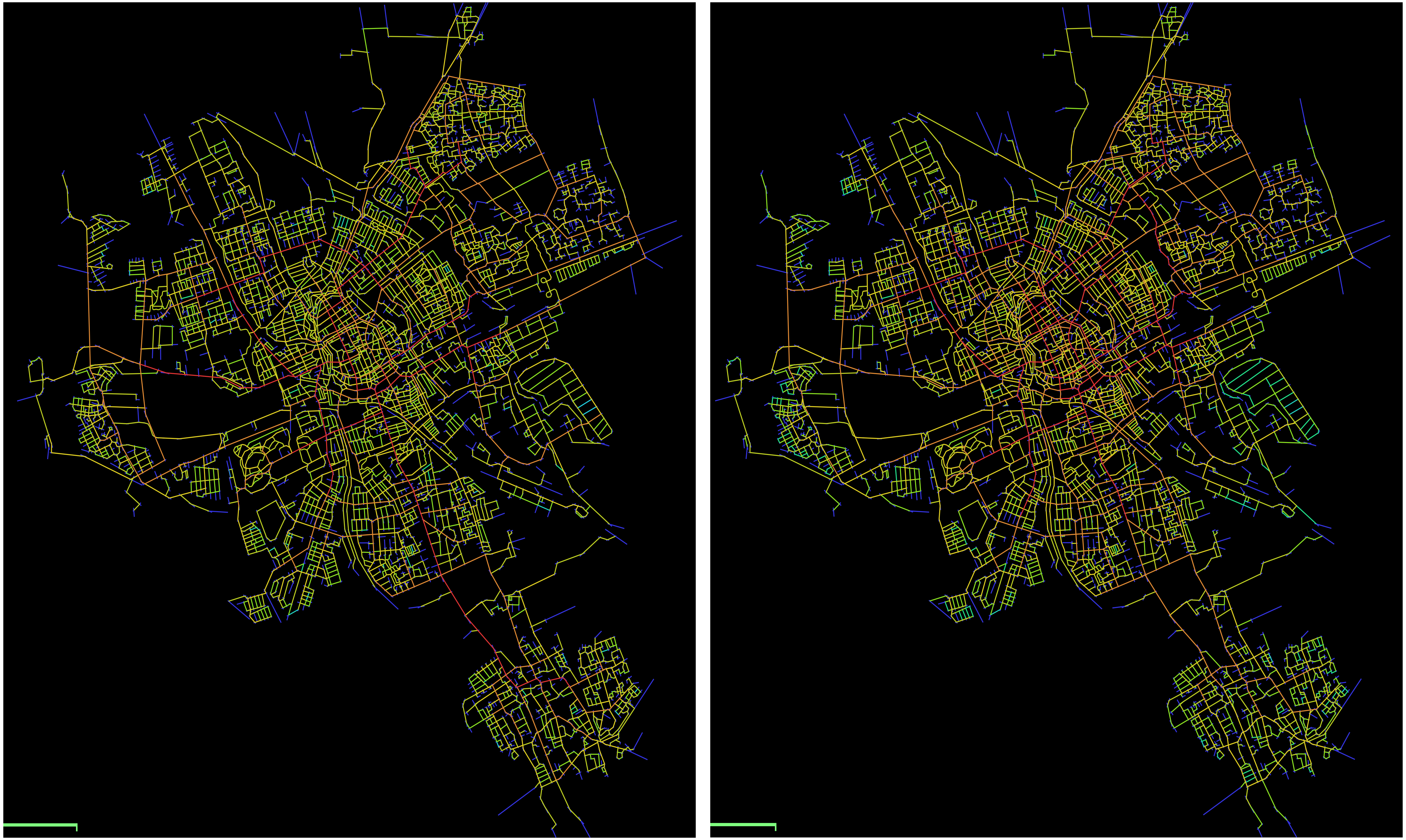
(a)

(b)

Figure 66: C IE+OS O choice (a) global and (b) local

(a) **(b)**

Figure 67: IE B integration (a) global and (b) local

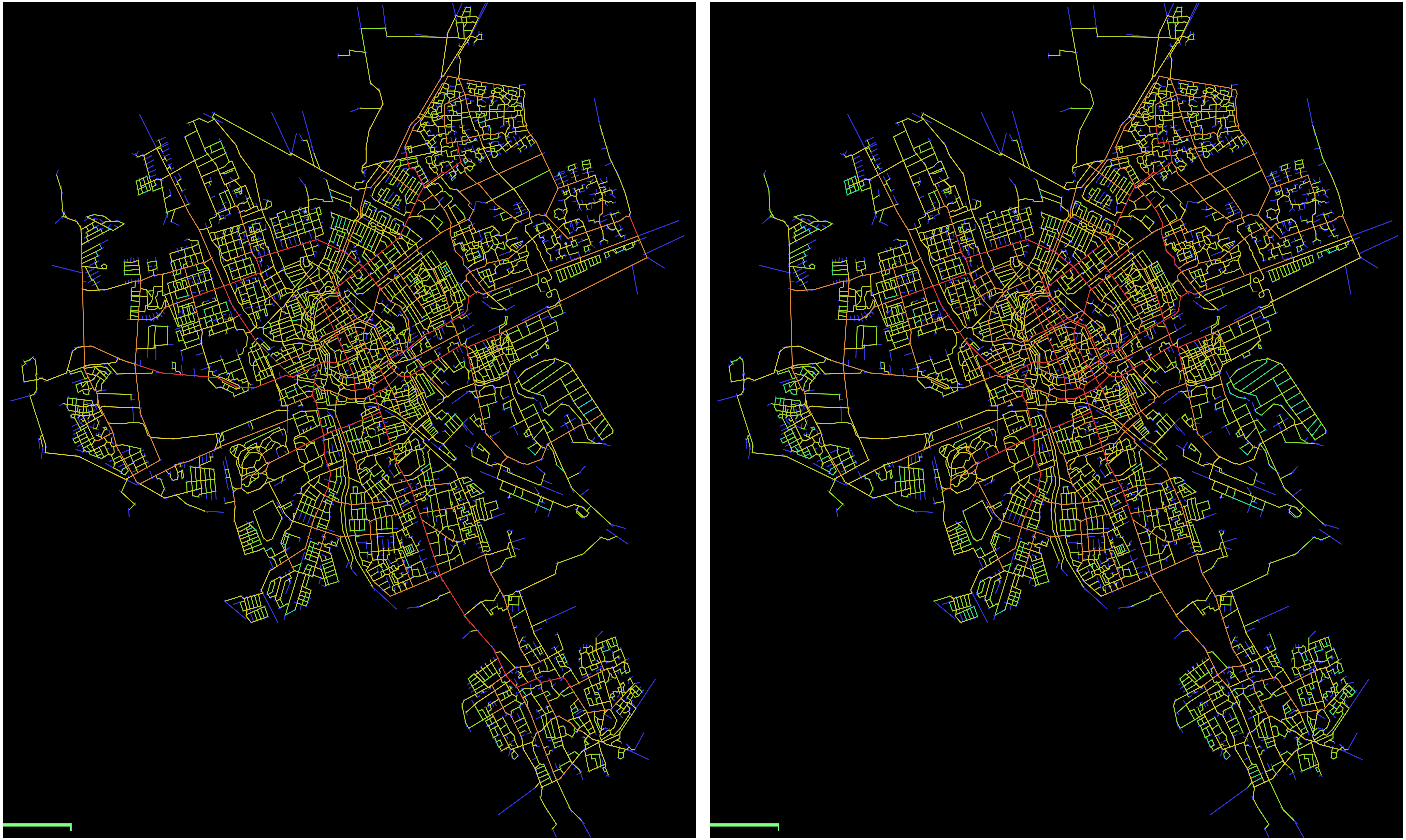


(a) **(b)**

Figure 68: IE B choice (a) global and (b) local

(a) (b)

Figure 69: IE IC integration (a) global and (b) local

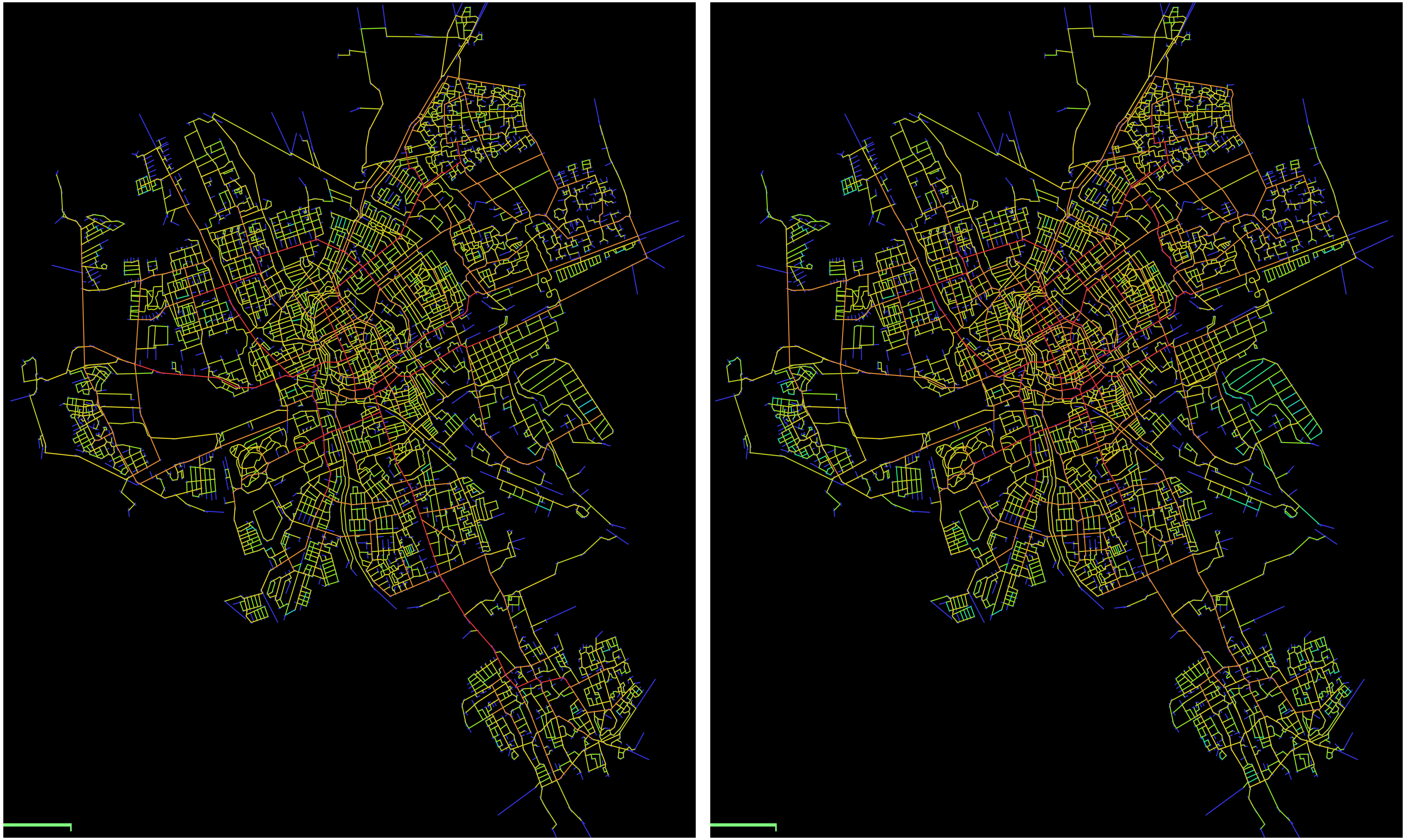


(a) (b)

Figure 70: IE IC choice (a) global and (b) local

(a) (b)

Figure 71: IE O integration (a) global and (b) local

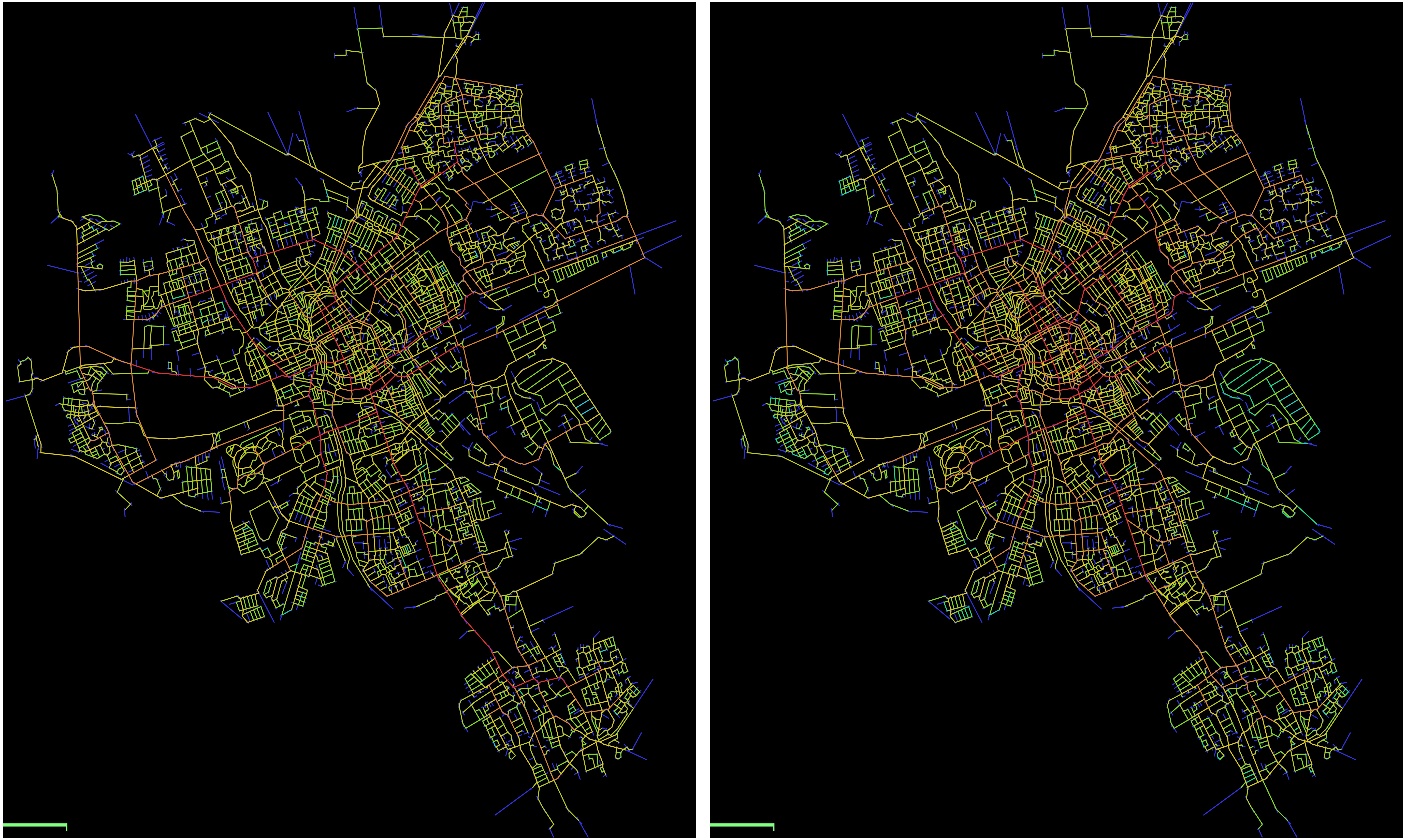


(a) (b)

Figure 72: IE O choice (a) global and (b) local

(a) (b)

Figure 73: OS B integration (a) global and (b) local

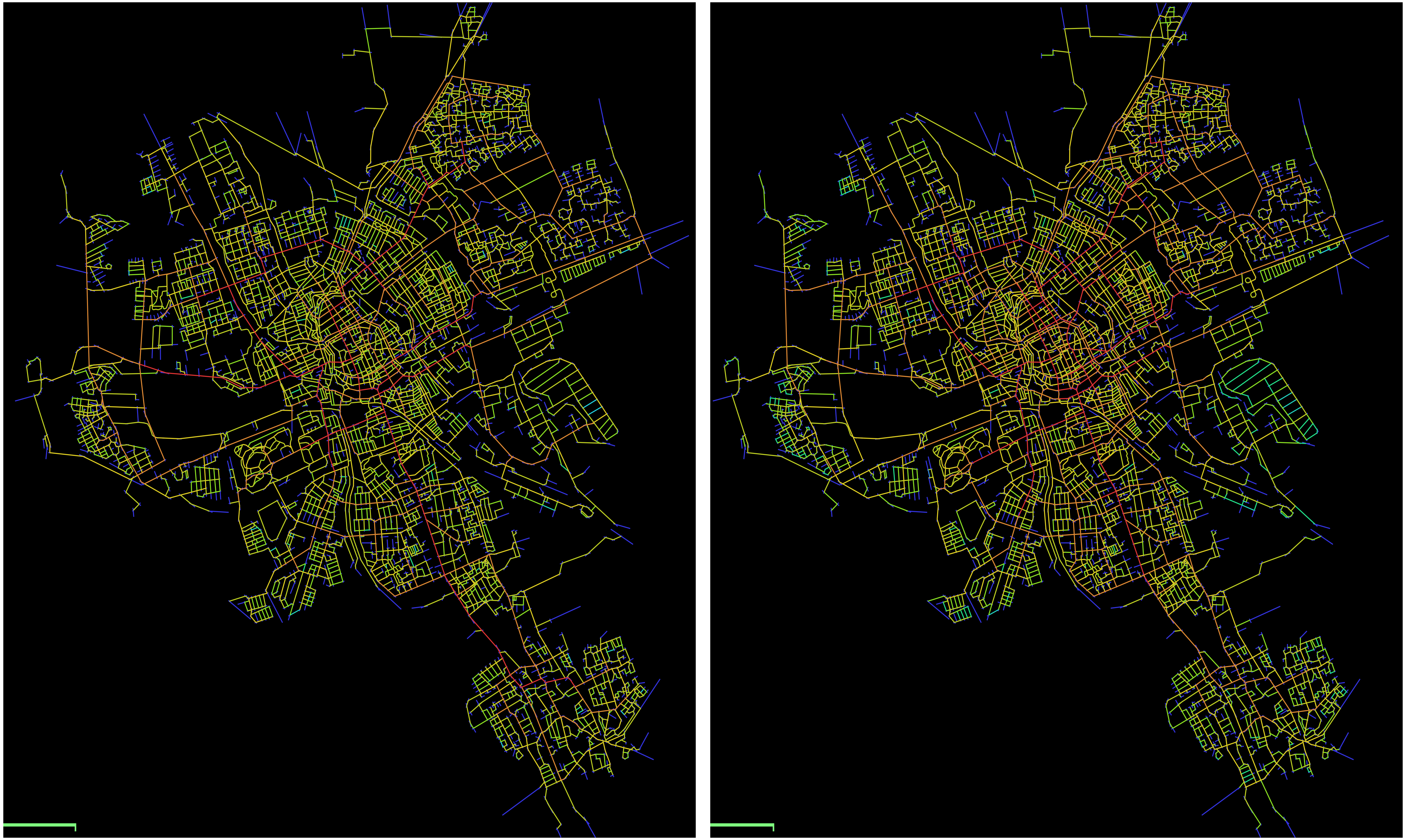


(a) (b)

Figure 74: OS B choice (a) global and (b) local

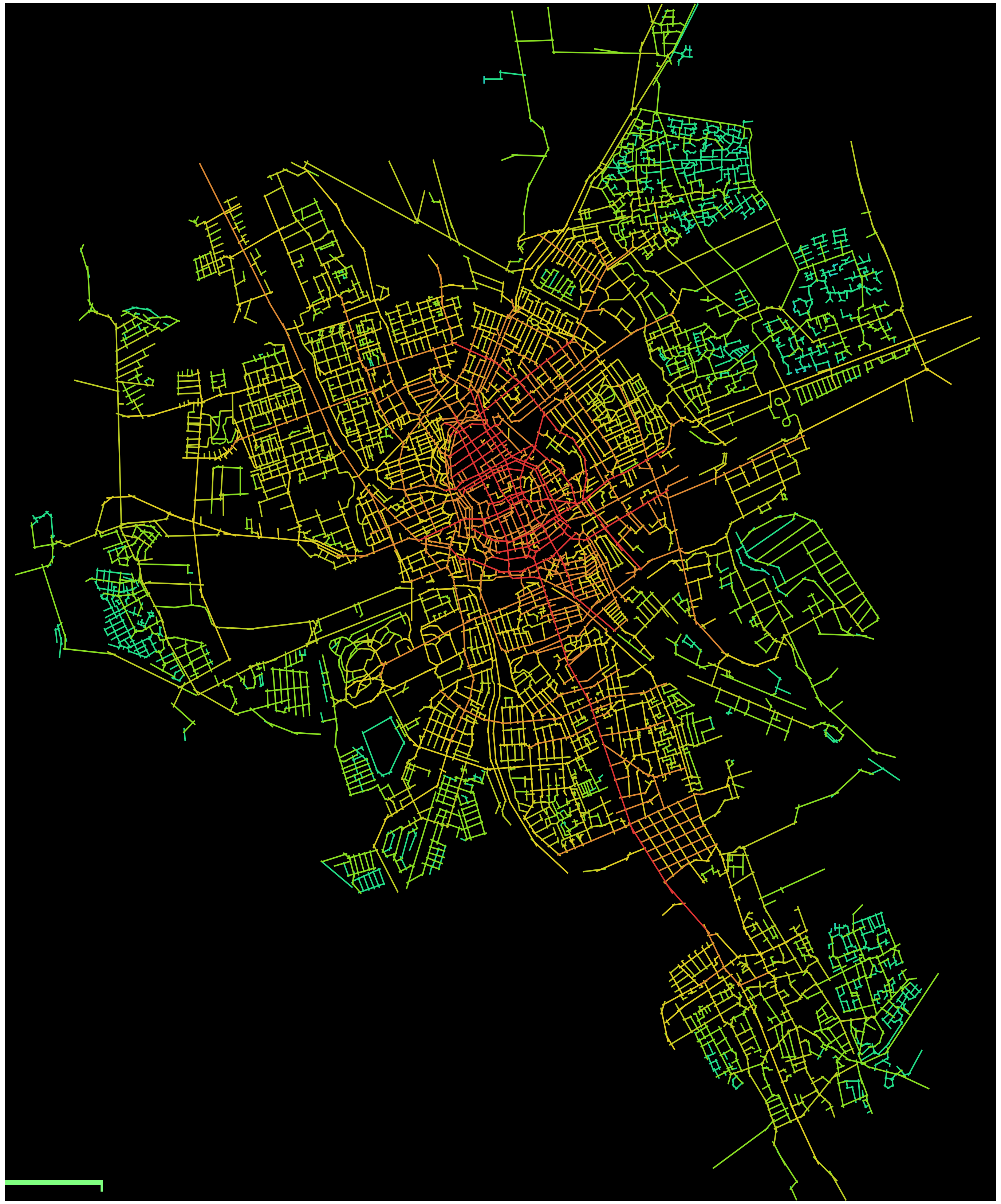
(a) (b)

Figure 75: OS IC integration (a) global and (b) local



(a) **(b)**

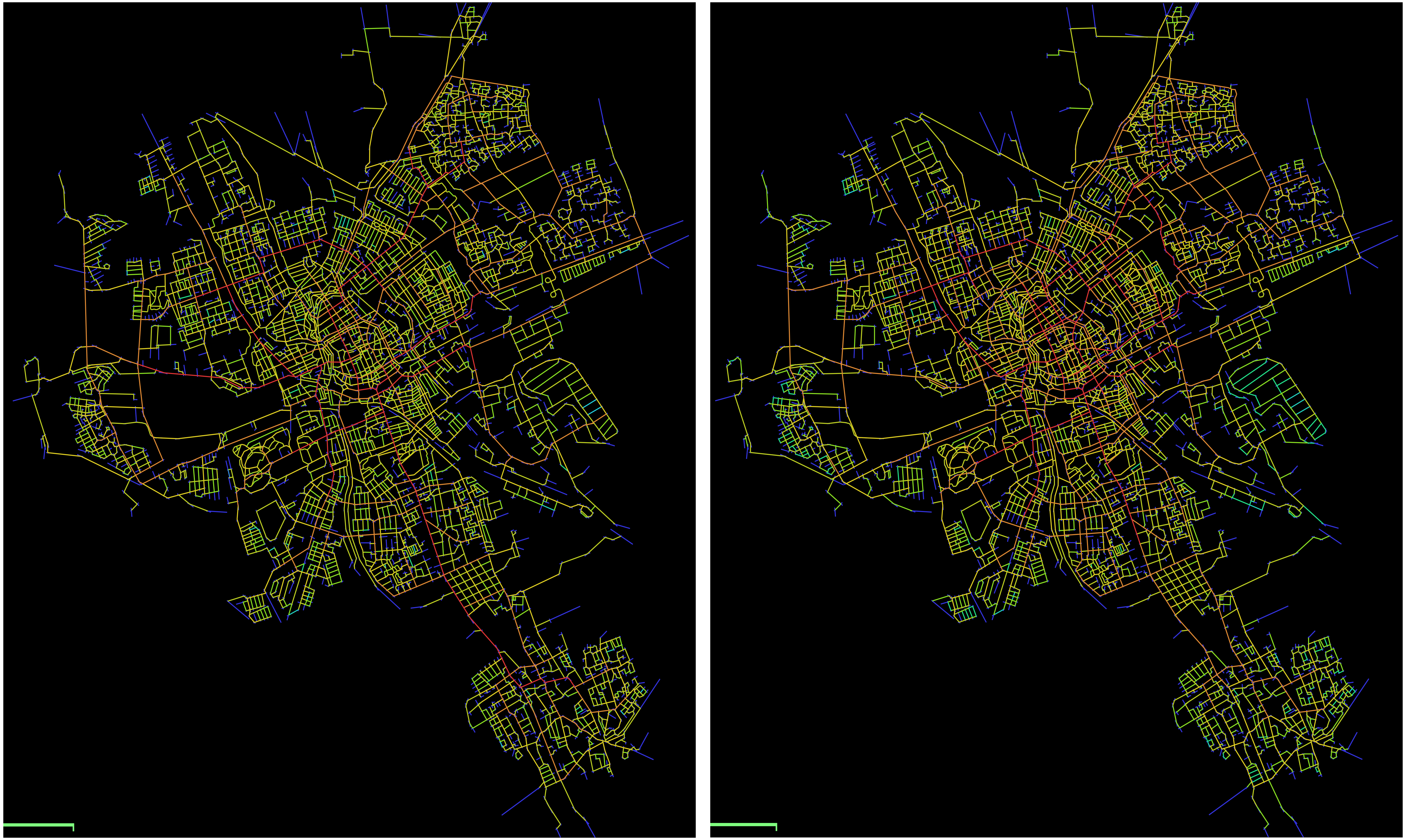
Figure 76: OS IC choice (a) global and (b) local



(a)

(b)

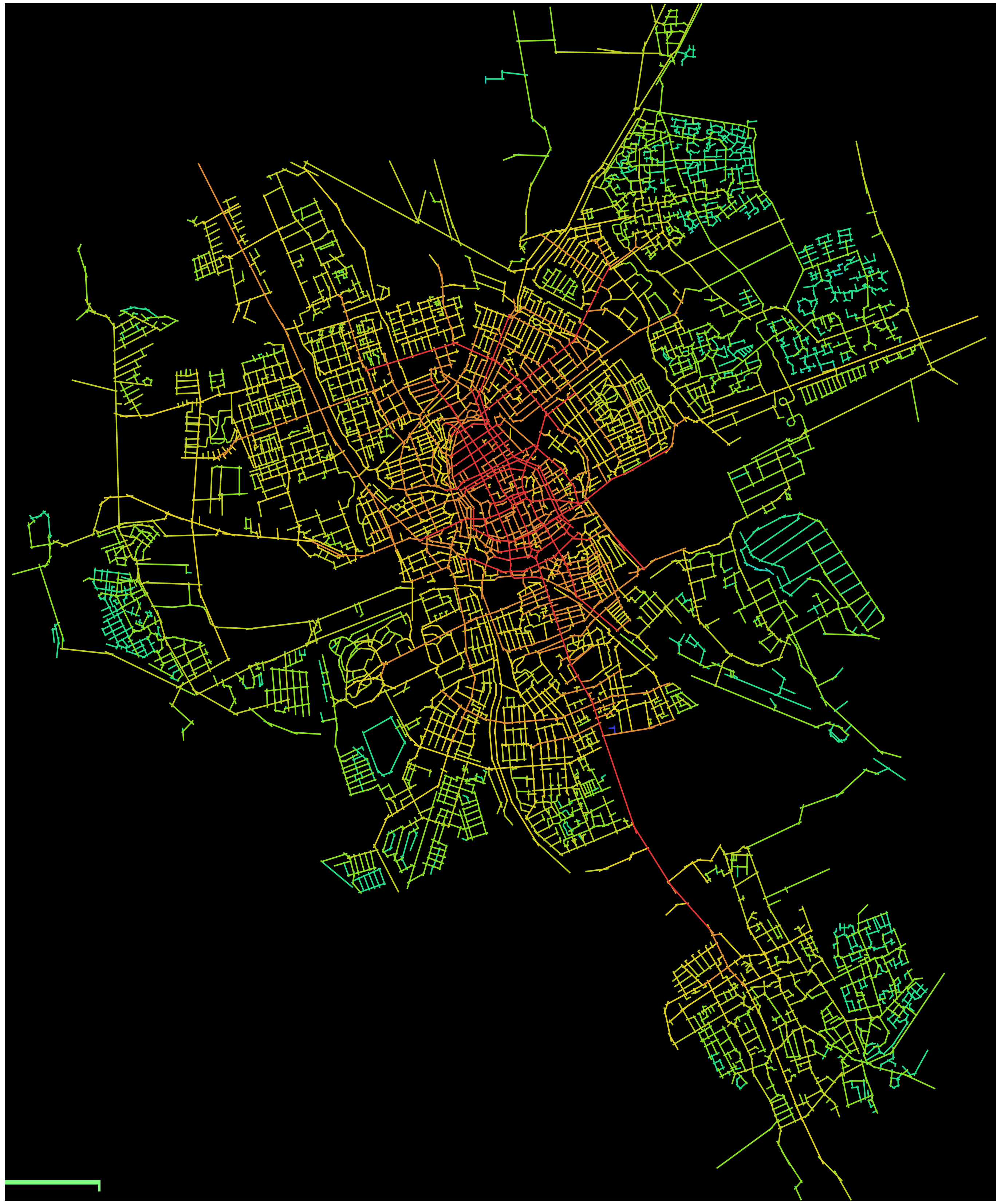
Figure 77: OS O integration (a) global and (b) local



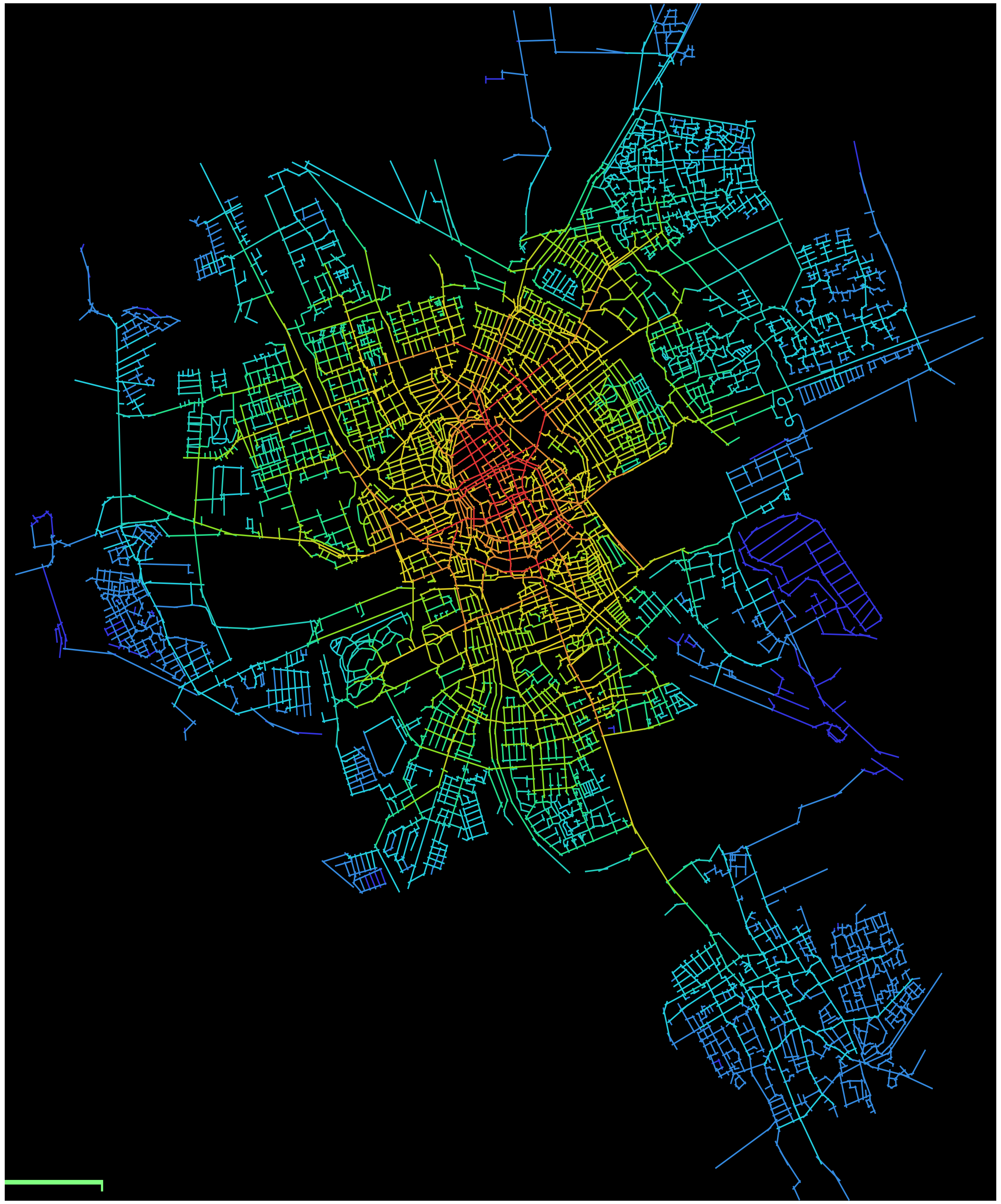
(a) (b)

Figure 78: OS O choice (a) global and (b) local

10.2.3 Experiment 2

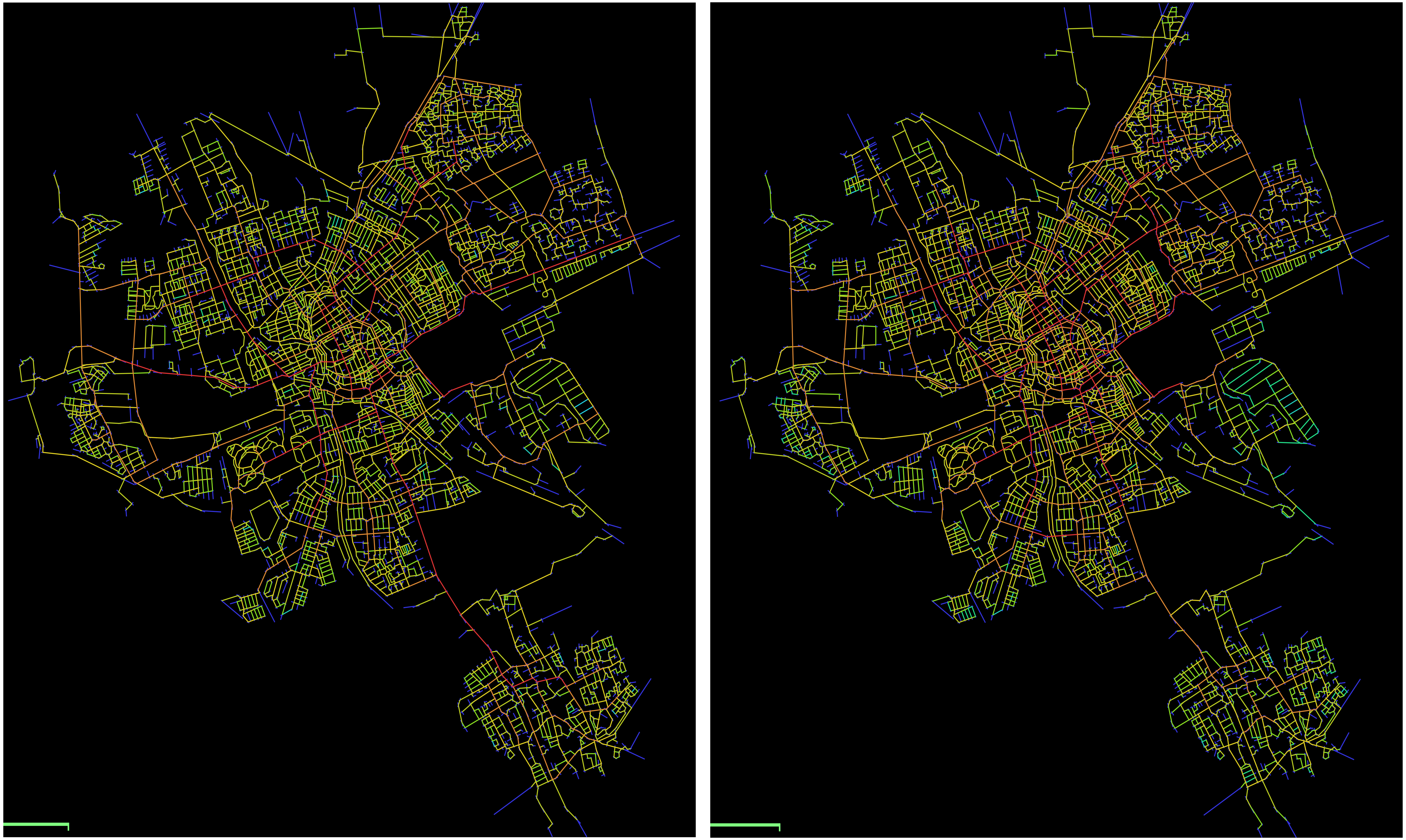


(a)



(b)

Figure 79: C IE+OS integration (a) global and (b) local

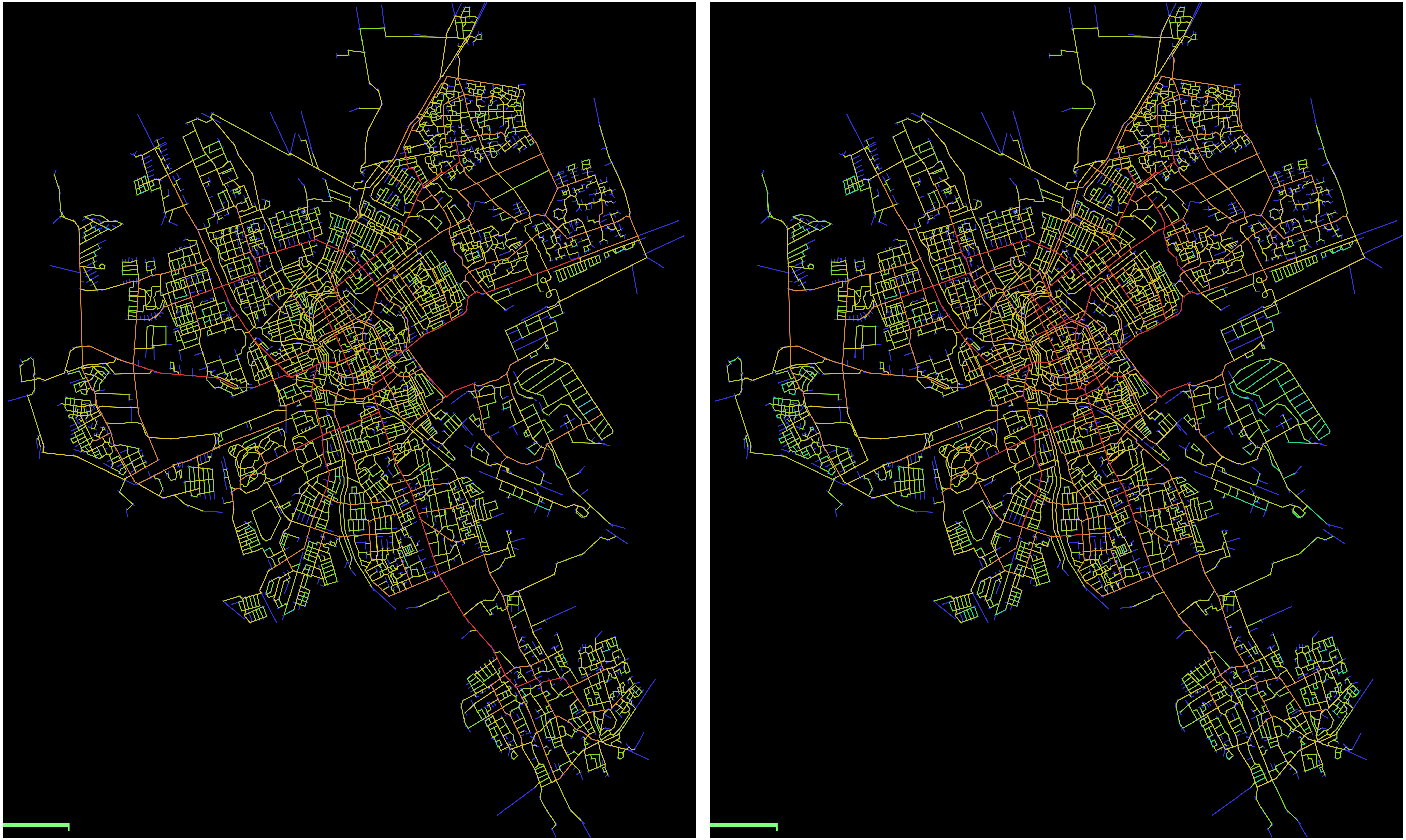


(a) (b)

Figure 80: C IE+OS choice (a) global and (b) local

(a) **(b)**

Figure 81: IE integration (a) global and (b) local

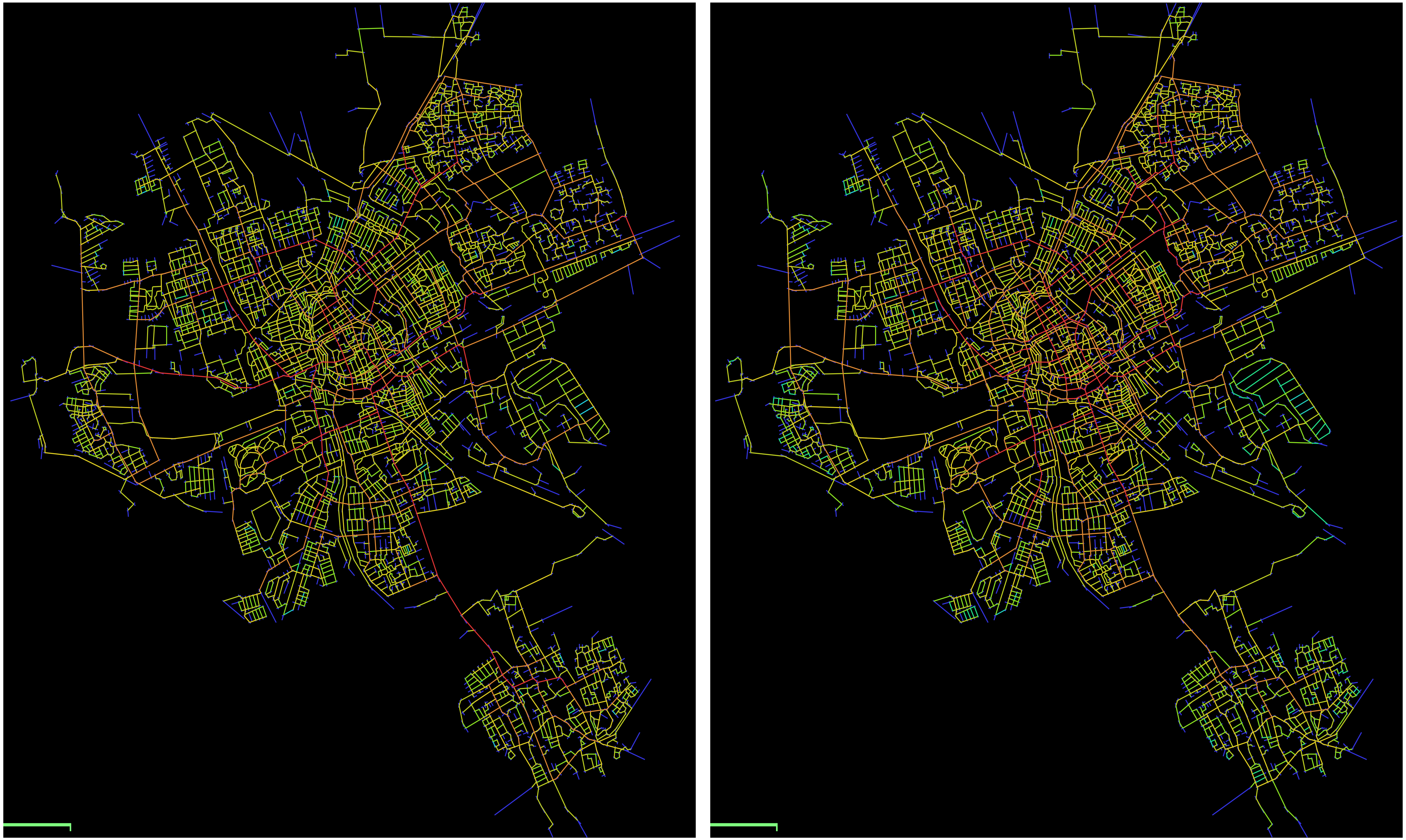


(a) (b)

Figure 82: IE choice (a) global and (b) local

(a) (b)

Figure 83: OS integration (a) global and (b) local



(a) (b)

Figure 84: OS choice (a) global and (b) local