A GIS toolkit to evaluate individual and joint accessibility to urban opportunities

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Bijdrage aan het Colloquium Vervoersplanologisch Speurwerk 2009
19 en 20 november, Antwerpen

Nederlandse samenvatting

In dit artikel wordt een GIS-toolkit ontwikkeld dat individuen helpt bij het plannen van hun dagdagelijkse activiteiten en het organiseren van face-to-face contacten. De toolkit is in staat om in te schatten waar, wanneer en voor hoe lang individuen kunnen samenkomen om een gemeenschappelijke activiteit te realiseren. Daartoe wordt de bestaande conceptualisatie van individuele bereikbaarheid uitgebreid naar gemeenschappelijke bereikbaarheid en op basis daarvan worden nieuwe bereikbaarheidsindicatoren opgesteld. Gebaseerd op informatie over het verkeersnetwerk, stedelijke faciliteiten en geplande activiteiten van individuen, kan een dynamische weergave worden gegenereerd van de mate waarin stedelijke faciliteiten zoals restaurants, sportfaciliteiten en bioscopen bereikbaar zijn voor een groep van personen. Als voorbeeld wordt een *rendez-vous* scenario uitgewerkt waarbij drie vrienden samen willen gaan lunchen in de stad Gent. Er wordt aangetoond hoe allerhande beperkingen in tijd en ruimte het aantal en de geschiktheid van restaurants voor een gezamenlijke lunch bepalen. Met onze praktische toepassing hopen we op ten minste twee manieren bij te dragen tot de wetenschappelijke literatuur.

Ten eerste, pogen we een bijdrage te leveren aan de sterk groeiende literatuur over tijd-ruimte bereikbaarheid, een afgeleide van Hägerstrand's klassieke tijdgeografie. Aangedreven door onder meer de vooruitgang in geografische informatiesystemen (GIS) en beschikbaarheid van data omtrent individueel verplaatsingsgedrag, heeft een toenemend aantal auteurs tijd-ruimte bereikbaarheidsmaten gespecificeerd en geïmplementeerd voor het evalueren van de individuele vrijheid om deel te nemen aan activiteiten. Hoewel sommige studies over bereikbaarheid de voorwaarden voor de interacties tussen individuen hebben onderzocht, bestaat er tot dusver geen analytisch kader die de fysieke ontmoetingsmogelijkheden tussen mensen van eenzelfde sociaal netwerk beoordeelt.

Ten tweede, willen we ook bijdragen aan de disseminatie van academische concepten uit de tijdgeografie naar een breder publiek toe. De vereiste beschikbaarheid van specifieke expertise en GIS-software vormt vaak een belemmering voor de verspreiding van tijdgeografische concepten. Dit is te betreuren omdat buiten de geografische en transportgemeenschap zowel academische als niet-academische doelgroepen bestaan waarvoor tijd-ruimte bereikbaarheidsanalyse nuttig kan zijn. Zo kan tijd-ruimte bereikbaarheidsanalyse academici in staat stellen een beter inzicht te verwerven in de ruimtelijke verspreiding van informatie en fenomenen, zoals de verspreiding van ziekten. Tijdgeografie kan ook een praktisch nut hebben voor niet-academici, bijvoorbeeld bij het controleren van alibi's in een politieonderzoek, ontwikkelen van online systemen voor de planning van de gezamenlijke activiteiten en uitbreiden van analysemogelijkheden van mobiele toepassingen die toelaten om je exacte locatie te publiceren voor familie en vrienden.

1. Introduction

Accessibility is a fundamental concept in a wide range of research areas including transportation planning, urban geography and geographical information science. In terms of conceptualization, two general perspectives to analyze accessibility have been proposed in relevant literature, viz. place-based accessibility and people-based accessibility. While place-based accessibility is considered a property of places indicating how easily they can be reached from other places, people-based accessibility is regarded as a property of persons showing how easily they can access a set of potential destinations within the urban environment. The people-based approach in particular has attracted increased interest in recent years, partly propelled by the advances in geographical information systems (GIS), the availability of individual activity-travel diary data and a general shift from supply-oriented towards demand-oriented transport policies. On the basis of the time-geographic framework (Hägerstrand, 1970), several authors have implemented so-called space-time accessibility measures to assess an individual's freedom to engage in particular activities in the built environment (e.g., Kwan 1998, Weber and Kwan 2002, Schwanen and de Jong 2008).

Despite the proliferation of studies that have sought to implement space-time accessibility measures in recent years, the number of studies that have explicitly addressed the assessment of accessibility of opportunities where individuals can conduct joint activities is rather limited to date. Indeed, most studies of space-time accessibility (ibid.) have concentrated on single individuals performing solo activities. There are, however, some exceptions. Miller (2005), for example, has studied the necessary conditions for physical and virtual interactions between individuals in space-time. Likewise, Yu and Shaw (2008) have put forward a 3D GIS design for representing such interactions by exploring the spatio-temporal relationships between two prisms, represented by a set of vertical spatio-temporal lines. Kang and Scott (2008), for their part, have developed a space-time framework to extract joint activity episodes undertaken by household members from observed activity-travel behaviour.

However, while acknowledging their useful contributions, these studies have not explicitly focused on the assessment of the desirability of an opportunity for joint activity engagement. Also, the majority of studies of space-time accessibility analysis have focused on realized behaviour to identify the opportunities that could have been accessed by an individual. Today platforms are emerging that allows sharing your location in real-time and seeing what your friends are up to (e.g., Google^{TM} Latitude, Yahoo^{TM} Eagle Fire). These platforms comprise an extremely rich set of volunteered geographic information about future activities for time geographers. Nevertheless, despite their rapidly increasing popularity, the current analysis functions provided by these platforms are rather limited to date. In this respect, measures of accessibility can be extremely useful to support members of a social network in planning their day-to-day activities and face-to-face contacts.

The aim of this paper is to analyze the space-time constraints that circumscribe the activity locations that are accessible to a person or a group of persons willing to engage in a particular activity. Five different accessibility algorithms are implemented to gain sound insights into how the potential to travel and conduct individual and joint activities evolves over time. Rather than representing time along the third dimension, resulting feasible opportunity sets are visualized in dynamic and animated views. Furthermore, query results can easily be exported to conventional GIS software.

The remainder of this paper is organized as follows. In section 2, we describe the conceptual and methodological framework underpinning the implemented accessibility algorithms. Section 3 discusses the implementation, data input and the algorithms of the geocomputational tool. In section 4, the capabilities of the implementation are illustrated through a simple day-to-day rendezvous scenario. We conclude with a brief discussion of potential application fields and outline avenues for further research.

2. Space-time accessibility

2.1 Conceptual background

In order to measure individual accessibility, many researchers have relied on Hägerstrand's (1970) time-geography. Time-geography provides a useful perspective for analyzing human movement and activities in an integrated space-time environment. Key concepts within time-geography are the space-time path, constraints and the prism. An individual's path is the uninterrupted string of his/her movements and stationary activities in space and time. Time-geography is most well-known for its 3D framework for the visualization of paths in which time is integrated orthogonally to a flattened topography (Figure 1). The slope of the path segments depend on the travel velocity of the individual; the faster an individual travels the more sloped the path segment will be. Hägerstrand emphasized the relevance of space-time constraints for the completion of human activities in space and time. Not only are individuals constrained by their physiological capabilities such as the need to eat, drink and sleep and instrumental limitations, such as the maximum attainable travel speed (i.e., capability constraints), but also by norms, rules and laws (i.e., authority constraints), and commitments that bind them to particular locations at specific times of the day (i.e., coupling constraints).

In time-geography activities are categorized as fixed or flexible. Fixed activities are difficult to reschedule and relocate in the short run; they tend to act as pivots around which activities with lower priority are scheduled as time progresses (Cullen and Godson 1975, Schwanen et al. 2008). An individual can travel and participate in flexible activities within the time budget between two successive fixed activities. The set of all possible space-time paths during that time budget is known as the potential path space (PPS) and is delimited by the space-time prism (Lenntorp 1976). The prism can be interpreted as an indicator of the individual's freedom to travel and participate in flexible activities. In analytical terms, the space-time prism is the intersection of two cones. The forward cone gathers all space-time points an individual could access when starting from the first fixed activity location. The backward cone, on the other hand, is the set of all space-time points where an individual could have come from when (s)he is to arrive at the second fixed activity location. The forward cone has its apex at the end of the first fixed activity; the backward cone has its apex at the start of the second fixed activity. Finally, the potential path area (PPA) is defined as the projection of the prism onto a 2D geographical plane. It depicts the spatial area that individual can cover during the time budget. Under the (unrealistic) assumption of a uniform travel velocity, this PPA is circular if the successive fixed activities are undertaken at the same geographical location and elliptical otherwise. The daily potential path area (DPPA) comprises the set of PPAs between all pairs of successive fixed activities that an individual needs to conduct during the course of the day.

The potential interaction space-time (PIS) for groups of persons willing to engage in a particular joint activity can be defined in analogy to the individual case (Neutens et al. 2007). The PIS is the set of space-time points that all group members can reach, given the different sets of constraints they face in space-time. The PIS is constructed by intersecting the PPSs of multiple individuals. Likewise, the PIA can be defined as the projection of the PIS to the geographical plane. The DPIA is then given by the set of PIAs that are accessible to multiple persons for conducting a joint activity throughout a particular day.

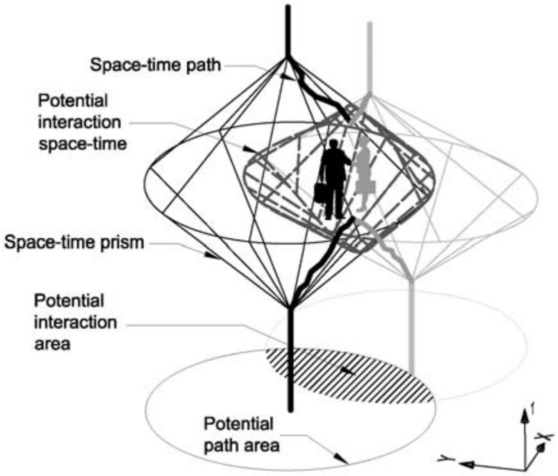


Figure 1. Conceptual framework: intersection of two space-time prisms.

The conceptual time-geographic apparatus offers not only visually appealing insights into the extent of an individual's travel possibilities, but also provides a useful means to measure accessibility from a people-based perspective, which will be discussed in the following subsection.

2.2 Methodological background: measuring accessibility

While classical time geography relies on the assumption that individual movement is undertaken in a travel environment with uniform travel velocities in all directions, recent developments in GIS have allowed straightforward calculation of PPSs and (D)PPAs within transportation networks on the basis of graph theory (Miller 1991, Kwan and Hong 1998, Wu and Miller 2001). Network-based space-time prisms assume that the maximum travel velocity of an individual is equal to the law-imposed travel speed that varies from edge to edge in a graph representation of the transportation network. Various measures of individual accessibility can be derived from such network-based prisms. We will consider four measures of individual accessibility, which were selected because they have been employed frequently in prior research. We then extend these measures of individual accessibility to measures of multi-person accessibility.

The first measure constitutes the *number of opportunities* contained in the DPPA, where opportunities correspond to type of location (workplace, facility, etc.) of interest. This measure reflects the freedom to choose between different alternatives in the opportunity choice set: the larger the size of the choice set, the more freedom to choose where to perform a particular activity and the higher the likelihood the individual may find an opportunity aligning with his/her preferences. This measure assumes that each opportunity, irrespective of its location, contributes to an individual's accessibility in equal measure.

The second measure is the *activity duration* an individual can spend at an opportunity of the choice set. This measure provides an indication of the temporal freedom to perform a particular activity: the larger the possible activity duration, the more freedom an individual has to choose when and for how long a particular activity is performed. Note that this measure implicitly accounts for the relative location of opportunities vis-à-vis fixed activities in a linear manner. This is because the activity duration depends on the length of the time budget minus the time required for traveling to/from the opportunity.

The third and fourth measures are established by combining time geography with utility theory (Ben-Akiva 1985). Utility theory assumes that a decision-maker has a perfect discrimination capability and assigns a cardinal utility to each alternative of a choice process. The decision-maker then selects the alternative associated with the maximum utility. More specifically, in accordance with Burns (1979) and Miller (1999), we define accessibility by means of *locational benefits*. A locational benefit is the utility an individual derives from participating in an activity at a particular location and expresses the desirability of an opportunity. As opposed to the first measure (i.e. the size of the opportunity choice set) that attributes the same weight to each opportunity, accessibility measures based on locational benefits differentiate the opportunities on the basis of attractiveness, possible activity duration and locational proximity. Following Burns (1979) and Miller (1999), a locational benefit can be defined as follows:

$$B_{ik} = a_k T_k \exp\left(-\lambda t_k\right) \tag{1}$$

where:

B_{ik} locational benefit of individual *i* at opportunity *k*

a_k attractiveness of opportunity *k*

T_k possible duration of an individual activity at opportunity *k*

t_k round-trip travel time from the first fixed activity to the opportunity and from the opportunity to the next fixed activity

λ travel time decay parameter

Based on this definition, we can specify an additive and maximative measure of individual accessibility. While the former assumes that each opportunity within the DPPA may contribute to an individual's accessibility, the latter assumes that the benefit an individual derives from the opportunities within the DPPA is equivalent to the opportunity with the largest benefit value. The additive space-time accessibility measure is given by:

$$A_{ik}^{add} = \sum_{k \in DPPA} B_{ik} = \sum_{k \in DPPA} a_k T_k \exp\left(-\lambda t_k\right) \qquad (2)$$

The maximative space-time accessibility measure is given by:

$$A_{ik}^{\max} = \max_{k \in DPPA} B_{ik} = \max_{k \in DPPA} \left(a_k T_k \exp\left(-\lambda t_k\right)\right) \qquad (3)$$

Which of these measures is to be preferred depends on activity of interest and type of destination to be visited. The maximative measure seems more appropriate as the type of destination has fewer unique characteristics. Thus the additive measure of accessibility is more suitable when say restaurants are considered. This is because the individual may be more likely to find a suitable restaurant that meets his/her preferences when the set of restaurants to choose from is larger. In contrast, a larger choice set tends not to produce more utility for such activities as drawing cash: it suffices to be able to reach only one cash dispenser very well.

We now extend these four measures of individual accessibility to measures of joint accessibility. In other words, we seek to identify and value those opportunities that are accessible to a group to perform a joint activity. Three modifications need to be made. First, instead of using network-based DPPAs to delineate the feasible opportunities for a solo activity, we calculate the network-based DPIAs to identify the feasible opportunities where a group of people can conduct a joint activity. Second, we restrict the possible activity participation time to the time available to a group to perform a joint activity that requires the co-presence of each group member at a particular location. In some cases, however, activities may also be partially shared by the group members – some may arrive later or leave earlier than others. For the sake of simplicity, we will leave such synchronization effects for future research and concentrate on opportunities for conducting fully shared joint activities. Third, we consider the average of the round-trip travel costs of all persons constituting the group. Although particular persons may experience the disutility associated with travel time differently than others in reality, we will restrict ourselves in the current prototype to the general case where each individual exerts the same influence on the determination on the travel time component.

Taking into account these modifications, we propose the following additive measure of joint space-time accessibility:

$$A_{Gk}^{add} = \sum_{k \in DPIA} B_{Gk} = \sum_{k \in DPIA} a_k T_{Gk} \exp\left(-\lambda \sum_{i \in G} \frac{t_{ik}}{n} \right) \tag{4}$$

where:

G	group of individuals
B_{Gk}	locational benefit of group G at opportunity k
T_{Gk}	possible duration of a joint activity at opportunity k
n	number of group members

The maximative measure of joint space-time accessibility transforms to:

$$A_{Gk}^{\max} = \max_{k \in DPIA} B_{Gk} = \max_{k \in DPIA} \left(a_k T_{Gk} \exp\left(-\lambda \sum_{i \in G} \frac{t_{ik}}{n} \right) \right) \tag{5}$$

3. Geocomputational toolkit

Having introduced a conceptual and methodological framework for evaluating the opportunities for individual and joint activity participation, we will now discuss the development of a geocomputational toolkit for calculating the proposed accessibility measures.

3.1. Implementation

Our point of departure was the requirement that the toolkit can be used by both experts who may or may not be familiar with time-geography and lay people interested in analyzing or organizing face-to-face contact. Therefore, the use of the toolkit should not require know-how or availability of specific GIS packages. Furthermore, to reduce financial barriers to usage, the toolkit should be free of charge and as a consequence it cannot employ existing algorithms available in commercial GIS. Nonetheless, the system should be able to communicate with popular geospatial software. Hence, we have put forward the following more detailed criteria that should be met by the GIS design:

1. The software works as a stand-alone GIS application and is not built on top of existing GIS programs. This implies that no additional GIS software or expert knowledge about commercial or open-source GIS packages (e.g., ArcGIS™ or Quantum GIS) is required.
2. The software is independent of the platform used (e.g., Microsoft® Windows, Mac OS, Linux). This reduces the technical barriers to the use of the geocomputational tool.
3. The GIS design is programmed in a modular way. A module represents a separation of concerns denoting distinct features and is implemented through an interface. Modular programming improves maintainability of the program by enforcing logical boundaries between the different components. As such, it allows updating and extending the software in a relatively easy manner.
4. In order to visualize spatio-temporal data, the geocomputational toolkit is able to provide animated views that can be explored dynamically by the user. Rather than representing time as a vertical axis perpendicular to a topographical plane, a time slider allows controlling the visualization of how the accessibility to activity locations

changes over time. Consequently, the user does not necessarily need to be accustomed with the time-geographic way of thinking.

These prerequisites were leveraged from a system point of view as follows. We have developed the geocomputational toolkit from scratch, writing it as a stand-alone application in Java on an Intel® Pentium® M 1,86 GHz laptop using Ubuntu 8.10 (Linux distribution) as operating system. We have used Eclipse 3.3.2 as Integrated Development Environment (IDE) and Open JDK 6 as Java Virtual Machine (JVM). The advantage of using Java is that it is an object-oriented programming language that is independent of the platform used. Furthermore, the program does not make use of preprogrammed algorithms of existing GIS software. Instead, the program incorporates some fundamental algorithms from open-source libraries. For example, graph-theoretical routines, like Dijkstra's shortest path algorithm, are extracted from the Java Universal Network/Graph (JUNG) framework, and two-dimensional spatial functions are borrowed from the JTS Topology Suite.

Five interrelated modules have been implemented: *transportation*, *activities*, *algorithms*, *visualization* and *graphical user interface* (*GUI*). The *transportation* module builds an object-oriented model of the urban infrastructure based on attributes attached to the arcs and nodes of the transportation graph and information about points of interest (POI). These POIs are locations where one or more individual(s) may conduct a particular activity. Examples of POIs include sport facilities, shops, service stations, restaurants, etc. The *activities* module contains an object-oriented model of fixed activities of the individuals involved in a particular meeting scenario. The *activities* module consists of various nested classes because a meeting scenario may consist of multiple persons each having their own schedule with fixed activities. The *GUI* module allows the user to create a meeting scenario of multiple persons and to save or load a particular meeting scenario by means of a parser using Extensible Markup Language (XML). Both modules (*activities* and *transportation*) are used to feed the *algorithms* module (see section 3.3). The results of the algorithms can be exported using the *visualization* module to Keyhole Markup Language (KML) files, Shapefiles and Comma Separated Values (CSV) files. These files can be visualized in Google™ Earth/Maps, ESRI®'s ArcGIS™ and open-source GIS software, respectively.

3.2. Data input

Three types of data sources have to be imported into the toolkit. First, transportation network data needs to be uploaded to estimate travel times from fixed activities to the potential activity locations. The network data describes ways and waypoints which are represented by directed and undirected links, and nodes of a graph. All kinds of attributes are attached to the links such as the street name, hierarchical level, length, maximum travel speed etc. Second, the user may upload information about specific POIs (e.g., restaurants, gas stations, dentists etc.) to which accessibility has to be evaluated. If the user does not upload POIs, accessibility will be calculated to each node of the transportation system. Third, information about the location and the start and end times of planned, fixed activities is necessary. The GUI allows the user to specify the fixed activity location by its address (street, number and postal code), which is automatically geocoded into coordinates by the system.

3.3. Algorithms

The level of space-time accessibility can be calculated using the input discussed in the previous subsection and five different algorithms. These include in order of increasing complexity:

1. *DistanceAccessibility* computes the physical network distance along the shortest path from/to a particular location to/from all nodes of the transportation network or alternatives of a set of POIs. As the distance between two points may differ due to one-way streets, the travel direction (to/from) can be selected by the user.
2. *TimeAccessibility* computes the minimum time required to travel from/to a particular location to/from all nodes of the transportation network or alternatives of a set of POIs. Again, the travel direction can be selected by the user.
3. *TimePrismAccessibility* computes the PPA associated with the time budget between two successive fixed activities of an individual. The minimum activity duration of the intended activity can be specified by the user. The algorithm outputs the set of opportunities where an individual may conduct the activity for at least a minimum period of time, together with the time interval during which these opportunities can be accessed within the time budget. Furthermore, the algorithm provides a report with the results of the four measures of individual accessibility discussed in section 2.
4. *MultiTimePrismAccessibility* extends *TimePrismAccessibility* towards multiple time budgets, i.e. the algorithm computes the DPPA associated with multiple time budgets between a series of successive fixed activities of an individual. The result of this algorithm is the set of feasible POIs, along with all time intervals during which they can be accessed by an individual. Likewise, an accessibility report is produced.
5. *Intersection* comprises a generalization of *MultiTimePrismAccessibility* towards multiple persons willing to conduct a joint activity. In other words, the intended activity at the opportunity is now considered to be a joint instead of a solo activity. A report is generated summarizing the results of the joint accessibility measures for all combinations of group members.

4. Empirical example

Because measuring the potential for joint activity participation extends the literatures on both space-time accessibility analysis and activity-based travel demand analysis (see Introduction above), we will now illustrate how the *Intersection* algorithm supports activity location decisions through a hypothetical empirical example. More specifically, we assume that different persons with representative activity patterns are planning to have lunch together. The study area is the city of Ghent, Belgium, which has a population of approximately 235 000 inhabitants and an area of 156 km² (Figure 2). Ghent's centre is the most densely populated of the city and comprises a peak concentration of transportation infrastructure and POIs; the harbor area in the northern part is populated rather sparsely.

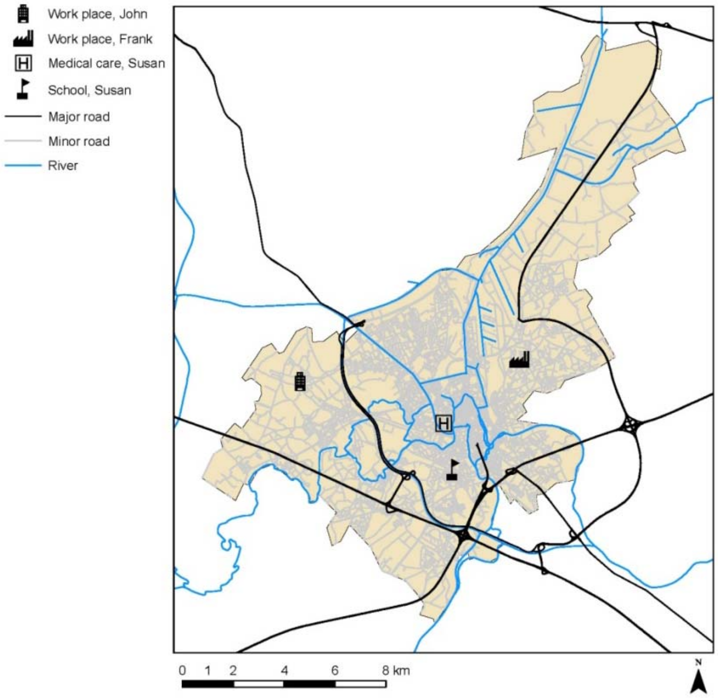


Figure 2. Study area: the city of Ghent, Belgium.

As input, we have used the TeleAtlas$^{®}$ MultiNet^{TM} data (version 2007.10) comprising a detailed topological representation of the Belgian road network, as well as geographical information about a large set of different POIs within the city of Ghent. As no specific attributes indicating the attractiveness of the POIs (e.g., ground floor area, quality grading) are included in the data, we have considered all POIs equally attractive. Further, we have used an activity-travel diary data set collected in 2000 in the same study area (Tindemans, 2005). A general value of the travel time decay ($\lambda = 0.01$) was estimated on the basis of the cumulative distribution of trips by car users according to travel time using a negative exponential deterrence function. We have selected representative activity programs of three individuals from the activity-travel diary data. These individuals will henceforth be named Susan, John and Frank. Their fixed activities such as paid labour, pick up/drop off and medical care are distilled from the data set and given in Table 1. Within the framework of this particular example, we will analyze the possibilities of all persons to have lunch together. First we will identify and evaluate the feasible restaurants for each person separately and then for all combinations of persons.

Table 1. Activity schedules of the sampled individuals.

Person	Activity purpose	Activity start time	Activity end time
Susan	chauffering children	11:45 AM	12:05 PM
	medical care	1:15 PM	2:30 PM
John	work	8:00 AM	12:00 PM
	work	1:30 PM	5:00 PM
Frank	work	9:00 AM	12:00 PM
	work	1:00 PM	5:30 PM

Susan has two fixed activities around lunch time. In the morning, she has to pick up her children from school between 11:45 AM and 12:05 PM. In the afternoon, she needs to be at the general practitioner at 13:15 PM. During the time budget available between these two fixed activities she wants to go out for lunch. Using our geocomputational tool, the accessibility to restaurants where Susan may have lunch can be computed. In order to ensure a reasonable lunch time, the minimum activity duration parameter was set at 45 minutes. Figure 3 depicts a snapshot of the accessible restaurants at 12:30 PM in Google^{TM} Earth. The time slider top left of the figure is embedded in the KML file and allows the user to control the display of accessible POIs along the timeline. The colour of the symbols depicts the locational benefit that can be gained at the POIs. Green symbols represent restaurants that are well accessible to Susan, while red symbols depict the most poorly accessible restaurants of the feasible opportunity choice set. Figure 3 shows that the restaurants where Susan may derive the highest utility at 12:30 PM are situated near the locations of her fixed activities. During the animation the user may dynamically explore the map depicting the temporal changes of accessibility to restaurants. The user may also want to obtain information about a particular restaurant by clicking on the symbol, including the name, address, possible activity duration, earliest and latest possible lunch time.

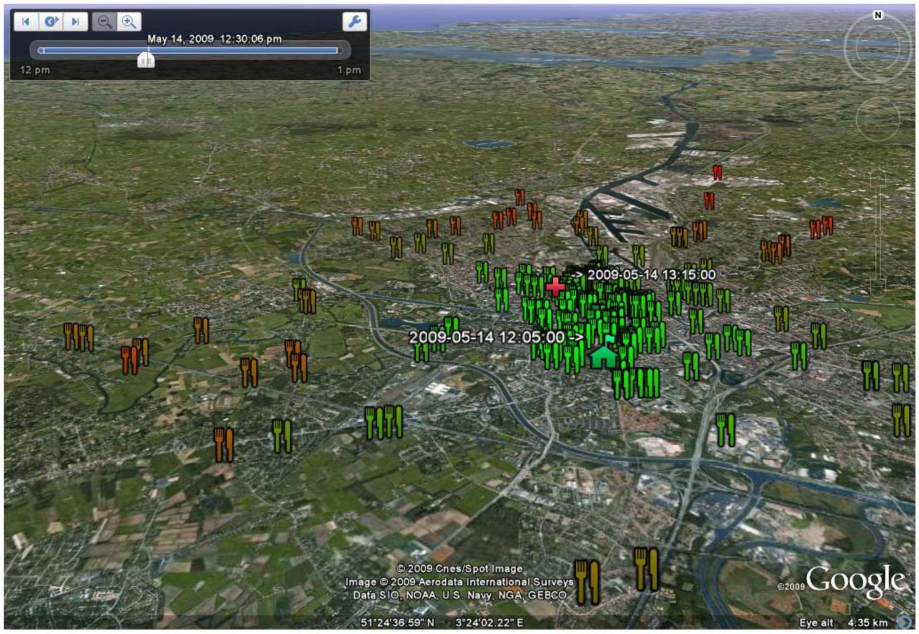


Figure 3. Dynamic view of the restaurants accessible to Susan at 12:30 PM in Google^{TM} Earth.

Likewise, the geocomputational toolkit computes the accessibility of restaurants for John and Frank separately. The feasible opportunity sets of John and Frank are depicted in Figures 4 and 5, respectively. Locational benefits at feasible opportunities are categorized using Jenks' natural breaks classification. Both persons have a typical work schedule (Table 1). The lunch breaks of John and Frank are limited to 90 minutes and 60 minutes respectively. The accessibility indicators of the feasible opportunity sets of all combinations of individuals are summarized in the accessibility report generated by the program (Table 2). The computation time for generating this report is less than two seconds. While John and Susan are able to reach the complete set of POIs (*n* = 264) in the city of Ghent, Frank is only able to reach 209 alternatives for a 45-minute lunch. If Frank wants to meet John or Susan for lunch, the number of feasible alternatives is diminished to 121 or 142 respectively. This is because in a meeting scenario, the feasibility of the POIs depends not only on Frank's spatial and temporal constraints, but also on the interactions of his constraints with Susan's or John's. The size of the feasible opportunity set shrinks to 73 if co-presence of all three persons is required for lunch. The meeting possibilities are then primarily located between the fixed activity locations of Susan and Frank (Figure 6).

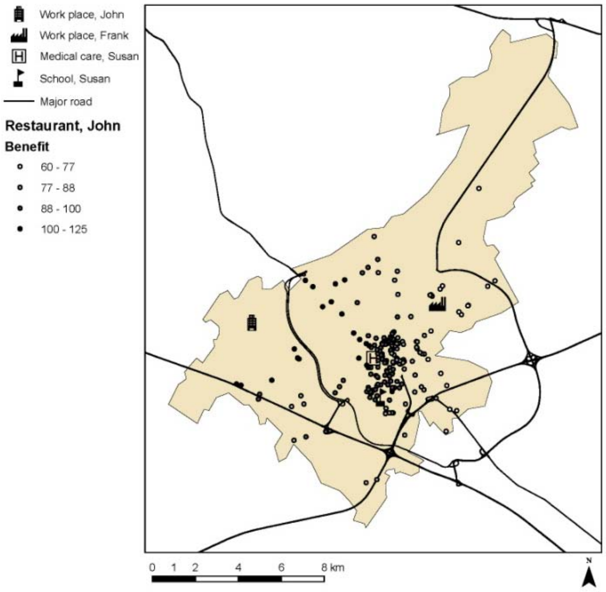


Figure 4. Restaurants accessible to John.

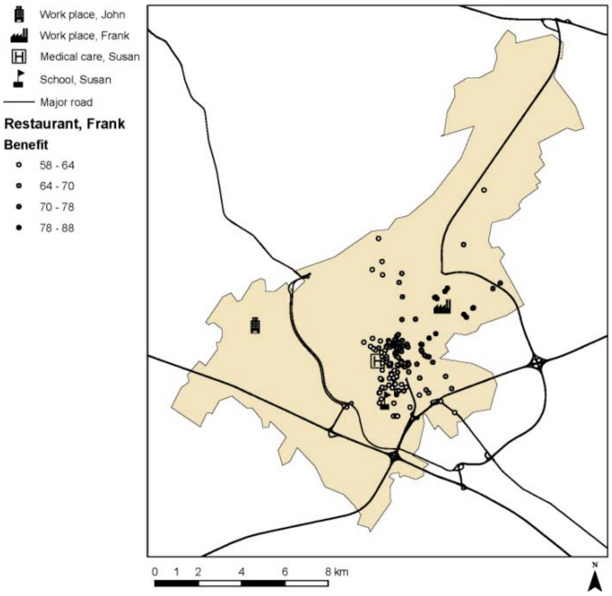


Figure 5. Restaurants accessible to Frank.

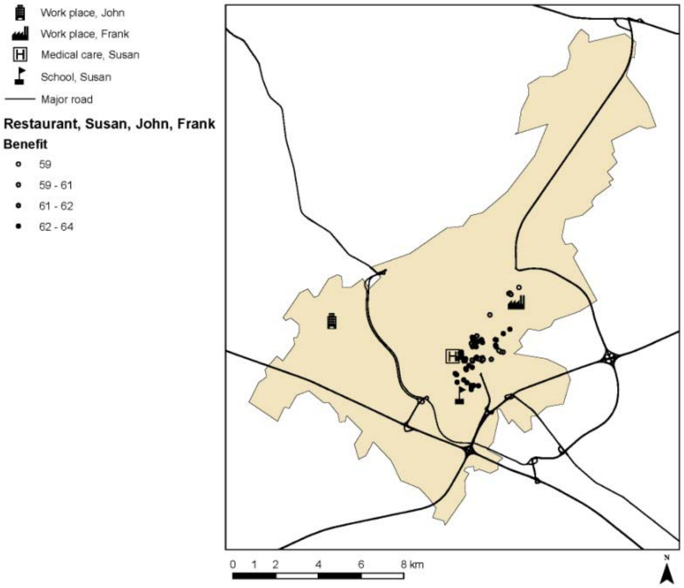
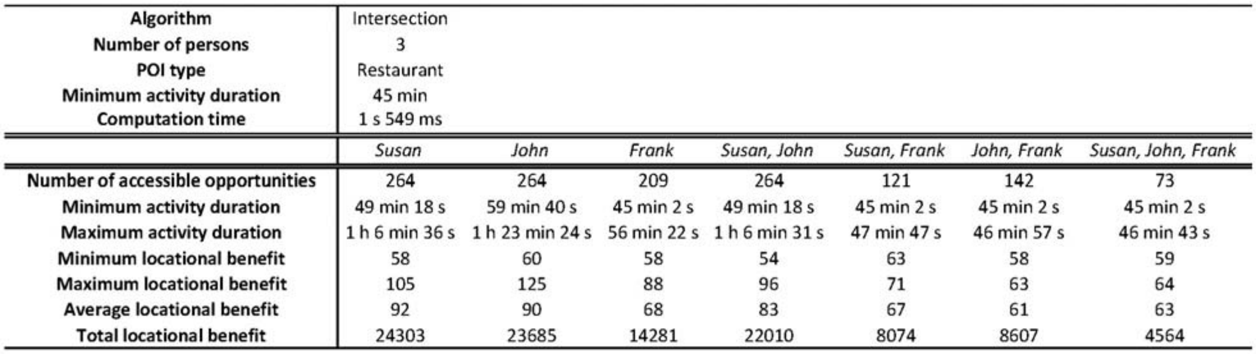


Figure 6. Restaurants accessible to Susan, John and Frank.

The minimum duration that can be spent at a POI exceeds in each of the combinations the presupposed threshold of 45 minutes; the maximum duration is largest for a solo activity conducted by John and smallest for an activity that is fully shared by all three individuals. In other words, if more individuals take part in an activity, there is not only less freedom to choose where to perform an activity but also when and for how long. The desirability of the potential destination is reflected by the minimum, maximum, average and total benefit of the set of restaurants. The aggregated and total locational benefits correspond to the additive and maximative accessibility measures expressed in Equation 4 and 5, respectively. The locational benefit values for a solo lunch at a restaurant are comparable for Susan and John but lower for Frank. While John has more temporal freedom for eating out in a restaurant, as reflected by the larger maximum activity duration in Table 2, Susan's fixed activities are more centrally located near the largest concentration of restaurants, implying shorter travel times to most of the restaurants and thus a higher average and total locational benefit. Frank's lower average locational benefit is a consequence of longer travel times and a shorter duration of the lunch. Of all combinations of two persons, Frank and Susan have the smallest feasible opportunity set (*n* = 121) for having lunch together. Nonetheless, the average benefit they derive at an opportunity is higher than for Frank and John. This is because the fixed activities of Frank and Susan are mutually close and nearby the highest concentration of restaurants in the city centre. The work location of John is more peripheral resulting in larger average travel times when John is involved in a rendezvous scenario. When all three persons are willing to meet at lunch time, the algorithm seeks to reconcile the space-time constraints of all persons which yields the smallest feasible opportunity set and a maximum activity duration of less than 47 minutes.

Table 2. Accessibility report.



Algorithm	Intersection
Number of persons	3
POI type	Restaurant
Minimum activity duration	45 min
Computation time	1 s 549 ms

	Susan	*John*	*Frank*	*Susan, John*	*Susan, Frank*	*John, Frank*	*Susan, John, Frank*
Number of accessible opportunities	264	264	209	264	121	142	73
Minimum activity duration	49 min 18 s	59 min 40 s	45 min 2 s	49 min 18 s	45 min 2 s	45 min 2 s	45 min 2 s
Maximum activity duration	1 h 6 min 36 s	1 h 23 min 24 s	56 min 22 s	1 h 6 min 31 s	47 min 47 s	46 min 57 s	46 min 43 s
Minimum locational benefit	58	60	58	54	63	58	59
Maximum locational benefit	105	125	88	96	71	63	64
Average locational benefit	92	90	68	83	67	61	63
Total locational benefit	24303	23685	14281	22010	8074	8607	4564

5. Final remarks

This paper presents a spatiotemporal GIS-based framework that identifies and evaluates the opportunities for individual and joint activity participation. The framework is implemented as a stand-alone geocomputational toolkit and enables complex accessibility analysis by scientific and lay researchers who may be familiar or unfamiliar with GIS and/or time-geography. Accessibility has been evaluated on the basis of the number of accessible opportunities, the possible activity duration and the locational benefit that an individual or group can derive at a potential activity location.

The usefulness of the geocomputational toolkit to support individuals in making decisions about where, when and with whom to conduct a particular activity has been demonstrated. Yet, it can be extended into other useful applications and so stimulate the dissemination of time-geographical thought among new expert and lay audiences. One example is the development of an online meeting planner for web-based communities whose members wish to meet face-to-face. This planner would extend such online applications as Doodle® that currently only allow the time and duration of a meeting to be determined through a reconciliation of the group members' temporal constraints. Our toolkit could integrate these temporal capacities with an analysis of the spatial characteristics of the activity schedules of the group members and their travel times to certain activity locations. The toolkit could also be developed into an application for checking alibis in police investigations, viz. to verify where, when and for how long suspected persons could have met, given they were spotted by witnesses (persons or cameras) at particular places and times. A last application field is related to ride-sharing. The essence of ride-sharing shows great resemblance with the concept of joint accessibility. Persons are eligible carpool partners, if their activity patterns exhibit a high joint accessibility and vice versa.

Nonetheless, our preliminary toolkit needs to be developed further if it is to effectively and truly maximize the accessibility of space-time accessibility analysis. An important next step is to further develop the toolkit into a Web 2.0 application. This would make local installation of the toolkit unnecessary and allows reaching a large web-based community of users who can add value to the application. Another important improvement would be to refine the basic time-geographic model by incorporating dynamic travel times, opening hours of POIs, non-synchronized joint activities and more complex activity scheduling. We hope to contribute to and report on these and related challenges in the near future.

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