Individual accessibility and travel possibilities: A literature review on time geography

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EJTIR, **7**, no. 4 (2007), pp. 335-352

In the late 1960s, Torsten Hägerstrand introduced the conceptual framework of time geography which can be deemed an elegant tool for analysing individual movement in space and time. About a decade later, the auspicious time-geographic research has gradually lost favour, mainly due to the unavailability of robust geocomputational tools and the lack of georeferenced individual-level travel data. It was only from the early 1990s that new GIS-based research gave evidence of resurgence in popularity of the field. From that time on, several researchers have steadily been publishing work at the intersection of time geography, disaggregate travel modeling, and GI-science. This paper reviews the most important time-geographic contributions. From this exercise, some prevailing research gaps are deduced and a way to deal with these gaps is presented. In particular, we focus on space-time accessibility measures, geovisualisation of activity patterns, human extensibility and fuzzy space-time prisms in relation to CAD.

Keywords: time geography, individual accessibility, activity patterns, CAD, GIS.

1. Introduction

Originally rooted from the domain of human geography in the late 1960s, time geography is deemed a productive perspective from which to analyse human movement through time and space. The pioneering work of Hägerstrand (1967) articulates the finitudes of space and time and highlights the necessary (but not sufficient) conditions for human interaction (Pred, 1977;

Burns, 1979). Hence, the focus of Hägerstrand's work is on various kinds of constraints restricting human movement, rather than on the impact of psychological and cultural factors on travel behaviour. Although tremendously simple in composition, the time-geographic framework has inspired a great deal of researchers in analytical studies of space-time behaviour (Pred, 1977; Timmermans et al., 2002). In particular, the approach has been fruitful for the analysis of human travel possibilities at a microscopic level and has led to a rethinking of accessibility expressed by a methodological shift from a place-based to a people-based approach to assess accessibility (see Dijst and Kwan (2005) and Miller (2005a) for a discussion of this topic). Since the availability of robust GIS-tools and travel diary data, we have witnessed a growing body of research which has sought to implement the space-time constructs as an analytical method. To this purpose, geospatial technologies - in this paper, the focus is on geographical information systems (GIS) and computer aided design (CAD) - yield powerful tools for the analysis of individual travel behaviour. Unremitting progress in GIS is proved to be effective for geovisualization purposes (e.g., Kwan, 2000; 2002), network-related geocomputations of travel possibilities (e.g., Miller, 1991; Wu and Miller, 2002) and appraising accessibility (e.g., Miller, 1999). CAD-systems are, among other application fields, mainly used in the field of civil engineering, electronic design automation, manufacturing process planning, (landscape) architecture, development of software applications, and cartography. Such systems are capable to render a large amount of data visible in a three-dimensional (3D) dynamic environment and are provided with Boolean and editing operators which can be used to create space-time constructions. Surprisingly, the use of CAD-based methods has received only scant attention in the realm of time geography.

This paper is motivated by the belief that CAD-systems could entail new opportunities for time-geographic research for both geovisualisation and geocomputation. This belief stems from a critical review of some issues of the current implementations of time-geographic research that focus on an operationalisation of Hägerstrand's constructs, including, more specifically, the determination of so-called space-time accessibility measures, the representation of individual travel possibilities in a space-time aquarium, and the expansion of time geography to incorporate modern communication technologies. It also stems from the new potential for the analysis and geovisualization of travel patterns in space and time using CAD.

The paper is structured as follows. In section 2, we briefly outline the basic time- geographic toolbox in order to understand and evaluate implementations based on the constructs of time geography further on in the paper. Section 3 provides an overview of existing GIS-based methods which have significantly contributed to the study of time geography. Section 4 seeks to extend the current framework. In subsection 4.1, we explore the capabilities of CAD-systems with respect to the field of disaggregate travel modeling. Subsection 4.2 shows how vague statements can be dealt with in time geographic research by introducing fuzzy space-time prisms. We conclude with a brief summary.

2. Background: some basic notions of time geography

From a visualization perspective, the quintessence of time geography is the construction of a space-time aquarium to depict the allocation in time and space of human activities, social interactions, and movement. The representation in which time is integrated orthogonally to a flattened topography simulates a clear (visual) thinking about human behaviour, accessibility, and geospatial patterns. The visualization also offers a neatly arranged view on spatio-temporal data sets (Kraak, 2003).

Time geographic research utilizes the key concept of the space-time prism, which reflects individual travel possibilities given a set of constraints. Hägerstrand (1970) recognizes three types of constraints which mould the shape of an individual's space-time prism: (i) Capability constraints are linked to an individual's physiological necessities such as eating or sleeping; (ii) Coupling constraints restrict travel by imposing where, when, and for how long individuals have to join other people, tools, or materials in space and time; (iii) Authority or 'steering' constraints relate to the institutional context, and refer to laws and other regulations which imply that specific areas are only accessible at specific times for specific people to conduct specific activities.

In practice, these three constraints must be seen as interrelated rather than additive, and manifest themselves by dictating the space-time anchor points between which activities undertaken to achieve predetermined goals (i.e., projects) can take place (Carlstein et al., 1978). The amount of time available for travel and activity participation is termed the time budget. The prism which can be created between two successive mandatory activities is called a discretionary prism. In fact, a space-time prism gathers all space-time paths an individual might have drawn during a specific time budget and delimits the feasible set of opportunities within a person's reach (Dijst and Vidakovic, 2000). The faster an individual travels, the more sloped the path segment will be. Space-time stations, usually conceptualized as vertical tubes, are fixed locations at which several space-time paths tend to converge to form an activity bundle. A potential path area (PPA) can additionally be defined as the projection of a space-time prism to the geographical plane (Miller, 1991). In figure 1, the basic notions (path, prism, and PPA) are depicted in a 3D reference frame.

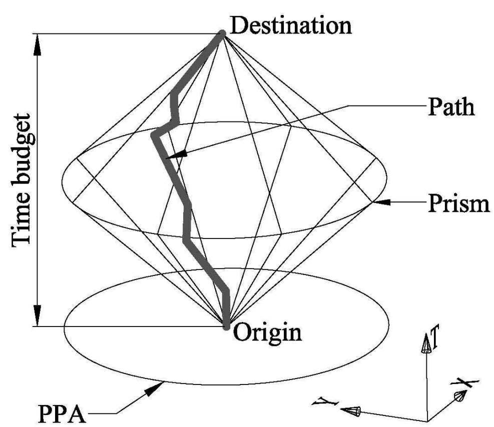


Figure 1. Time geographical concepts: space-time path, space-time prism, and potential path area.

3. Analysing human activity patterns: existing time-geographic contributions

The first noteworthy implementation of time-geographic constructs goes back to the late 1970s, viz to Lenntorp's PESASP model (Programme Evaluating the Set of Alternative

Sample Paths). PESASP (Lenntorp, 1978) constitutes a constraint-based model which evaluates to what extent the spatio-temporal environment is facilitating the performance of activity programmes. Given an extensive, manually collected data set on the individual and environmental constraints (e.g. residence-workplace pairs, locations of stations and their opening hours, and information about the transport network), the model verifies the feasibility of a sequence of activities in order to obtain an impression about the accessibility of locations within the study area. Due to the data hungry character of the research and the immature geocomputational tools at that time, Lenntorp's simulation model involved immense computing times and also required considerable time for the construction of geographic data. In line with Lenntorp's approach, other, less prevailing constraint-based models such as CARLA (Combinatorial Algorithm for Rescheduling Lists of Activities) (Jones et al., 1983) and BSP ((Dutch abbreviation for) Reach Simulation Program) (Huigen, 1986) were developed.

An early and widely cited contribution to the field of, let say, modern time geography can be found in Miller (1991). Miller was the first to provide a profound discussion of the manipulation of space-time prism concepts within a GI-system and introduced a generic procedure for the derivation of network-based PPA's. His approach offered leverage for a succession of publications in which GIS-based geocomputational methods have been used to apply Hägerstrand's theory. Kwan and Hong (1998), for instance, implemented a GIS-procedure for generating restrictive spatial choice sets. Relying on set theory, they presented the concept of cognitive feasible opportunity sets (CFOS's) which accounts for spatio-temporal feasibility as well as for spatial awareness and locational preferences.

In what follows, we will first discuss some applications with respect to issues of accessibility. Then the discussion is continued by reviewing some significant contributions on the visualization of activity patterns. The current section is ended with an overview of studies that fit recent interest in linking time geography to human extensibility.

3.1 Space-time accessibility measures

It goes without saying that Hägerstrand's paradigm offered a better understanding of the integration of the spatial and temporal components of travel in the context of accessibility (Pirie, 1979). Measures of accessibility are used to evaluate the performance of the transport infrastructure and to describe the level of access to spatially scattered facilities. Although accessibility is a critical component in research concerning transport and urban planning, the term is highly elusive, presumably due to the variety in methodological tackling for the calculation of accessibility. A general definition of the concept is given by Morris et al. (1979, p. 91) who defined accessibility as "the ease with which activities may be reached from a given location using a particular transportation system". Geurs and van Eck (2003) distinguish three main categories of accessibility measures: (i) infrastructure-based (e.g., Linneker and Spence, 1992; Thomas et al., 2002 (for freight transport)), (ii) utility-based (e.g., Ben-Akiva and Lerman, 1979; Handy and Niemeier, 1997), and (iii) activity-based accessibility measures (e.g., Kwan, 2002). Clearly, space-time accessibility measures, based upon the time-geographic framework, belong to the third category. The space-time approach is a disaggregate one and accounts for a range of individual, land-use, and transport-related constraints affecting a person's access to facilities. An extensive, comparative analysis of large range of activity-based accessibility measures was conducted by Kwan (1998). It was shown that space-time accessibility measures are able to reveal interpersonal differences in individual accessibility which could not be detected using conventional measures. However, these measures are usually inapplicable for relatively large regions, due to the severe data requirements and computational intensity, and do not include competition effects (like in Fotheringham, 1986) between opportunities (e.g., jobs, health services).

A formal framework for measuring space-time accessibility benefits and computational procedures for deriving these measures within network structures can be found in Miller (1999). The aim was to reconcile the utility-based measures with the activity-based approach. As an extension of the utility formulations of Burns (1979), the formal framework meets the axiomatic requirements formulated by Weibull (1976, 1980) which guarantees the internal and external consistency of the measures.

A tangible illustration of constraint-oriented accessibility was performed by Huisman and Forer (1998, 1999). Aggregating information about individual space-time paths, they developed a GIS-based model which estimates the likelihood of presence of students in Auckland (New-Zealand). In the same vein, O'Sullivan et al. (2000) studied how to handle the assessment of accessibility by public transport by generating isochrone maps. Their approach relies, however, on many assumptions and simplifications concerning train timetables and bus travel. For example, it is assumed that buses travel at a constant speed along their route. By doing so, the model obviously underestimates bus speeds in the suburbs and overestimates them in the city centre, particularly during rush hours. Another operationalization of time-space geography was developed by Weber and Kwan (2002). Their study shows that the incorporation of the temporal dimension under the simple form of business hours and evening congestion can significantly reduce individual accessibility. Using two-day travel diary data, network information and a large land-use data set of Portland, Oregon, five space-time measures of individual accessibility were calculated in a GIS environment: (i) the length of road segments in the DPPA[1]; (ii) the number of opportunities in the DPPA; (iii) the total area of the DPPA; (iv) a weighted area based on the square footage of the opportunities within the DPPA; and (v) a so-called timed area, which can be calculated relying on the assumption that opportunities are only available between 6:00 a.m. and 9:00 p.m. However, a shortcoming of the approach is that all opportunities which lie within the DPPA are equally weighted, without accounting for the spatial distribution of opportunities within the DPPA and without evaluating whether activity participation is possible during the opening hours. To address these limitations, Kim and Kwan (2003) suggested another GIS-based algorithm to more realistically represent the spatio-temporal characteristics (opening hours and location) of the opportunities. Moreover, their implementation also includes additional delay time, minimum activity participation time, and a more accurate performance of the network topology.

Several bottlenecks in the models reviewed above still call for additional research. One is that the network analysis used to calculate the measures merely concentrates on car users. It could be interesting to widen the approach to other ways of transport such as walking and cycling. Furthermore, joint trip making is not considered in the methods discussed above. Note that the study of joint activities has recently received increased attention from the field of activity-based modelling and transport geography, in particular with respect to within-households interactions (e.g., Gliebe and Koppelman, 2005; Srinivasan and Bhat, 2005; Ettema and Van der Lippe, 2006; Roorda et al., 2006). The study of a joint accessibility measure for groups -

[1] DPPA stands for daily potential path area. This is the aggregate of the PPA's between all successive space-time anchor points of the respective day.

possibly other than households- willing to conduct a joint activity seems an intriguing topic for future research. A third issue, as mentioned earlier, has to do with the computational intensity of the GIS-based algorithms and the requirement of an exhaustive set of individual-level data which is quite laborious to collect. This explains why the space-time approach has only been applied to relative small samples of the population up to now.

3.2 Geovisualisation of activity patterns

The geovisualisation of human activities is important to gain sound insights in how people schedule their activities and how they interact with each other. Since GIS is typically designed for the production of static, two-dimensional (2D) maps (Peuquet, 2002), conventional GIS packages are currently only provided with tools for extrusion in a 2.5D but are unable to create and edit complex 3D objects such as space-time prisms. Hence, effectively representing spatio-temporal behaviour in a GIS is still an intricate task to fulfill. When also accounting for the virtual interaction possibilities of individuals, scale differences in both space and time hamper an easy representation.

From a conceptual base, Hornsby and Egenhofer (2002) used Hägerstrand's framework to represent moving objects over multiple granularities. They described the nature of the information change when coarsening or refining granularity. Efforts have also been expended on the development of an entity-relationship model for activity sequencing (Wang and Cheng 2001) and on an object-oriented implementation of a spatio-temporal, GIS-based model to query space-time paths (Frihida et al., 2004).

In seeking to realize an efficacious visualisation of human activities in a 3D space-time aquarium, scholars have been applying raster as well as vector GIS. The raster approach was explored by Forer (1998) who used voxels of space-time (also referred to as taxels) for the representation of lifelines, facilities (static or moving), and action volumes which were stored as binary 3D-arrays. Within a prototype of raster geometry, different hypotheses about path selection were evaluated by Hendricks (2004). The prototype considered only a small tessellation of 144 space units and a time extent of 101 discrete time units, which was large enough for the purpose of conceptual simulation but is unsatisfactory for dealing with real-world environments. Although volumetric data can efficiently be stored by treelike data structures, the data capacity needed for portraying a relative small space-time portion at a reasonable resolution remains enormous. Another drawback is that, unlike vector geometry, the discontinuous raster representation is unsuitable for dealing with complex network topologies.

From a vector GIS perspective, Kwan and Lee (2004) described various geovisualisation methods for respresenting activities and travel behaviour. They showed that conventional GI-systems are capable of revealing activity clustering of different social groups. More specifically, they indicated significant gender differences in the spatial and temporal distribution of activities (see also Kwan, 1999). In order to detect (dis)similarities between activities and population groups, they also generated draped views on the density of activities, using a kernel density estimation function described by Silverman (1986). In a last simulation, Kwan and Lee demonstrated how to create individual space-time paths in a 3D scene, based on GPS tracking data. More recently, Yu (2005, 2006) and Yu and Shaw (2005) are also doing important work with respect to the visualisation of human interactions. They implemented several analysis functions for detecting distinct forms of interaction, using

Visual Basic for Applications (VBA) for ArcObjectsTM (the development platform in ArcGISTM).

3.3 Human extensibility

An increasing volume of literature is recently focusing on the implications of continuing advances in information and communication technologies (ICT's) on accessibility and geographical analysis (Janelle and Hodge, 2000; Graham, 2005). These technological developments have led to increased connectivity and a higher level of space-time dynamics of activities in a shrinking world (Janelle, 1973). In this context, Couclelis (2000) uses the term activity fragmentation, meaning that activities which used to be tied to a particular place are now dispersed at various levels of geographical scales. A theoretical conceptualization for analysing interactions in cyberspace was introduced by Janelle (1995). In his view, physical and virtual communication modes can be categorized in four different groups depending on their spatial and temporal constraints: (a)synchronous presence (i and ii) and (a)synchronous telepresence (iii and iv).

It is argued by O'Sullivan (2005) that renewed interest in time geography is primarily linked to the increasing importance of ICT's in people's daily lives. Expanding space-time models to encompass both the physical and the virtual world has been a challenging topic for more than a decade now. From the perspective of Adams (2000), we should see the virtual, spatial connections, enabled by emerging technologies, as a property of individuals rather than just relations between people. Furthermore, he rightly argues that Hägerstrand's firm assumption that a person can only be at one place at the time should be reconsidered in the context of the Information Age, since "people do not simply occupy a place" (Adams, 1995, p. 268). In order to better grasp the notion of accessibility in virtual space-time, new methods should be evolved which abandon the common interpretation of distance. In response to meet these objectives, Adams (2000) created diagrammatic extensibility models which depict an individual's, physical space-time path along with the social scale of his/her activities, represented as bars. These bars are divided in six categories of proximity that can be reached through tele-presence, ranging from proximate to international. The distinction between one-way and two-way communication modes is also represented in the extensibility diagrams. Since social power is strongly linked to the extensibility pattern of human beings in terms of frequency and duration of travel and incoming/outgoing communication, these diagrams offer clear insights into the individual's social power relations in society. Kwan (2000) explored a multi-scale representation using linked graphical windows to overcome the geographical and temporal discrepancy of scale between the physical and the virtual world. Later on, Kwan (2001) relies on studies from the behavioural-cognitive domain in order to provide a better understanding of cyber-accessibility and a re-examination of the key issues in accessibility research. For a profound discussion about the changes that the Information Age might bring for the assessment of space-time accessibility, we refer to the work by Kwan and Weber (2003). Miller (2005b) employs the typology of Janelle (see previous paragraph) and introduced new time-geographic objects such as message windows (communication events) and portals (locations of ICT access). Necessary conditions for physical interaction, implied by traditional time geography, were rigorously extended to interactions taking place in the virtual world. Despite the creative solutions, mentioned above, there is still a need for an adequate conceptual apparatus for quantifying individual accessibility in a hybrid (physical and virtual) way.

4. Extending the time-geographic framework

As opposed to the GIS applications reviewed in the previous section, the applications of CAD-systems within the time-geographic framework have scarcely been tried out. At the most, evidence of bringing together both domains can be encountered in Adams (2000) (see section 3.3).

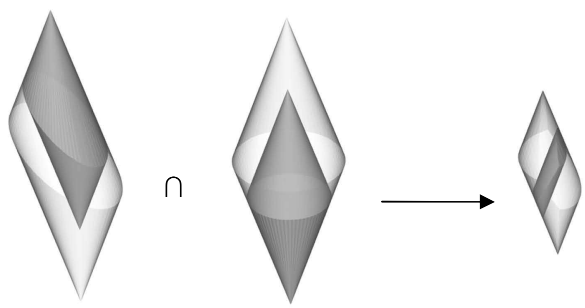
With respect to geovisualisation, the benefits of CAD for time-geographic research are quite straightforward. After all, the basic time-geographic constructs are in se 3D objects (e.g., path, prism) or derived from 3D objects (e.g., PPA). Additionally, CAD also offers powerful analytical tools for combining 3D space-time prisms. To more formally state our case in favour of using CAD in time-geographic research, we put forward three examples drawn from our own recent research in section 4.1. In addition, in section 4.2, we add a new research application involving fuzzy space-time prisms using CAD.

4.1 Dealing with interaction spaces, uncertainty and network-based prisms

In a first study (Neutens et al. 2007a), we presented a novel approach to analyse the interaction possibilities of multiple agents, willing to schedule a joint activity and having multiple travel modes at their disposal. Relying on concepts of time geography, we proposed a conceptual framework in order to determine interaction spaces for groups of individuals. Besides availability of means of transport and the locations of each individual, minimum activity duration and opening hours of opportunities were taken into account. The model was implemented in a CAD environment. The implementation allowed an automatic creation of facilities and prisms out of a database in which travel information about multiple individuals is stored. In addition, the use of CAD offers a dynamic view on the space-time opportunities available for conducting the joint activity, and enables to identify potential activities and visualize activity patterns in a simultaneous way.

A second study (Neutens et al., 2007b) focused on the implications of a person's imperfect knowledge on space-time constraints on individual accessibility. A model was developed to evaluate the feasibility of rendezvous scenarios. The conceptual framework constitutes a cross-pollination of Hägerstrand's time geography and Pawlak's (1982) rough set theory and aims to support agents pointing out a feasible meeting place while respecting the individuals' fixed activity programmes. Building on the approach by Hendricks (2003), we presented the concept of rough space-time prisms. Three different types of uncertainty were addressed: temporal, spatial, and speed uncertainty. These forms may complicate respectively, the temporal coordination process (synchronisation; chronos (Greek) = time), the spatial coordination process (synchorisation; choros (Greek) = place) or both (Hägerstrand, 1970). Moreover, they decrease the individual space through which certainly can be travelled, and as a consequence, they may reduce the available space and time for joint activity. From these three types, a fourth composite type can be derived which combines various types of uncertainty among individuals who are planning a joint trip. These combinations were established by means of Boolean operators in a CAD environment.

To further illustrate the constructing of a rough interaction prism using an intersection operator take figure 2. Suppose a first agent is unsure about the exact earliest departure time of leaving a certain previous activity. The lighter part of the prism of the first agent illustrates this uncertainty and delineates the possibly accessible space-time part of the prism. The darker part of the prism denotes the space-time portion which is certainly accessible, whatever the outcome of the temporal uncertainty might be. Suppose additionally that there is a second agent who is unsure about the latest arrival time at the next fixed activity. The same way of representation applies for the rough space-time prism of this second agent. These rough space-time prisms can then be combined using an intersection operator in order to determine where they can meet. Again, the darker part of the interaction prism gathers all space-time points where the individuals can meet each other; the lighter part depicts the where they can only possibly meet. Note that the prism of the first agent is oblique since start and end point are dislocated in space as well as in time, whereas the prism of the second agent is right meaning that start and end point are co-located in space but shifted in time.



Agent 1 **Agent 2** **Rough Interaction Prism**

Figure 2. Constructing a rough interaction prism using an intersection operator.

A drawback of the model is that neat conical prisms were used to represent a person’s reach in space-time. Uncompromising conical prism representations assume a steady progress in all directions at a constant speed. In reality, however, travelers are mostly confined to the geometry of the transportation network and possibly to time schedules in case of public transport.

In a third study (Neutens et al., 2007c), we therefore attempted to incorporate the anisotropy of the transportation network into the definition of space-time prisms. Instead of changing the calculation method for evaluating space-time accessibility, we generated a more realistic rendering of the shape of classical space-time prisms and established a mathematical foundation of the model proposed. It was shown that the traditional space-time prism is a particular case of our general network-based model of the space-time prism. Again, we went back to the root of time geography and used a 3D analytical framework as a point of departure. As depicted in the figure 3, we used irregular (“jaggy”) solids based on GIS-based travel areas instead of cones based on circles to construct the space-time prism. It was established that these network-based prisms more realistically reflect the actual travel possibilities of an agent.

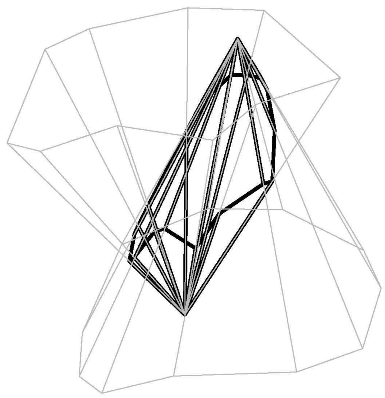


Figure 3. The construction of a network-based space-time prism.

4.2 A fuzzy space-time prism

In subsection 4.1 we reported on our research that seeks to evaluate the impact of uncertainty on the arrangement of co-presence by using the key concepts of rough set theory. There exists however another established technique which might be suitable to analyse travel possibilities under uncertain knowledge: fuzzy sets (Zadeh, 1965). Fuzzy set theory differs from rough set theory in that it permits a gradual assessment of membership implying a partial truth set (i.e. completely false (0) to completely true (1)) instead of the purely three-valued truth set (i.e. definitely, maybe and definitely not) used in rough set analysis. Hence, fuzzy set theory can be used to handle vague statements such as ‘just before noon’ or ‘in the evening’. The idea of introducing fuzziness in the context of time geography boils down to the assignment of a membership function of accessibility to every point within the considered space-time cube. Again, the approach is based on the central tenet of Hägerstrand’s theory, viz the three constraints imposed by the space-time prism:

- (C1) an agent cannot leave a previous activity at the location and the time given by the earliest departure (ED) point;
- (C2) an agent must arrive no later than and at the location required by the latest arrival (LA) point; and
- (C3) an agent cannot move faster than a certain threshold value (which is imposed by the slope of the prism cones). In what follows, this last constraint will be included in the analysis of the other two constraints. Below, we will only concentrate on temporal uncertainty.

ED constraint set

Let $P = \{p(x, y, t)\}$ be the finite set of space-time locations p bounded by the limits of a considered space-time cube Ω; where (x, y, t) denote the coordinate of p in a time-geographic framework XYT. Let A be the crisp set defining the forward cone, i.e. the accessible travel space of Ω based on the earliest departure constraint:

$$A = \{(p, \mu_A(p) \mid p \in P)\} \tag{1}$$

with the binary membership function:

$$\mu_A(p)=\begin{cases}1 & if \quad (x-x_{ED})^2+(y-y_{ED})^2 \le \tan^2\varphi(t-t_{ED})^2 \\ 0 & if \quad (x-x_{ED})^2+(y-y_{ED})^2 > \tan^2\varphi(t-t_{ED})^2\end{cases} \tag{2}$$

where $p_{ED}(x_{ED},y_{ED},t_{ED})$ is the ED point and φ is the apex angle of the ED cone. Note that $\tan\varphi$ represents the third space-time constraint since it corresponds with the speed value threshold. Hence, equation 1 dictates that the agent's movement must satisfy the constraint requirements (C1) and (C3). Now we want to objectify a vague statement about the temporal component of p_{ED}. Given the purpose of this preview, let us try to determine the effect of the fuzzy ED anchor point statement 'no later than noon' on the accessibility within the space-time prism. Therefore, we must fuzzify the set *A*:

$$\tilde{A}=\{(p,\mu_{\tilde{A}}(p))\,|\,p\in P\} \tag{3}$$

where $\tilde{A}$ denotes an ordered set of pairs of space-time locations together with their membership of accessibility. Now we need to adopt a membership function $\mu_{\tilde{A}}(p)$ which maps *P* into the membership space *M*. This membership function denotes the degree of membership of *p* in $\tilde{A}$ with respect to variable t_{ED}. According to fuzzy set theory, the range of $\tilde{\mu}(p)$ must be a subset of nonnegative real numbers whose supremum is infinite. Let us normalize M to the interval [0,1], then $\mu_{\tilde{A}}(p)$ is given by:

$$\mu_{\tilde{A}}(p)=\begin{cases}1 & if \quad (x-x_\beta)^2+(y-y_\beta)^2 \le \tan^2\varphi(t-t_\beta)^2 \\ f(t_{ED}) & if \quad \left[(x-x_\alpha)^2+(y-y_\alpha)^2 \le \tan^2\varphi(t-t_\alpha)^2\right]\wedge\left[(x-x_\beta)^2+(y-y_\beta)^2 > \tan^2\varphi(t-t_\beta)^2\right] \\ 0 & if \quad (x-x_\alpha)^2+(y-y_\alpha)^2 > \tan^2\varphi(t-t_\alpha)^2\end{cases} \tag{4}$$

where $\alpha(x_\alpha,y_\alpha,t_\alpha)$ and $\beta(x_\beta,y_\beta,t_\beta)$ (α<β) are context-dependent anchor points between which $f(t_{ED})$ describes the vagueness inherent in the considered temporal statement and where t_{ED} corresponds with the time point for reaching *p* with the maximum speed value and is therefore a function of the coordinates of *p*:

$$t_{ED}=t-\left(\sqrt{(x-x_\alpha)^2+(y-y_\alpha)^2}\Big/\tan\varphi\right) \tag{5}$$

In our case with statement 'no later than noon' t_β will be 12 a.m. and t_α will be somewhere before 12 a.m. Note that there are no strict rules to define the membership function and the parameters. As an example, we now apply two possible shapes of $f(t_{ED})$ that are frequently used throughout literature: linear and S-shaped membership functions. Assuming a linear course to express our fuzzy statement, $f(t_{ED})$ is given by:

$$f(t_{ED})=\vartheta(t_{ED}-t_\alpha) \tag{6}$$

where ϑ is the slope which depends on the anchor points *α* and *β*. Assuming an S-shaped function between α and β, $f(t_{ED})$ is given by:

$$f(t_{ED})=\begin{cases}2\left((t_{ED}-t_\alpha)/(t_\beta-t_\alpha)\right)^2 & if \quad t_{ED}\in[t_\alpha,t_\gamma] \\ 1-2\left((t_{ED}-t_\beta)/(t_\beta-t_\alpha)\right)^2 & if \quad t_{ED}\in[t_\gamma,t_\beta]\end{cases} \tag{7}$$

where $\gamma\left(x_\gamma, y_\gamma, t_\gamma\right)$ is the inflexion point:

$$\gamma = (\alpha + \beta)/2 \tag{8}$$

LA constraint set

Having established the forward cone under a non-crisp earliest departure time, we now analogously define the fuzzy backward cone. Equation [1] and [2] now reduce to:

$$B = \{(p, \mu_B(p) \mid p \in P)\} \tag{9}$$

with the binary membership function:

$$\mu_B = \begin{cases} 1 & if \quad (x - x_{LA})^2 + (y - y_{LA})^2 \leq \tan^2 \varphi (t - t_{LA})^2 \\ 0 & if \quad (x - x_{LA})^2 + (y - y_{LA})^2 > \tan^2 \varphi (t - t_{LA})^2 \end{cases} \tag{10}$$

where B denotes the backward cone and $p_{LA}(x_{LA}, y_{LA}, t_{LA})$ is the latest arrival point.
After *fuzzification*, B can again be written as an ordered set of pairs:

$$\tilde{B} = \left\{\left(p, \mu_{\tilde{B}}(p)\right) \mid p \in P\right\} \tag{11}$$

In the event of a vaguely formulated latest arrival time, the membership function $\mu_{\tilde{B}}(p)$ can be given by:

$$\mu_{\tilde{B}}(p) = \begin{cases} 1 & if \quad (x - x_\delta)^2 + (y - y_\delta)^2 \leq \tan^2 \varphi (t_\delta - t)^2 \\ g(t_{LA}) & if \quad \left[(x - x_\lambda)^2 + (y - y_\lambda)^2 \leq \tan^2 \varphi (t_\lambda - t)^2\right] \wedge \left[(x - x_\delta)^2 + (y - y_\delta)^2 > \tan^2 \varphi (t_\delta - t)^2\right] \\ 0 & if \quad (x - x_\lambda)^2 + (y - y_\lambda)^2 > \tan^2 \varphi (t_\lambda - t)^2 \end{cases} \tag{12}$$

where λ and δ ($\delta < \lambda$) are context-dependent parameters between which $g(t_{LA})$ is defined and where t_{LA} is given by:

$$t_{LA} = t + \left(\sqrt{\left(x - x_\gamma\right)^2 + \left(y - y_\gamma\right)^2} \Big/ \tan \varphi\right) \tag{13}$$

Fuzzy space-time prism

Simultaneously imposing the three constraints (C1, C2 and C3), we derive the space-time prism as the intersection of sets. In the binary case of 'accessible' (1) or 'inaccessible' (0), we derive the traditional crisp prism $T(p)$ as:

$$T = A \cap B \tag{14}$$

The space-time prism is comprised by the space-time points for which holds:

$$\mu_{A \cap B} = 1 \tag{15}$$

Analogously, we define the fuzzy space-time prism $\tilde{T}$ under non-crisp temporal knowledge about the anchor points:

$$\tilde{T} = \tilde{A} \cap \tilde{B} \tag{16}$$

with a membership function related to those of $\tilde{A}$ and $\tilde{B}$ by:

$$\mu_{\tilde{T}}(p) = \mu_{\tilde{A}\cap\tilde{B}}(p) = \min\left[\mu_{\tilde{A}}(p), \mu_{\tilde{B}}(p)\right] \quad (17)$$

The fuzzy space-time prism is given by the support of $\tilde{T}$, denoted by ${}^{0+}\tilde{T}$, which is the set containing all elements of *P* having a nonzero membership in *P*. It ought to be noted that we used the typical *min* operator here. Other compensatory aggregation operators exist, but their use is out of the scope of this preview.

The fuzzy space-time prism, defined above, can be used to evaluate the individual travel possibilities under temporal vagueness. The framework, if extended appropriately, might be used to check alibis under uncertain travel information. In a further stadium, we will use this concept to assess interaction possibilities under vague statements by combining fuzzy prisms of multiple persons willing to conduct a joint activity.

5. Conclusion

This paper discussed existing GIS-based methods which belong to the domain of time-geographic research sensu strictu. This review clearly documented different techniques with respect to space-time accessibility measures, geovisualisation, and human extensibility. Furthermore, the paper describes novel approaches to ameliorate the classical time-geographic framework. Within the light of the narrowing gap between geographical information systems (GIS) and computer aided design (CAD), we advocated the use of CAD in the realm of time geography and demonstrated that it can be a valuable alternative for GIS by pointing to the authors' previous research. Finally, the space-time prism concept was extended to incorporate vague statements about space and time.

Although previously mainly applied to deal with passenger transportation problems, there are no obstacles to make the connection between time geography and freight transportation as well. For example, time geography might be useful to limit the solution space for optimization problems. We hope this article stimulates researchers from the field of operation research and logistics to consider the potential of the suggested concepts in their field of expertise.

Acknowledgements

We would like to thank the anonymous referees for their helpful comments and acknowledge the financial support given by the University Research Foundation (BOF-UGent) and the Research Foundation Flanders (FWO) to conduct this research.

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