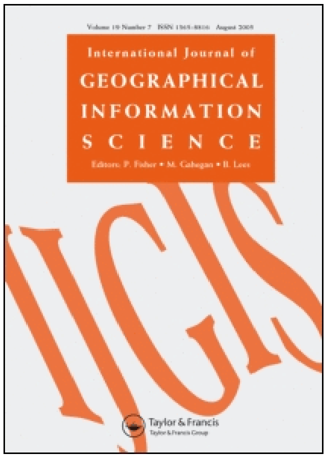

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Space-time opportunities for multiple agents: a constraint-based approach

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Research Article

Space–time opportunities for multiple agents: a constraint-based approach

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Constraint-based models and models constructing accessibility measures mainly focus on single agents having only one available transport mode. However, numerous cases exist where multiple agents or groups of individuals with different available transport modes want to participate in a joint activity at a certain location. The aim of this paper is to provide new insights into representing and reasoning about feasible space–time opportunities for multiple agents. Relying on concepts of time geography, we propose 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 are taken into account. The reasoning about space and time is visualized in three dimensions using a hybrid (CAD/GIS) system.

Keywords: Time geography; Space–time accessibility; CAD/GIS; Interaction spaces

1. Introduction

In daily life people are often confronted with various kinds of so-called rendezvous scenarios. Due to growing time pressure and tightening individual activity schedules, determining a joint meeting place and time for several participants is not always an easy task. Individual action spaces are constrained by the fixed activities of the participants and their access to mobility. Access to mobility is in turn dependent on where individuals live and work as well as on their mobility resources (Berglund 2001). Since the individualized agendas of all participants need to be taken into account, verifying the feasibility of a joint activity in space and time is an elaborate process. However, despite its complexity, research focusing on joint activity planning is vital to gain sound insights in how, where, and when groups of people can interact with one another in order to make proper appointments.

The propensity of people making solo and joint trips was studied by Chandrasekharan and Goulias (1999). They argued that joint trip-making is particularly influenced by household size, household lifecycle, age, number of vehicles, and accessibility measures. In recent years, the study of joint activities has received increased attention from the field of activity-based modelling and transport geography, in particular with respect to within-households interactions (e.g. Ettema and Van der Lippe 2006, Gliebe and Koppelman 2005, Roorda *et al.* 2006,

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Srinivasan and Bhat 2005). In transport system analysis and travel behaviour research, the problem of how individuals schedule their activities as a function of available time, transport mode, etc. has been extensively studied. Agent-based micro-simulation systems which simulate the dynamic behaviour of an individual over both space and time have been applied with increasing frequency over the past decade or so. Examples of such activity scheduling systems include *DYNASMART* (Hu and Mahmassani 1995), *DynaMIT* (Bottom *et al.* 1999), *ALBATROSS* (Arentze and Timmermans 2000), *TRANSIMS* (Nagel and Rickert 2001), *ILUTE* (Miller *et al.* 2004), and *AURORA* (Joh *et al.* 2001). From a time–geographic perspective *sensu strictu*, however, the treatment of multiple agents with several means of transport is often neglected. Research that seeks to enhance space–time accessibility measures for instance, mainly concentrates on individual motorists (Kim and Kwan 2003). There have been few attempts to analyse travel interaction spaces between agents who are at different places and times, but who want to carry out a joint activity. The intersection of geospatial lifelines was studied by Hariharan and Hornsby (2000). They defined a general method for testing the intersection of two (right or oblique) beads. Miller (2005) identified necessary conditions for both physical and virtual interaction by introducing new time–geographic objects such as *portals* (ICT access locations) and *message windows* (communication events).

Using time geography as a point of departure, the purpose of this paper is to model and visualize the interaction possibilities of multiple individuals. The concepts proposed aim to support agents to select appropriate opportunities in order to conduct a joint activity in space and time. Unlike other geocomputational algorithms (see e.g. Kim and Kwan 2003, Kwan 2000a,b, Miller and Wu 2000, Weber and Kwan 2002) which use a conventional GI system, the present paper intends to explore the possibilities of a hybrid* (CAD/GIS) system such as Autodesk Map® for representing and reasoning about spatio-temporal concepts. Applying such systems enables a three-dimensional approach to analyse the interaction possibilities between multiple agents. Useful thoughts are provided for the study of a group-based accessibility measure which could offer a criterion to obtain appealing insights in a group's ability to participate in certain events. In this paper, travel parties are not merely restricted to households but must be seen in a broader context. The term 'group' thus refers to each set of individuals willing to conduct a joint activity. In conformity with classical time geography, it is not our intention to explain or predict preference and choice among facilities or transport modes. Rather, we only want to set up a conceptual framework that deals with multiple agents with multiple available transport modes. Also in tradition to classical time geography, the travel environment of the agents is assumed to be a homogeneous space in which travel speed remains constant. The method described herein focuses on the identification of facilities with known location and opening hours at which individuals could participate jointly and uninterruptedly for at least the full required minimum duration of the activity meaning that they should synchronize the start and end time of the activity. Furthermore, only the activity is subject to coupling constraints; the transport modes are not. In other words, participants are assumed to travel separately instead of meeting at some point and travel jointly from there.

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* The term 'hybrid' usually refers to the integration of raster and vector GIS, but can also be applied to define a dual (CAD/GIS) functionality of software. The latter is used here.

The remainder of this paper is organized as follows. In section 2, after providing background knowledge about time geography (2.1), we demarcate and categorize the possible interaction space for a group of individuals by partitioning space–time prisms (2.2). Then, in subsection 2.3, we present a technique to identify feasible facilities for multiple agents. Subsequently, in section 3, an implementation of the proposed concepts is developed and the use of hybrid systems is briefly discussed. In the fourth section, we elaborate two random space–time scenarios as an illustration. The paper concludes with an overview of the major findings and outlines some avenues for further research.

2. A constraint-based approach to joint trip making

2.1 *Time geography*

In 1970, the Swedish geographer Torsten Hägerstand introduced the concept of time geography as a useful conceptual framework for understanding human spatial behaviour. Ever since, his seminal paper (Hägerstrand 1970) has inspired many researchers in the domain of activity-based analysis and travel behaviour (Arentze *et al.* 2001, Burns 1979, Kitamura *et al.* 1981, Lenntorp 1978). Time geography essentially provides a foundation for recognizing paths through space and time (Hendricks 2004, Wachowicz 1999) and measuring accessibility (Kim and Kwan 2003, Miller 1991, 1999, Weber and Kwan 2002, Wu and Miller 2001). As a modelling framework, time geography can be considered a constraint-based approach not attempting to predict exact travel behaviour, but instead indicating individual travel possibilities (Pred 1977). Both space and time are considered to be scarce resources. To represent their mutual relationship, a space–time prism can be constructed, delimiting all possible locations an individual can reach within a certain time budget (available time for travel and activity participation). Three well-known types of spatio-temporal constraints which restrict the shape of this prism can be distinguished: (i) *Capability constraints* refer to physical limitations of an individual such as eating or sleeping or the fact that an individual can only be at one location at a particular point in time; (ii) *coupling constraints* restrict travel by the requirements to meet other people in space and time. This means that space–time paths of co-workers must temporarily be bundled to conduct a joint meeting; (iii) *authority or 'steering' constraints* relate to the institutional context, and refer to laws and other regulations which imply that particular activities are only available or accessible at certain times. Shop acts, for example, impose regulations on the opening hours of stores and thus they dictate when shopping activities can be pursued.

To analyse rendezvous scenarios, *space–time prisms* yield a powerful tool. As time progresses, an individual describes a *space–time path* from origin to destination, which can be modelled as a *geospatial lifeline thread* (Hariharan and Hornsby 2000, Hornsby and Egenhofer 2002). The faster the individual travels, the more sloped the path segment will be. Given a certain maximum speed, a starting point and an end point, a *lifeline bead* can be constructed, containing all points an individual could have occupied within a certain time budget. The bead is formed by the intersection of two inverted half cones: the lower half cone marks all space–time points where an individual could have been if he/she leaves from the origin, while the upper half cone delimits all possible space–time points an individual could have come from if he/she is to arrive at the destination. Successive lifeline beads form a *lifeline necklace* (Hornsby and Egenhofer 2002). The area that a specific individual can cover given the set of constraints is called the *potential path area* (PPA) (Wu and Miller 2001); it is the projection of the *potential path space* (PPS = the interior of the prism) to a two-dimensional geographic plane (Miller *et al.* 2004). The basic notions of time geography (space–time path, space–time prism, and PPA) are depicted in figure 1a. The apexes of the cones are collocated in space but shifted in time. Figure 1b represents an extension of the prism depicted in figure 1a, in the sense that an activity with certain duration is now being pursued within the available time budget. The cylindrical body between the cones represents the minimum required activity duration. We now extend figure 1b by permitting multiple transport modes for a single individual. Figure 1c shows the intersection of the space–time prisms of two individuals willing to conduct an out-of-home activity; both individuals have the same three means of transport available. Possible human interaction space* can be found within the intersection of the beads of both individuals. Note that in figure 1c we assume the minimum time budget an individual is willing to spend on the activity depends on the travel time and thus on the transport mode. After all, people are usually not willing to travel long distances just to undertake a very short (non-obligatory) activity. Hence, a certain amount of activity participation time is needed to make travel worthwhile (Kim and Kwan 2003). These travel time thresholds reduce the size of the space–time prisms related to each vehicle.

2.2 *Determination of interaction spaces*

In order to determine (the nature of) possible interaction spaces of multiple agents, their space–time prisms are partitioned in qualitative categories (Hendricks *et al.* 2003). To describe these partitions properly, some notations are introduced.

Suppose A denotes the finite travel party set, i.e. a group of n people willing to conduct a joint space–time activity:

$$A = \{a_1, a_2, \ldots, a_i, \ldots, a_n\} \tag{1}$$

Let V be the finite set of k transport modes to travel to where the activity takes place:

$$V = \{v_1, v_2, \ldots, v_j, \ldots, v_k\} \tag{2}$$

Each mean of transport is characterized by a maximum speed. Consequently, a set of corresponding speed values S can be defined with every set of available transport modes V^{a_i} for a_i:

$$S = \{s_{v_1}, s_{v_2}, \ldots, s_{v_j}, \ldots, s_{v_k}\} \tag{3}$$

The subset of V containing the available means of transport for individual a_i is denoted as V^{a_i}. Analogously, we define S^{a_i} as the set of speed values corresponding to the transport modes in V^{a_i}.

Next, we need space–time anchor points of mandatory activities, i.e. start and end points of activities which are relatively difficult to re-schedule such as home and work (Miller 2005). These anchors limit physical accessibility by compelling start and end points of discretionary activities (Miller 2005), and thus they can be utilized

* Two types of interaction exist: virtual and physical interaction. It should be noted that only physical interaction, which requires coincidence in both space and time, will be addressed in this paper. This type of interaction corresponds to synchronous presence, one of the four communication modes specified by Janelle (1995).

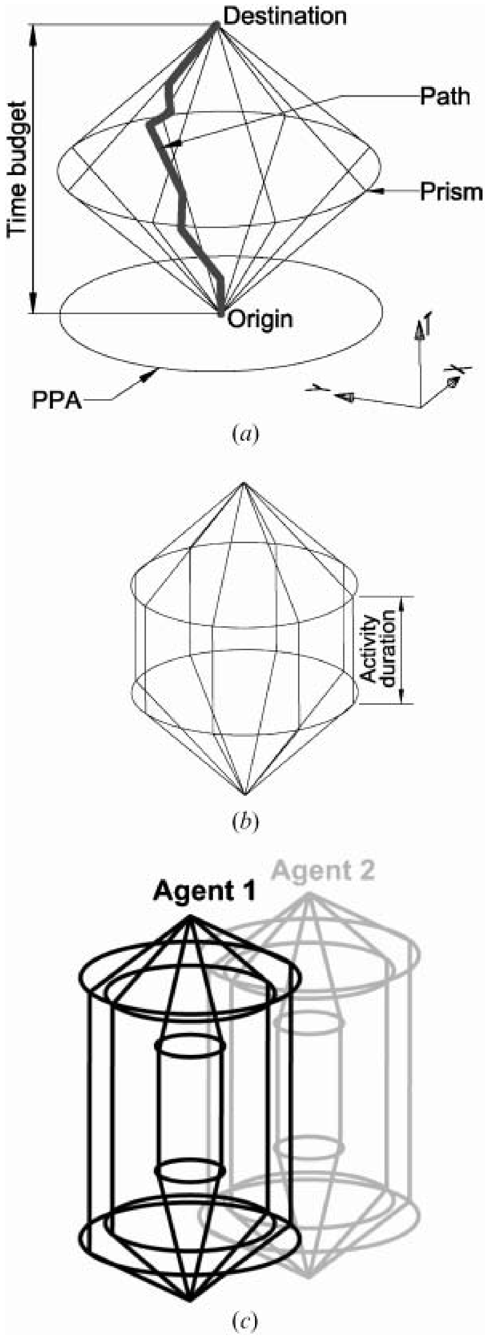

Figure 1. (a) Space–time path, space–time prism, and PPA. (b) Space–time prism incorporating an activity between starting and end point. (c) The intersection of the space–time prisms of two individuals with three transport modes available.

as pivots for defining the relevant space–time prisms (Dijst and Kwan 2005). Let $O^{a_i}=\left\{o_1^{a_i}, o_2^{a_i}, \ldots, o_b^{a_i}, \ldots, o_w^{a_i}\right\}$ be the finite set of all origin points $\left(x_{o_b}^{a_i}, y_{o_b}^{a_i}, t_{o_b}^{a_i}\right)$ and $D^{a_i}=\left\{d_1^{a_i}, d_2^{a_i}, \ldots, d_b^{a_i}, \ldots, d_w^{a_i}\right\}$ the finite set of all destination points

$\left(x_{d_b}^{a_i}, y_{d_b}^{a_i}, t_{d_b}^{a_i}\right)$ for a discretionary activity of individual a_i within a specific time window. Then, the pair $\left(o_b^{a_i}, d_b^{a_i}\right)$ denotes the starting and end point of a given time budget $\left(T_b^{a_i} = t_{d_b}^{a_i} - t_{o_b}^{a_i}\right)$ of an individual a_i, where $t_{o_b}^{a_i}$ is the earliest departure time for the discretionary activity to be scheduled and $t_{d_b}^{a_i}$ is the latest arrival time for the next fixed activity.

Using the introduced notations, for each individual a_i we have a triplet $\left(o_b^{a_i}, d_b^{a_i}, S^{a_i}\right)$ of constraints restricting the individual's possible movements in space and time. By combining these triplets for all individuals within a given time window, the possible interaction space of the travel party can now be created. Once interaction spaces are distinguished, it is possible to solve a number of well-defined spatio-temporal queries with respect to joint activities. For example, it is then possible to unravel all feasible space–time facilities of, say, three persons that would like to engage in a joint sports activity on a Saturday afternoon, given their particular transportation options.

To solve these kinds of questions, we need to determine the intersection of different space–time prisms constrained by $o_b^{a_i}$, $d_b^{a_i}$, and S^{a_i} for all n agents. Confining and representing space–time intersection volumes can be done using a computer-aided design (CAD) system. For each individual a_i, a lifeline bead is created by uniting two half cones. This is done for each v_j in V^{a_i}. Then, the intersection space of all beads of the different agents is created. If the intersection is empty, then interaction is impossible within a given time window. A cross-section of the intersection of the two prisms depicted in figure 1c (see subsection 2.1) is shown in figure 2. Note that various regions can be distinguished in terms of means of

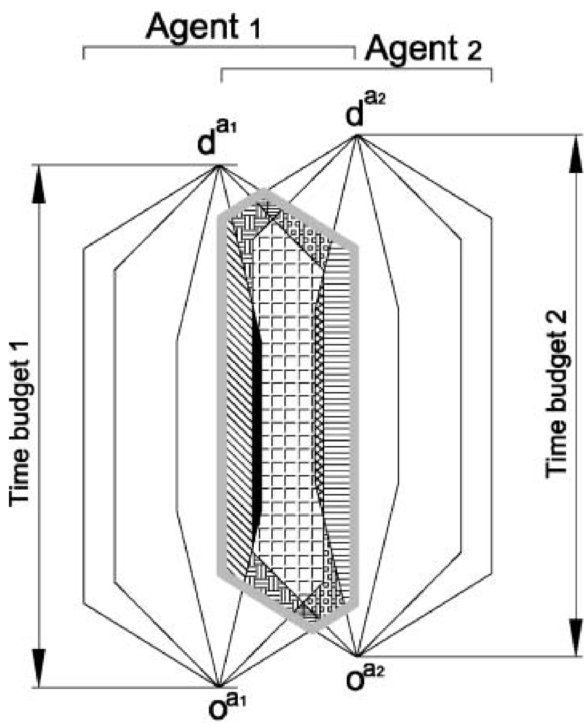

Figure 2. A prism representation of the possible interaction spaces of two agents.

transport by which they are accessible. The total interaction space is delineated by the thick grey line.

In figure 3, a tree-like representation illustrates all possible kinds of interaction spaces between two individuals. Although other authors (e.g. Raper and Livingstone 1995) have explored four-dimensional models, we opt for the traditional three-dimensional depiction where time is represented as a dimension orthogonal to a two-dimensional travel space. Let the individual's three-dimensional space–time container (denoted as STC^3) be the space–time volume bounded by the limits of the studied space and time. Figure 3 gives a schematic representation of the situation considered in figure 2 (but without taking into account the minimum activity duration constraint).* As in figure 2, for each individual three available means of transport are assumed. The left-hand side of figure 3 depicts the travel possibilities of a_1; the right-hand side depicts the travel possibilities of a_2; the centre of the drawing visualizes the interaction space by taking the intersections between different kinds of travel spaces. The notations M_1, M_2, and M_3 define the potential path spaces (PPS) that can be reached by an individual using s_{v_1}, s_{v_2}, and s_{v_3}, respectively. M_1–M_2 thus denotes the travel space that an individual can only reach by using transport mode s_{v_1} and M_2–M_3 denotes the travel space that cannot be reached using transport mode s_{v_3}. The possible travel space M^{a_i} of individual a_i can be obtained by taking the union of travel spaces attainable by all available means of transport of a_i.

$$M^{a_i} = \bigcup_{j=1}^{k} M_j^{a_i} \tag{4}$$

Note that M^{a_i} also equals travel space corresponding with the maximum speed value, if all transport modes are available within the same time window.

The distinct categories of interaction volumes shown in figure 3 are only fully applicable for two agents. However, if more than two agents are involved (n>2), then a more general approach is desirable. Therefore, we denote the total interaction

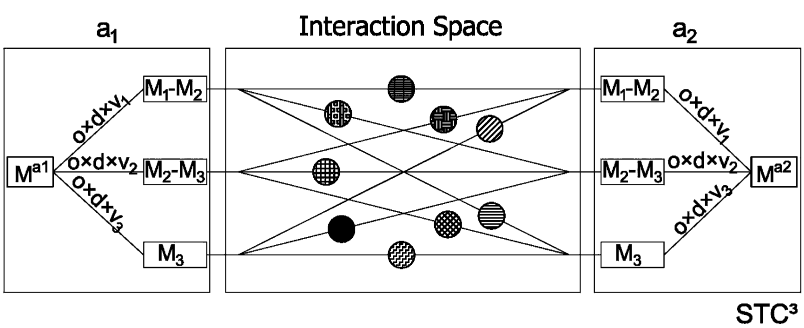

Figure 3. A tree-like representation of all possible interaction spaces of two agents.

* The constraint on the minimum activity duration is not considered in this figure. This is actually unnecessary because incorporating this constraint in the prism of every individual does not automatically impose this constraint on the resulting interaction space of multiple agents.

space I as:

$$I = \bigcap_{i=1}^{n} \bigcup_{j=1}^{k} M_j^{a_i} \tag{5}$$

The space–time volume that can be reached by all individuals, using transport mode j (if available), is then given by:

$$I_j = \bigcap_{i=1}^{n} M_j^{a_i} \tag{6}$$

As will be shown in the next sections, the intersections and unions described in equations (5)–(7) can be put in practice by using modify commands for three-dimensional solids. The result will be a complex space–time prism.

2.3 *Confronting interaction spaces with facilities*

The next step in solving the envisaged joint activity problem is to identify all facilities which lie within a particular interaction space. Although throughout the literature the distinction between facilities and opportunities often remains unclear, we consider only those facilities which are feasible as true spatio-temporal opportunities. The set* of available facilities F is denoted as:

$$F = \{f_1, f_2 \ldots, f_r, \ \ldots, f_m\} \tag{7}$$

Feasible facility selection can be done by constructing three-dimensional cylindrical solids, which enables the use of Boolean operators to create intersections between volume models *in casu* the interaction spaces and the facilities. Successive opening hours determine the height of the cylinder. The centre of the base circle is given by the coordinates of the geocoded address of the considered facility. By choosing the radius of the base circle equal to the square root of $1/\pi$, the volume of each cylinder will represent the opening hours of a facility. To select those facilities available for all agents, an intersection between the facilities and the total interaction space I has to be realized.

In figures 4a–d, the selection of feasible facilities is illustrated. For simplicity reasons, we assume only two agents (a_1 and a_2) each having three possible travel options to reach a set of seven (m=7) potential facilities. Figure 4a is a frontal view of the original space–time settings of two individuals planning a meeting. Figures* 4b, 4c, and 4d are three-dimensional representations of complex space–time prisms, derived from Figure 4a by applying intersection-commands in CAD software. They illustrate the interaction spaces delimited by s_{v_1}, s_{v_2}, and s_{v_3}, respectively. Clearly, a decreasing travel speed s_{v_j} results in a diminishing amount of available facilities and a shortening of the opportunity in time.

In the case where more than two agents are considered, an identical approach as described above has to be performed, but then repeated for all a_i.

* The set F contains all possible activity locations and encompasses the feasible opportunity set (*FOS*) as defined by Kwan and Hong (1998).

* For reasons of clarity, no attention has been given to the relative sizes of the interaction spaces.

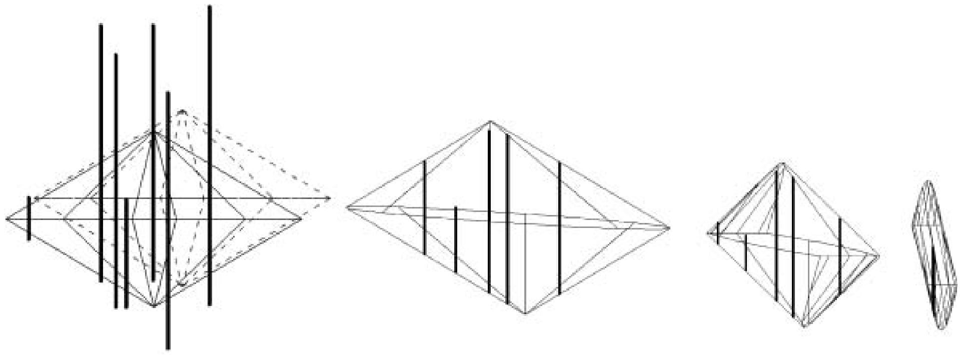

Figure 4. (a) Facilities and possible travel spaces of two agents (frontal view). (b) Opportunities within interaction space I_1 (3D view). (c) Opportunities within interaction space I_2 (3D view). (d) Opportunities within interaction space I_3 (3D view).

3. Implementation of the proposed concepts

Using the Visual Basic programming environment of a CAD system, a geocomputational method has been set up to determine the space–time opportunities for a joint activity. First, several appropriate layers are automatically created in order to classify similar time–geographic objects that will be shaped in the following steps. Next, a subroutine is implemented which creates lifeline beads directly from an external worksheet containing the triplets of constraints $\left(o_b^{a_i}, d_b^{a_i}, S^{a_i}\right)$ of all participants a_i within the time window of interest. The different beads formed by two intersecting cones are drawn, rotated, and put at the exact coordinates. These beads represent potential path spaces according to individual activity schedules and possible means of transport. In the third step, a subroutine has been programmed to visualize possible space–time facilities as cylindrical objects. These facilities are constructed with respect to their location and openings hours. Subsequently, the interaction space can be determined by selecting the intersecting beads interactively on the screen. The interaction space and the facilities are put in the predefined layers, resulting from step one. Finally, the intersection between the facilities and the interaction space is determined and the maximum possible activity duration at each opportunity is written to a worksheet.

The implementation comprises a valuable time–geographic visualization tool for representing possible interaction spaces of multiple agents. In contrast to other geocomputational algorithms which employ conventional GIS packages, we opted to use a hybrid CAD system which offers significant advantages with respect to visualization. Among other applications, the field of use of such a system consists of (landscape) architecture, civil engineering, electronic design automation, manufacturing process planning, development of software applications, and cartography. With respect to the latter, CAD is mainly used in the production of plans and sketches for a variety of purposes (such as land registry and surveyor's plans) and for the handling of geospatial information. The term hybrid refers to the GIS component which can be integrated in the system. It should be noted, though, that the GIS tools embedded in this component are (currently) restricted to the base functionalities of traditional GI systems. In the Autodesk Map® 3D 2006 software, for example, some basic map algebra commands that allow for the buffering, dissolving, and overlaying of topologies are present. The overlay functions include intersect, union, identity, erase, clip, copy, and paste. Topology generation can be done for nodes, links, and polygons. Regarding network analysis in Autodesk Map®, tools are restricted to shortest path calculation and flood trace analysis. Complicated and intensive computations like generating service areas and determining closest facilities, however, cannot be performed. Nevertheless, CAD offers robust three-dimensional design tools which are unavailable in present-day GIS packages, and fits, therefore, perfectly well for the simultaneous performance of time–geographic analysis and visualization.

Besides geovisualization aspects, the presented approach also hands interesting perspectives for the analysis of joint trip making. Several spatio-temporal queries concerning multiple agents with different means of transport can be handled. On the one hand, the method enables to compare accessibility between groups (i.e. *inter-group* differences). For example, what influence does the incorporation of additional participants have on the group's accessibility? On the other hand, *intra-group* differences can be detected. For example, to what extent does an increased availability of means of transport affect the group's accessibility; what is the effect of a smaller individual time budget on the size of the interaction space? Accessibility can be measured by means of differences in the interaction space volumes, the amount of opportunities, the total possible activity durations or combinations of these factors with criteria measuring the attractiveness of the facilities.

4. An illustration

In the previous sections we introduced the conceptual framework and developed an implementation of the concepts proposed. Now, we want to illustrate our model using a real-life example. At first, we will briefly describe the spatio-temporal settings of the considered day-to-day situation and point out the individual access to mobility. Then, two random rendezvous scenarios are developed. Finally, we make use of the GIS component of the hybrid system to create depictions of the interaction spaces and areas.

Assume five teenagers want to conduct a particular joint activity (e.g. swimming, shopping, going to the cinema) on a Wednesday afternoon, and they would like to identify all feasible facilities they can reach given their individual activity schedules and available means of transport. Apart from their fixed activities on Wednesday, they must also bear in mind that their transport modes can be lacking or can be restricted in time. The overall transport mode set V is given by three predominant transport modes:

$$V = \{foot, bicycle, car\}. \tag{8}$$

The considered set S of maximum speed values related to V is:

$$S = \{4km/h, 20km/h, 90km/h\} \tag{9}$$

Table 1 summarises the constraint triplets for each teenager with his/her individual available means of transport. This table was used as input for the VBA* module which creates the space–time prisms. The spatial coordinates of the

* VBA stands for Visual Basic for Applications. Visual Basic exists as a stand-alone environment, but has also been integrated as a specific programming language in other software packages (e.g. AutoCAD). It is then termed VBA. Applications which are written in VB or VBA can be linked to other programs that support VBA.

Table 1. Spatio-temporal settings of the agents: triplets of constraints.

a_i	$o_x[m]$	$o_y[m]$	o_t	$d_x[m]$	$d_y[m]$	d_t	$s_{v_j}[km/h]$
a_1	88,996	197,680	2:00 p.m.	111,930	199,099	4:00 p.m.	90
a_2	102,822	202,662	1:00 p.m.	102,822	202,662	5:00 p.m.	20
a_2	102,822	202,662	1:00 p.m.	102,822	202,662	5:00 p.m.	4
a_3	102,766	200,731	1:30 p.m.	102,766	200,731	4:00 p.m.	20
a_3	102,766	200,731	1:30 p.m.	102,766	200,731	4:00 p.m.	4
a_4	104,548	193,177	2:00 p.m.	104,548	193,177	4:30 p.m.	20
a_4	104,548	193,177	2:00 p.m.	104,548	193,177	4:30 p.m.	4
a_4	104,548	193,177	2:00 p.m.	104,548	193,177	4:30 p.m.	90
a_5	105,221	208,365	1:30 p.m.	105,221	208,365	3:30 p.m.	20
a_5	105,221	208,365	1:30 p.m.	105,221	208,365	3:30 p.m.	4

anchor points are georeferenced and can be derived by geocoding the addresses of the participants. Note that the first agent's earliest departure time for leaving home is 2 p.m. At 4 p.m., however, he/she must arrive somewhere else for another fixed activity. As a result the anchors of a_1 are dislocated in space and shifted in time. The situations of agents a_2, a_3, a_4, and a_5 are more or less similar but here, origin points equal destination points, implying a home–facility–home chain. Due to independent scheduling of different mandatory activities, the available time budget for conducting the out-of-home activity varies among the individuals.

Next, a facility set F is simulated, containing different facilities situated within an urban district. Table 2 gives an overview of the location and the opening hours of the facilities. These data allow for the construction of the facility objects.

We will now take a closer look at two rendezvous scenarios with different transport conditions. The agent's transport modes are tabulated in table 3.

Making use of the implemented algorithm described in the previous section, we determine those facilities within the group's potential interaction space. As depicted in figure 5a, only four facilities (fac2, fac4, fac6, and fac10) are eligible for conducting the activity in scenario 1. The maximum possible activity duration at these facilities amounts to 20, 42, 17, and 43 min, respectively. Figure 5b shows the same process for the second scenario. In this case, only facility 4 (18 min) and facility 10 (52 min) are feasible. Due to different transport mode settings, the amount of opportunities has been reduced in the second scenario. Nevertheless, the maximum possible activity time has become larger at facility 10.

Table 2. Location and opening hours of the facilities.

FacilityID	$x[m]$	$y[m]$	t_{open}	t_{close}
fac1	120,564	205,833	4:00 p.m.	5:30 p.m.
fac2	105,194	191,733	2:00 p.m.	3:30 p.m.
fac3	94,517	208,051	5:00 p.m.	8:00 p.m.
fac4	102,656	197,197	2:00 p.m.	5:00 p.m.
fac5	86,752	195,325	2:00 p.m.	3:30 p.m.
fac6	110,881	210,334	1:00 p.m.	6:00 p.m.
fac7	118,103	196,221	2:00 p.m.	7:00 p.m.
fac8	97,081	185,115	3:00 p.m.	6:00 p.m.
fac9	103,871	178,846	1:00 p.m.	3:30 p.m.
fac10	103,223	200,555	0:30 p.m.	5:00 p.m.

Table 3. Transport conditions of two rendezvous scenarios.

	a_1	a_2	a_3	a_4	a_5
scenario1	car	bicycle	bicycle	bicycle	bicycle
scenario2	car	foot	bicycle	car	bicycle

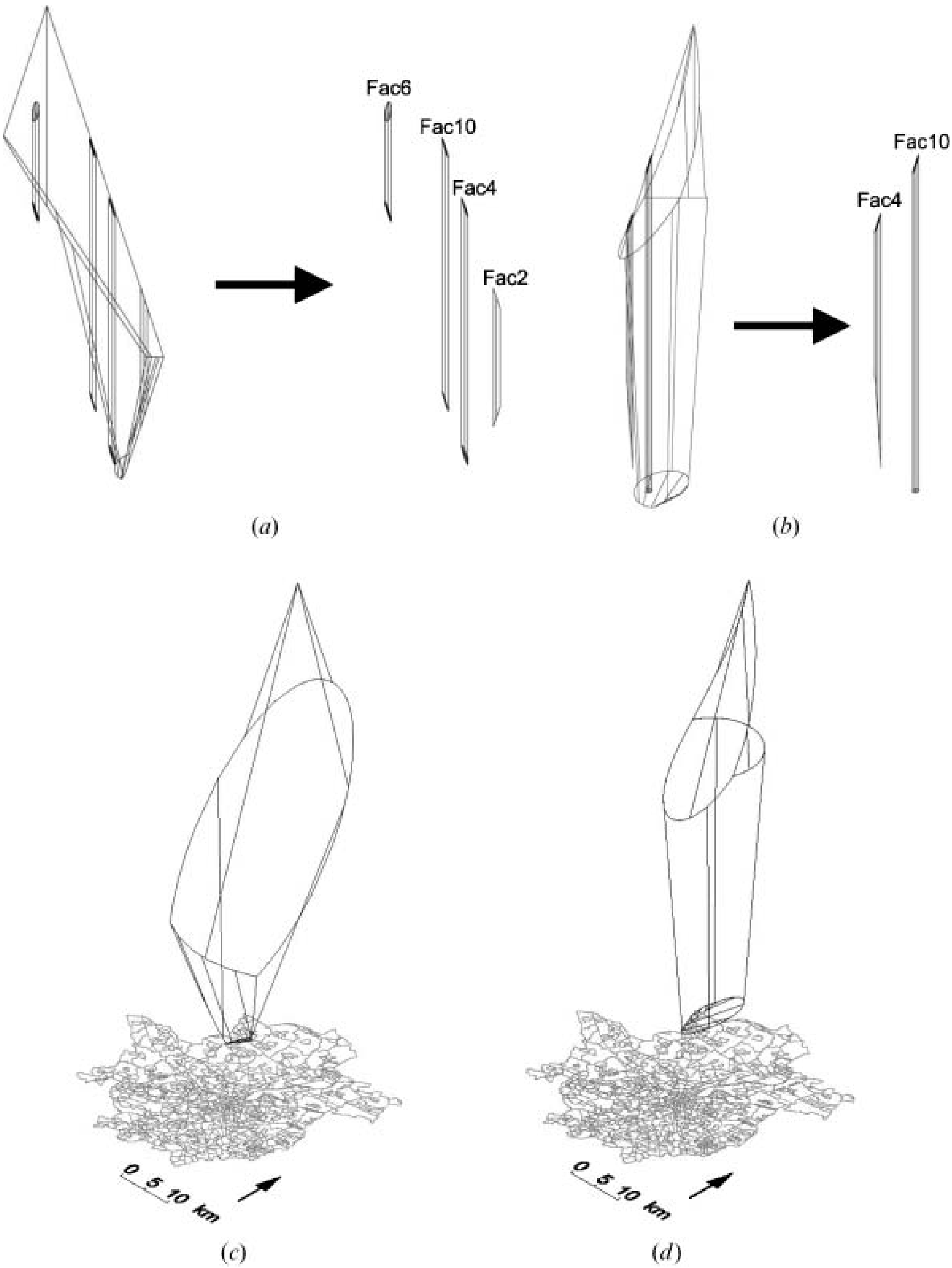

Figure 5. Feasible facility selection: three-dimensional depictions of the interaction spaces of scenario 1 ((a) and (c)) and scenario 2 ((b) and (d)).

So far no typical GIS functionalities of the hybrid system have been applied. For visualization purposes, however, we need to integrate the presented concepts with representations of maps. Figure 5c (scenario 1) and 5d (scenario 2) depicts a southeast isometric view of the interaction spaces with respect to the urban district.

Figure 6 shows the group's *potential interaction area* (PIA), which can be defined as the spatial footprint of the potential interaction space. The facilities and the homes of the agents are also depicted. Clearly, the PIA resulting from the second scenario is smaller which is due to the transport mode (foot) of a_2 in scenario 2.

5. Conclusions and future research

The objective of this paper is to model the feasible space–time interaction possibilities of multiple agents. The starting point is Hägerstrand's theory on time geography which provides an understanding of how a single agent's space–time prism is constructed. The simple case is then extended to multiple agents interacting in space and time trying to have a joint activity. The conceptual model is implemented in a hybrid system and illustrated using a day-to-day example. It has been shown that hybrid systems can be a valuable alternative for conventional GIS packages. Since (hybrid) CAD systems offer powerful tools to calculate intersections of complex three-dimensional objects, they are particularly useful for the study of interaction spaces.

The current paper presents an innovative approach in that it uses new techniques to delimit interaction spaces and to identify feasible opportunities. Several interesting related topics that are worth analysing come to the fore. First, an analysis is needed to determine to what extent our approach can contribute to the study of accessibility measures. The idea of developing a group-based accessibility measure is an interesting avenue for further research and could offer appealing insights in the easiness of meeting each other by revealing intra-group (based on individual travel conditions) and inter-group differences. Second, the incorporation

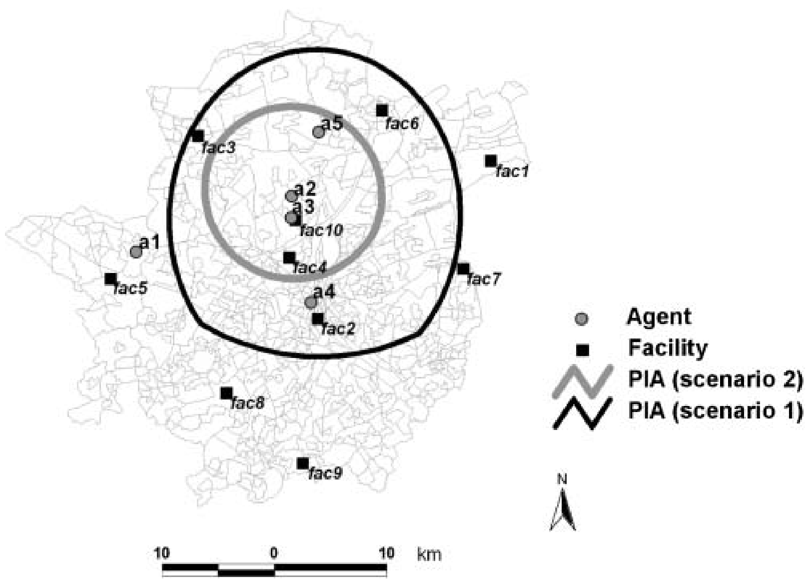

Figure 6. Urban district: potential path areas of scenario 1 and 2.

and representation of vagueness within the scope of time geography is also interesting. Here the application of rough set theory, as introduced by Pawlak (1982), offers potential. The use of broad boundaries has been explored before by Hendricks *et al.* (2003). It could be interesting to extend his approach for multiple agents by introducing (rigorous definitions for) rough approximations of space–time prisms in a CAD environment. Third, the issue of joint decision-making should be addressed as well. Such a process differs quite a lot from an individual decision-making process because it involves making compromises, dealing with joint constraints, and more complex behaviour. In this respect, rule-based expert and decision support systems can be deemed helpful. Fourth, generalizing our scheme with respect to recent and continuing advances in information and communications technologies (ICTs) offers a challenge for future research (see Kwan and Weber (2003) for a discussion of the impact of ICTs for accessibility research and geographical analysis). Since CAD systems allow—as shown in this paper—the detection of intersections in a dynamic three-dimensional environment, they are a suitable tool for analysing and mapping virtual interaction of people in the Information Age (Adams, 2000). Here, the initiative by Miller (2005) is particularly relevant because it formulates spatio-temporal (side) conditions for virtual (a)synchronous interaction using the Janelle (1995) framework. Fifth, we are aware that the illustrations, given in section 4, do not take into account the geometry of the transport. However, this does not alter the fact that the key concept provided in the paper remains clearly expounded. Quite the reverse, the use of classical three-dimensional prism representations enables an easy explanation of the concepts. Several researchers have done important work to incorporate the effects of the transportation system into the analysis of space–time accessibility (among them Kwan and Hong (1998) and Wu and Miller (2001)). Our ongoing research is currently focusing on this issue and attempts to create a three-dimensional object in a CAD environment that captures anisotropic movement and is based on existing network algorithms and editing techniques for three-dimensional solids. Research that seeks to improve the uncompromising conical representations using CAD could yield new opportunities, certainly within the light of the narrowing gap between GIS and CAD.

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