

MORAVIAN GEOGRAPHICAL REPORTS

Czech Academy of Sciences, Institute of Geonics
Palacký University Olomouc, Faculty of Science

Journal homepage: www.geonika.cz/mgr.html

doi: <https://doi.org/10.2478/mgr-2026-0013>



Defining daily urban systems from individual everyday behaviour: A time-geographic perspective on census commuting flows and mobile phone location data

Pavel Klapka ^{a *} , Marián Halás ^a 

Abstract

We use the theoretical and conceptual apparatus of the time geography to follow the way from individual behaviour in time-space to the definition of daily urban systems (DUSs). We proceed from locations, through areas organised around the locations and time use limits within the areas towards the aggregation of activity time-spaces into DUSs. We stress the importance of the concept or origin and destination anchor points, rhythms of individual movements and the principle of return. Using two datasets, the sum of daily labour and school commuting census data and the mobile phone location data, we apply regionalisation algorithm to define respective DUSs. We discuss their self-containment with regard to the time-geography, and we compare two spatial patterns. We conclude that, despite the distinctions between the datasets, spatial patterns are very similar. We acknowledge the viability of the relation between DUSs and the time geography and mutual enrichment of both concepts.

Key words: Daily urban systems; time geography, daily commuting, mobile phone location data, regionalisation, the Czech Republic

Article history: Received 16 March 2026, Accepted 28 August 2026, Published 30 September 2026

1. Introduction

Daily urban systems (DUSs) can be seen as special cases of functional regions (Klapka & Halás, 2016). A functional region is one of human geography's basic concepts helping to analyse and understand the organisation of space and spatial interactions between places. Functional regions are generally understood as spatial structures based on flows (aggregated individual movements), having autonomy regarding other functional regions in a given regional system. The autonomy means that most and intensive flows occur between places inside a functional region and that their smaller proportion cross its borders (Karlsson & Olsson, 2006; Farmer & Fotheringham, 2011; Klapka & Halás, 2016). Daily urban systems, apart from the general requirement for the autonomy, should fulfil two other conditions to be called like that: (i) they should include one or more urban core, (ii) they are based on the spatial interactions having daily basis (Klapka & Halás, 2016). The term 'DUS' was coined by Doxiadis (1968), spread through the works of Berry (1970, 1973), Hall (1974), Hall & Hay (1980), Coombes et al. (1979) and used within similar framework as presented in this article e.g. by Wyly (2004), Zandvliet and Dijst (2006), de Graaf (2019), Halás and Klapka (2021), and Poorthuis and Van Meeteren (2021).

The research into functional regions has particularly paid attention to the methods of their definition and to their use (see for instance relatively recent outlines in OECD 2002; Karlsson & Olsson, 2006; Cörvers et al., 2009; Coombes, 2010;

Casado-Díaz & Coombes, 2011; Farmer & Fotheringham, 2011; Drobne & Lakner, 2016; Kim et al., 2016; Klapka & Halás, 2016; Drobne, 2017). Theoretical underpinning and conceptualisation of functional regions has remained somewhat neglected, though. Using the notion of time in general and the theoretical and conceptual background of the time geography, we strive to revive and explore one specific way of theoretical thinking. In this respect, the concept of daily urban systems has one important implication: through the word 'daily', it brings the resonance of temporality, rhythmicity and time into the theory of functional regions, which is well in line with the aim of the article.

Furthermore, to stress the behavioural vein of inquiry into the nature of daily urban systems, we understand the region-building spatial interactions as aggregated movements of persons – flows, which are covertly responding to various aspects of individual human spatial behaviour/behaviour in space (*cf.* Golledge & Stimson, 1997). These movements reflect demands, needs, motivations, preferences, and perceptions of individuals, which are hard to obtain and analyse at aggregate level for large territories, but which are manifested by time-space existence and behaviour of individuals. Behavioural links to the theory and application of functional regions, including daily urban systems, have been discussed for instance already by Berry (1968) and his general field theory of spatial behaviour, and van den Berg et al. (1982) who discuss in detail behavioural factors affecting spatial interactions, such as decisions and motivations of households to

^a Department of Geography, Faculty of Science, Palacký University Olomouc, Czech Republic (*corresponding author: P. Klapka, email: pavel.klapka@upol.cz)

migrate (*cf.* Halás & Klapka, 2021). Mitchell and Watts (2010) mention economic and commuting behaviour as the basis for the identification of functional regions. Farmer and Fotheringham (2011) consider a functional region to be the result of collective travel-to-work behaviour. Halás et al. (2015), Klapka and Halás (2016) and Klapka et al. (2020) touch upon the relationship between functional regions and time-space behaviour.

The article develops a framework linking individual time-space behaviour to the delineation of daily urban systems. The article has following objectives:

- First, it provides a theoretical account of how behaviourally conditioned time-space movements can be transformed into daily urban systems drawing on the conceptual and methodological apparatus of the time geography (see e.g. Hägerstrand, 1970; Lenntorp, 1976; Pred, 1977; Ellegård, 1999, 2019; Sui, 2012).
- Second, it applies this framework to two distinct datasets (statistical records of daily mobility and mobile phone location data) in order to define corresponding daily urban systems and compare their spatial configurations.
- Third, it tests the assumption that the two resulting patterns will be broadly congruent, given their shared behavioural and time-geographic foundations.

The theoretical section of the article following the introduction is concerned with the emergence of DUS from individuals' behaviour. Specific time-geographic concepts are used to show the way in four focused subsections. Data and methodological section discusses the nature of both datasets, specifies the processing of the data, and presents the regionalisation algorithm used to define daily urban systems. The following section presents and discusses the results in terms of the self-containment and comparison of daily urban systems. In the concluding section we present findings and return to the issue of daily urban systems and their time-geographic interpretation.

2. From individual behaviour to the definition of daily urban systems

While the analytical tradition of the research into spatial behaviour/behaviour in space concentrates particularly on the spatial aspects (e.g. Couclelis & Golledge, 1983; Golledge & Timmermans, 1990; Golledge & Stimson, 1997; Timmermans et al., 2002; An et al., 2015), the time geography considers time to be equally important as space (Hägerstrand, 1970; Pred, 1977; Ellegård, 2019). In a broad sense, the time geography is concerned with time-space existence and behaviour of individuals, their everyday lives, projects and programmes (Ellegård, 2019) and this is what we particularly pursue in this section with regard to the concept of the daily urban system. Terms used within the field of the time geography are italicised when appropriate.

The time-space behaviour is projected to the concepts of path – both time and space coordinates change) and station – only time coordinate changes (Hägerstrand, 1970; Lenntorp, 1976; Miller, 2005; Ellegård, 2019). Individual behaviour tackles capability, coupling, and authority constraints (Hägerstrand, 1970; Lenntorp, 1976; Pred, 1977), which condition the occurrence of bundles in the time-space. A bundle refers to the situations when two or more individual paths meet (get in touch) in time-space (usually at a station), enabling to accomplish various projects (e.g. making a living, educating) of individuals. This can be the result of institutionalisation of individual behaviours asserted by various organisations (employers, schools) and their goals. As such, bundles significantly affect the rhythms of time-space behaviours.

2.1 Locations: anchor points and pockets of local order

Stations can have different significance in the existence of individuals in time-space. In this respect, the anchor point theory

(Golledge, 1978; Couclelis et al., 1987; Golledge & Stimson, 1997) is useful; Couclelis et al. (1987) explicitly mention 'the regionalisation of cognitive space'. In this theory the spatial structure of stations and their hierarchical ordering according to relative significance to individuals and spatial fixity are taken into account. There is a consent that primary (salient) anchor points are homes and workplaces (Golledge, 1978; Couclelis et al., 1987; Dijst, 1999; Schönfelder & Axhausen, 2004). Golledge and Stimson (1997) add to these two also shopping locations and we point to the rather neglected significance of schools for children and younger adults (Klapka et al., 2020). Primary anchor points are determining for capturing time-space existences of individuals, other (secondary, etc.) can have temporal and ephemeral nature (Klapka et al., 2020). An inspiring typology of anchor points is presented by Ahas et al. (2010), who distinguish between common (commonly recognised as significant) and personalised anchor points (significant for an individual).

A station – an anchor point – can be viewed under certain circumstances as a pocket of local order (Hägerstrand, 1985; Lenntorp, 2004; Ellegård & Vilhelmson, 2004; Ellegård, 2019). Pockets of local order are necessary for individuals to accomplish the goals of their projects through intrinsic arrangement (what individuals arrange for themselves) and extrinsic control (what is imposed on individuals by other individuals and the environment). Pockets of local order are organised, scheduled and infrastructure-equipped places to facilitate projects (Lenntorp, 2004; Klapka et al., 2020). Home, workplace and school, i.e. anchor points where individuals spent most of their time, are the main pockets of local order (*cf.* Ellegård & Vilhelmson, 2004).

2.2 Areas: activity time-spaces and prism

On our way to search for a meaningful 'blend' of the daily urban system concept and the time geography we have dealt with lines and points so far; however, a DUS is an areal geographical category. In this respect, the concept of activity space (also action space) is useful. The projection of individual time-space movements and opportunities to move into areal categories was put forward by Lenntorp (1976) and followed by Golledge and Stimson (1997), Dijst (1999) and Patterson and Farber (2015). An individual activity space can be seen as a set of all locations (stations, anchor points) and movements (paths) among them either actually visited and made by individuals, or being potentially accessible to them (Golledge & Stimson, 1997; Dijst, 1999; Schönfelder & Axhausen, 2004; Patterson & Faber, 2015). Thus, activity time-spaces reflect complex interaction between an individual and geographic environment, including the issues of accessibility, distance and constraints, and the expression of their existence and behaviour in time-space. Schönfelder and Axhausen (2010, p. 127) suggest that activity spaces include: home location, duration of residence, number of activity locations near individual's home, trips within the neighbourhood, travel to and from primary anchor points, travel between and around other anchor points.

Dijst (1999) distinguishes between actual and potential action spaces. The former includes observed visits and movements in the past, while the latter refers to one of the most fundamental and yet inspiring time geographic concepts: a prism. The time-geographic prism is focused on the future and comprises the set of potential visits and movements in time-space that are reachable with regard to the constraints (Hägerstrand, 1970; Lenntorp, 1976; Pred, 1977; Miller & Bridwell, 2009; Neutens et al., 2011; Ellegård, 2019). In order to capture a prism, the current origin (station, anchor point), the intended destination (either the same as origin or any other station, anchor point) and the velocity of movement are needed. In 3D time-space a prism consists of a lower and an upper cone and optionally of a hull representing stationary activity. When a prism is projected to the 2D space, it is called potential path area (Lenntorp, 1976; Miller, 1991, 2005; Patterson & Faber, 2015).

There is extensive literature on measuring the activity time-spaces and prisms, particularly using visualisation in GIS (Schönfelder & Axhausen, 2010; Paterson & Faber, 2015; Li & Tong, 2016; Vich et al., 2017; Hasanzadeh et al., 2019). One group of measures for activity time-spaces is based on geometries when an ellipse constructed around two primary anchor points is the simplest approach (Dijst, 1999). Apart from that confidence minimum convex hull polygons, ellipses, standard deviation ellipses, superellipses, Cassini ovals, bean curves represent more advanced measures (Schönfelder & Axhausen, 2004; Rai et al., 2007). Sila-Nowicka et al. (2023) propose the concept of activity triangles. The second group uses spatial statistics such as kernel densities (Schönfelder & Axhausen, 2004). The third group is based on network analysis such as minimum spanning trees and daily path areas (Schönfelder & Axhausen, 2004; Li & Tong, 2016; Vich et al., 2017). Measurement of a prism and a potential path area in GIS was pioneered by Miller (1991) and the concept has been since used to analyse potential human activities, mobilities and to model accessibility (Kwan, 1998, 2004; Miller, 2005; Miller & Bridwell, 2009; Neutens et al., 2011; Elias & Kuijpers, 2020).

2.3 Time use: rhythms and principle of return

Time use of individuals includes routines and their rhythms during a given period, and it is constrained by the principle of return (Lenntorp, 1976; Hägerstrand, 1985; Ellegård & Vilhelmson, 2004). It means that many activities are fixed to specific locations, stations such as home, work, school, shop, etc. From the point of the frequency of the routines and their spatial fixity/flexibility, we speak of regular (travel-to-and-from-work, travel-to-and-from-school), semi-regular (some shopping travels) and irregular activities (some shopping travels, leisure travel, migration), having various rhythms (Axhausen, 2007). However, the most important and frequent routines recur within the period of a day. These daily activities and their rhythms are centred around homes, places where people sleep and return to.

Thus, the time span of a day, need for projects to be accomplished, spatial location of crucial anchor points and bundles, prisms, activity rhythms and principle of return shape individual activity time-spaces and potential path areas. All this gives us complex arenas of time-space patterns of individual behaviours. Now, the question of agglomeration of these individual patterns comes forth to capture the geographical organisation of society.

2.4 Aggregation: daily urban systems

The idea of aggregation within the time geography can be traced back to Lenntorp (1976) and thus there have already been efforts, particularly facilitated by the use of GIS, to consider individual activity time-spaces and prisms to be aggregations (Miller, 1991). In theory, Miller (2005) points to intersections of n individuals' time-space prisms, which is necessary to form a bundle. Neutens

et al. (2008) are concerned with joint time-space accessibility regarding the individuals willing to be engaged in a joint activity. In this respect, Lee and Miller (2019) develop the concept of average space-time prism for a group of individuals and aggregate spatial units. Average space-time prism needs not necessarily be an intersection of individual prisms, it is rather the expression of their central tendency. Xu et al. (2015) identify aggregate mobility patterns based on home anchor points, mobile phone data and base stations, and define areas with similar aggregate mobility patterns. Xi et al. (2020) study patterns of overlapping activity spaces and identify 'ecological communities' in networks based on shared locations.

The aggregation of time-space patterns of individual behaviours into daily urban systems requires the identification of origins and destinations (as the definition of any kind of functional regions depends on the analysis of origin-destination matrix). From what has been discussed so far it follows that anchor points 'home' act as origins, and other crucial anchor points (e.g. 'workplace, school') act as destinations of individual movements resulting from a routine activity with a daily rhythm, conditioned by the principle of return (such as daily travel-to-work). As anchor points, origins (homes) tend to be generally more dispersed in space than destinations do (workplaces, schools, shops, services).

However, the aggregation of individual activity time-spaces and potential path areas/prisms as referred to at the beginning of this subsection based just on the individual anchor points is not sufficient for the construction of origin-destination matrix. Resulting spatial patterns can be very complex, uncertain, overlapping and 'unorganised' (Vich et al., 2017, p. 428, advocate a different opinion). To avoid this, we pursue higher level of certainty, when the whole territory under consideration is covered with regions in a non-overlapping manner; we value the contiguity, compactness, and coherence of the regions (*cf.* Casado-Díaz & Coombes, 2011). For this purpose, rather than the aggregation of individual activity time-spaces we favour the aggregation of anchor points into the framework of basic spatial units to tackle with quite complex sets of individual activity time-spaces. The construction of origin-destination matrix is now easily feasible. Both types of aggregation are presented in Figure 1: on its left there is an intersection of aggregated simple ellipses; on its right there is an aggregation of anchor points into basic spatial units.

3. Data and method

Two datasets are analysed in the article: (i) 2021 census commuting data, and (ii) mobile phone localisation data. The following subsections include information on the nature of the data, on the process of the construction of origin-destination matrix, and on the regionalisation algorithm used to analyse the matrix and define daily urban systems.

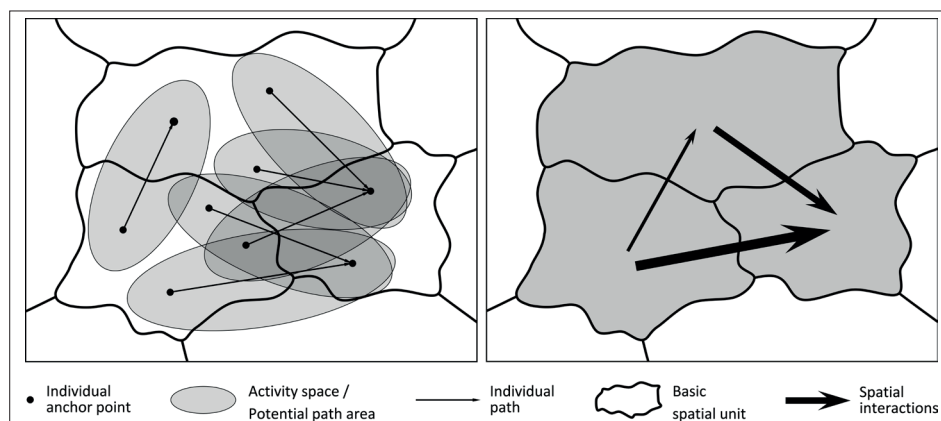


Fig. 1: Aggregation of daily activity time-spaces based on individual anchor points vs. aggregation of individual anchor points into coverage of basic spatial units, including aggregated interaction between them. Source: Authors' elaboration

3.1 Nature of data

As the first dataset we use statistically registered information on the sum of daily labour and school commuting, which is the part of the 2021 census. The data were collected during the Covid-19 pandemic and lockdown; however, the Czech population was strictly advised to fill in the census questionnaire forms as if there was no pandemic. Nevertheless, we can assume that the data might have been affected by the pandemic situation, although there are no official estimates of the possible bias.

As the second dataset we use passive mobile phone location data (*cf.* Ahas et al., 2007), when each mobile phone connects to base transceiver stations (BSTs) in their respective cells. Records of the connections to a particular BST are stored automatically in memory files of mobile operators and thus we have information on time-space locations of a device. We use the data provided by the biggest operator, which covers approximately 40% of the Czech market. The operator claims that their representation is relatively equal in the whole territory and corresponds to general spatial population distribution. We can corroborate because Pearson correlation coefficient for the comparison of regular daily flows based on mobile phone location data and daily labour and school commuting flows is 0.989 for inflows and 0.960 for outflows. Our data were collected in four weeks (from September 16 to October 13, 2019), which was the period of culminating mobility before the outbreak of the Covid-19 pandemic.

3.2 Construction of origin-destination matrix

The definition of DUSs starts with the analysis of origin-destination matrix, which stores flows between basic spatial units (BSUs) representing building blocks for regional system. Both datasets, we use, reflect individual time-space behaviours. However, in both cases they are or have to be reported in an aggregate form due to personal data protection concerns.

We start with the mobile phone location data for the sake of clarity. The first step involves the process of identifying the origins and destinations. Origin anchor point, i.e. home, was defined as a location where a person had spent the largest amount of time between 22:00 and 6:00 during mentioned four weeks. Destination anchor points were defined as locations that occurred at least 12 times during mentioned four weeks, and a person had spent at least three hours there. We can assume that destination anchor points are mostly workplace and school, even though other exceptional possibilities cannot be ruled out. In terms of rhythms, we denote the movements between origin and destination anchor points defined like this as daily regular flows.

The second step involves the process of aggregation of individual origin and destination anchor points into BSUs, which had to be done by the operator upon our request. Several approaches can be used to transform mobile phone location data into basic spatial units. Šveda et al. (2024) have tested ten of them and the highest precision was reached by dasymetric interpolation utilising building volume, which was also used in this article. Origin and destination anchor points were aggregated to so-called elementary units. They are based on the units used by Musil and Müller (2008), and they are groups of municipalities organised around a municipality having a central function – it has a school, a post office, a health centre, sometimes also a town authority, a registry office and a building authority, and linked to it by nodal relations (labour and school commuting). Cities (municipalities) with more than 75 thousand inhabitants are taken separately. In total, we have defined 1,451 elementary units.

There are several reasons why we use elementary units and not municipalities to aggregate individual origin and destination anchor points: (i) some municipalities have no relevant data for the given period, (ii) some municipalities have only a small

number of incident flows and these data cannot be acquired based on the limitations imposed by the Czech legislation (personal data protection), (iii) data for municipalities are extremely expensive (the Czech Republic has a very large number of small municipalities compared to most of European countries).

As for the census data, they are reported in an aggregate form for the municipalities (6,258 units) acting as origins and destinations. To ensure more efficient comparability of the results, we further aggregated the census data on daily labour and school commuting from the municipalities into the above-mentioned 1,451 elementary units. Thus, we gained two square origin-destination matrices of the same size ($1,451 \times 1,451$), which entered the regionalisation algorithm. A note about so-called inner flows (cells along the main diagonal of the matrices) has to be made. In the matrix storing daily labour and school commuting data, the inner flow includes only persons that work or study locally. In the matrix storing mobile phone location data, the inner flow includes every person with a mobile phone fulfilling the condition regarding the origin anchor point. It means that inner flows in the latter matrix are larger than in the former one, which has further consequences (see the self-containment section below).

3.3 Regionalisation algorithm

The origin-destination matrices are analysed by the third variant of the CURDS regionalisation algorithm (Coombes, 2010), with minor adjustments put forth by Halás et al. (2015). The algorithm is a rule-based iterative procedure in which each basic spatial unit is considered a proto-region at the outset. Proto-regions are ranked in descending order according to the value of the constraint function. If the proto-region, which ranks the lowest, fulfils the quantitative requirements set by the constraint function, the algorithm stops. If it does not, the respective proto-region is amalgamated with a proto-region to maximise the interaction measure. The origin-destination matrix (now in the form $(n - 1) \times (n - 1)$ where n is the number of basic spatial units) and constraint functions are recalculated, and the procedure is repeated.

The crucial role in the algorithm is played by the constraint function, which controls the parameters of the size and self-containment of regions (in fact, the trade-off between them; see also Fig. 2). It is convenient to set the size and self-containment to low values. Then the resulting regions are plotted on an x-y graph according to the respective values of the size and self-containment. When a significant 'gap' in the fields of points is identified, new parameters of the size and self-containment of regions are estimated, and the algorithm can run again. It means that the parameters of the resulting regions are set normatively only for the first (preliminary, testing) run of the algorithm and that for its consequent runs the parameter estimations reflect basic geographical organisation of a territory and overall aggregated time-space behaviour of individuals.

4. Results and discussion

In the regionalisation algorithm, the minimum size and self-containment parameters were set to provide us with the individually optimised patterns of DUSs for each dataset. Both patterns are, however, comparable in terms of the size and content of DUSs at the same time. The analysis of daily movements recorded in the 2021 census (the sum of daily labour and school commuting) has given us 117 daily urban systems (*cf.* Klapka et al., 2016). Their spatial pattern is shown in Figure 3. The analysis of regular flows based on mobile phone location data has produced 113 daily urban systems and their spatial pattern is shown in Figure 4. Figure 2 shows general patterns of DUSs with regard to the constraint function. We will comment of the result from two perspectives: (i) the self-containment of DUSs and its time-geographic interpretation, and (ii) comparison of spatial patterns.

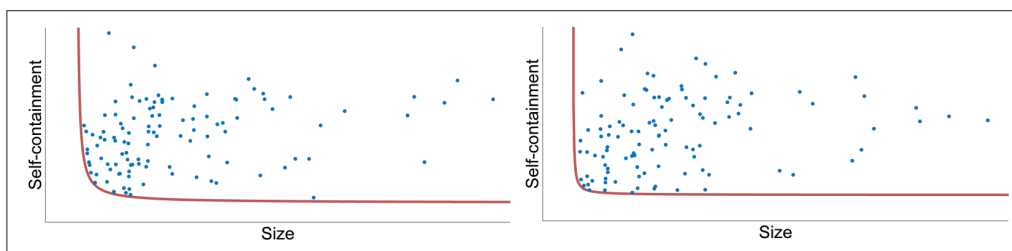


Fig. 2: Position of DUSs with regard to the constraint function (census data on the left, mobile phone location data on the right)

Note: Due to graphical reasons four largest DUSs (Prague, Brno, Ostrava, Plzeň) are left out

Source: Authors' elaboration

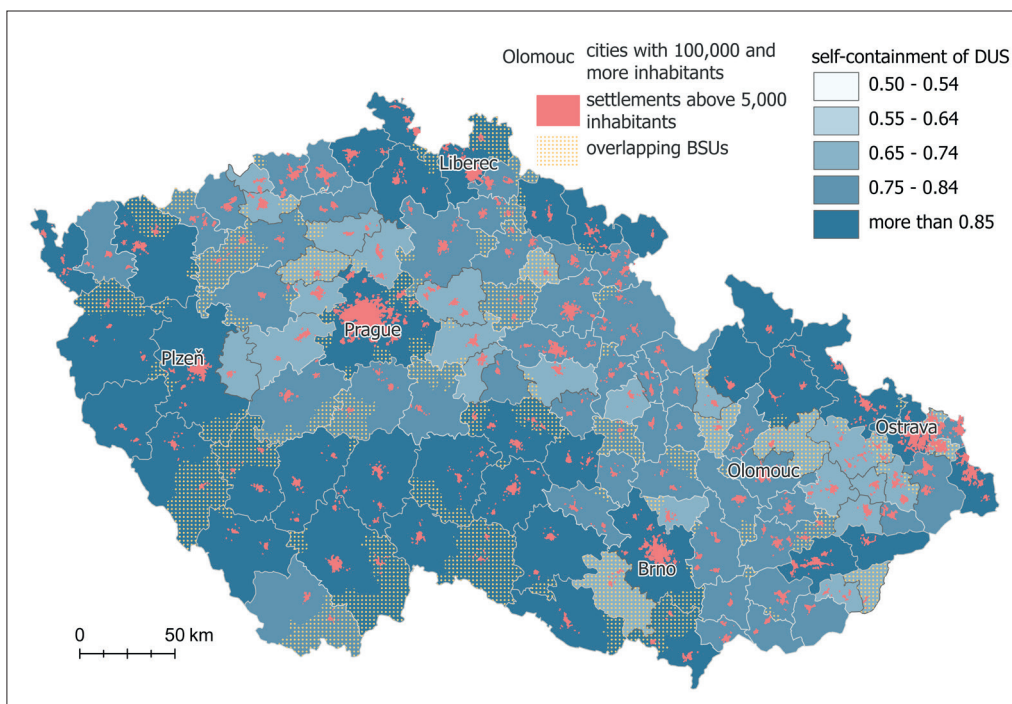


Fig. 3: Daily urban systems based on daily labour and school commuting flows (2021 census)

Source: Authors' elaboration

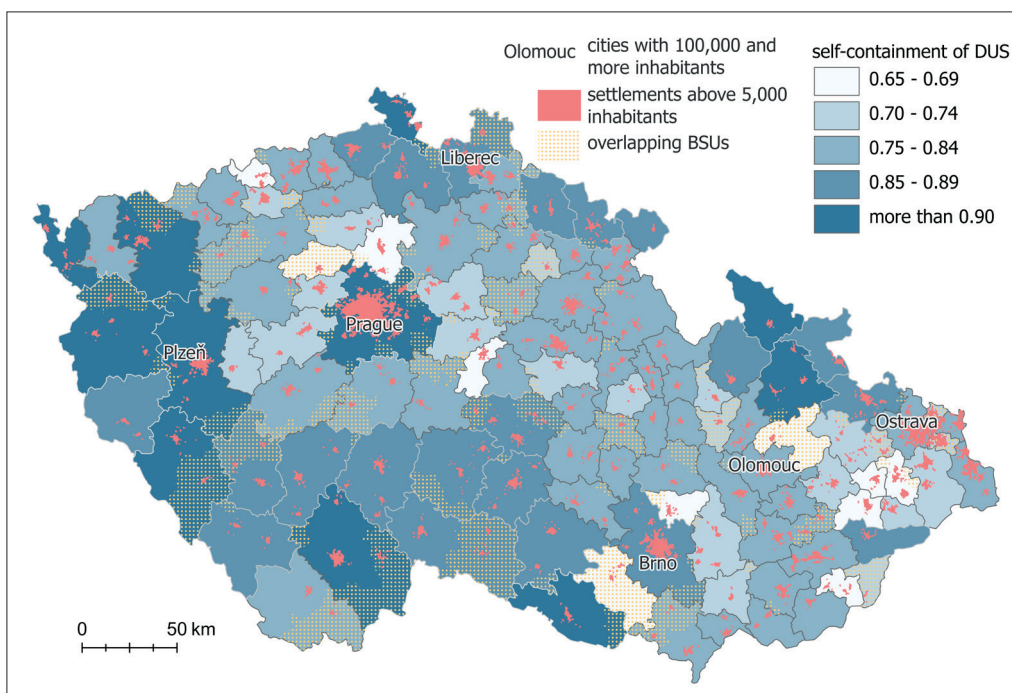


Fig. 4: Daily urban systems based on mobile phone location data

Source: Authors' elaboration

4.1 Self-containment and time

Daily urban systems are examples showing how time influences the formation of functional regions. The main time-geographic constraints are the daily rhythmicity of aggregated individual movements and the principle of return. Borders of daily urban systems are both spatial, and time-limited. DUSs can be interpreted as aggregated activity time-spaces, but also as limits to potential path areas (and prisms). In this respect, higher level of the self-containment of DUSs indicates more strictly limited activity time-spaces and potential path areas, while its lower level offer probability that activity time-spaces and potential path areas are distended for relatively significant number of individuals. From another perspective, the self-containment relates to the shape of distance-decay curve from central parts of DUSs towards (and sometimes beyond) their borders (*cf.* Lenntorp, 1976), which is steeper in the case of DUSs with higher self-containment and gentler in the case of DUSs with lower self-containment.

DUSs with higher self-containment can therefore be understood as areas in which individuals' main daily projects are organised within relatively enclosed and recurrent spatiotemporal settings. In contrast, lower self-containment indicates that the daily projects of a substantial share of the population are regularly organised beyond the boundaries of the respective DUS. This interpretation is consistent with studies of individual accessibility, which emphasise that the spatial extent of everyday mobility is constrained by temporal limitations, transport options, and the location of mandatory activities (Kwan, 1998; Schönfelder & Axhausen, 2010; Neutens et al., 2011).

The self-containment of DUSs is shown in Figures 3 and 4. It is generally higher in the case of DUSs based on the mobile phone location data. It is the result of higher numbers of internal flows as mentioned above. Higher levels of the self-containment can be seen in DUSs of large centres (e.g. Prague), DUSs along the state border, and DUSs in the areas where there is weak competition between centres. In contrast, lower levels of the self-containment are witnessed in DUSs in hinterlands of the largest centres (again Prague, but also others) and DUSs in the areas with competing centres. These factors (vicinity of the largest centres, competitiveness of centres) together with advantages of transport infrastructure and system affect individual time-space behaviours, which is then manifested in aggregate form in the self-containment levels, and also in the spatial extent and population size of DUSs.

At the same time, self-containment should not be interpreted as a straightforward indicator of regional 'strength' or 'weakness'. A lower value may indicate dependence on a dominant external centre, but it may also reflect a polycentric spatial organisation, well-developed transport infrastructure, overlapping labour markets, or more flexible daily routines. The boundaries of DUSs should therefore be understood as probabilistic and time-sensitive limits of aggregated activity spaces rather than as sharply delineating lines. This is consistent with the broader time-geographical argument that everyday regions emerge through the repeated coordination of individual projects in space and time, while remaining open to changes in mobility technologies, work organisation, and institutional schedules (Miller & Bridwell, 2009; Ellegård, 2019; Lee & Miller, 2019).

4.2 Comparison of two spatial patterns

The difference in the total numbers of DUSs in both spatial patterns is four. However, regionally nine DUSs based on the mobile phone location data are missing in the spatial pattern based on the census data. In contrast, thirteen DUSs based on the census data are missing in the spatial pattern based on the mobile phone location data. In the former case, the 'extra' DUSs are

mostly organised around centres in the vicinity of hierarchically larger centres, and, with one exception, their population is around 10,000. In the latter case, the 'extra' DUSs are organised by smaller centres in areas without dominant hierarchically larger centre (with one or two exceptions), which in a way 'emancipated' from nearby slightly stronger or comparable centres.

Basic features of both spatial patterns (Figs. 3 and 4) are significantly similar. 81.4% of basic spatial units can be found within the same DUS in both spatial patterns, which amounts for 89.3% of the country's population and for 80.6% of its area. BSUs that do not belong to the same DUS in both spatial patterns are labelled as 'overlapping BSUs' in Figures 3 and 4. As mentioned above, in both cases the parameters of the regionalisation algorithm were set to produce optimal number of DUSs rather than the same number of DUSs. If the comparability in the number of DUSs were preferred, the similarity numbers would increase by further 5–10 percentage points.

The geometry of both spatial patterns can also be compared using global and local measures of spatial association between zones (see Nowosad & Stepinski, 2018 for mathematical details), which is based on the spatial overlap between both patterns. The measure of global spatial association between zones (theoretically assuming values between 0 and 1; one meaning complete correspondence between spatial patterns) equals 0.93. Local pattern of spatial association represents the correspondence of DUSs based on daily labour and school commuting within DUSs based on mobile phone location data. In this case, the zero value means that a zone (i.e. DUS) of the input spatial pattern lies completely within a respective zone (i.e. DUS) of the overlaying spatial pattern. It should be noted that it does not mean that the borders of both zones are necessarily exactly the same (though they can be, of course). In our situation (Fig. 5), 46 out of 117 input DUSs are completely within respective overlaying DUSs. In contrast, higher values of the local measure of spatial association are concerned with 9 input DUSs, particularly as the result of different numbers of DUSs for both spatial patterns. This occurs mostly in wider hinterlands of large cities (Prague, Brno, Ostrava, Pilsen and Olomouc).

The overall similarity of both spatial patterns is particularly conditioned by the daily rhythmicity of the movements and by the committed character of the movements between primary anchor points, which imposes spatial (physical) limitations on the extent of daily urban systems. Therefore, two datasets can be assumed to include similar trajectories. Of course, daily activity time-spaces include also other less regular or irregular trips (shopping, service, leisure, culture and sport, social visits, etc.), but they have to be presumably synchronised with crucial movements between origin and destination anchor points.

The differences between two spatial patterns of daily urban systems are caused by several reasons. The regionalisation algorithm is sensitive to any minor changes in the data, especially in the Czech Republic, where daily movements are not limited by physical traits of the space (relief, distribution of settlements, transport network). The mobile phone location data cover 40% of the population and they include other trips than to work and school (this reason is assumed to be minor; *cf.* the preceding paragraph, but it exists). There is a difference in volumes of so-called inner movements (i.e. flows within basic spatial units), which, in the case of the mobile phone location data, include also non-working and non-studying persons, such as the significant segment of older adults.

The high degree of correspondence between these two spatial patterns supports the assumption that DUSs capture robust structures of everyday functional organisation rather than artifacts specific to a particular dataset. The resulting similarity therefore suggests that the strongest daily mobility relationships are sufficiently stable to be detected using both conventional

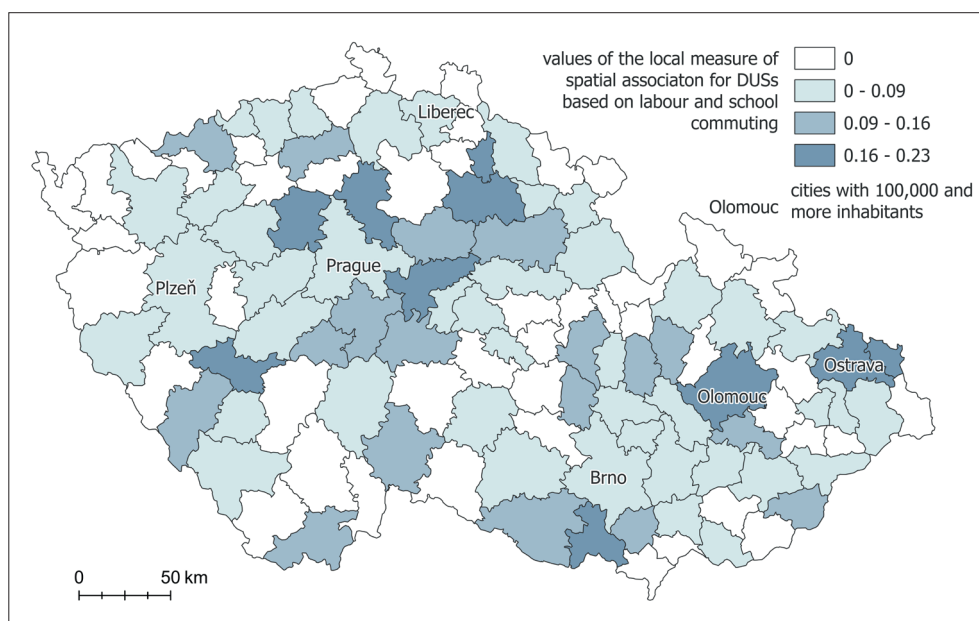


Fig. 5: Local measure of spatial association (DUSs based on labour and school commuting as the input spatial pattern, DUSs based on mobile phone location data as the overlay spatial pattern)

Source: Authors' elaboration

and alternative data sources. This finding is consistent with the literature on functional regionalisation, which emphasises that daily flows, particularly commuting flows, provide a reliable basis for identifying relatively autonomous regional systems (Karlsson & Olsson, 2006; Coombes, 2010; Casado-Díaz & Coombes, 2011; Farmer & Fotheringham, 2011; Klapka & Halás, 2016). The differences between the two regionalisations point to locations where the delineation of DUSs is sensitive to the type of flow being measured, the aggregation of the underlying spatial units, and the treatment of internal flows. Similar issues have been discussed in studies using passive mobile positioning data, where the identification of meaningful places, home-based mobility patterns, and aggregated activity spaces depends on temporal thresholds and spatial aggregation procedures applied to raw records (Ahas et al., 2010; Xu et al., 2015; Šveda et al., 2024).

5. Conclusion

In the theoretical section, we have shown how we used the spatial projection of individuals' time-space behaviour at aggregate level, and from this process we defined daily urban systems (DUSs). DUSs were identified according to standards for functional regionalisation (they cover the whole territory of the Czech Republic), using the CURDS algorithm, and results conform to the concept of functional region (individual DUSs are self-contained). Two datasets were used: (i) the daily labour and school commuting from the 2021 census, and (ii) the mobile phone location data. While the former dataset is given, as a matter of fact, in terms of spatial units, rhythm (periodicity) and goal of flows (travel-to-work, travel-to-school) and does not allow for alterations, raw database for the latter dataset had to be considerably processed, so that both datasets were comparable as much as possible.

The aim of the processing was to gain origin-destination matrix of basic spatial units storing flows based on aggregate daily rhythms of individual movements, similarly to the origin-destination matrix storing the census daily labour and school commuting flows. Therefore, the mobile phone location data had to be refined through the identification of crucial anchor points in individual time-space trajectories seeking for regular (daily) rhythms. The conditions imposed on the identification process enabled us to define origin anchor points as homes, and destination

anchor points as workplaces or schools. The origin and destination anchor points were aggregated into basic spatial units and origin-destination matrix constructed.

The analysis of both datasets provided us with two considerably similar spatial patterns of daily urban systems, which we see as the evidence for viability of the aggregation of individual time-space behaviours, and acknowledgement of the crucial role of the time geography for the conceptualisation and definition of daily urban systems. Apart from the comparability of both datasets, there is an apparent complementarity in their use for the analysis of time-space behaviour and for the definition of daily urban systems. Their combination enables one to capture more realistic patterns of time-space behaviours (both individual and aggregated), which is becoming increasingly irregular, distended, ephemeral and mingled. It is caused by more efficient transport, teleworking, multiple jobs and part-time working, shift to a virtual space, change in social behaviour and recently by the impacts of the pandemic. Consequently, we obtain more plastic and dynamic view of spatial patterns of aggregated time-space behaviours.

From a practical perspective, the results suggest that DUSs can serve as meaningful spatial units for regional and urban policy. As they capture areas in which everyday activities are organised around recurring movements between homes and major destinations, they provide an empirically grounded alternative or complement to administrative boundaries. This is particularly relevant for policies that depend on everyday functional relationships, such as transport planning, the coordination of public services, school and labour catchment areas, or inter-municipal cooperation. In this sense, DUSs can help identify areas where planning, service provision, and governance should be coordinated across municipal boundaries.

The analysis of self-containment also has practical implications. Higher self-containment indicates relatively coherent spaces of daily activity, where most everyday movements remain within the same system. Lower self-containment, in contrast, may point to areas where residents' daily routines extend across several centres, and where transport connections, labour-market relationships, or access to services warrant closer examination. Such areas may deserve particular attention from regional planners and transport authorities, as they can reveal mismatches between formal territorial arrangements and actual spatiotemporal behaviour.

The comparison of commuting data with mobile phone location data is also relevant to data practices and evidence-based policymaking. The high degree of similarity between the two spatial patterns confirms that traditional census data remain valuable for delineating everyday urban systems, while mobile phone data can enrich this picture by providing more flexible, time-sensitive, and potentially more frequently updated information on everyday mobility. Their combined use may be particularly valuable during periods of changing mobility behaviour, such as the increasing prevalence of remote work, multiple-job holding, irregular work schedules, or post-pandemic transformations of daily routines.

Finally, we comment generally on the relationship between the time geography *per se* and the issue of the definition of daily urban systems. DUSs can be interpreted as spatio-temporally limited regions of aggregate activity time-spaces and potential path areas (and prisms). Even though more aspects of DUSs should be acknowledged (geographical: physical, settlement and economic geography and demography of a territory, characteristics of transport systems; behavioural), in this article we turned our attention to the integrating role of time, expressed in the rhythmicity concept and principle of return.

In our case, the time limits of DUSs are framed by daily rhythms and spatial limits by the locations of crucial origin and destination anchor points, which have to obey the principle of return, and which organise daily activity-time spaces and potential path areas (and prisms). The identification and categorisation of anchor points and related commitments in time-space behaviour of individuals (e.g. bundles) determines (apart from spatial limits to activities) rhythmicity, regularity and temporality of projects and routines. The aggregation of anchor points into basic spatial units is essential for the definition of DUSs.

The above-mentioned time span, rhythms, identification, spatial distribution and aggregation of anchor points and movements between them affect the level of self-containment of daily urban systems. The self-containment of DUSs can be seen as the function of interaction intensities and distance decay. Thus, the levels of self-containment can show to which extent the aggregate activity time-spaces and potential path areas (and prisms) conform to defined daily urban systems, and where time-space behaviours ask for closer inspection (lower level of the self-containment) and search for the reasons of such patterns of geographical organisation of society.

Acknowledgement

This work was supported by the Faculty of Science, Palacký University Olomouc, internal grant "Conventional vs. alternative spatial data: interpretation with comparison options" [IGA_PrF_2026_023].

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Please cite this article as:

Klapka, P., & Halás, M. (2026). Defining daily urban systems from individual everyday behaviour: A time-geographic perspective on census commuting flows and mobile phone location data. *Moravian Geographical Reports*, 34(3), 161–169. <https://doi.org/10.2478/mgr-2026-0013>