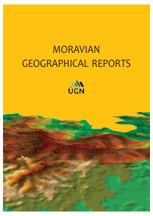

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Spatial regularities in Internet performance at a local scale: The case of Poland

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Abstract:

At present the digital divide has started to be considered not so much in the context of Internet access itself or the skills of Internet users, but in terms of Internet performance. The COVID-19 pandemic has revealed that faster Internet made it easier to adapt to the new reality. But not all areas can benefit from good Internet connection. Therefore, the aim of this study is to identify spatial regularities in Internet performance on a local scale. This study is based on a set of data generated by Internet users, collected using the publicly available Ookla Speedtest measurement tool. The information about Internet speed and latency obtained in this way shows the actual Internet speed experienced. The analyses have indicated significant characteristics of the spatial differentiation of Internet performance. First, in the case of the Internet, the core-periphery dimension is not universal and obvious, as regional systems are strongly marked. Second, perceiving the digital divide mainly through the prism of Internet access is an insufficient approach.

Keywords: *Internet performance, digital divide, local scale, Poland*

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1. Introduction

At present, access to digital technologies, particularly the Internet, has become a key factor in local development (Kolko, 2012), contributing to the reduction of poverty (Mora-Rivera and García-Mora, 2021) and, thus, enabling many people to become involved in social life. As with any other resource, however, it is not equally available to everyone. In the context of uneven access to the Internet, the key problem is a digital divide, which can be considered on many levels, including the spatial one (Warf, 2019; Reddick et al., 2020).

The Internet has been evolving along with its growing popularity. This concerns both how it is used (for example, methods of access) and its practical applications (Blank and Dutton, 2014). These changes are observed in the spatial aspects of the Internet. As emphasised by Salemnik et al. (2017), a lack of access to the Internet or poor-quality access (low technical parameters) exclude some communities and social groups from full participation in the modern information society. In geographical terms, they are most often residents of rural areas, particularly those located far away from development cores – large cities and metropolises. Thus, the issue of unequal access to the Internet is important when creating the foundations for regional and national development policies. For such measures to be effective, local differences must be identified in detail and the relationship between metropolises (development cores) and their surroundings and peripheral areas must be defined.

Changes taking place in the use of digital technologies and their impact on the economy and society are defined in various ways, for example as digital transformation and digitalisation (Soto-Acosta, 2020; Rijswijk et al., 2021). Regardless of the terminological approach, all research on the functioning of the Internet emphasises that it has become a ubiquitous and inseparable component of social, economic, and political life. What is more, the COVID-19 pandemic has shown the scale of society's dependence on access to a well-functioning Internet. Changes in the functioning of the public and private sectors as well as the general population's everyday life (for example, Ozil and Arun, 2020), remote education (introduced in most countries of the world) (Nicola et al., 2020), increases in online shopping, and the universal adoption of work-at-home technologies (Barnes, 2020), have clearly accelerated the growth of the Internet's importance, which was already observed for years (Hu, 2020; Soto-Acosta, 2020).

The Internet, along with related technologies, has ceased to be a convenience and has become an essential tool for everyday functioning. Hence, as Sun (2020) notes, the digital

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divide has become a digital chasm during the pandemic. Moreover, the digital divide has started to be considered not so much in the context of Internet access itself or the skills of Internet users, but in terms of Internet performance. This is pointed out by Lai and Widmar (2020), who emphasise the increased importance of Internet performance (particularly speed) during the forced isolation due to the COVID-19 pandemic. A faster Internet has made it easier to adapt to the need to stay at home, enabling effective access to both education (for example, Cullinan et al., 2021) and work, as well as entertainment and live-streaming forms of socialisation such as weddings, funerals, and religious services (Sun, 2020).

The aim of this study is to identify spatial regularities in Internet performance on a local scale. Internet speed (download and upload) and latency are treated as the defining characteristics of Internet performance; they testify to the quality of Internet access. The reference point for analysing the research results is the relations between metropolises, which are treated as cores, and their surroundings, with particular emphasis on rural areas. This approach makes it possible to refer to one of the key dimensions of the digital divide. The research area is Poland, and the research period is 2020. The analysis is based on data about Internet performance collected in local administrative units (LAUs). For the purposes of this study, we assume that spatial differentiation in the characteristics of Internet performance is one aspect of the digital divide. Poland offers interesting possibilities for analysing the spatial aspects of the digital divide. Poland is one of the few countries in the European Union with a well-developed and balanced pattern of structure and the most polycentric pattern of development; there are significant development disparities between the largest urban centres, taken together with their immediate vicinities, and peripheral areas (Czapiewski and Janc, 2010).

This study is based on a data set generated by Internet users, collected using the publicly available Ookla Speedtest measurement tool. Using this tool, the authors have obtained information about the actual speeds[1] in the areas, rather than those declared by service providers or determined during one-off tests. Importantly, the procedure and conclusions resulting from the research process can be transferred and replicated on any spatial scale and in any spatial context. A large, homogeneous set of data that allows comparisons on a global scale is the key asset of this study. Identification of the ways this data set might be explored, as well as its information potential in the context of spatial analysis, is an important contribution to current research on the digital divide. Moreover, it should be noted that there is a research gap which takes the form of insufficient knowledge about Internet performance at the local scale. In the context of the changes (observed and potential) caused by the COVID-19 pandemic – for example in terms of work and education, spending free time and staying in forced isolation – recognising local scale Internet performance is becoming one of the priorities in the spatial approach to the subject.

Therefore, the novelty of this study consists primarily in identifying and defining the spatial differentiation of Internet performance at a local scale for the entire country. At present, the scholarly literature contains analyses that address the issue of Internet speed; however, in the context of the digital divide, discussion must be developed around the spatial aspects of this phenomenon. This is essential, because in our formulation, Internet performance is treated as being associated with Internet access, but also as having significant impacts on the benefits derived from that access. This sort of approach is essential when considering the perspectives for combatting the exclusion of certain areas, particularly in the context of challenges associated with the pandemic and other crises, as well as the acceleration of digitalisation.

2. A digital divide: different approaches from the spatial perspective

Society, facilities, and infrastructure are becoming more and more dependent on information technologies, regardless of the spatial (urban or rural) context (Streitz, 2018). It is indisputable that Internet infrastructure, particularly broadband, is necessary for business development and general economic development (for example, Magnusson and Hermelin, 2019; Tranos, 2013). From a spatial perspective, an important benefit arising from the use of digital technologies is the reduction of information asymmetry (Jeffcoat et al., 2012) – that is, equalisation of opportunities for the functioning of entities and communities regardless of location and physical access to information sources. Therefore, it is among those factors that eliminate locational discrimination, which affects many areas, primarily peripherally located (mainly rural) areas in relation to the centres of economic and social development. Importantly, villages benefit from the Internet more than cities because of their greater distance (as compared to cities) to alternative locations offering specific goods and services (Williams et al., 2016).

The literature on the subject clearly emphasises that the emergence of new technologies (including the Internet) and their adaptation and use are usually associated with cities. Cities provide the requisite conditions for their functioning and development – a high concentration of individual users and business entities (for example, Kitchin, 2015), the urban lifestyle associated with dependence on the latest technologies (Poncet and Ripert, 2007) and, thus, a greater tendency to absorb them. Although issues and problems in rural areas differ from those in cities (because of differences in economic and social structure), all Internet-based solutions have the same potential impact on development, regardless of location (Cowie et al., 2020). It is important to recognise that, in rural areas, however, the quality of Internet services often hinders attempts at taking advantage of opportunities offered by the Internet. Internet performance is not the only issue involved here: rural residents have less choice of Internet service providers and often pay higher prices for lower quality services (Sanders and Scanlon, 2021).

From a strictly geographical perspective, Graham (2011) separates digital divide into material and virtual exclusion. The former refers to the separation of people from access to digital space, the latter is connected to the blocking or hindrance of movement within digital space. It should also relate to invisible inequalities: the lack of visibility of some social groups and areas in digital space (Ferreira et al., 2021). As noted by Graham and Dittus (2022),

[1] The term "actual speed" should be understood as the speed experienced by users. This need not match the values offered by Internet service providers. Depending on hardware and impediments related to building structure, a user may experience lower connection speeds.

exclusion from content creation (participation) is to a large degree dependent on access to and cost of broadband. The issue of digital divide is closely connected with the geography of participation (Graham et al, 2015). The geography of participation analyses how individual communities are involved in the creation of digital content, primarily via posts on social media, or on services that take advantage of collective work (activities) to create content that is then used (or can be used) by all users of the Internet.

Since the beginning of the Internet, analyses of unequal access to it in various spatial systems have been carried out: between regions and countries and between rural and urban areas (for example, Gorman and Malecki, 2000; Grubesic and O'Kelly, 2002; Whitacre and Mills, 2007; Stephens and Poorthuis, 2015). But as Internet access becomes increasingly universal, other factors are coming to determine who enjoys the full benefits of the Internet and who is excluded from the digital realm. Beyond access, what is important is how the Internet is used and by what kind of users (Brandtzæg et al., 2011). Hence, over time, scholars began considering the role played by the range of skills and knowledge needed for appropriate and effective Internet usage. Hargittai (2002) and introduced the concept of the second-level digital divide, which analyses one’s level of Internet skills, particularly the ability to search for information. This is quite a significant extension of the concept of digital divide, as the mere fact of access cannot be treated as a synonym for using the Internet (DiMaggio and Hargittai, 2001).

The term ‘third-level digital divide’ has also been used in the literature. It refers to differences in benefits obtained from using the Internet (van Deursen and Helsper, 2015). Van Dijk (2005) systematises these different approaches and presents four levels of access to new technologies: motivation to use new technologies; physical access (access to a computer, access to the Internet); skills (strategic, informational, operational); and usage (different ways of using the Internet). Another approach to digital divide is related to the development of mobile technologies that enable the use of the Internet (such as tablets and smartphones). We can see the formation of a so-called ‘next-generation user’. This is a user who uses several devices to connect to the Internet, often ‘on the move’ and from multiple locations (Blank and Dutton, 2014; Lee et al., 2015).

The digital divide is associated with access to the Internet or, in a broader sense, digital technologies, skills, motivations and sociocultural preferences that translate into different ways of using them (Selwyn et al., 2005; Courtois and Verdegem, 2016; van Deursen and van Dijk, 2014). The digital divide is identified with social exclusion, where all members of a community are not able to fully participate in social and economic life. For instance, the way one uses the Internet can affect the socio-economic situation of the user. Better-educated individuals are more likely to use the Internet for the purpose of personal development rather than for entertainment (Taipale, 2013). This leads to an obvious conclusion: the digital divide is tantamount to social exclusion. The digital divide is not a static and homogeneous problem. Its characteristics change in both time (the rate at which new solutions appear and their diffusion) and space. We notice new forms of the digital divide linked to the emergence of new Internet applications, such as the smart divide (Li et al., 2020), related to smart device use.

The emergence of smartphones, other portable devices and the mobile Internet was one of the important stages in the development of the Internet, making it possible to use the Internet from almost any location. The mobile Internet can be treated, on the one hand, as a complement to the fixed version and, on the other hand, as an alternative to the fixed version in situations where individuals lack any other means of accessing the Internet – particularly in developing countries (for example, Srinuan et al., 2011), or in areas with unfavourable conditions for creating a fibre-optic infrastructure (for instance, mountainous areas), which are often also peripheral areas. The determinants of broadband mobile adoption and the characteristics of using this type of Internet in general are the same as in the case of the fixed Internet, with particular emphasis on the location, education, and age of users (Quaglione et al., 2020; Puspitasari and Ishii, 2016). At the same time, as noted by Tsetsi and Rains (2017), those who are less educated and earn less are more dependent on using the Internet only through smartphones.

In many developed countries, the issue of the first-level digital divide (in terms of access) is no longer very important. Most, if not all, residents can use the Internet and have access to it. The key issue, therefore, is to understand not so much broadband penetration as the effects of the broadband quality divide (Philip and Williams, 2019). Due to the increase in the number of potential applications of the Internet, the ability to transmit large volumes of data is important from the perspective of running a business or simply enjoying free time. In this case, symmetry is important – high download and upload speeds. Together with technological progress, new issues come into play, such as the speed of connection (for example, Prieger, 2003; Philip et al., 2015), or the possibility of using devices and the Internet freely outside of the home. Hence, the problem of broadband access, particularly in households, continues to be important. This has been particularly highlighted by the COVID-19 pandemic. Internet performance is, therefore, one aspect of the digital divide. Research in England shows that there are clear spatio-temporal disparities in Internet performance (Riddlesden and Singleton, 2014). Better Internet performance, with the same amount of time spent on the Internet, means an increase in the consumption of news, which translates into more knowledge about events (Lelkes, 2020). According to Lobo et al. (2020), broadband speeds could reduce unemployment, especially in rural areas. This is related, for example, to the development of so-called online labour platforms. They bring benefits, particularly in rural areas, in terms of opportunities to not only perform but also find a job (Braesemann et al., 2020). Kongaut and Bohlin (2017) demonstrate that faster broadband services have a greater impact and stimulate the economic growth of rural areas. Referring to the impact of speed on economic development, Stocker and Whalley (2018) state that it can be seen across the whole economy.

The events related to the transition of a significant part of the population to remote work and learning (due to the COVID-19 pandemic) have particularly shown that Internet speed is important not only in everyday life but also in terms of work and access to services. The most popular online meeting applications (such as Zoom and MS Teams) do not have high requirements for Internet speed – up to 10 Mbps download. In the case of streaming services (such as Netflix), the minimum requirements are also few Mbps, but the highest quality is 25 Mbps. Although these values are not high, if several services are used at the same time or by several users from one connection, the Internet speed must be much higher. Becker et al. (2020) define an Internet speed of 25 Mbps as ‘basic’ (it supports 1–2 users), 100 Mbps as ‘average’ (supporting 3–4 users) and 250 Mbps as ‘fast’ (supporting 4–5 users). Therefore, according to Dahiya et al. (2021), when paying attention to performance, one should focus not only on download, but also on upload (striving for symmetry) because upstream for home users has increased significantly due to the use of video conferencing applications during the COVID-19 pandemic. The so-called ‘online education deserts’ have been defined as those whose Internet speeds are below 25 Mbps download and 3 Mbps upload (Rosenboom and Blagg, 2018). For example, in Canada, the ‘basic services’ required for social and economic participation are 50 Mbps and 10 Mbps, respectively (Hambly and Rajabiun, 2021).

In this way, we should note that Internet performance and concrete access to high-speed Internet should be treated as elements of first level digital divide. What is essential, is that a growth in the scope of Internet use means ever greater dependence of achieved benefits on connection parameters. That dependence clearly corresponds to third-level digital divide. The extraction of benefits from having a fast Internet connection is an essential criterion for subsequent, ongoing social stratification. In this way, Internet performance, being an element of the first level, shapes the third level to a significant degree.

3. Data and methods

3.1 Data: Ookla as a source of information about Internet performance

The basic source used in this study is fixed broadband and mobile (cellular) Internet performance data provided by Ookla[2]. Ookla is a world leader in testing and evaluating Internet speed. The data are collected on a crowdsourced basis, from speed tests conducted by users around the world using stationary and mobile devices, applying the Speedtest tool. Data from crowdsourced speed tests have already been used in geographic studies on a local scale (Riddlesden and Singleton, 2014). Importantly, however, microscale analyses were limited to England. Data from crowdsourced tests (consumers’ feedback) are more reliable (if numerous) than those declared by providers, especially in the case of mobile data geographic coverage (Grubesic and Mack, 2015). Hence, the advantage of crowdsourced data over others is that the information about Internet speed and latency obtained in this way shows the actual Internet speed experienced (Lüdering, 2015).

In the context of measurements describing the state of broadband Internet connectivity, speed tests are performance measurements (Bronzino et al., 2021). In the case of Ookla, these are the so-called client-based tests. Ookla is not the only tool for testing Internet speed. It should be emphasised that, depending on the research methods adopted, individual tools can provide diametrically varied results for the same area[3] – nevertheless, Ookla is regarded as the best source of data for evaluating Internet speed (see Bauer et al., 2010). An important limitation is, therefore, the fact that data are obtained based only on the actions of those who conducted the tests. We do not have information about Internet speed from most Internet users, nor do we know about the conditions of the tests conducted (for example, hardware, operating system and so on). Potential data bias is also connected with the fact that we do not know the reason why tests were performed, nor the specific demographic and social attributes of the user population performing the tests. As noted by Paul et al. (2021), tests are usually performed in very specific situations (for example after setting up a new device or arriving at a new location). Aside from these limitations, we assume that with an adequately large number of tests attributed to the analysed spatial units, data are reliable and a representative indicator of general Internet performance.

The data provided by Ookla are spatial and cover the whole world. The values from individual tests have been aggregated to tiles of about 610 × 610 metres (at the equator), marked with a specially dedicated, unique ‘quadkey’. The following information can be obtained for each tile: download speed, upload speed, latency, the number of tests conducted, and the devices used to conduct the tests, broken down into quarters of a given year. Data quality depends on the activity and location of users, so the number of tiles is different for each quarter. There are two databases to download: one each for mobile and fixed Internet (based on tests performed for mobile and fixed connections, including Wi-Fi, respectively). In the case of Poland, the average number of tiles for the four quarters of 2020 was 103,567 for fixed Internet and 89,582 for mobile Internet.

3.2 Data aggregation

To obtain the average annual value of download, upload and latency for fixed and mobile connections, a two-stage data aggregation (temporal and spatial) was performed in each research unit.

Temporal aggregation involved calculating the average annual value (for 2020) for individual tiles based on the quarterly values of each parameter:

$$X_T = \frac{1}{n}\sum_{Q=1}^{n} X_Q$$

where: X_T = average annual value of a characteristic in each tile and X_Q = value of a characteristic in a single quarter of a given tile.

Spatial aggregation was performed next. In this study, communes (the smallest administrative unit in Poland) were adopted as the basic research unit. The aggregation of tiles to commune boundaries was performed in ArcGIS Pro, using the “union” tool, which computes a geometric union of the input features. On that basis, all tiles were assigned a commune code – in other words, a new field in the attribute table was added for each tile. This new field was the code of the commune in the territory of which a given tile is located. In cases where commune boundaries passed through a tile (where a tile was located on the territory of more than one commune), the tile was assigned the identifying code of the commune whose territory encompassed the greatest share of the tile in question. After establishing the prescription of tiles to communes, we could proceed to calculating the values of particular measures:

[2] Data are provided based on CC BY-NC-SA 4.0. Speedtest by Ookla Global Fixed and Mobile Network Performance Maps were accessed on 06.05.2021 from https://registry.opendata.aws/speedtest-global-performance. Speedtest® by Ookla® Global Fixed and Mobile Network Performance Maps.

[3] Feamster and Livingood (2020) discuss the technical matters that can impact speed test results. They include, among others, test duration, test server capacity, distance to Wi-Fi Access Point, and client hardware and software.

$$X_U = \frac{1}{n}\sum_{T=1}^{n} X_T$$

where: X_U = average annual value of a characteristic in all tiles within a given unit and X_T = annual value of a characteristic in a single tile within a given unit.

Ultimately, each research unit was assigned the values of six characteristics: the average annual download for fixed and mobile Internet; the average annual upload for fixed and mobile Internet; and the average annual latency for fixed and mobile Internet.

Within urban–rural communes[4], however, cities and rural areas have been separated, making two types of units. On average, 111 tests on 57 devices with mobile connections and 283 tests on 141 devices with fixed connections were carried out in each research unit. In almost 99% of the research units, measurements were taken in each of the quarters, and only in a few cases was no measurement recorded in any of the quarters covered by the analysis.

3.3 Classification method

To achieve the aims of the study, attention was paid to the relationships between the basic parameters characterising Internet performance in spatial terms – through the classification and analysis of research unit rings around the largest cities: province capitals.

We divided the community based on positional measure – in this case, the median was the dividing value. Using this approach, for fixed–mobile Internet pairs for the download, upload and latency variables, the community was divided into four classes and simultaneously evaluated – from I (the best) to IV (the worst) (see Fig. 1). It should be noted that in the case of classes II and III, the one in which the fixed and mobile connection was characterised by a higher value of a given parameter was treated as more important (better)[5]. In the case of the latency parameter, the principle according to which classes were assessed was the inverse of that for download and upload. The lower the latency the better. The order of the classes was determined by the higher value of a given parameter for fixed connections. The base classifications obtained in this way became the starting point for the final classifications[6]. They are a combination of base classifications for individual parameters of the functioning of fixed and mobile Internet performance (download, upload, latency), followed by their comparison with each other. In this way, 16 categories (4 × 4) were created and finally grouped into seven classes. The idea of the applied approach is presented by comparing the basic classifications for download and upload speeds (Fig. 2).

Individual categories were assigned to individual classes based on the number of parameters that were higher (download, upload) or lower (latency) than the median for each Internet connection (fixed, mobile). Thus, the individual categories belonging to each of the seven classes

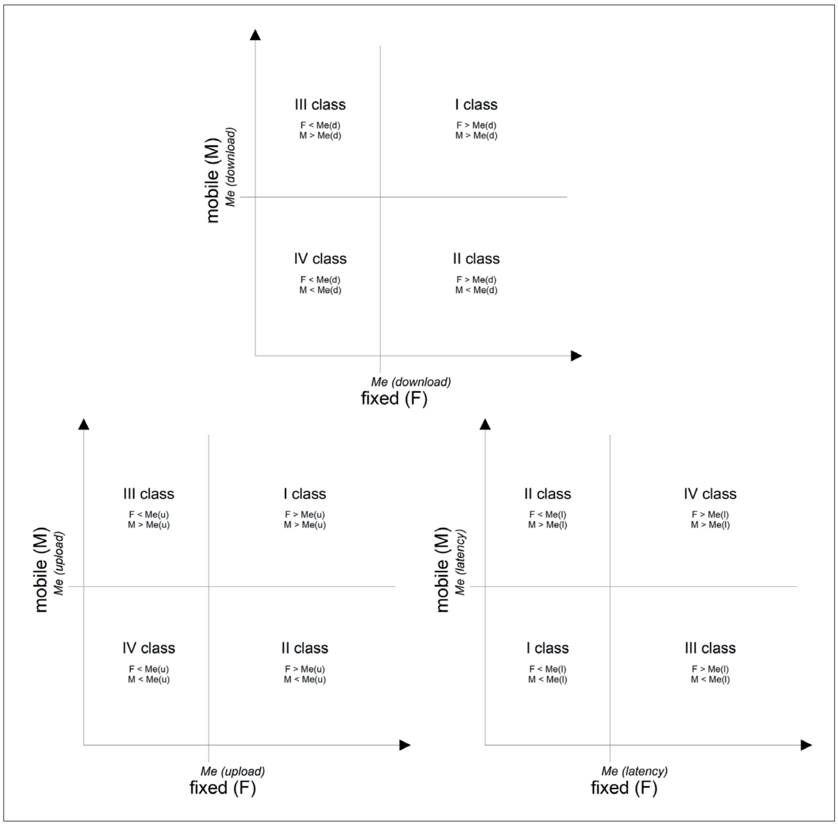

Fig. 1: Schemes of base classifications for individual Internet performance characteristics (download, upload, latency). Source: authors' elaboration

[4] In the smallest administrative unit in Poland, a division into three categories has been adopted: urban communes, rural communes and urban–rural communes.

[5] Higher values are desirable for download and upload, as opposed to latency.

[6] The results show two classifications, namely download–upload and upload–latency. This approach results from the fact that the upload–latency and download–latency classifications in fact show the same spatial differentiation.

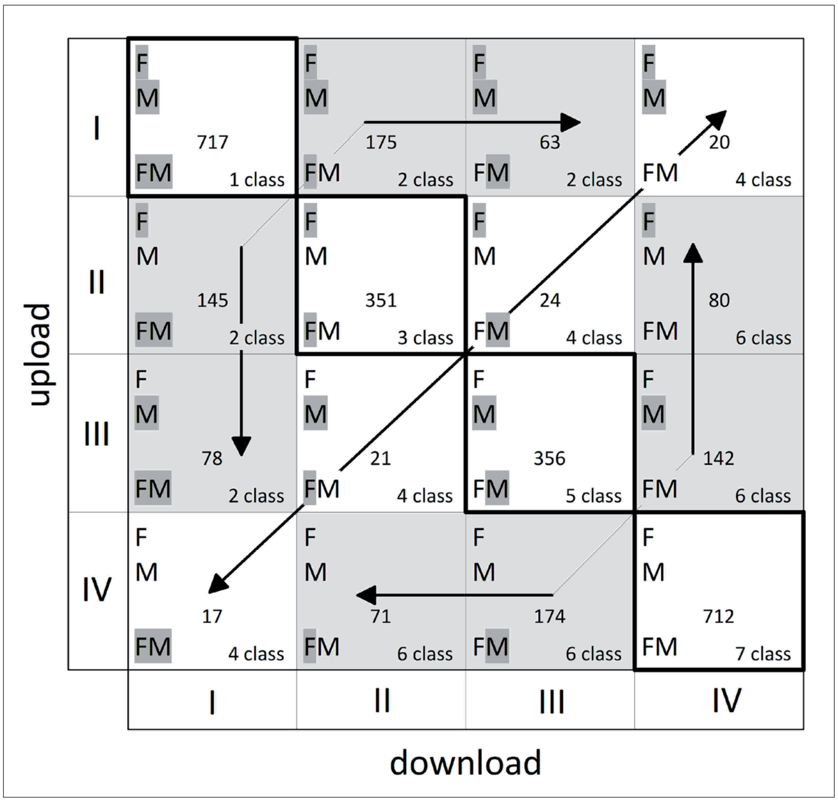

Fig. 2: Scheme of final classifications with categories (16) assigned to individual classes (7) using the example of the download–upload system. Source: authors' elaboration
Legend: (1) the darker grey colour marks those the Internet parameters (upload/download) that are characterised by values above the median for a given type of Internet connection (fixed, mobile) in a given category; (2) those categories that belong to one class are marked with a lighter grey colour in order to make the whole classification easier to understand; (3) the types of Internet connection for the download parameter that are above the median are marked in the lower left corner of each category—as for individual classes of the base classification (see Fig. 1); (4) the types of Internet connection for the upload parameter that are above the median are marked in the upper left corner of each category – as for individual classes of the base classification (see Fig. 1).

are unambiguous (see Fig. 2). For example, in the first class, the values of the Internet performance parameters (upload and download) for fixed and mobile connections are in each case above the median. Similarly, in the 7th class, the values of the Internet performance parameters (upload and download) for fixed and mobile connections are in all cases below the median. Analogously, in the 2nd class, the values of only three parameters are above the median, and in the 6th class, the values of only one of the parameters are above the median. The 3rd, 4th and 5th classes are those that have two Internet performance parameters above the median in each category belonging to these classes. Their order is firstly a consequence of the sequence of categories, from the one that makes up the first class to the last, 7th class. Second, this order results from whether the Internet performance parameters (upload, download) are above the median for fixed or mobile Internet. Thus, for the 3rd class, download and upload were above the median for fixed connection as opposed to the 5th class, where the values above the median related to the mobile Internet. This distinction, based on the consequence resulting from the logical sequence of the categories, is also justified by the fact that both download and upload for fixed Internet are higher than for mobile Internet. The manner and idea by which individual categories were ordered into distinct classes is further presented in tabular format (Tab. 1).

An additional comment is necessary to justify the categorisation in classes III, IV and V (see Tab. 1). In all three of these classes, we are dealing with various combinations of parameters in which the values of two of those parameters are greater than the median. As mentioned above, the upload and download parameter values for the entire grouping of the analysed entities constitute the basic criterion distinguishing one classification from another. When establishing the order of the classes, however, in addition to the number of classes above the median value we also assigned priority based on whether those values are for fixed or mobile connections. Fixed connections were more important, considering their higher upload and download values as compared with mobile connections. Aside from the fact that we are dealing with various combinations of individual parameters that apply to download and upload in differentiated classifications, the order of those classifications can additionally be justified by way of the mean value of all parameters defining a given classification. Such is the case for class III category 6 (see Tab. 1): the average transfer is 45,222 kb/s. For Class IV this value is only 34,908 kb/s. On the other hand, in the last of the classes under discussion (V) average transfer in those of its categories above the median is merely 25,270 kb/s. In this way, such clear differences in Internet speed can serve as the basis for the elaboration of variegated policy aimed at equalising Internet access.

In this study, the issue of the relationship between metropolises and their surroundings was presented through the analysis of data for subsequent rings of units (communes) surrounding the cores, that is, the capital cities of regions. This approach results from identifying

Classes	Categories	Number of Internet performance characteristics above the median	Upload		Download	
			fixed	mobile	fixed	mobile
I	1	4	+	+	+	+
II	2	3		+	+	+
	3		+		+	+
	4		+	+	+	
	5		+	+		+
III	6	2	+		+	
IV	7	2			+	+
	8			+	+	
	9		+			+
	10		+	+		
V	11	2		+		+
VI	12	1			+	
	13					+
	14			+		
	15		+			
VII	16	0				

Tab. 1: Assigning of categories (16) to individual classes (7), as well as indication of how they were assigned: number of Internet performance characteristics above the median. Source: authors' elaboration
Legend: (1) assignment performed according to upload and download Internet performance characteristics; (2) for classes II, IV and VI the number of Internet performance characteristics above the median value is 3, 2, and 1, respectively. In the case of classes II and IV, differences between individual categories is determined by various arrangements or configurations of the Internet performance characteristics. For the categories that are part of class VI only one Internet performance characteristic was above the median value.

the urban–rural digital divide as a metro/non-metro divide (Whitacre et al., 2015). The unit rings have been defined based on the principle of having a common border. Thus, the first ring surrounding the core included those units that adjoined its border (they had a common border at a point or line). The second ring was made up of units that were tangential to the first. The analyses were carried out for 16 (18)[7] cores, as well as for the next three rings, and for the remaining areas (those outside the previously defined rings). The adoption of the core–periphery system as a reference point for the analysis assumed that values in successive rings decrease, and the units in the rings are more like each other than to the units from the remaining rings. This assumption is because the further from the core of a given area, the suburbanisation processes are less and less advanced (for example, Wolny, 2019; Szmytkie, 2020). It is important to determine the distance beyond which development impulses sent from the core are weaker or disappear completely. In the case of Poland, the range of influence of core centres usually covers the first three rings of a research unit around a core. This area is 50–60 kilometres away from its centre – the core. The first ring includes the direct surroundings of the core (Szmytkie, 2019; Ilnicki and Janc, 2021). The second ring, due to the presence of urban units in it, is characterised by a simultaneous strong bond with the core and its immediate surroundings (Ilnicki and Janc, 2021). In the third ring, links between rural areas and the core and towns in the second ring are primarily observed (Fig. 3). Given the fact that the Internet performance characteristics (download, upload, latency) are regional (see classification results), each ring has been limited to the area of a given region or province. This means that when some parts of the research units forming any of the rings were outside the borders of a given region, they were not considered. This is justified because the proximity of some regional capitals would also result in the overlapping of rings and their 'double' classification to the characteristics of individual rings.

4. Results

4.1 General correlations

In July 2021, for mobile Internet, the global average was 55.07 Mbps download and 12.35 Mbps upload speeds, and latency was 37 ms; for fixed broadband, the values were 107.50 Mbps, 58.27 Mbps and 20 ms, respectively. Compared to July 2018, a significant increase in values was observed for each characteristic. Back then, the averages were 22.81 Mbps download and 9.13 Mbps upload speeds for mobile Internet, and for fixed broadband 46.48 Mbps and 22.5 Mbps, respectively (Speedtest Global Index, 2021). Poland was in 45th place in terms of mobile Internet with the following parameters: 55.06 Mbps download and 11.03 Mbps upload

[7] In the case of two provinces (Cuiavian-Pomeranian Province and Lubusz Province), two cities act as the capital, Bydgoszcz/Toruń and Gorzów Wielkopolski/Zielona Góra, respectively. In Poland, a province is the highest-level administrative division (the term "province" is a synonym for "voivodship" – *województwo*).

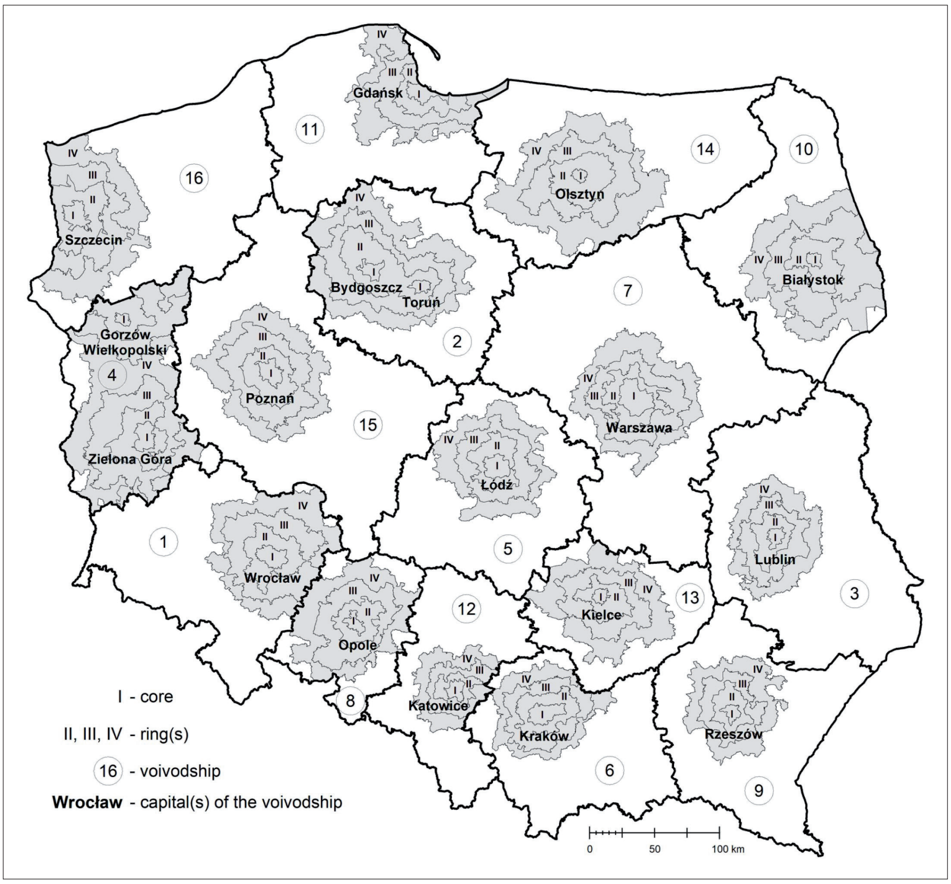

Fig. 3: Research unit cores and rings around them. Source: authors' elaboration
Legend: (1) Lower Silesia Province, (2) Cuiavian-Pomeranian Province, (3) Lublin Province, (4) Lubusz Province, (5) Lodz Province, (6) Lesser Poland Province, (7) Mazovia Province, (8) Opole Province, (9) Subcarpathia Province, (10) Podlasie Province, (11) Pomerania Province, (12) Silesia Province, (13) Świętokrzyskie Province, (14) Warmia-Masuria Province, (15) Greater Poland Province, (16) West Pomerania Province.

speeds, and latency of 32 ms, while for fixed broadband the values were 43.15 Mbps download and 50.57 upload speeds, and latency of 20 ms.

In the case of Poland, there are visible correlations between all three performance measurements (see Fig. 4). This applies to both fixed and mobile Internet connections. There is a strong positive linear correlation between download and upload speeds. Taking account of the entire set of units (n = 3,143), the correlation is higher for fixed than for mobile (Pearson's linear correlation coefficients are 0.795 and 0.722, respectively).

On the other hand, comparing upload and download speeds with latency, the presence or absence of curvilinear correlations can be stated for fixed and mobile Internet. Taking account of the differentiation of units in cities and rural areas, it is noticeable that there is much less latency in cities.

4.2 Spatial differentiation: classification

Reference to a settlement network is crucial to understanding the spatial diversity of issues related to Internet performance. In 2020, the Polish settlement network included 944 cities (Fig. 5). Small cities (up to 20,000 residents) accounted for over 75% of all cities. Sub-regional centres of up to 50,000 residents made up just over 14% of cities. Less than 9% of cities (73) had more than 50,000 residents. There were 14 large cities (over 200,000 residents). The Polish urban settlement network is polycentric in nature, dominated by regional capitals, including the 'big five'[8]. The current shape of the settlement network is a derivative of the intensive suburbanisation processes that began to take place primarily in cities with a population of at least 100,000 residents in the second half of the 1990s. It is important that a positive balance of migration for permanent residence remains between cities and their surroundings (Ilnicki, 2020; Ilnicki and Szczyrba, 2019).

When analysing the spatial differentiation of the basic parameters of Internet performance (Fig. 6), several general regularities should be noted. First, the two classifications presented create a similar pattern of spatial differentiation. Secondly, there is no direct reference to the city-village dimension at the scale of the entire country, and regularities are not subject to regionalisation referring directly to the settlement network (core-periphery systems). Two regions stand out clearly, namely Silesia and Greater Poland, as having the best performance. Also, in the case of some regions, practically all their units, except for cities and possibly their surroundings, can be assigned to the worst performance classes. The core-periphery system is visible in the case of some of the largest centres. Warsaw, with a large suburban area, and most of the regional centres stand out in this regard, as all Internet performance parameters indicate their privileged position. At the other extreme are many rural areas, particularly in the central and north-eastern regions.

[8] Kraków, Poznań, the Tricity metropolitan area (Gdańsk, Gdynia, Sopot), Warszawa, Wrocław.

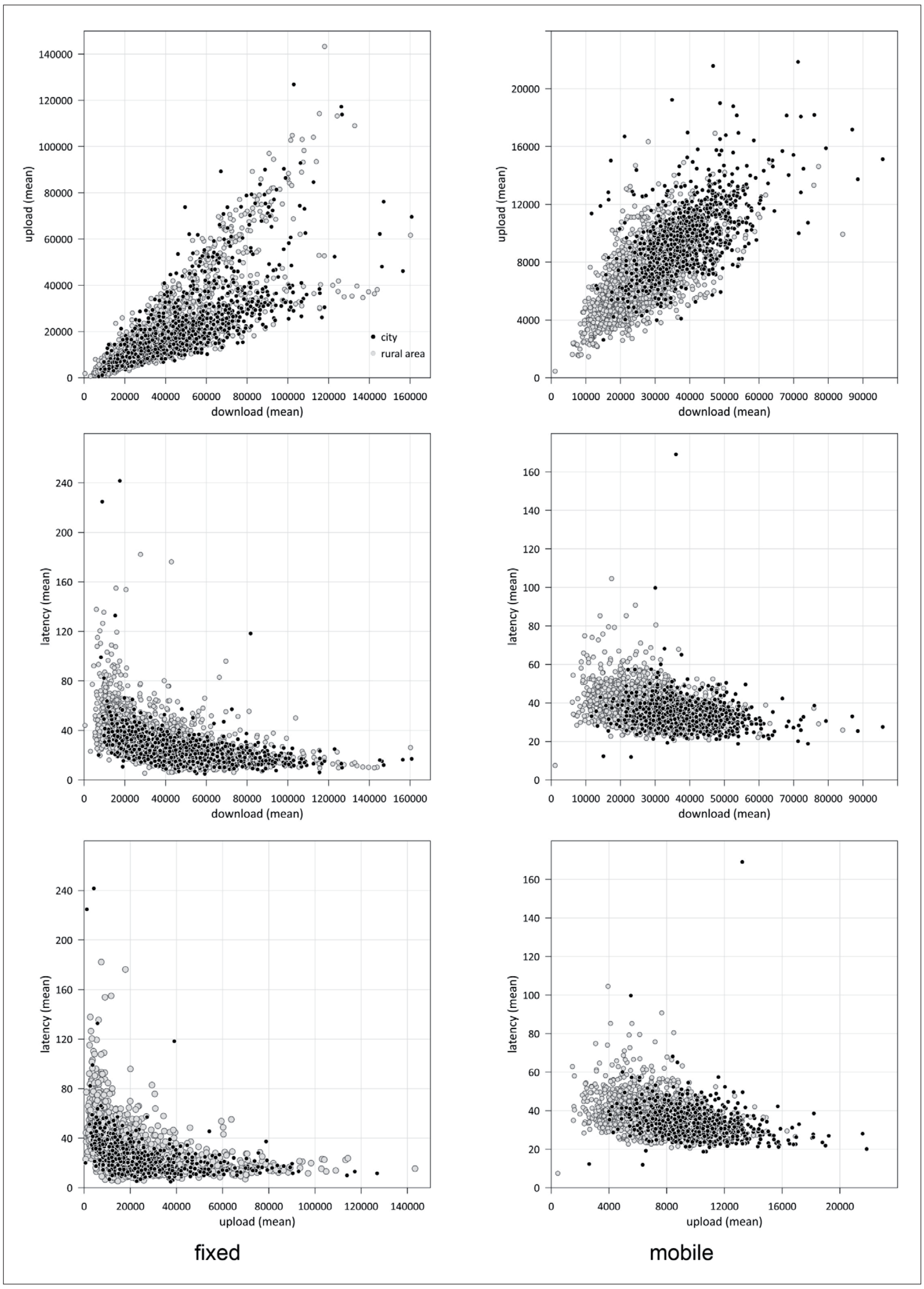

Fig. 4: Correlation between performance measurements (download, upload versus latency) for fixed and mobile Internet by city and rural area. Source: authors' calculations

Thus, the classifications create a picture of the diversity of Internet performance, which consists of two dimensions: regional and core-periphery. The regional dimension, particularly the strong position of the Greater Poland province, is a consequence of individual investment-related activities implemented under the Digital Poland Operational Programme and the operability of the regional Internet providers resulting from their investments. In the case of the Greater Poland province, the Internet provider Inea operates there[9], offering the fastest Internet in Poland. It is one of only a few providers offering access to a fully symmetrical Internet – the same (high) upload and download speeds. Similarly, PPCOM operates in Katowice (Silesia province) and offers symmetrical Internet plans for individual users. It is worth noting that the largest Polish Internet providers – providing services throughout the country or a significant part of it – do not usually offer symmetrical Internet speed.

4.3 Spatial differentiation: the core versus surroundings and the periphery

The observations resulting from the presented classification are confirmed in the concentric ring approach to the analysis for regional centres, which are treated as cores. Comparison of the basic parameters of Internet performance (see Fig. 7) clearly shows the following correlation: the further away from the capital of the region – the core – the less favourable values are for Internet speed and latency. There is a virtually linear, proportional variation in the values of upload and download speeds for both fixed and mobile connections.

[9] This company is based in Poznań and has been operating primarily in the Greater Poland province for over 12 years.

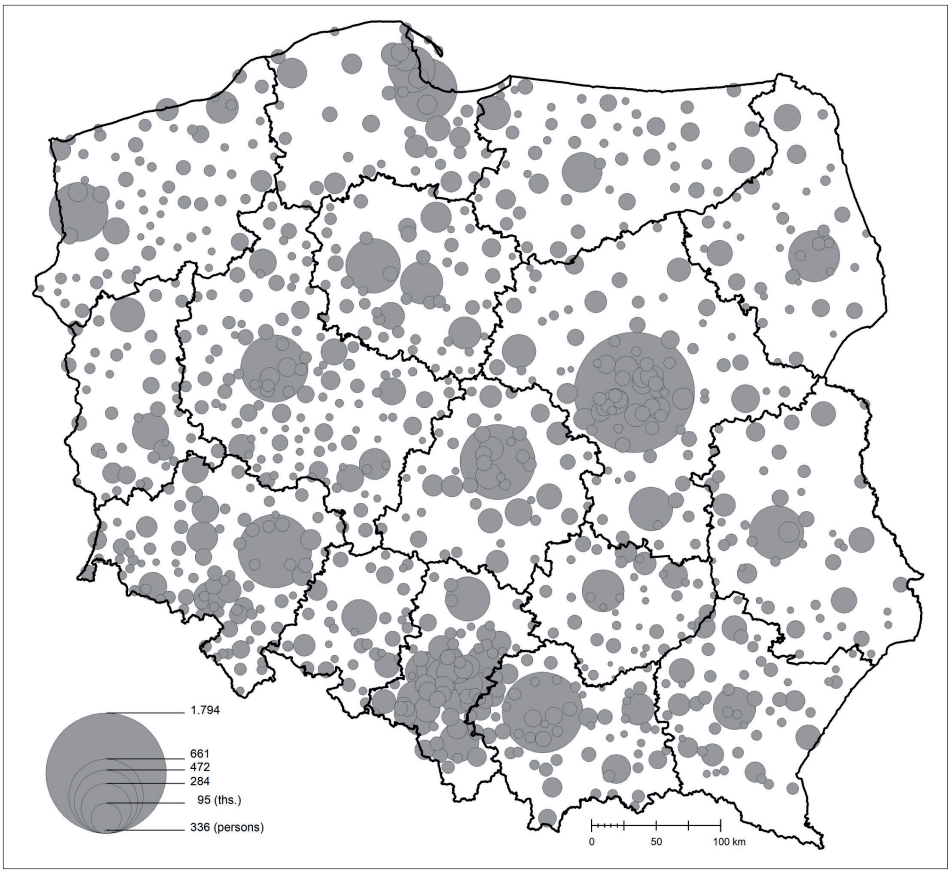

Fig. 5: Population of cities in 2020: square root scaling
Source: authors' research based on Statistics Poland

Moreover, there is also a general regularity: namely, the analysed values decrease from the core outwards through consecutive rings (the highest values – the core, ring I, ring II, ring III – the lowest values).

These observations are confirmed in the juxtaposition of the median values for Internet speed parameters (download, upload, latency) for "core/rings" and "other areas" in general perspective, without their disaggregation into core and surrounding rings (Tab. 2). Firstly, general Internet speed parameters for core and rings overall are better than for other areas. Secondly, in the case of core and subsequent rings, there is a visible decrease in Internet speed values with increasing distance from the core (for which said values are the highest).

Other correlations for rings (download–latency, upload–latency) are not as clearly linear as in the previous case. Nevertheless, there are similar values within individual groups of units (core, rings I–IV). It is also worth paying attention to one more issue, namely, the values of the analysed Internet parameters for other areas relative to

Specification			Core/rings				Other areas
			I	II	III	IV	
Fixed	download	cities	97,865	69,326	53,111	44,908	42,523
		rural areas	–	41,940	29,687	23,497	22,444
	upload	cities	34,166	26,675	20,962	17,542	16,499
		rural areas	–	17,783	12,043	9,972	9,723
	latency	cities	14	16	19	23	24
		rural areas	–	27	32	32	34
Mobile	download	cities	42,545	36,976	38,987	37,456	37,592
		rural areas	–	29,807	27,005	27,390	26,747
	upload	cities	12,369	9,605	9,909	9,531	9,633
		rural areas	–	7,445	7,076	6,987	6,886
	latency	cities	25	30	31	33	34
		rural areas	–	34	35	36	37

Tab. 2. Internet speed for core, rings and other areas in general perspective
Source: authors' calculations

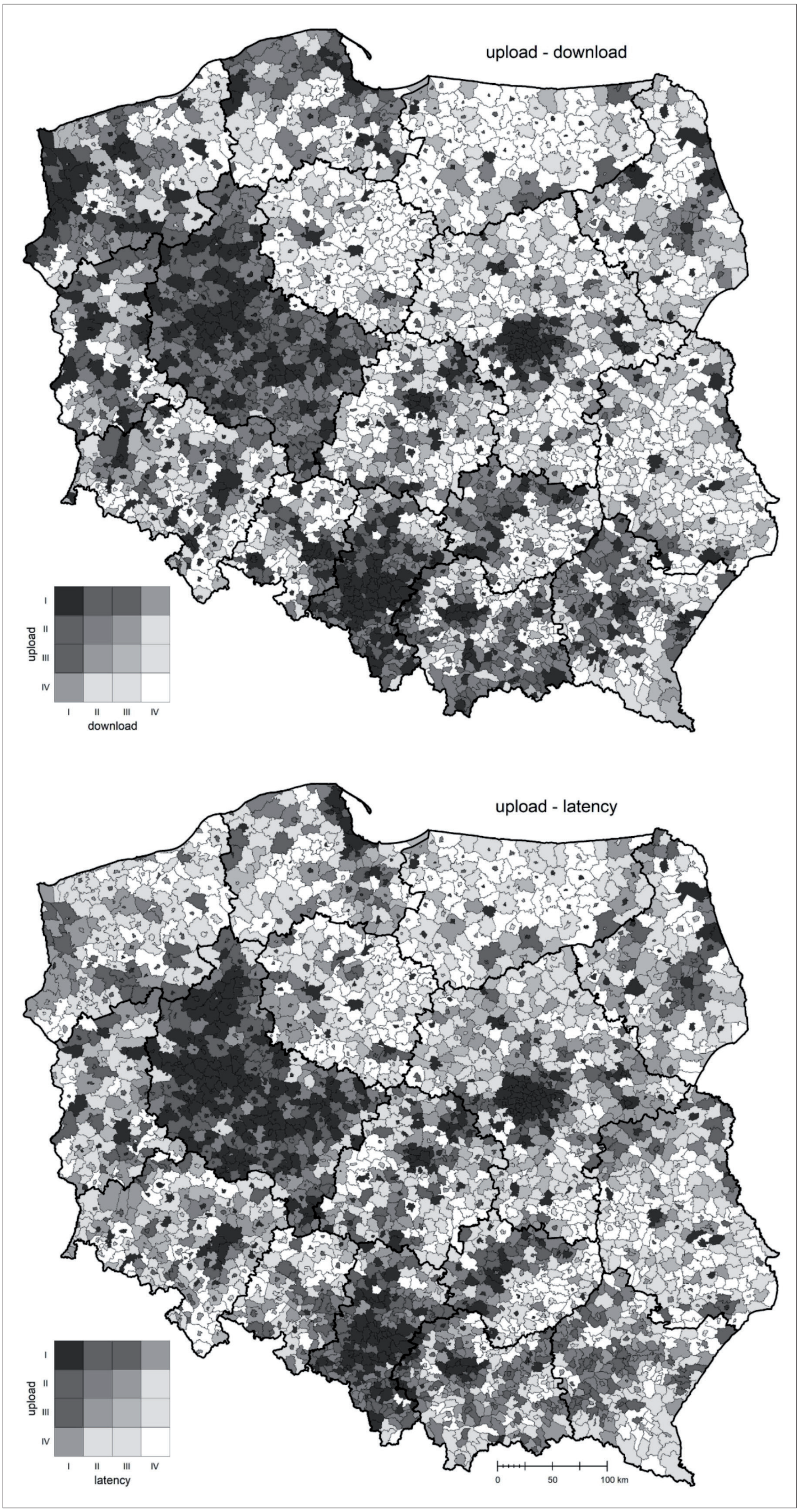

Fig. 6: Final classifications for two sets of performance measurements: download–upload and upload–latency
Source: authors' elaboration

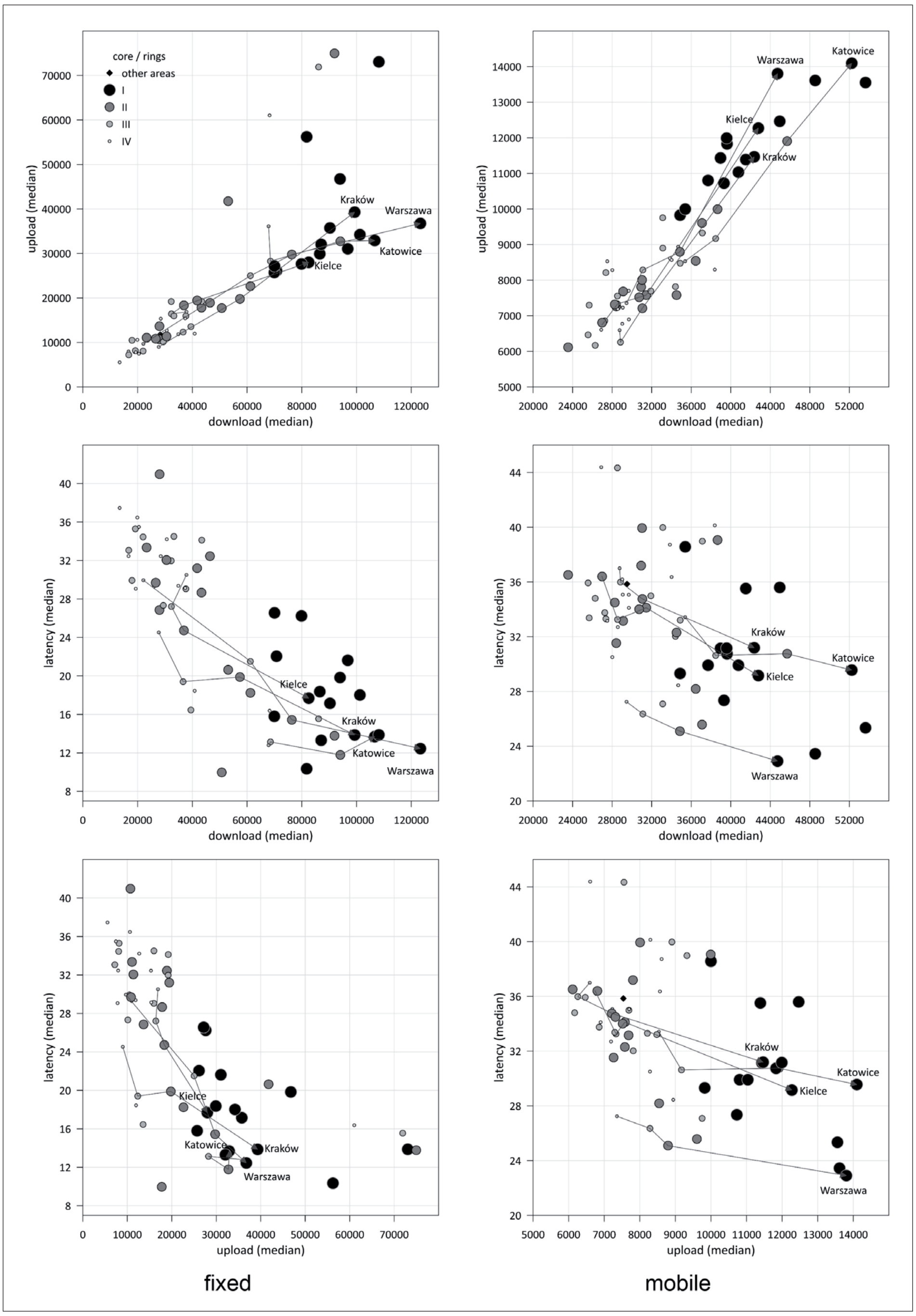

Fig. 7: Correlations between performance measurements (download, upload, latency) for fixed and mobile Internet for the core and the rings of regional centres. Source: authors' elaboration

those describing the cores and subsequent rings. Other areas, to a large extent, have clearly lower and less favourable characteristics of Internet performance than core and ring areas, especially the cores and the first (I) ring units.

5. Discussion and conclusions

Many studies have indicated the presence of the core–periphery system in various aspects of the development and performance of the Internet, particularly in terms of infrastructural differences (for example, Grubesic, 2008; Warf, 2013). Based on the example of Poland, this study shows that, in terms of the Internet performance experienced, we can observe the existence of a system with a 'superimposed' regional dimension. This is important because, from the perspective of creating the foundations for development, it indicates the possibility of reducing unfavourable conditions resulting from the peripheral location of rural areas. Regional Internet providers who make significant investments in infrastructure enable significant reductions in the digital divide. Of course, as is the case with other types of infrastructure that meet basic human needs, the investments are usually carried out to equalise the level of accessibility and improve quality. Thus, it can be assumed that fast, symmetrical Internet will eventually appear in less developed regions. The key question, however, is what consequences will result from the delay in investment. A few months, a year or several years may be a sufficient period for the residents of areas to lose/gain from online work, education, or participation in culture. The formation of differences, magnified by forced isolation, may contribute to the creation of a vicious cycle that deepens the digital divide

(Warren, 2007): namely, people and households with high quality Internet performance will gain a real advantage over those with a poorer level of Internet performance.

In the case of Internet performance, it should be noted that we cannot regard mobile Internet as a perfect substitute for a fixed connection for the residents of remote areas (Srinuan et al., 2012). The analysis carried out for Poland clearly shows that mobile and fixed Internet are closely related. What is important, however, is that, on a larger scale, there is no substitution for a fast connection. Of course, the progress made in the operation of mobile broadband (5G technology) may be the basis for the claim that mobile Internet in rural areas will meet expectations. 5G, however, is currently more common in urban areas; it is being rolled out first in large urban centres. The previous statement can also be applied to another solution enabling high-speed Internet access in rural areas. Satellite Internet, specifically the Starlink service, promises high-speed Internet access regardless of location. This service is currently unavailable in many areas, however, and relatively expensive compared to other types of access. The Internet performance parameters offered, the lack of symmetry and relatively high latency, are also not satisfactory. Bearing in mind the perspective of technological development, improvements and assuming the dissemination of satellite access, however, it is reasonable to ask how and whether it will affect the identified regularities.

As Lüdering (2015) points out, in the case of digital divide analyses, it is crucial not so much to define the participation of people through their level of Internet access, but to define Internet performance (for example, latency and speed). Our study has revealed an important dimension of the digital divide by showing the real speeds of the Internet. Ensuring that measures declared by Internet providers are not used as a source of data in spatial analyses is crucial for understanding the analysed phenomenon. This is particularly important and visible in areas distant from metropolises, where the 'effective bandwidth available to users can diverge significantly from the maximum theoretical "best effort" (up to "X" Mbps) speeds' (Hambly and Rajabiun, 2021, p. 3).

Despite the limitations related to the specificity of data, the analyses presented here have indicated several significant characteristics of spatial differentiation of Internet performance, simultaneously indicating new directions and areas for further research. First, in the case of the Internet, the core–periphery dimension is not universal and obvious, as regional systems are strongly marked. Second, perceiving the digital divide mainly through the prism of Internet access is an insufficient approach. At present, it can be treated as an unauthorised simplification. The importance of Internet performance has been additionally reinforced by the Covid-19 pandemic. The increase in the scope of Internet use has increased its dependence on good connection parameters. This clearly corresponds with the third-level digital divide. The benefits obtained from having a high-speed Internet – preferably symmetrical – are an important criterion for progressive, subsequent social stratification.

As Sanders and Scanlon (2021, p. 136) note, "With the advancement of technology comes the evolution of need". Hence, expectations of Internet performance are growing and will continue to do so as the range of services offered expands and their quality increases. In spatial research, we should look at the Internet from the perspective of its most important parameters, relations between them and particularly in terms of the symmetry of Internet speeds.

The results of this study are of vital importance for policy recommendations. In the case of Poland, we should note that regional and local Internet providers have turned out to be the most effective at providing a fast Internet connection. As such, they should be supported, especially in areas where investment is unprofitable from an economic point of view. This study also emphasises the important role of programs supporting high-quality Internet access, and their impact on the digitisation of the country, broadly conceived. This study has also enabled us to positively verify the usefulness for spatial analyses of data drawn from crowdsourced speed tests. The ability to use data that provide information about important aspects of Internet performance (for example, its symmetry) on a local scale is an invaluable resource in understanding the relationship between the individual categories of areas (for example, the core-peripheries, areas of growth-areas of stagnation, city-rural areas) and correlations between them.

We should also note the necessity of undertaking further research into the issues described (which can be performed in other countries as well, thanks to the comparability of data). It would seem particularly important that data regarding Internet performance be juxtaposed with data on social group characteristics and on levels of income and education. Doing so will enable us to grasp the invisible divide – that is, situations in which social and economic issues make it so that people cannot permit themselves access to high-speed Internet. Identifying such issues will enable better us to better understand how aspects of the digital divide relate to Internet performance. Of similar interest is research that accounts for the infrastructural dimension of space (e.g. highways). In both cases, however, there is a dilemma regarding the appropriate selection of units of analysis and research areas. We should also emphasise that, as regards the differences that emerge between various tests, it would be ideal to base research on data from multiple speed-test providers, averaging them out to get the best estimate of local speeds. A key challenge, however, is data coverage – whereas Ookla provides data for the entire world, many other databases are limited, for example, to the national scale.

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