Original article

Analysis of morphological changes of rural settlement patterns after World War II in the metropolitan area of Łódź using a graph theory based method

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ABSTRACT

This research concerns the complex problem of morphological transformations of villages in the intra-urban area (i.e. settlements incorporated into city), as well as the suburban area, using the example of the metropolitan area of Łódź, Poland. The main aim of the research was to analyse the diversity of selected rural settlements and their spatial changes after World War II. The study was based on preserved historical maps and today's plans. An analysis of morphological changes of selected villages was conducted using graph theory methods. It was noticed that the graph development index should depend on the relative number of edges in relation to the number of nodes and the number of graph cycles, which express the degree of complexity of a settlement unit. Three main groups of villages, characterised by different scales of morphological transformations, were distinguished as a result of the study. Settlement units with orthomorphic transformations, where all spatial modifications were mainly additive and the initial layouts have been preserved almost completely, represent the first group of villages. The second group is composed of units with semi-metamorphic transformations, where the spatial reorganization was significant, but not total. The third group includes villages with metamorphic changes, where the initial layouts have been totally transformed.

KEY WORDS: rural morphology, urban morphology, incorporation, sub-urbanization, graph theory based method

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1. Introduction

The aim of this article is to identify the main directions of morphological transformations to which the villages located in the Łódź metropolitan area have been subjected during most of the last century. This includes the former villages located in the peripheral zone of Łódź, which were incorporated into the city after World War II. The study focuses exclusively on changes in the village layout caused by urbanisation processes, but omits their physiognomic aspect (WHITEHAND, 1987; KOTER, 1994a; FIGLUS, 2016). The analyses concerning changes in the spatial arrangement of buildings were made using a method based on graph theory.

The time scope of the article includes the period from the end of the 1930s to the present day and is historically determined and based on the availability

of the cartographic materials. The intensification of the suburbanisation processes in villages in the vicinity of Łódź has been observed after World War II, and was accompanied by clear territorial development. During this period the area of Łódź increased from 58.75 to 293.25 km² (SZAMBELAN & STĘPNIEWSKI, 2009). The greatest morphological transformations of villages in the study area have taken place in the present time and resulted directly from political and economic transformation after 1989.

The spatial scope of the study covers the area of former rural settlements in the peripheral zone of Łódź, which were successively incorporated after 1945, and the area of neighbouring counties, located within the Łódź metropolitan area (WÓJCIK, 2013). General analyses consisted of comparisons of the condition of development on topographic

maps from two extreme research moments which were made for all villages incorporated into Łódź after 1945 and for most of the villages in the suburban zone. Detailed research was conducted for twelve settlement units, including six former villages that were incorporated into Łódź after World War II and six villages located outside the

city limits, located in the metropolitan area (Fig. 1). The selection of villages for quantification analyses was deliberate and consisted of the creation of representations of settlement units, which are characterised by different degrees of morphological transformation.

Fig. 1. Study area and location of settlements included in detailed analyses. Source: own studies

The literature on the suburban area includes many theoretical problems, concerning terminology and research methods, as well as specific empirical studies. This problem is often analysed in the context of the urban sprawl process and in the concept of the rural-urban continuum (CLAWSON, 1962; REISSMAN, 1970; CONNEL, 1974; SQUIRES, 2002; WOODS, 2005). The suburban zone develops: within the administrative boundaries of the city (internal suburbanisation), outside the city limits, urban fringe, and is characterised by the relative spatial continuity of investment; and is outside the direct administrative neighbourhood of the city, urban-rural fringe, and has a predominance of extensive forms of land use (LISOWSKI & GROCHOWSKI, 2009). In Polish research on the urbanisation of villages near the city, or within its borders, the issue of the general considerations about this process were often taken into account (E.G. PROCHOWNIK, 1975; KOTER, 1985; LISZEWSKI, 1987; DZIEGIEĆ, 1995; SOKOŁOWSKI, 1999; BAŃSKI, 2005; 2012; KACPRZAK & STASZEWSKA, 2011; MAIK, 2012; STASZEWSKA, 2012). The issue of morphological transformations of former rural settlements and suburban zones were quite often examined in studies of large Polish cities, such as Wrocław, Warsaw, Poznań, Lublin (e.g.

GOLACHOWSKI, 1966; RAKOWSKI, 1975; MISZEWSKA, 1996; 2002; JAKÓBCZYK-GRYSZKIEWICZ, 1998; WESOŁOWSKA, 2006; KACPRZAK & STASZEWSKA, 2008; BAŃSKI & WESOŁOWSKA, 2010; KAJDANEK, 2011; MANTEY, 2011; SZMYTKIE, 2011; SOBOTKA, 2014; SZCZEPAŃSKA & WILKANIEC, 2014; MISZEWSKA & SZMYTKIE, 2015; 2017). The process of spatial transformation of the villages near Łódź was also undertaken by researchers (e.g. STRASZEWICZ, 1954; JAKÓBCZYK-GRYSZKIEWICZ, 1991; MATCZAK, 1991; WÓJCIK, 2006; 2013; FIGLUS, 2020). These works analyzed various aspects of spatial and functional changes in rural areas, including some elements of the morphological structure. The authors of this article decided to verify the previous findings of researchers on the transformation of villages in metropolitan zones with the example of Łódź, using a method based on graph theory.

2. Methods and source materials

Graph theory was used to analyse the morphological changes to which the villages incorporated into Łódź after World War II and currently located in the suburban area of the city were subjected to during the last century. In algebraic

topology, a graph is understood to be a geometric figure consisting of vertices and the edges that connect them. On the basis of this concept, it is possible to describe elements of a structure, or to identify the complicated relationships between them (HAGGETT & CHORLEY, 1969; TAYLOR, 1974; RATAJCZAK, 1977; TINKLER, 1977; KORZAN, 1978; KULIKOWSKI, 1986; ÖRE, 1990; GROSS & YELLEN, 1999; RODGERS, 2005; RUNGE, 2006; JAŹDŹEWSKA, 2008b; NEWMAN, 2010).

The mathematical models formulated on the basis of graph theory have been used quite extensively in socio-economic geography (TINKLER, 1977; SZMYTKIE, 2014). Graph theory methods have often been used in research on the structure of transport systems (GARRISON & MARBLE, 1963; KANSKY, 1963; GARRISON, 1968; JAMES ET AL., 1970; TAYLOR, 1975; 1979; RATAJCZAK, 1980; 1992; RYKIEL, 1981; POTRYKOWSKI & TAYLOR, 1982; SLENCZEK, 1982; RUNGE & SURMACZ, 1986; PALKA ET AL., 2001; RYDZEWSKI, 2001; BAGIŃSKA, 2007; XIE & LEVINSON, 2007; DUCRUET & LUGO, 2013). In the field of settlement geography, graph theory was reflected in studies of settlement networks and systems (HAGGETT, 1965; NYSTUEN & DACEY, 1968; ZAGOŹDŹON, 1970; 1977; CZARNECKA, 1971; KOSTRUBIEC, 1971; GOLACHOWSKI ET AL., 1974; MISZEWSKA, 1976; MORICONI-EBRARD, 1993; JAŹDŹEWSKA, 2008b), hierarchization of elements of the settlement system (DOMAŃSKI, 1970; MAIK, 1976b; 1977; 1979; JAŹDŹEWSKA, 2008b), and in the study of morphology of settlement units (ZAGOŹDŹON, 1970; 1971; 1977; KRÜGER, 1979a; 1979b; HEFFNER, 1987; THOMSON & RICHARDSON, 1995; DROBEK, 1999; JIANG & CLARAMUNT, 2002; MARSHALL, 2004; PÁEZ & SCOTT, 2004; SZMYTKIE, 2009; DMITROV, 2012).

ZAGOŹDŹON (1970; 1977) may be considered a precursor of the application of graph methods in research on the spatial structure of settlements in Poland. Based on theoretical assumptions resulting from the general graph theory (ÖRE, 1990; PULCZYN, 1968; KULIKOWSKI, 1986; ROSS & WRIGHT, 1999; WILSON, 2000), he concluded that the spatial structure of a settlement can be identified with a properly developed graph and described using a formalised language. The shape of the graph therefore illustrates the structure of the settlement, understood as the buildings situated along individual roads. The vertices of the graph are single, isolated buildings and the ends of road sections filled with compact buildings. The edges of the graph represent the connections between the vertices, i.e. an edge refers to the sequence of buildings along a road. A cycle represents a space enclosed by a few edges along which buildings are present (thus forming an urban block). Depending on the degree

of morphological complexity, a settlement unit may sometimes constitute a complex system of vertices and their connecting edges, while the increasing number of connections results in an increase in the rank of individual vertices, understood as the number of edges coming out of a particular vertex.

The simplest form is the null graph, which consists only of vertices and is characteristic for dispersed settlements. In this case, individual buildings are isolated and are located at large distances from each other. A connected graph refers to a situation in which a simple settlement consists of two vertices, which are both ends of the settlement. They are connected by an edge which is a country road, along which compact development is situated. Next, tree-shaped connected graphs can be distinguished (consisting of n nodes and the number of edges meets the condition: $e = n - 1$). This is typical for complex settlements, consisting of two spatially linked morphological units. A more complicated form is a graph with cycles, characteristic of settlements with a very complex morphological structure, consisting of many edges (Fig. 2). In this case, we are seeing closed-ended graphs where the number of edges is equal to, or greater than, the number of vertices ($e \geq n$) (CRUSH, 1970).

Fig. 2. Graphs identifying morphological layouts of settlements: A – a dispersed settlement, single buildings or a small concentration of buildings (local in character) located a considerable distance between buildings (a null graph); B – a typical rural settlement with a simple morphological layout (the simplest connected graph); C – settlements with a complex structure consisting of two topographically coupled morphological units (a tree-shaped connected graph); D – the most complex morphological structure (a cycle graph). Source: ZagoŹdŹon 1970, Szmytkie 2014.

By analysing the evolution of settlement layouts, it is possible to try to characterise the process of morphological transformation by means of the formation of the graph structure. It is possible to see the emergence of isolated clusters in the form

of single buildings, arranged in points and forming a dispersed layout, at some distance from the historical settlements. These are typical null graphs. In the immediate vicinity of the historical settlement, the processes of formation of compact development along side roads (e.g. former field roads) take place. In this way, the spatial layout of the village is expanded, and the connected graph corresponding to its spatial structure takes the form of a tree, as new edges emerge. The next stage of spatial development consists not only in further increase of the number of buildings, but also in the creation of closed connections, forming blocks. Thus, not only do new branches of the graph appear, but cycles are created, which are an important stages of shaping a full graph, consisting of all possible connections between nodes. The last stage of shaping the layout is the creation of a complex structure, consisting of many morphological elements, including merging several former settlement units into one complex (Fig. 3). In this case, we are seeing a complex graph, including several connected subgraphs (ZAGOŹDŻON, 1970; SZMYTKIE, 2014).

Fig. 3. The shaping stages of a graph structure:

A – single null graphs, formation of new nodes, which do not yet create a complete graph, in this case a graph is a set of unstructured nodes (not coupled topographically); B – development of a tree-shaped graph, next to existing parts of a graph new nodes and edges are formed, they expand the structure of the existing connected graph; C – further development of the graph structure, the formation of closed connections (cycles) within the graph structure; D – complex graphs, and even groups of graphs, higher ranks of structures are created through external inter-settlement connections (the structure resembles a stream capture). Source: Zagożdżon 1970, Szymtkie 2014.

It is possible to indicate certain relationships between the morphology of a settlement and its evolution, social structures and function, which can be expressed by referring to graph theory. Simple graphs (null and connected) indicating an uncomplicated spatial arrangement, usually refer to structures that are relatively homogeneous in genetic and social terms and are monofunctional. More complex graphs and networked graphs (tree-shaped connected graphs or ones including closed systems, i.e. cycles) indicate, in turn, a complex spatial layout, often heterogeneous in genetic and socio-cultural terms, which show features of a polyfunctional structure (SZMYTKIE, 2014).

The village layout can be treated as a physical arrangement of developed elements (i.e. settlements) and the roads connecting them (MISZEWSKA, 1976). In order to determine the morphology of settlements by means of graphs, ZAGOŹDŻON (1977) used indicators previously used by KANSKY (1963) for elements of the transport network. Due to the lack of synthetic indicators, they can be used in parallel, as none of them fully reflect all the features of the graph structure. One of them is the β -indicator, which expresses the relationship between the elements of a graph structure, i.e. it describes the relative number of edges in relation to the number of nodes:

$$\beta = \frac{e}{n}$$

where: e – number of edges, n – number of nodes.

The analysed indicator may take different values depending on the form of a graph. In null graphs, regardless of the number of nodes, it is 0. In semi-connected graphs (where there are also separate nodes, as null subgraphs) the value is between 0 and 1. In connected graphs (where the number of edges meets the condition: $e = n - 1$) the value is between 0 and 1. In connected graphs with a single cycle (i.e. where $e = n$), it takes the value of 1, while in graphs where the number of cycles exceeds 1 (i.e. $e > n$) it is always above 1. The β index was used in this article for graph-based morphological analyses.

The degree of development of the graph is an extremely important indicator for analysing the structure of settlements. It is a value relative to a given graph class measured by the number of nodes and expresses the number of connections missing from a full graph per node (KANSKY, 1963). In his works, ZAGOŹDŻON (1970; 1977) proposed a modification of this indicator, which expresses the average fraction of the lack of connections and has a form:

$$G_D = \frac{1}{2} \left(1 - \frac{e}{e_{\max}} \right)$$

where: G_D – graph development degree; e – number of edges; $e_{\max}$ – degree of connectivity (number of edges in a full graph based on n nodes)

$$e_{\max} = \frac{n(n-1)}{2}$$

SZMYTKIE (2009), analysing the morphology of units comprising conglomerate cities, proposed a modification of the graph development index. This formula was later used by DYMITROW (2012) to analyse the distribution of degraded and restituted cities:

$$G_D = \frac{e \cdot (n^2 - n)}{n^2}$$

where: G_D – graph development degree; e – number of edges; n – number of nodes

As a result of further analysis, it appears that the indicator is too dependent on the graph class expressed by the number of nodes and edges. Therefore, it was necessary to propose a new measure, which would synthetically determine the degree of development of the spatial layout, regardless of the size of the settlement unit. SZMYTKIE (2014; 2017) therefore modified the previously used indicator, which took the following form:

$$G_D = \sqrt{\frac{\sum_{i=1}^n r_i^2}{2e}} \times \frac{e + 2c}{n}$$

where: G_D – graph development index; e – number of edges; n – number of nodes; c – number of cycles;

$\sqrt{\frac{\sum_{i=1}^n r_i^2}{2e}}$ index expressing the average rank of nodes; where r_i – rank of node

Several basic assumptions were taken into account when designing the new graph development index. It must take into account the relative number of edges in relation to the number of nodes (β -indicator), the number of cycles that show the complexity of the spatial layout and are typical of the urban landscape, and the average rank of nodes in the graph, which in turn expresses the complexity of the street network. The ranks of nodes should be determined based on the incidence matrix (TINKLER, 1977; SZMYTKIE, 2017). The analysed index was used by these authors for comparison purposes in morphological analyses of the examined settlement units.

The value of the indicator expresses the degree of complexity of the spatial layout of a settlement

and, in an indirect way, its compactness (the value of the indicator is lowered if there are subgraphs within the graph). The graph development index proposed by SZMYTKIE (2014; 2017) takes values between 0 and ∞ . High values are characteristic for complex settlements with a large number of cycles, while low values are for units with simple and not very connected spatial layouts. The index expressing the average rank of the nodes in a graph takes a minimum value of 1 if the rank of all the nodes in a graph is 1, while the second part of the formula takes values close to β (which are increased by the presence of cycles).

On the basis of topographic maps, graphs were made for all spatial units in both studied periods (in the 1930s and currently). This was followed by comprehensive statistical analyses, including counting the number of nodes, edges and cycles for all villages in both periods (Table 1). On this basis, dynamics indices of particular graph structure elements and beta indices for particular villages and changes in their values in the analysed period were calculated, which illustrates the degree of cohesion of spatial layouts and its variability (Table 2). Then, in accordance with the methodology presented in the previous part of the article, indicators of graph development for all villages in both periods and changes in their values were calculated, which provided a basis for the analysis of the dynamic development of spatial layouts, taking into account the complexity of the layout (Table 3).

Cartographic materials from two different periods were used for the analysis of morphological changes and the development of graphs (CONZEN, 1968). Detailed topographic maps issued by the Military Geographic Institute at the scale of 1:25.000 and modern cartographic maps at the same scale were used. Historical maps from the mid-1930s were available in the form of German copies made during World War II. Corresponding map sheets are well preserved in many reprints. The authors used maps collected in the Library of the Faculty of Geographical Sciences of the University of Lodz. For comparative purposes, the authors used the topographic background on the national geoportal: www.geoportal.gov.pl, containing current spatial information. The graphs were created in ArcMap (version 10.4.1).

3. Results

As mentioned in the introduction, the survey covered the areas of former rural settlements within the boundaries of Łódź, which were subject to a multi-stage incorporation after 1945, and in the areas of the neighbouring counties located within

the Łódź metropolitan area. Detailed research using a graph theory method was conducted for twelve settlement units, including six former villages that were incorporated into Łódź after World War II and six villages located outside the city limits but in the metropolitan area. The first category of settlement units includes the former villages of Retkinia, Chocianowice, Stare Złotno, Olechów, Henryków, and Nowosolna. The first three were established in the Middle Ages, the latter three were created at the turn of the 18th and 19th centuries in connection with the development of the Olęder and Prussian settlements. Taking into account the morphological aspect, in the period preceding their incorporation into Łódź, these villages showed a diversity in terms of layout types. Chocianowice and Henryków were linear villages consisting of one main axis of the development composition. Olechów was a linear village consisting of two main compositional axes, while Nowosolna included 8 basic axes of loosely concentrated construction (radial layout). Retkinia consisted of several morphological elements in the form of rows and dispersed settlements, which

were formed after the enfranchisement of peasants in the second half of the 19th century. Złotno, on the other hand, has preserved a partially transformed street layout with an element of the colony formed after the parcelling of the manor (KOTER, 1994b). Within the second category of the surveyed settlement units lying outside the city limits, but within the zone of its direct impact, the following villages were included: Stary Imielnik, Dobroń, Janówka, Zofiówka, Maciejów, and Sokolniki-Las. The first two were founded in the Middle Ages. Janówka is a settlement established in the first half of the 19th century, Zofiówka and Maciejów are colonies formed as a result of parcellation in the second half of the 19th century, while Sokolniki-Las is a summer settlement established in the inter-war period. Before World War II, Stary Imielnik exhibited features of a compact street village, Dobroń consisted of two compositional axes in the form of a post-regulation *row village* and the remains of a manor farm with the addition of scattered buildings. Janówka, Zofiówka and Maciejów were typical linear villages, while Sokolniki had the form of a dispersed settlement (FIGLUS, 2016).

Table 1. Change in the number of nodes, edges and graph cycles in the studied units in the inter-war and contemporary period (Source: own studies)

Rank of morphological changes	Location in relation to Łódź	Name of the settlement unit	Number of graph elements before the WWII			Number of graph elements at present		
			Nodes	Edges	Cycles	Nodes	Edges	Cycles
Low	intra-urban area	Chocianowice	2	1	0	2	1	0
		Henryków	11	2	0	10	5	0
	extra-urban area	Stary Imielnik	13	3	0	31	9	0
		Maciejów	4	2	0	16	7	0
Average	intra-urban area	Stare Złotno	8	3	0	35	22	0
		Nowosolna	54	17	0	156	172	32
	extra-urban area	Zofiówka	27	7	0	162	123	8
		Dobroń	26	8	0	184	184	26
High	intra-urban area	Olechów	7	3	0	148	175	43
		Retkinia	39	21	0	172	226	68
	extra-urban area	Janówka	16	5	0	109	134	29
		Sokolniki-Las	116	14	0	276	350	106

The presented spatial layouts, in the period preceding the mid-20th century morphological transformations, are reflected in the structure of the attached graphs (Figures 4–9). Hence, the graphs corresponding to the layouts in the form of linear villages, which constitute a dominant group due to the specificity of settlement processes in central Poland, at that time usually consisted of one, or a maximum of several, edges and included from a few, to a dozen or so, nodes (e.g. Chocianowice, Maciejów). In villages with several morphogenetic components, or a complex original structure (e.g. Nowosolna, Retkinia) the number of edges was correspondingly higher. In loosely concentrated villages with the admixture of scattered buildings,

several dozen nodes can be identified (e.g. Dobroń, Zofiówka), while a settlement consisting almost exclusively of scattered buildings has over 100 nodes (Sokolniki-Las). The graph connectivity index (β) varies for this period from 0.12 (Sokolniki-Las), where the graph is closest in appearance to the null type, to 0.5 (Chocianowice) and 0.54 (Retkinia), which show the characteristics of a connected graph. It should be emphasised that before World War II no villages were identified (regardless of location) whose graphs would include cycles, hence the relatively low values of the connectivity index. On average during this period the β -index is 0.34 for all surveyed villages (with a standard deviation of 0.13). The graph development index

was 0.37 on average for all analysed villages in that period with significant variability from 0.14 to 0.68 (standard deviation 0.15). The low values of this indicator result from a weak level of suburbanisation during this period, which translates into a lack of cycles in the graph and the low rank of nodes. Moreover, there was a slight difference

in the index between villages very close to the city (today within the boundaries of Łódź), which was 0.43, and those with further locations (0.3). However, this difference resulted from the morphogenetic specificity of the analysed villages, rather than the development of suburban housing.

Table 2. Changes in the dynamics of the number of nodes and edges and the value of β index in the studied units in the inter-war and contemporary period (Source: own studies)

Rank of morphological changes	Location in relation to Łódź	Name of the settlement unit	Change in the number (before WWII – 100%)		β index		
			Nodes	Edges	Before WWII	At present	Value difference
Low	intra-urban area	Chocianowice	100.0	100.0	0.50	0.50	0.00
		Henryków	90.9	250.0	0.18	0.50	0.32
	extra-urban area	Stary Imielnik	238.5	300.0	0.23	0.29	0.06
		Maciejów	400.0	350.0	0.50	0.44	-0.06
Average	intra-urban area	Stare Żółtno	437.5	733.3	0.38	0.63	0.25
		Nowosolna	288.9	1011.8	0.31	1.10	0.79
	extra-urban area	Zofiówka	600.0	1757.1	0.26	0.76	0.50
		Dobroń	707.7	2300.0	0.31	1.00	0.69
High	intra-urban area	Olechów	2114.3	5833.3	0.43	1.18	0.75
		Retkinia	441.0	1076.2	0.54	1.31	0.78
	extra-urban area	Janówka	681.3	2680.0	0.31	1.23	0.92
		Sokolniki-Las	237.9	2500.0	0.12	1.27	1.15

Table 3. Changes in the degree of development of graphs of the surveyed units in the inter-war and contemporary period (Source: own studies)

Rank of morphological changes	Location in relation to Łódź	Name of the settlement unit	Graph development index		Difference of GDI value
			Before WWII	At present	
Low	intra-urban area	Chocianowice	0.50	0.50	0.00
		Henryków	0.18	0.55	0.37
	extra-urban area	Stary Imielnik	0.23	0.39	0.16
		Maciejów	0.50	0.66	0.16
Average	intra-urban area	Stare Żółtno	0.38	0.84	0.46
		Nowosolna	0.43	2.51	2.08
	extra-urban area	Zofiówka	0.26	1.34	1.08
		Dobroń	0.34	2.07	1.73
High	intra-urban area	Olechów	0.43	3.02	2.59
		Retkinia	0.68	3.66	2.98
	extra-urban area	Janówka	0.31	3.01	2.69
		Sokolniki-Las	0.14	3.64	3.50

The processes of functional transformations taking place in the studied area led to a gradual morphological transformation of villages within the Łódź metropolitan area. The intensification of suburbanisation and semi-urbanisation processes in villages surrounding Łódź occurred after World War II, and is particularly noticeable in the last decades, due to the political and economic conditions. In this way, a large part of the simple settlement forms, typical for rural areas, have evolved into complex, or multiple complex, forms. Increased construction traffic has been observed, which results in the creation of residential settlements with villas, terraced or multi-family housing. In some cases, morphological units specific

to the urban landscape have emerged as a result of suburban settlements becoming progressively more and more like towns or neighbouring peripheral urban settlements. On the other hand, some villages have changed their previous layout to a lesser extent, and the land parcelling and construction traffic is relatively small or has only started recently. Radical morphological changes in the former villages of Retkinia and Olechów completely erased their former layouts. After their incorporation into Łódź, it was decided to establish large estates of multi-family houses there, which were created as a result of planned construction investments in the 1970s and 1980s. In Dobroń and Janówka, numerous housing estate roads have

been built over the last decades and there has been a clear development of single-family buildings. However, the considerable distance from Łódź is compensated for by excellent transport accessibility. The proximity of roads of transit importance (S14), railway lines and stations have contributed to the increased interest in living in these villages due to the limited time of travel to the city. A significant degree of planning complication can be seen in relation to other peripheral settlement units, namely in the villages of Zofiówka and Sokolniki-Las. Their modern, complex spatial structure is the result of long-term parcelling and the creation of villas in an attractive landscape. Both

Fig. 4. Graphs depicting the low rank of morphological changes of the former villages Chocianowice and Henryków (in the intra-urban area) (Source: own work)

The spatial layouts analysed in the present are reflected in the structure of the attached graphs (Figures 4–9). In case of some villages (Chocianowice, Henryków, Stary Imielnik, Maciejów) the number of edges does not exceed ten. This means that it remains at a similarly low level as in the previous period, and the dynamics index shows us that the growth is no more than 3.5 times higher relative to the situation before World War II. The number of edges either remained at the same level or increased several times due to the increase in dispersed development. In villages such as Stare Żółtno, Nowosolna, Zofiówka and Dobroń, we usually see a much greater increase in the number of edges, which is due to the development of side roads with compact buildings. However, it is not a completely homogeneous group. The increase in the number of edges, which is shown by the dynamics indices, was from 7.3 times (Żółtno) to 23 times (Dobroń) in relation to the previously analysed period. The increase in the number of nodes is also clear and varies between 3 and 7 times in relation to the pre-war period. In the third group, which includes

villages are to a large extent summer resorts and constitute a traditional base for rest and recreation for the inhabitants of the agglomeration. On the other hand, many villages have kept their previous layouts almost unchanged, or the changes were only partial, not disturbing the original morphogenetic structure. Small spatial development can be seen in both former villages within the boundaries of Łódź (e.g. Chocianowice, Henryków) and suburban areas (e.g. Stary Imielnik, Maciejów). In some cases, the interest of development companies in creating new housing estates is still at an early stage and the former spatial layout of the village (e.g. Stare Żółtno) has only been partially transformed.

Fig. 5. Graphs depicting the low rank of morphological changes of the villages Stary Imielnik and Maciejów (in the extra-urban area) (Source: own work)

the villages of Olechów, Retkinia, Janówka, Sokolniki-Las, there was a very large increase in the number of edges in graphs, on average 30 times more in the group under consideration, and reaching as much as 58 times (Olechów), which indicates a very large complicated spatial layout. The increase in the number of nodes, on average several times, was not, however, greater in the case of most villages in this group than in the previously surveyed group of settlement units. While analysing contemporary spatial layouts of villages, it can be observed that in the case of the first group of settlements with the lowest dynamics of morphological development, it is still impossible to identify cycles in graphs. In the case of the group of villages with medium and large scale morphological changes, on the other hand, cycles did appear, in the numbers from 8 to 106. Thus, in the case of some villages, a quasi-urban layout has developed, corresponding to a typical so-called truss (Tkocz, 1998). The graph connectedness index (β) shows a wide range of values for the modern period. It varies from 0.29 (Stary Imielnik), where the graph is relatively simple

and consistent, to 1.31 (Retkinia). On average, the β -index is 0.85 for all surveyed villages, but with a high variability of values (standard deviation of 0.37). In the case of half of the surveyed villages, the graph connectedness index exceeds 1, which results directly from the presence of a significant number of cycles. In the case of villages with a small range of morphological changes, the β index increased no more than 2.5 times; in the case of villages with a medium and high degree of transformation, the value of the coefficient increased in the examined period on average 3-4 times in relation to the pre-war period. The graph development index for contemporary spatial layouts was 1.85 on average and showed very high variability of values (standard deviation 1.28). In the case of some villages where the morphological development was small, the value of the index remained at a similar level in relation to the inter-war period or increased slightly (e.g. 0.39 – Stary Imielnik, 0.5 – Chocianowice, 0.55 – Henryków, 0.66 – Maciejów). The differences in the values of the indicator in this group of villages are no greater than 0.5. At the other extreme, there are settlement units in which morphological changes

were very intensive due to suburbanisation processes, which resulted in a rapid increase in the number of edges and cycles in the graph. The values of graph development index in settlements such as Olechów, Retkinia, Janówka or Sokolniki-Las range from 3.01 to 3.66 and the difference of values in both periods exceeds 2.5, which indicates radical changes in the spatial layout. In settlements of this type the transformation was complete and led to the spread of urban planning forms. Additionally, a comparison was made of the graph development index values for the currently surveyed settlements, taking into account their location in relation to the boundaries of Łódź. The average value for villages incorporated into the city after World War II was 1.85. Exactly the same (1.85) average value was found for the analysed indicator for villages outside the city limits, which proves that similar processes took place in the peripheral zones of the city and in the suburban zones. In both of these groups, settlement units showing small morphological changes in the studied period were identified, as well as villages (or former villages) where the transformation of the spatial system was very large.

Fig. 6. Graphs depicting the average rank of morphological changes of the former villages Stare Żółtno and Nowosolna (in the intra-urban area) (Source: own work)

Fig. 7. Graphs depicting the average rank of morphological changes of the villages Zofiówka and Dobroń (in the extra-urban area) (Source: own work)

The analysis of former villages within the boundaries of Łódź and villages located in the city's surroundings using the graph theory method provides a basis for proposing a typology of morphological changes. The first type includes settlements where a low level of changes in layout was observed (orthomorphic transformation). The development of the spatial system was therefore

insignificant and the transformations that took place were generally insignificant, which allowed the structure of the morphogenetic nucleus of the village to be preserved. This group includes: Chocianowice, Henryków (both now within the boundaries of Łódź), and Stary Imielnik and Maciejów (in the suburban zone). This group is characterised by a low degree of complexity of the

spatial layout (initial phase of transformations). This is evidenced by the relatively small number of edges and nodes in the graph. The graph connectivity index for this category of villages was on average 0.35 in the pre-war period and 0.43 now, which indicates the connectivity of non-cycle graphs. The graph development index for the pre-war period was 0.35 on average (with a standard deviation of 0.17), while nowadays it reaches an average value of 0.52 (with a standard deviation of 0.11).

The second type includes settlements where an average level of changes in layout was observed (semi-metamorphic transformation). The development of their spatial layout was therefore quite significant, but the transformations observed were not complete, thus only partially disturbing the historical layout. This group includes Stare Żłotno, Nowosolna (both settlements currently within the boundaries of Łódź) and Zofiówka and Dobroń. For this category of villages, the average degree of complexity of the spatial layout is characteristic, showing that the suburbanisation processes started with some delay and are still ongoing (transition phase of transformations). This is indicated by the relatively large number of edges and nodes in the graph. The graph connectivity index for this category of villages was on average 0.31 in the pre-war period and 0.87 now. The graph development index for the pre-war period was 0.35 on average (with a standard deviation of 0.07), while nowadays it reaches an average value of 1.69 (with a standard deviation of 0.75). A significant

increase in the value of the index is dictated not only by the increasing number of edges and nodes during this period, but also by the appearance of cycles in the graph.

The third type includes settlements where a high level of changes in layout was observed (metamorphic transformation). The development of the spatial layout was very significant in this case. The morphological transformations were of a total character, leading to the erasure of the historical layout and development of multiple complex systems. This group includes Olechów, Retkinia (both settlements currently within the boundaries of Łódź) and Janówka and Sokolniki-Las. For this category of villages, the high degree of complication of the spatial layout is characteristic, showing that the suburbanisation processes are well-advanced (culmination phase of transformations). This is indicated not only by the very large number of edges and nodes in the graph, but above all by the large number of cycles that were not recorded at all in the previous period. The graph connectivity index for this category of villages was on average 0.35 in the pre-war period and 0.9 now. The graph development index for the pre-war period was 0.39 on average (with a standard deviation of 0.23), while nowadays it reaches an average value of 3.33 (with a standard deviation of 0.37). Therefore, we see a radical, more than eight-fold, increase in the value of this index, which indicates a rapid morphological development of these settlement units.

Fig. 8. Graphs depicting the high rank of morphological changes of the former villages Olechów and Retkinia (in the intra-urban area) (Source: own work)

Fig. 9. Graphs depicting the high rank of morphological changes of the villages Janówka and Sokolniki-Las (in the extra-urban area) (Source: own work)

The process of complication of settlement spatial structures results directly from many conditions. The present study has shown that the distance of a settlement unit from the city centre is not a factor determining the scale of the transformation. What is extremely important, however, is the accessibility of transport, the landscape attractiveness of the village's location, and possibly the location of production and service facilities, which entail the intensification of construction traffic.

4. Discussion and conclusions

The conducted analyses are part of a series of works concerning the use of mathematical methods in geographical research related to the issue of settlement. In this respect, the work is an empirical development of hitherto theoretical and methodological considerations (ZAGOŹDŻON, 1970; 1977; JAŹDŻEWSKA, 2008a; RUNGE, 2006). The graph development index used in the study, modified by SZMYTKIE (2014), brought satisfactory results due to its synthetic qualities. This is because it allows the possibility to take into account many elements of the graph structure at the same time, and its value is not strongly determined by the size of the settlement unit. Therefore, it can be considered that the indicator used in this article can be useful in further geographical research on rural morphology, both in static and dynamic analyses, and in comparative studies.

The analysis of morphological changes of former villages within the boundaries of Łódź and villages located in the city's surroundings using graph theory methods brought numerous interesting conclusions. Taking into account the scale of morphological transformation processes, three basic categories were distinguished, referring to the typology proposed by CONZEN (1962). The first one includes settlements in which the changes in the layout observed in the period under study were orthomorphic in nature. They were small, mainly additive, preserving the structure of the village's morphogenetic core. The second group includes villages that have undergone semi-metamorphic changes. These are medium-level transformations leading to the large-scale development of new morphological elements and complex layouts, which partially disrupt the historical layout. The third group includes villages for which the changes turned out to be metamorphic. In this case, the morphological transformations were of a total character, leading to the erasure of the historical layout and development of multiple complex systems. This typology, taking into account the three categories of morphological

transformations, is largely universal and is also successfully used in the analysis of changes in the layout of large city centres (MUSIAKA ET AL., 2020).

In a similar study on morphological changes of villages in the suburban zone of Wrocław using the graph theory method, SZMYTKIE & NOWAK (2017) distinguished six categories of villages due to their specificity of transformations. The author took into account as many as three time horizons (additionally, the state of the layouts in the 1970s was taken into account), which allowed the typology to be extended to include other elements that are the result of a multi-stage analysis. It should be stressed that in this work only suburban villages, located in the immediate vicinity of Wrocław, which have undergone significant transformation, were examined. Due to the fact that the authors treated the city's sphere of influence (the metropolitan area of Łódź) more broadly than in the study by SZMYTKIE & NOWAK (2017) on Wrocław, the range of variation of the observed morphological changes in this article is therefore much wider. SZMYTKIE (2017) included a larger spectrum of settlement forms located in areas beyond urban agglomerations in another study, which also covered large villages with peripheral geographical location of south-western Poland. Conclusions concerning the structure of graphs corresponding to individual villages of different origin, morphological type and economic conditions of development, largely coincide with the results of research presented in this article. It should be added, however, that in the quoted work the author, probably due to the large spatial scale of the analyses, applied only a static approach, which makes it impossible to carry out comparative studies of both regions in relation to morphological changes, and limits them only to juxtaposing the contemporary spatial arrangements of rural settlements.

The authors' research confirmed that the morphological changes of settlements expressed for the purposes of the article by means of graphs depend on many conditions. The factors differentiating the nature and dynamics of spatial changes in villages in the Łódź metropolitan area include: distance from the centre of the urban agglomeration and location in relation to major transport routes. An important role is also played by the former morphogenetic type of individual settlements, in terms of their size and location. These conclusions are confirmed by the results of research by other authors dealing with suburban zones, both in Łódź (STRASZEWICZ, 1954; JAKÓBCZYK-GRYSZKIEWICZ, 1991; MATCZAK, 1991; WÓJCIK, 2006; 2013) and other large cities in Poland (GOLACHOWSKI, 1966; RAKOWSKI, 1975; MISZEWSKA, 1996; 2002; JAKÓBCZYK-

GRYSZKIEWICZ, 1998; WESOŁOWSKA, 2006; KACPRZAK & STASZEWSKA, 2008; BAŃSKI & WESOŁOWSKA, 2010; KAJDANEK, 2011; MANTEY, 2011; SZMYTKIE, 2011; SZCZEPAŃSKA & WILKANIEC, 2014; SOBOTKA, 2014; MISZEWSKA & SZMYTKIE, 2015; 2017). Theoretically, the greater the distance between the village and the city centre, the lesser the metropolitan impact in the social and economic sense, and thus the lower the volume of construction traffic and morphological transformation. However, this trend is modified by other functional and infrastructural factors of a non-zonal character, which in an evolutionary way imply housing investments or implementation of large projects initiated by development companies. The importance of communication accessibility is worth emphasising in this respect. The proximity of transit roads (especially motorways and expressways) and railway lines contributes to the increased interest in living in rural areas due to the limited time for accessing the city (e.g. Dobroń). Thus, it happens that some villages, even though they are located further away from the city centre, experience more intensive development of buildings than other towns, including the former villages within the city boundaries, which, however, offer much worse opportunities for the daily migration of residents (e.g. Henryków). Another factor determining these morphological transformations, independent of the distance from the centre, may be the location of production plants, shopping and service centres, investments in the form of logistics centres, which in themselves strongly modify the space but also offer a large number of jobs and are an important stimulus for economic development. A similar dependence concerning the increased morphological development of villages, regardless of their distance from the city, is observed in some areas which are attractive in terms of nature, which may constitute a base for rest and recreation for the inhabitants of the agglomeration (e.g. Sokolniki-Las). Progressive land parcelling and increased construction traffic consequently leads to a far-reaching complication of the spatial layout (the appearance of a large number of edges and cycles in the graphs).

The synchronous interaction of the discussed factors results in various morphological changes in the villages situated in the metropolitan area. According to the research, the distance from the city centre is not the most important factor determining the transformation of rural settlements. The diversification of the transport network, as well as investment attractiveness and the interest of development companies strongly determine the various changes in the spatial structure which

occur in villages. Where the influence of these factors was destimulating, rural settlements underwent slight, orthomorphic changes. Meanwhile, metamorphic changes can be observed in locations that are characterized by high dynamics of socio-economic development.

The urbanisation of villages results in the disappearance of the dichotomous division of settlements as an effect of the phenomenon of the rural-urban continuum (KIRK, 1980; SOKOŁOWSKI, 1999; KRZYSZTOFIK, 2008). The issue of morphological transformation of villages can be also related to the theoretical concept of urban sprawl (CHIN, 2002; SQUIRES, 2002). This is a process of 'spreading the city' beyond its administrative boundaries. Diffusion and succession are characteristic processes for changes in the functional and spatial structure of villages. The most important processes that take place in the metropolitan area include migrations, dynamic development of individual housing and the disappearance of agricultural activities (BAŃSKI, 2008). Morphological transformations of villages can result from both the concentration and dispersion of built-up areas. On the one hand, new housing developments are founded in conjunction with existing ones, which extends the former village's habitat. On the other hand, new urban housing estates degrade the traditional rural landscape, because the former agricultural lands are divided into small plots and the residential areas develop within former arable fields (MISZEWSKA, 1996; WÓJCIK, 2013; FIGLUS, 2020).

The processes of functional transformation taking place in rural areas lead to their gradual morphological transformation. The intensification of sub-urbanisation and semi-urbanisation processes (GOLACHOWSKI, 1965) after World War II in the closer and further surroundings of Łódź resulted in simple settlement forms, typical of rural areas (open, extensively used), turning into complex or multiple complex forms specific to the urban landscape. A process of gradual morphological unification can be observed, involving the spread of urban layout patterns in the metropolitan area of Łódź.

The morphological transformation of villages in areas spatially and functionally related to a large city is highly variable in terms of character and intensity. As a result of the dynamic construction traffic and the increase in demographic potential, many settlement units have undergone significant expansion, which has contributed to the complexity of their layout (expressed by the high value of the graph development index). In relation to other villages, these processes are much slower and less intense, owing to which the morphological

transformation is small (which is confirmed by a slight increase in the graph development index), while the former spatial arrangement has been preserved or has only partially disappeared.

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