The Impact of Socio-Spatial Factors on the Shrinkage of Medium-Sized Cities in Poland Based on the Experiences of Comparable German Cities.

Wpływ Czynników Przestrzenno-Społecznych na Kurczenie się Średniej Wielkości Miast w Polsce na Podstawie Doświadczeń Porównywalnych Miast Niemieckich.

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Streszczenie

Niniejsza praca doktorska, składająca się z trzech artykułów naukowych, bada zjawisko kurczenia się miast, koncentrując się na jego związku ze zmianami formy urbanistycznej. Badanie opiera się na doświadczeniach kurczących się miast w Niemczech, szczególnie tych, które doświadczyły urbanistycznego regresu na początku lat 2000. Programy takie jak *Stadtumbau Ost* oraz IBA Saxony-Anhalt 2010 *International Building Exhibition* pokazały, że średniej wielkości miasta mogą osiągnąć stabilność poprzez zarządzany proces de-wzrostu. Przypadki te sugerują, że kompaktowa (zwarta) forma urbanistyczna może zwiększać odporność na spiralę kurczenia, co znajduje potwierdzenie w literaturze wskazującej na kurczenie się miast jako okazję do zrównoważonej transformacji.

Praca ma cele zarówno metodologiczne, jak i empiryczne. Celem metodologicznym jest opracowanie narzędzi do monitorowania kurczenia się miast oraz kompaktowości (zwartości) formy urbanistycznej. Cele empiryczne obejmują zastosowanie tych narzędzi w polskich miastach średniej wielkości w celu przetestowania głównej hipotezy badawczej: czy, a jeśli tak, to w jakim stopniu, istnieje związek między kurczeniem się miast a ich zwartością.

Aby osiągnąć te cele, w badaniu zastosowano trzyetapową metodologię opartą na przeglądzie literatury oraz ilościowej analizie danych przestrzennych i statystycznych. Wykorzystano zaawansowane narzędzia obliczeniowe, w tym język Python i QGIS, co umożliwiło przetwarzanie dużych zbiorów danych i zapewniło rygor metodologiczny.

Etap 1 (Pierwszy artykuł naukowy): W tym etapie autorka przyjęła i dostosowała wielokryterialną metodę wskaźnikową Milbert (2015, 2020) do pomiaru kurczenia się miast w oparciu o polskie dane. Proces kurczenia się miast oceniono dla wszystkich polskich miast w trzech pięcioletnich okresach: 2006–2011, 2011–2016 i 2016–2021. Każdemu miastu przypisano wskaźnik wzrostu/kurczenia (score), który umożliwił klasyfikację miast na pięć kategorii – od rozwijających się do kurczących.

Etap 2 (Drugi artykuł naukowy): Ten etap obejmował opracowanie metody oceny kompaktowości formy urbanistycznej za pomocą dwóch wskaźników: wskaźnika zwartości fizycznego kształtu obszaru miejskiego (Compactness index, Ci) oraz gęstości zaludnienia (Populationd density, Pd). Kompaktowość oceniono dla wszystkich polskich miast na podstawie danych CLC z lat 2006, 2012 i 2018.

Etap 3 (Trzeci artykuł naukowy): W ostatnim etapie przetestowano hipotezę badawczą, analizując zależność między kurczeniem się miast (score) a kompaktowością formy urbanistycznej (Ci i Pd). Do oceny siły i charakteru tej zależności zastosowano współczynnik korelacji Pearsona (r).

Wyniki przedstawiają złożony obraz, wskazując, że zależność między formą urbanistyczną a kurczeniem się miast zależy od takich czynników jak ramy czasowe, typ obszaru miejskiego i sposób jego delimitacji. Jednakże zaobserwowano istotną statystycznie dodatnią korelację między wskaźnikiem zwartości formy (Ci) a wskaźnikiem wzrostu/kurczenia, co oznacza, że miasta o bardziej zwartej formie są mniej podatne na procesy kurczenia się. Wnioski z badań dostarczają cennych wskazówek dla planowania urbanistycznego. W szczególności wspierają formułowanie wytycznych planistycznych dla miast średniej wielkości, które mogą zostać uwzględnione w nowych dokumentach planistycznych w 2025 roku.

Słowa klucze: kurczenie się miast, metoda multikryterialna, kompaktowość, Polska, CLC

“Złamane zęby bram seplenią historię
Podbite oczy kamienic nie widzą pejzaży miast
Stłuczone serce dzielnicy wybija ostatnią melodię
W arteriach rur i studzienek zalega popiół i piach

Nie ma sąsiada co sadził to drzewo
I nie ma sąsiadki co plotła makatki
Zniknął ten stary co chował dolary
W oczach niknie ten świat.”

Fragm. Piosenki
L.Stadt (2017) Oczy kamienic, L.Story. Mystic Production

Summary

This doctoral dissertation, composed of three research articles, explores the phenomenon of urban shrinkage, focusing on its relationship with changes in urban form. The study begins by drawing on the experiences of shrinking cities in Germany, particularly those affected by urban decline in the early 2000s. Programs like *Stadtumbau Ost* and the *IBA Saxony-Anhalt 2010 International Building Exhibition* demonstrated how medium-sized, shrinking cities could achieve stability through managed de-growth. These cases suggest that a compact urban form might enhance resilience against the decline spiral, a hypothesis supported by existing literature that positions urban shrinkage as an opportunity for sustainable transformation.

The dissertation pursues both methodological and empirical objectives. The methodological goal is to develop tools for monitoring urban shrinkage and urban form compactness, while the empirical objectives focus on applying these tools to Polish medium-sized cities to test the central research hypothesis: whether, and to what extent, a relationship exists between urban shrinkage and compactness.

To achieve these aims, the study employs a three-stage methodology grounded in literature review and quantitative analysis of spatial and statistical data. This approach leverages advanced computational tools, including Python and QGIS, to process large datasets and ensure methodological rigour.

Stage 1 (First Research Paper): This stage identifies and adapts the Milbert (2015, 2020) multi-criteria indicator method for measuring urban shrinkage to align with Polish data. Urban shrinkage is assessed for all Polish cities in three five-year intervals: 2006–2011, 2011–2016, and 2016–2021. Each city is assigned a growth/shrinkage score, which is classified into five categories ranging from growing to shrinking cities.

Stage 2 (Second Research Paper): This stage develops a method to measure urban form compactness using two indicators: the compactness index of an urban area's physical shape (Ci) and urban population density (Pd). Compactness is evaluated for all Polish cities using CLC data from 2006, 2012, and 2018.

Stage 3 (Third Research Paper): This final stage tests the research hypothesis by investigating the relationship between urban shrinkage (growth/shrinkage scores) and urban form compactness (Ci and Pd). Pearson’s correlation coefficient (r) is used to determine the strength and nature of this relationship.

The results present a nuanced picture, highlighting how the relationship between urban form and shrinkage varies depending on factors such as time frame, urban area type, and delineation

method. However, a statistically significant positive correlation emerges between the compactness index (Ci) and shrinkage/growth scores, indicating that cities with a more compact form are less susceptible to urban shrinkage. These findings offer valuable insights for urban planning. Specifically, they support formulating planning guidelines for medium-sized cities, with practical recommendations to be integrated into new planning documents in 2025.

Keywords: urban shrinkage, multi-criteria indicator, compactness, Poland, CLC

“Broken teeth of the gates are lisping out a story
Bruised eyes of the tenements don't see city landscapes
The shattered heart of the district is playing its last melody
In the arteries of pipes and drains, ash and sand are piling up

There's no neighbour who has planted that tree
And there is no neighbour who would weave tapestries
The old man who would hide dollars is gone
This world is fading in the eyes.”

Fragment of a song titled: Eyes of Buildings
L.Stadt (2017) Oczy kamienic, L.Story. Mystic Production
Translated from Polish by the author

Publication list for the dissertation

Accepted publications in peer-reviewed journals as a first author:

1. **Szymczyk, E.**, Bukowski, M. (2023). Identification of shrinking cities in Poland using a multi-criterion indicator, *Przeglad Geograficzny*, 95(4), 447-473, *IF n/a, CiteScore 0.9, 70 points MNiSW*, https://doi.org/10.7163/PrzG.2023.4.5

2. **Szymczyk, E.**, Bukowski, M. (unpublished). Compactness of Polish urban areas - methodologies and analysis based on CLC dataset, *Architectus, IF n/a, 70 points MNiSW,* unpublished *(accepted for publication on the 14th of November 2024)*.

3. **Szymczyk, E.**, Bukowski, M., Kenworthy, J. R. (2024). Understanding the Relationship between Urban Form and Urban Shrinkage among Medium-Sized Cities in Poland and its Implications for Sustainability, Sustainability, *IF 3.3, 100 points MNiSW,* https://doi.org/10.3390/su16167030

Data publications:

1. Data outcomes of the “Urban Shrinkage and Growth - Multicriteria assessment” in Poland https://doi.org/10.5281/zenodo.14286245
2. Data outcomes of the “Urban Form Compactness Assessment” in Poland https://doi.org/10.5281/zenodo.14286283

List of abbreviations and symbols

Abbreviations include translations into English from original Polish and German names.

AI – Artificial Intelligence

API – Application Programming Interface

BBSR – The Federal Office for Building and Regional Planning (originally called Bundesinstitut für Bau-, Stadt- und Raumforschung)

BDL – Local Data Bank (orig. Bank Danych Lokalnych)

BMWSB – The Federal Ministry for Housing, Urban Development and Building (orig. Bundesministerium für Wohnen, Stadtentwicklung und Bauwesen)

CEE – Central and Eastern European countries

CIRES – Cities Regrowing Smaller

CLC – Corine Land Cover

DAAD – German Academic Exchange Service (orig. Deutscher Akademischer Austauschdienst)

EC – European Commission

EU – European Union

GDR – German Democratic Republic

GIS – Geographic Information Systems

GUS – Polish Statistics (orig. Generalny Urząd Statystyczny)

IBA – International Building Exhibition (orig. Internationale Bauausstellung)

INSEK – Integrated Urban Development Concept (orig. Integriertes Stadtentwicklungskonzept)

IOER – Leibniz Institute of Ecological Urban and Regional Development (orig. Leibniz-Institut für ökologische Raumentwicklung)

IRMiR – The Institute of Urban and Regional Development (orig. Instytut Rozwoju Miast i Regionów)

IT – Information Technology

IoT – Internet of Things

MNiSW – Ministry of Science and Higer Education (orig. Ministerstwo Nauki i Szkolnictwa Wyższego)

MPZP – Local development plans (orig. Miejscowe Plany Zagospodarowania Przestrzennego)

MRM – Modelowa Rewitalizacja Miast

NCN – National Science Centre (orig. Narodowe Centrum Nauki)

NIK – Supreme Audit Office in Poland (orig. Najwyższa Izba Kontroli)

SCIRN – Shrinking Cities International Research Network

TERYT – National Official Register of the Territorial Division of the Country (orig. Krajowy Rejestr Urzędowy Podziału Terytorialnego Kraju)

UN – United Nations

WZiZT – Individual land development decisions (orig. Decyzja o Warunkach Zabudowy i Zagospodarowania Terenu)

1. Introduction

This doctoral thesis presents and discusses three research papers that examine the phenomenon of urban shrinkage, aiming to deepen understanding of this complex issue and promote more sustainable urban management strategies. Conducted between 2020 and 2024, the research reflects the author's in-depth exploration of planning and urban development contexts in Germany and Poland, facilitated by fieldwork in both countries. The study was supported by the Doctoral School at the Cracow University of Technology (orig. Szkoła Doktorska Politechniki Krakowskiej), under the supervision of Dr. hab. inż. arch. Kinga Racoń-Leja, and by two DAAD Research Scholarships in Germany, supervised by Prof. Dr.-Ing. Michael Peterek.

From January to June 2022 and October 2023 to June 2024, the author was a guest researcher at the Frankfurt University of Applied Sciences, hosted by the department led by Prof. Dr.-Ing. Peterek, who later became a supervisor of this PhD. Additionally, from June to September 2024, the author conducted research at the Dresden Leibniz Institute of Ecological Urban and Regional Development (IOER), thanks to an invitation from Prof. Dr.-Ing. Robert Knippschild. This collaboration, along with numerous conferences (see Appendix), consultations with Antonia Milbert from the Federal Office for Building and Regional Planning (BBSR) and extensive research trips across Germany, provided valuable insights into how medium-sized cities can leverage shrinkage as an opportunity for sustainable transformation.

Participation in expert trips organised by the Institute of Urban and Regional Development (IRMiR) allowed the author to deepen their understanding of urban shrinkage, ultimately leading to the successful application for the National Science Centre PRELUDIUM 22 research grant. The proposed research, building on the doctoral thesis, introduces a comparative analysis of shrinking cities in Poland and Germany, offering an international perspective on the relationship between urban form and shrinkage.

Notably, thanks to the IRMiR Institute, the author conducted expert visits to German shrinking (or formerly shrinking) cities in Saxony and Saxony-Anhalt in November 2021. During these visits, the author gained valuable knowledge from local authorities, institutions, and architects involved in the "IBA Stadtumbau Ost" programs. Additionally, fieldwork included visits to shrinking and growing medium-sized Polish cities across Lesser Poland, Silesian, and Lower Silesian voivodeships, contributing to a nuanced understanding of urban development in both national contexts.

1.1. Structure of this work

This dissertation is divided into seven following parts:

1. Introduction	The Introductory section provides an overview of the research's significance, contextualising it within global and European urbanisation trends. It narrows the focus to urban shrinkage in Germany, which inspires the study of the relationship between urban shrinkage and the physical form of urban areas.
2. Research background	The Research background outlines the context of urbanisation in Poland, urban shrinkage research, and planning practices. It identifies key research gaps that guide the subsequent section, which reviews the state of research on urban shrinkage assessment and urban form analysis in relation to these gaps.
3. Research description	The Research description defines the research aims, objectives, questions, and hypotheses. It also explains the methodological choices, the data utilised, and the structure of the three research stages.
4. Summary of results	The Summary of results presents the key findings from each research stage. While the detailed outcomes are included in the attached papers, this section distils the core insights for better clarity.
5. Discussion of results	The Discussion of results evaluates how the research objectives were achieved by addressing the research questions and hypotheses, and it situates the findings within the broader literature.
6. Conclusions	The Conclusions summarise the research findings and their implications.
7. Attachments	The Attachments include the three interrelated research papers.

The dissertation concludes with references, a list of tables and figures, and an appendix, which provides additional resources and supporting materials.

1.2. Shrinking and growing urban world

As the proportion of urbanised land and the urban population continues to rise, urbanisation in the 21st century is predominantly linked to growth. This growth-centric perspective remains the prevailing paradigm among architects, urban planners, and policymakers. Consequently, the language and planning tools emphasise development, progress, expansion, and growth management. However, urban scholars express concern that “the scenario of growth for all (...) is hardly the case for most countries” (Martinez-Fernandez and Wu, 2009, p.29). The UN-Habitat - World Cities Report 2022 underscores that nearly half of the cities in so-called developed nations experienced depopulation from 2000 to 2018 (see Figure 1), with a significant number located in Europe, Japan and North America (UN-HABITAT, 2022). More recently, substantial population losses have also been documented in cities across Australia, Latin America and China (Wang and Fukuda, 2019; Pallagst et al., 2021; Wang et al., 2022; Yu et al., 2023).

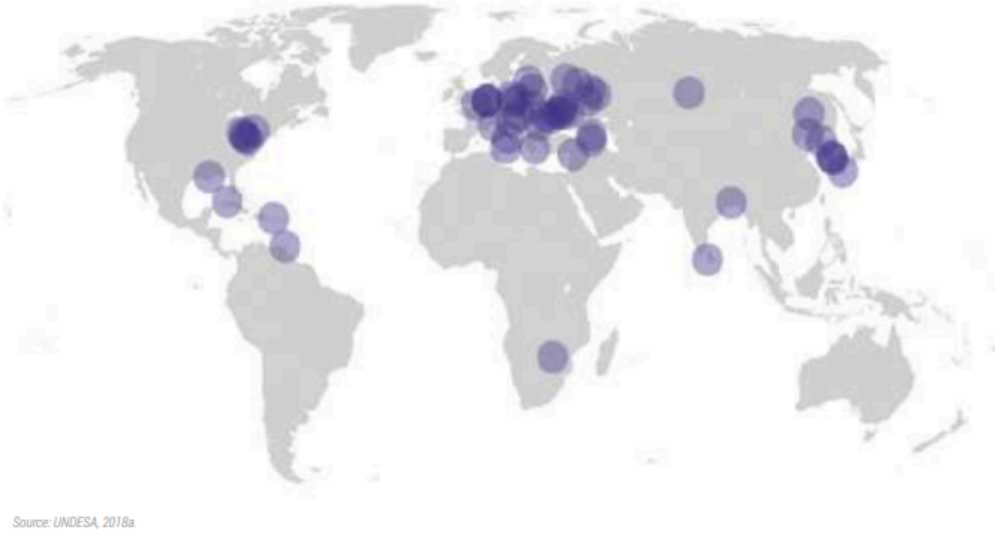


Figure1. Cities with a declining population in the period 2000-2018. Source: UN-HABITAT, World Cities Report, 2022

Urbanisation mechanisms are undermined by various processes that have multiscalar and temporal characters, thus disrupting the well-established settlement networks. The contemporary debate on urban decline emerged in the second half of the 20th century when so-called *urban shrinkage* became a common transformation pathway for many industrial large cities across Europe and North America. The term ‘shrinking city’ was first used by German researchers Häußermann and Siebel in the 1980s (initially as *Schrumpfende Stadt*) – to name long-term demographic and economic changes taking place in urban areas of the Ruhr region (Häußermann and Siebel, 1988). However, while city growth can be understood quite well, the term ‘shrinking city’ is less obvious and poses empirical and heuristic challenges. How can a city shrink?

City without citizens?

"The idea persisted that 'city' meant two different things – one a physical place, the other a mentality compiled from perceptions, behaviours and beliefs. The French language first came to sort out this distinction by using two different words: *ville* and *cité*" (Sennett, 2019, p.1). But can one exist without the other? Is a physical *ville* with empty buildings and underutilised infrastructure a city? Do citizens alone form a *cité* without a physical place? Such scenarios are not new to human history. Whether it was due to war, natural hazards, epidemics, environmental or political change or depletion of resources – changes in settlement structures were experienced throughout centuries, leaving some cities without citizens and some citizens without cities. For example, a community in Chaitén in Chile survived the volcanic eruption that swept away most of their city and remained united in reconstitution efforts (see Figure 2). Reconstruction was an opportunity to include necessary modifications to build resilience and adapt to future climate risks. Here, the community secured the survival of the place. What about the other way around, where vacant buildings and empty streets are the only remains of the once vibrant city?

Figure 2. Chaitén, the capital of Palena Province, was a hub of services and connectivity for the isolated communities of the Chilean Patagonia until a volcanic eruption followed by a flood swept it away. The displaced community of Chaitén reconstructed the city. Source: MarcaChile (2013).

Such examples can be found worldwide, with causes ranging from economic decline, like in the case of Detroit, to a post-industrial transformation in the UK, globalisation, metropolisation, and peripheralisation. According to Turok and Mykhnenko (2007), urban systems in the 21st century have been subjected to constant change that ranges from shrinkage through growth to non-linear trajectories (Turok and Mykhnenko, 2007).

1.3. Urbanisation patterns in Europe

In Europe, urban shrinkage has emerged as one of the most frequently discussed topics in urban research over the past two decades (Slach et al., 2020). Deindustrialisation and demographic trends were seen as the leading cause of the decline of large cities in the late '90s (Pallagst et al.,

2009; Döringer et al., 2019). In Eastern Europe alone, three out of four larger cities experienced population declines in the early 2000s (Mykhnenko and Turok, 2007). However, 2010 saw the beginning of re-urbanisation in Europe (Haase et al., 2021). According to research by Rink et al. (2012), the large European cities are the ones that recover first and become a migration destination. This was confirmed by Cortinovis et al. (2022), who investigated the urban density trends of 331 European cities with more than 50,000 inhabitants between 2006-2018. Authors captured a shift in the predominant trend from loss of densification (called 'de-densification') (2006–2012) to an increase in densification (2012–2018). While this trend was observed on the scale of Europe, there are notable differences between regions and cities (Figure 4). Cortinovis et al. (2022) evidence that large cities are densifying more strongly and shifting more easily from de-densification to densification, a trajectory uncommon for medium and small cities (Cortinovis et al., 2022).

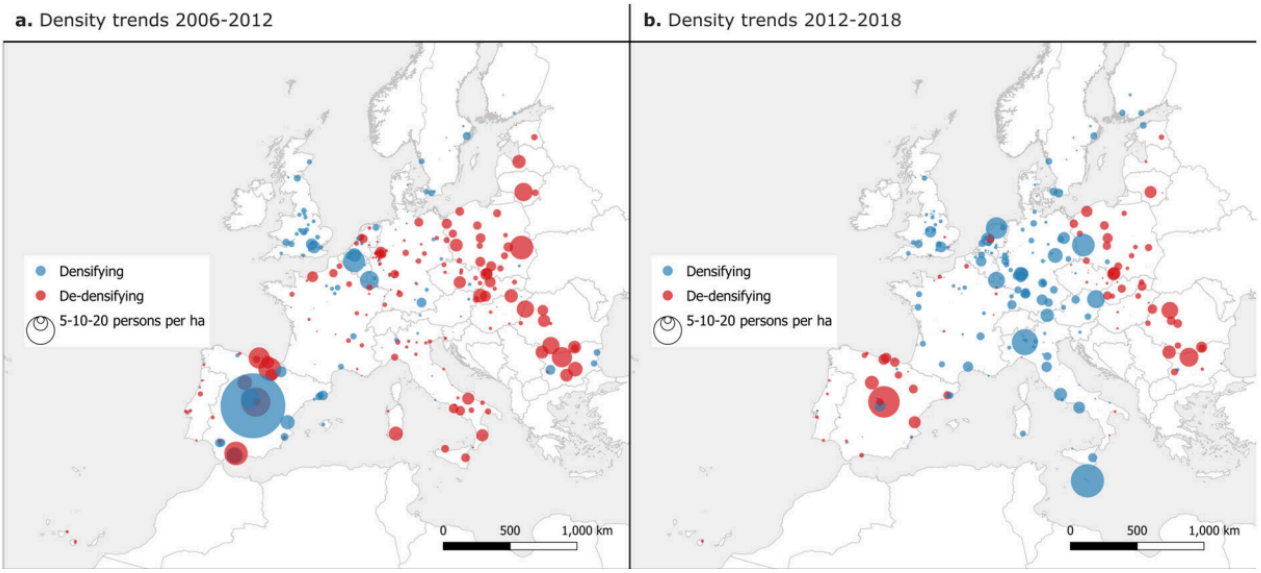


Figure 4. Residential density trends in Europe. Source: Cortinovis et al. (2022).

While European cities possess distinct characteristics, particularly the prevalence of numerous small and medium-sized urban settlements, often with deep historical origin (Le Galès, 2002), this diversity is currently challenged. Amid metropolisation trends, urban shrinkage significantly impacts Europe's medium-sized cities' socio-economic and spatial dynamics (Śleszyński, 2019; Chouraqui,2021). Thus, current trends of population clustering in large cities have created imbalances in spatial development (Uskova and Sekushina, 2021), posing challenges for a considerable number of medium-sized cities.

Central and Eastern European countries (CEE)

As described earlier, urban shrinkage manifests differently across various countries (Haase, Bernt, et al., 2016). National-scale studies have illustrated these differences in countries such as France

(Cunningham-Sabot et al.,2010; Chouraqui, 2021), Germany (Gatzweiler et al., 2003, 2009; Milbert, 2015; Radzimski, 2015; Nelle et al., 2017;), Portugal (Alves et al., 2016), and Spain (Escudero-Gomez et al., 2023). As depicted in Figure 5, many shrinking cities between 1990 and 2010 were in Eastern and Central Europe, referred to as CEE. According to a study by Stryjakiewicz et al. (2014a, b), shrinkage was most prominent in post-socialist European countries such as Latvia, Romania, Estonia, Lithuania, Serbia, Czech Republic and Croatia. The phenomenon was widely analysed in Poland (Jaroszewska, 2019; Sroka, 2021, 2022; Stryjakiewicz et al., 2014a, b; Zborowski et al., 2012 and many others) and Romania (Eva et al., 2021; Paun Constantinescu et al., 2017) where it is particularly widespread.

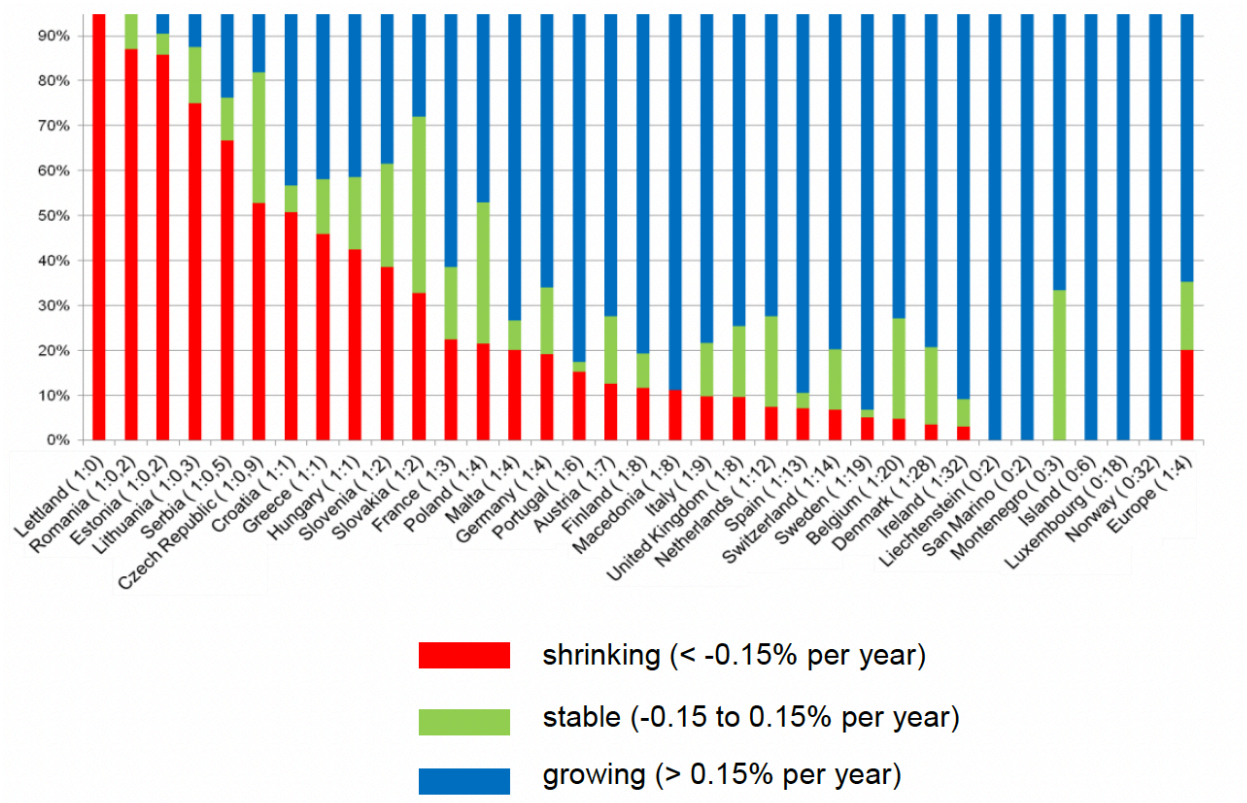


Figure 5. Change in city population in European cities in the period 1990–2010. Source: Stryjakiewicz, 2014a

While certain cities in this region have experienced rapid transformations in recent decades, many continue to face the challenges of shrinkage that originated during that transition period. The sharp decline in fertility rates, coupled with the impacts of de-industrialisation, suburbanisation, post-socialist transformation, and out-migration, has resulted in a distinctive pattern of urban decline in the CEE countries (Oswalt, 2006a).

Research conducted by Stryjakiewicz et al. (2014a, b) indicates that most of populations in 1990-2010 resided in cities experiencing a decline exceeding 0.15% annually. CEE urban shrinkage is often exacerbated by suburban losses, particularly in post-socialist states, where economic

downturns have affected ageing industrial cities with fragile infrastructures and low fertility rates. These factors have resulted in intricate development trajectories intersecting with demographic changes (cf. Wolff and Wiechmann, 2017, p. 7). Additionally, a study on urban sprawl in post-socialist countries by Schmidt et al. (2014) identified shared characteristics, including metropolitan areas marked by low-density suburban development, land-intensive businesses and industrial enterprises, an automobile-centric transport system, and a deteriorating urban core suffering from population decline (Wolff and Wiechmann, 2017). Moreover, the legacy of post-socialism, coupled with post-Fordist transformation processes often referred to as "shock therapy" (Bontje, 2004), continues to pose challenges for city governance, especially in medium-sized cities.

1.4. Urban shrinkage in Germany

German planning policies are highly regarded in the international academic discourse on urban shrinkage (Bernt, 2019). The so-called 'German School' (Pallgast et al., 2009) approach to managing urban decline is often commended for its proactive emphasis on '"right-sizing", combining building demolitions with a holistic "smart decline" strategy (Hollander and Nemeth, 2011). Overall, German policies are viewed positively compared to many other countries, especially concerning the *Stadtumbau Ost* (eng. Urban Redevelopment East program), which has become a central example of these efforts.

Figure 6. Population (upper) and employment (lower) change by city size in Germany in 1997-2001 with a division to Western federal states (left) and Eastern states (right). Source: Gatzweiler et al., 2003

East German shrinkage context

In Germany, the shrinking processes of the early 2000s were particularly prominent among medium-sized cities in East Germany, the former German Democratic Republic (GDR) (Gatzweiler, Meyer and Milbert, 2003), as shown in Figure 6 (in orange medium-sized cities, orig. Mittelstädte). During the period of transition, emigration outweighed immigration in almost all cities in East Germany, as well as in some cities in the West, particularly in the central, western and northern regions (Radzimski, 2015). These dynamics resulted from the simultaneous occurrence of two

processes: emigration towards the federal states of former West Germany in search of employment and a process of suburbanisation. The first one began shortly after the opening of the border and was particularly intense in the first decade after reunification. Meanwhile, in former East Germany, suburbanisation rapidly gained significant proportions compared to the developments in other post-socialist countries (Brake et al., 2001), causing further losses in the urban population. However, Herfert (2003) argues that the economic situation was the decisive factor shaping migration movements at the macro level (Herfert, 2003).

Saxony-Anhalt

In the federal state of Saxony-Anhalt, established as one of the new states in former East Germany after reunification, most cities and municipalities were heavily affected by the structural and demographic changes indicated above, leading to considerable population loss since the fall of the Berlin Wall. As a relatively sparsely populated state with few larger centres, Saxony-Anhalt was struck by depopulation, deindustrialisation and de-urbanisation. From 1989 to 2009, the overall state population decreased from 2,965,000 to 2,367,000 inhabitants (IBA Urban Redevelopment, 2010). Among typical challenges were vacant flats, especially in the prefabricated housing from the socialist period, derelict industrial estates, redundant infrastructure, decay of the inner-city areas with simultaneous suburbanisation due to the dream of the single-family house as a sign of personal ‘freedom’ under the new political circumstances (Geipel und Kowa, 2010). With an overall housing vacancy rate of 15.5% in 2008 (IBA Urban Redevelopment, 2010), costs for the maintenance of underutilised infrastructure (such as street lighting, water supply, and school buildings, which were no longer needed) could hardly be borne by the municipalities any longer, coinciding with a severe decline in public revenues and resources (Geipel und Kowa, 2010).

Stadtumbau Ost program

Diagnosing “one million empty flats” (Pfeiffer et al., 2001) significantly influenced the political and public discourse surrounding urban shrinkage and the narrative emphasising right-sizing in urban renewal initiatives. In response to the potential for further urban decline, the German government determined to intervene by establishing the joint federal and state initiative in 2002-2017 known as Stadtumbau Ost (Urban Redevelopment East) (BMVBS, 2012; Bernt et al., 2014; Pallagst et al., 2021). The principal objective of this program was to facilitate the sustainable development of cities and municipalities within the new federal states, which were adversely affected by the demographic and economic structural transformations prevalent during the 1990s. The Stadtumbau Ost initiative primarily aimed to stabilise urban areas through the “right-sizing” by demolition of vacant housing units that were deemed no longer necessary, as well as through the enhancement of city centres and urban neighbourhoods. Specifically, three sub-goals were articulated (BMVBS, 2012):

- **Eliminating the oversupply in the housing** sector by demolishing permanently vacant apartments and thus stabilising the housing market.
- **Upgrading the urban districts** by renovating the remaining building stock, including preserving ensembles with architectural significance.
- **Concentrating investment on older buildings and in inner-city areas**.

By 2012, 442 cities and municipalities in Eastern Germany had benefited from the financial assistance provided by the program (see Figure 7). The federal states and local governments collectively allocated approximately 2.7 billion EUR for this initiative (the federal government contributed around 1.3 billion EUR) (BVMBS, 2012). Moreover, various funding sources from different state programs and investments from private property owners played a critical role in facilitating the implementation of a range of urban redevelopment projects. Consequently, Stadtumbau Ost emerged as the most significant urban development support program in numerous East German cities at the onset of the 21st century, enabling these municipalities to adopt a new trajectory of stable de-growth despite persistent regional depopulation trends. As a result, housing vacancy rates markedly decreased, and many city centres were successfully regenerated and strengthened (BBSR, 2017; Brueckner, 2007).

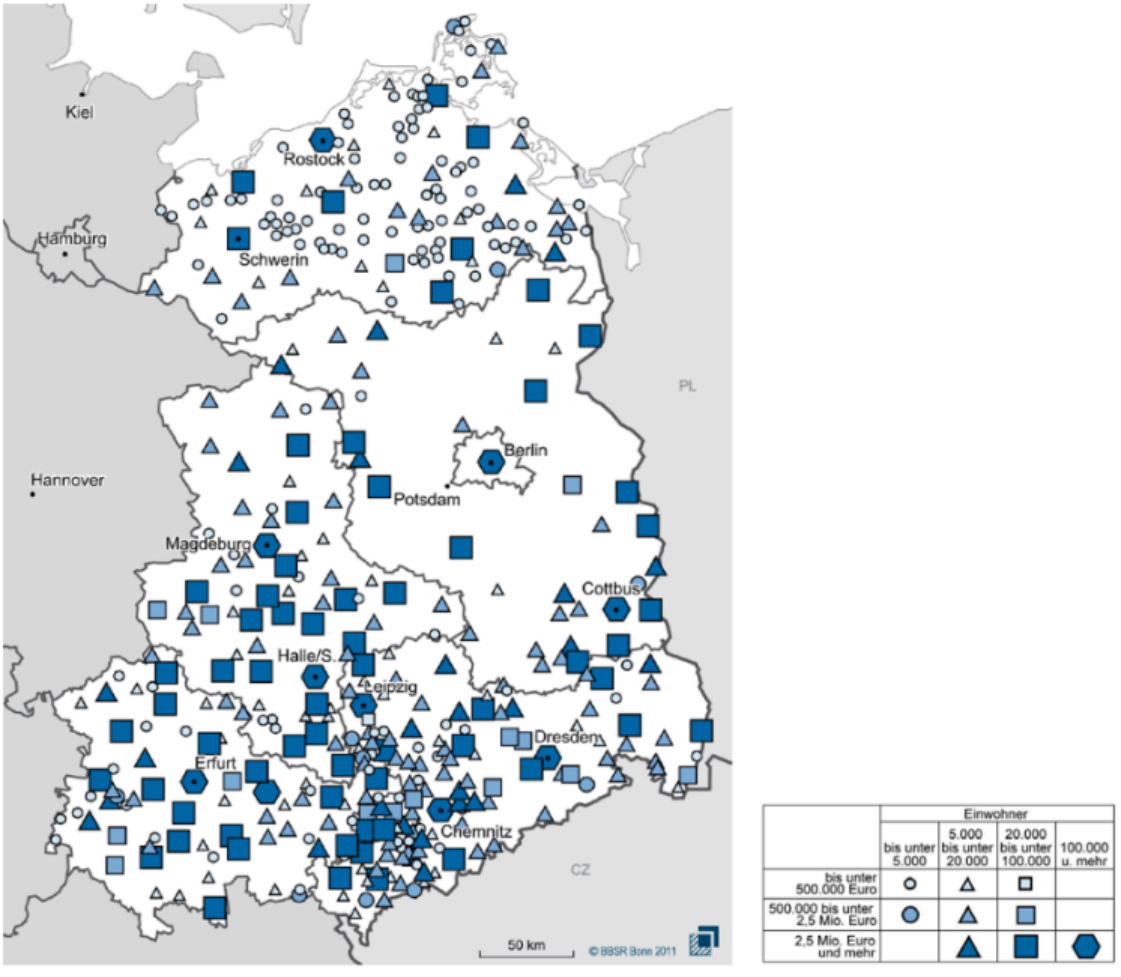


Figure 7. Cities and municipalities (orig. Städte und Gemeinden) that received aid from the Stadtumbau Ost programme between 2002-2010. Source: Liebmann et al., 10 Jahre Stadtumbau Ost, 2013

Integrated Urban Development Concepts (INSEK)

Simultaneously, the *Stadtumbau Ost* program catalysed the comprehensive introduction of *Integrated Urban Development Concepts* (orig. Integrierte Stadtentwicklungskonzepte, subsequently referred to as INSEK) as a planning tool to establish mid-term development frameworks for the impacted cities. The formulation of such concepts by local governmental entities constituted one of the binding prerequisites for formalising urban redevelopment areas eligible for support through the Stadtumbau Ost program (BVMBS, 2012; BBSR, 2017). The shrinking city phenomenon, primarily perceived as a challenge, was reconceptualised as a foundation for envisioning new developmental trajectories (Grelak and Pasternack, 2015). In this context, and to counteract the prospective risk of 'functional irrelevance' (Kil, 2004) associated with shrinking cities, the government of Saxony-Anhalt opted in 2002 to pursue an International Building Exhibition (IBA) as a component of the Stadtumbau Ost policies through 2010. Encompassing the entire territory of the federal state, the IBA was conceived as an informal, innovative, strategic planning instrument to foster more sustainable future developments of cities and municipalities.

IBA Saxony-Anhalt 2010

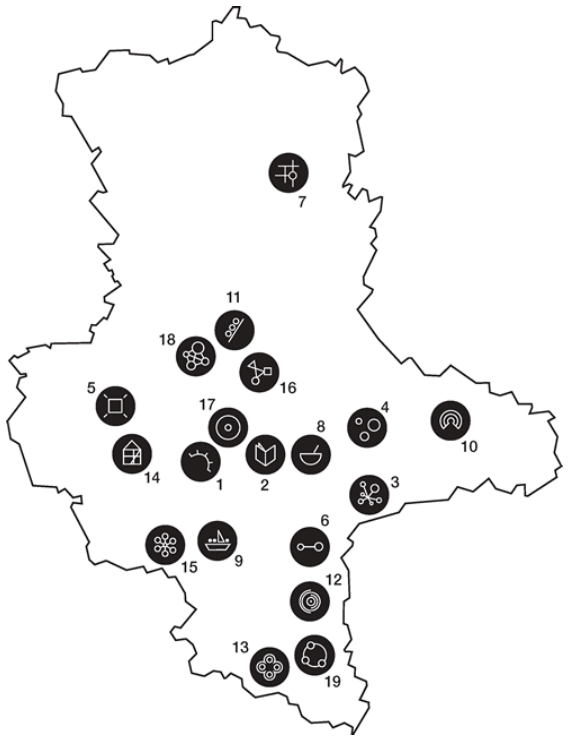
The central aim of IBA Saxony-Anhalt 2010 was to develop appropriate tools for dealing with urban shrinkage and simultaneously increase the quality of life by developing and implementing appropriate strategies to reshape the urban space. Under the slogan "Less is More", the objective abandoned the established growth paradigm and recognised shrinkage as irreversible. It addressed a topic hardly discussed till then: How to deal with cities in a situation where growth is not to be expected in longer terms? How can we deal with shrinkage and de-growth by developing positive perspectives and structures?

In the manner of an innovation lab, IBA programs focused on experimental and diverse approaches, where the participating cities develop exemplary responses and demonstrate new urban perspectives for how to react to shrinkage challenges. Each city participating in the IBA was supposed to pursue its key theme for individual profiling of its urban development (see Figure 8). Overall, the aim was to strengthen the specific economic, social and cultural potentials and to develop a guideline for the future structural and spatial development of the cities involved (BVMBS, 2012). The following were some of the guiding principles the IBA Saxony-Anhalt (IBA Urban Redevelopment, 2010):

- Urban development concerns various actors (inhabitants, property owners, businesses, and local authorities) who must participate in the development process.
- Structural change can allow urban planning to discover and develop unknown potentials creatively.

- Model projects can attractively redevelop cities through experimental design and a new mix of uses.
- Every city has its unique path of development.
- Urban redevelopment can create a compact city with new open spaces and new relations between the city and the landscape.
- As media and communication also define a city's image, designing city marketing strategies is part of the redevelopment process.

Although, in the beginning, there were no clear ideas of the measures for sustainable de-growth, all 19 participating cities finally conceived their programs and profiles of how to develop in the long term in a more sustainable form and without population growth. Experiments were allowed and advised, and all cities were supposed to analyse and build on their specific strengths, identities and heritage (and not just on their problems). As a result, the IBA became a significant innovation and urban planning laboratory.



1. Aschersleben: From the Outside to the Inside – Focussing on the Centre
2. Bernburg (Saale): Generating a Future in Education – Learning at the Centre
3. Bitterfeld-Wolfen: Network Town
4. Dessau-Roßlau: Urban cores – Landscape Zones
5. Halberstadt: Cultivating Empty Space
6. Halle (Saale): Balancing Act: Dual City
7. Hansestadt Stendal: Central Town in a Rural Region
8. Köthen (Anhalt): Homoeopathy as a Development Force
9. Lutherstadt Eisleben: Common Responsibility – Redeveloping Luther's Town
10. Lutherstadt Wittenberg: Campus Wittenberg
11. Magdeburg: Living alongside and with the Elbe
12. Merseburg: New Milieus – New Opportunities
13. Naumburg (Saale): City Formation – Citizenry and Building Culture
14. Quedlinburg: Perspective: World Cultural Heritage
15. Sangerhausen: Rating – Livable Neighbourhoods
16. Schönebeck (Elbe): Seventeen Seventy-Four
17. Staßfurt: Relinquishing the Old Centre
18. Wanzleben: Family Town
19. Weißenfels: A Time for Founders

Figure 8. Beneficiaries of IBA Saxony Anhalt urban redevelopment. Source: IBA, 2011

1.5. In search of better urban shrinkage management

Poland is anticipated to experience a significant urban population decline, with projections indicating a 6.5% drop by 2030 and an 18.5% decline by 2050 (Statistics Poland, 2023). This trend highlights the need to move away from the traditional "steady growth" paradigm (Stryjakiewicz, 2014a) and explore new urban planning approaches incorporating shrinkage scenarios. Bontje (2004), Hollander et al. (2009), and Pallagst et al. (2021) argue that viewing urban shrinkage as an

opportunity for change can create a new perspective on its chances and possibilities. Pallagst et al. (2021) argue that similar patterns of policymaking can be observed in many geographical contexts where urban shrinkage is the dominant problem. Coping strategies evolve from ignoring to observation without acceptance to partial acceptance and, later, acceptance and communication. While the importance of the problem in Poland was evidenced by the Senate Report entitled “Management of a Shrinking City” (Polish Senate, 2013) and “The National Spatial Development Concept 2030” (MFPR, 2019), no planning policies were implemented to target it. Pallagst et al. (2021) argues that urban shrinkage circumstances eventually "lead to an adaptation of traditional, long-established ways of dealing with planning problems and therefore to a change in local planning culture. This could mean a stronger focus on redevelopment of existing urban structures or densification and compact developments” (Pallagst et al., 2021, p.58).

Comparative studies on shrinking and re-growing cities reveal that compact, inward-oriented planning — focusing on revitalising housing, green spaces, and public services — can improve urban density and attract new residents (Haase et al., 2021). Researchers argue that instead of focusing solely on growth, cities should actively shift toward policies that innovate and manage decline, from revitalising urban cores to promoting compact development that limits urban sprawl and maximises efficient land use. However, the difficulty in post-socialist countries is often related to persistent faith in market forces, which limit proactive shrinkage management (Couch et al., 2012), often resulting in delayed responses to visible urban decline.

While there is no “one-fits-all” strategy to deal with urban shrinkage, Western European cities offer valuable insights, having developed strategies to manage shrinkage through economic, social and spatial approaches. Adopting a similar perspective, with strong local leadership and support from EU programs, could help CEE countries adapt to shrinkage while enhancing urban quality and sustainability (Großmann et al., 2013; Herrmann et al., 2016). Poland’s urban shrinkage challenges reflect previously observed European patterns, where suburbanisation and urban sprawl have often shifted populations away from city centres, creating high vacancy rates and underutilised infrastructure (Koziol, 2004; Reckien and Martinez-Fernandez, 2011; Pallagst et al., 2021).

Urban shrinkage in Poland is a pressing issue that challenges traditional, growth-oriented urban planning strategies, highlighting the need for innovative approaches. With currently available IT methods and data science tools offering ways to manage big data, understanding the relationship between socio-spatial dynamics and spatial urbanisation patterns is within reach. The author believes that analysing shrinkage from an urban planning perspective can lead to meaningful insights for enhancing sustainability, mitigating climate change, and fostering urban resilience.

2. Research background

Considering the growing challenges Polish cities face in managing shrinkage, this section aims to define critical research problems that will shape the direction of this work. Drawing on experiences from urban shrinkage management in Germany and critical literature findings outlined in the previous part, this section delves deeper into essential aspects of analysing shrinkage patterns and their relationship to urban form. The initial chapters present a background literature review. The significance and necessity of the research are highlighted by reviewing the literature on methods for measuring urban shrinkage, the context of current urbanisation patterns in Poland with a focus on the role of medium-sized cities and how urban shrinkage is managed in them. Consequently, this chapter exposes gaps in research on the relationship between spatial form and urban shrinkage processes. Subsequently, the research gaps are outlined to inform the specification of the research aim and objectives.

2.1. Research background

Research on shrinking cities

The term shrinking city is a frame of reference for a wide range of topics (Haase et al., 2014) that has gained wide use in urban studies research, including the fields of geography, social economics, and urban planning. The domain of urban shrinkage has determined much academic and practical discussion, conferences as well as several international research projects including but not limited to SCIRN (The Shrinking Cities International Research Network), CIRES (Cities Regrowing Smaller), and Shrink Smart (Governance of shrinkage within a European context). Scholars have searched for a more precise definition to capture the complexity of urban shrinkage (Turok and Mykhnenko, 2007; Haase et al., 2008, 2013; Mykhnenko and Turok, 2008; Pallagst et al., 2009; Haase et al., 2014; Grossmann et al., 2013; Sroka, 2021 among others), analysed growth and shrinkage theories (Alves et al. 2015; Van den Berg et al., 1982; Wolff and Wiechmann, 2017;), investigated the causes and effects of this process (Reckien and Martinez-Fernandez, 2011; Wiechmann and Pallagst, 2012; Wolff and Wiechmann, 2014), and analysed governance scenarios to avoid the spiral of decline (Bernt et al, 2012; Haase et al.,2014; Ogrodowczyk et al., 2021; Pallagst et al., 2021 among others).

Scales of urban shrinkage

The process of urban shrinkage varies due to historical, geographical, and socio-economic factors (Stryjakiewicz et al., 2014a). It can occur alongside urban growth, complicating comprehension (Hollander et al., 2009; Kazimierczak and Szafrańska, 2019). Integrating different research scales offers a comprehensive view of the process. As shown in Figure 3, Kazimierczak and Szafrańska (2019) outline three scales for analysing the physical aspect of urban shrinkage: national and

regional studies that identify causes and effects across cities; an urban scale that assesses local depopulation impacts on city and surroundings and an intra-urban scale studies that examine specific districts to understand shrinkage patterns within a city. In each scale a different set of indicators can be measured. A meta-analysis on urban shrinkage conducted by Reis, Silva, and Pinho (2016) indicates that research on urban shrinkage is less comprehensive than that focused on growth patterns. This disparity arises because the spatial patterns associated with shrinkage are often less clearly defined; built-up areas do not necessarily vanish when populations decline (Reis et al., 2016). Großmann et al. (2013) suggest examining shared spatial characteristics across various scales that may reveal indicators of shrinking urban areas.

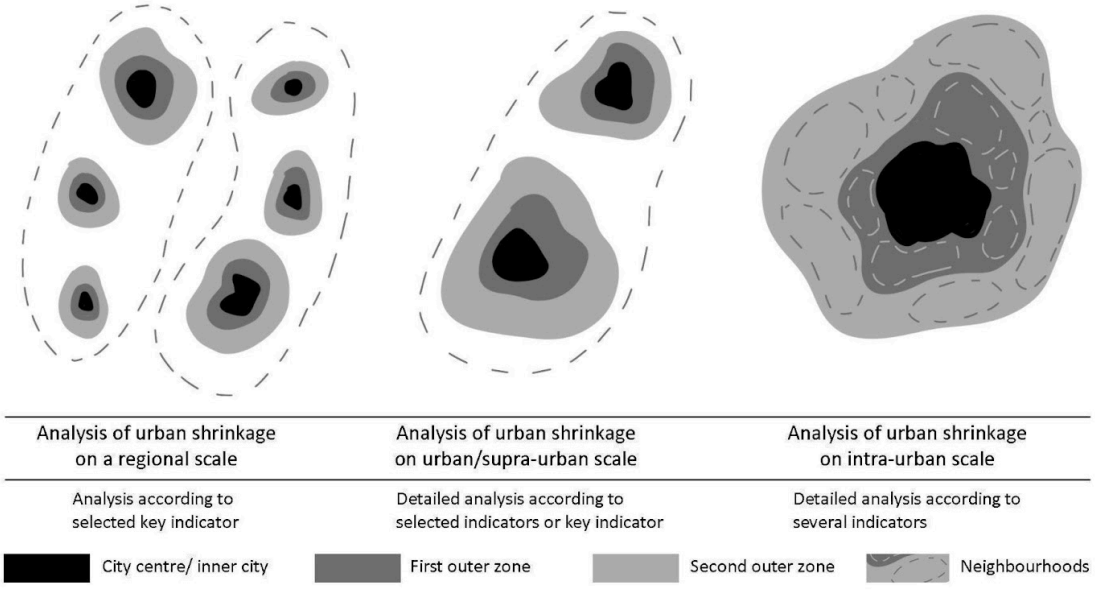


Figure 3. Scale of analysis of urban shrinkage process. Source: Author's own elaboration based on Kazimierczak and Szafrańska (2019).

Growth and shrinkage theories

Theories aimed at understanding the cycles of urban growth and shrinkage suggest that shrinkage can be viewed as part of a city's life cycle, alternating with periods of growth (Klaassen, 1988; van den Berg,1982) or as a process driven by conditions that lead a city into a continuous decline, with no prospects for population growth (Alves et al., 2016). This latter scenario is often related to path dependence (Pinoncely, 2022) or a spiral of decline, where population and economic downturns serve as both causes and effects of ongoing shrinkage (Jaroszewska, 2019; Pallagst et al., 2021). A meta-analysis by Döringer et al. (2019) identifies several key factors contributing to urban shrinkage, including deindustrialisation, suburbanisation, an ageing population, out-migration, low birth rates, post socialist transformation, and disasters, particularly those related to climate change. Their analysis highlights three main themes regarding the impacts of shrinkage on cities in Europe:

housing vacancy, unemployment, and economic decline, with issues of urban decay and diminishing economic activity (Döringer et al., 2019).

2.1.1. Measuring urban shrinkage

The term urban shrinkage encompasses the multifaceted nature of the process, including economic, demographic, geographic, social, and physical implications. It continues to evolve in response to changing global and local realities, shaping theories and research aimed at diagnosing, forecasting, and addressing these challenges (Couch et al., 2012; Döringer et al., 2019; Haase et al., 2013; Martinez-Fernandez et al., 2012a,b, 2016). The phenomenon of urban shrinkage has been extensively examined in numerous research initiatives, including the COST Action TU 0803 “Cities Regrowing Smaller” (CIRES) and the Shrinking Cities International Research Network (SCiRN), alongside significant global publications (Oswalt, 2006a,2006b; Oswalt and Rieniets, 2006; Pallagst et al., 2009; Martinez-Fernandez et al., 2009, 2012a, b, 2016; Großmann et al., 2013; Haase et al., 2013, 2014, 2021). Nonetheless, the challenge of precisely defining this urban phenomenon endures (Bernt et al., 2014; Haase et al., 2014; Kantor-Pietraga, 2014; Sroka, 2022). Stryjakiewicz and Jaroszewska (2016) noted that the shrinkage phenomenon lacks a singular explanatory theory. This process's multifaceted nature necessitates applying various theoretical frameworks to comprehensively understand its mechanisms, patterns, and consequences (Stryjakiewicz and Jaroszewska, 2016).

Problems with demographic indicators

The complexity of analysing shrinkage stems partially from the dual role of population decline, which acts as a causative factor and a consequence of urban shrinkage. Consequently, a substantial portion of research has concentrated on the demographic dimensions of shrinkage, with population change as the predominant indicator (Döringer et al., 2019). For example, the CIRES project, executed across various European cities, defines shrinkage quantitatively as a depopulation rate exceeding 0.15% annually over a minimum duration of five years. Conversely, Turok and Mykhnenko (2007) characterise it as a reduction in population across consecutive five-year intervals, incorporating relative population change to national demographic trends as an additional metric to illustrate shrinkage at the national level. Despite declining populations, it is crucial to acknowledge that some urban centres may maintain resilient economic structures and continue to prosper. According to Wolff and Wiechmann, “there are many examples where the demographic and the economic development do not go hand in hand. Cities losing population can keep a strong economic structure and development” (Wolff and Wiechmann, 2014, p. 1). This observation, according to the authors, underscores the necessity for a more nuanced, multidimensional perspective of shrinkage — one that associates the process with urban centres'

social, spatial, and economic restructuring, which may occur with a consistent population decline (Zborowski, 2012; Wolff and Wiechmann, 2014).

Analysis time frames

The meta-analysis conducted by Döringer et al. (2019) revealed that the temporality of urban shrinkage was underrepresented in research. “The narrow focus on the temporal aspect of population trajectories hampers not only a comprehensive understanding of urban shrinkage but also the interpretation of any applied responses” (Döringer et al., 2019, p.15). Authors emphasise that many empirical case studies lacked a timeline for the analysed processes, while other methods did not allow for temporal classification.

Multi-criteria indicator

Considering this context, SCIRN has formulated a definition encompassing not only population decline but also indicators of economic transformation, showcasing specific symptoms of a structural crisis (Bernt, 2018). “A ‘shrinking city’ can be defined as an urban area – a city, part of a city, an entire metropolitan area or town – that has experienced population loss, economic downturn, employment decline and social problems and symptoms of structural crisis” (Martinez-Fernandez et al., 2012, p.214). Therefore, this perspective indicates that a spectrum of spatial scales and economic, social and demographic indicators should be considered when identifying shrinking cities. However, as highlighted in a meta-study by Döringer et al. (2019), research that addresses multiple dimensions of urban shrinkage tends to be conducted primarily as case studies (Döringer et al., 2019). Consequently, this approach is seldom applied nationally due to the challenges associated with the robustness, availability, and processing of diverse socio-economic and demographic data. As a result, comprehensive multi-criteria indicator analyses of urban shrinkage across all cities within the settlement network are rare.

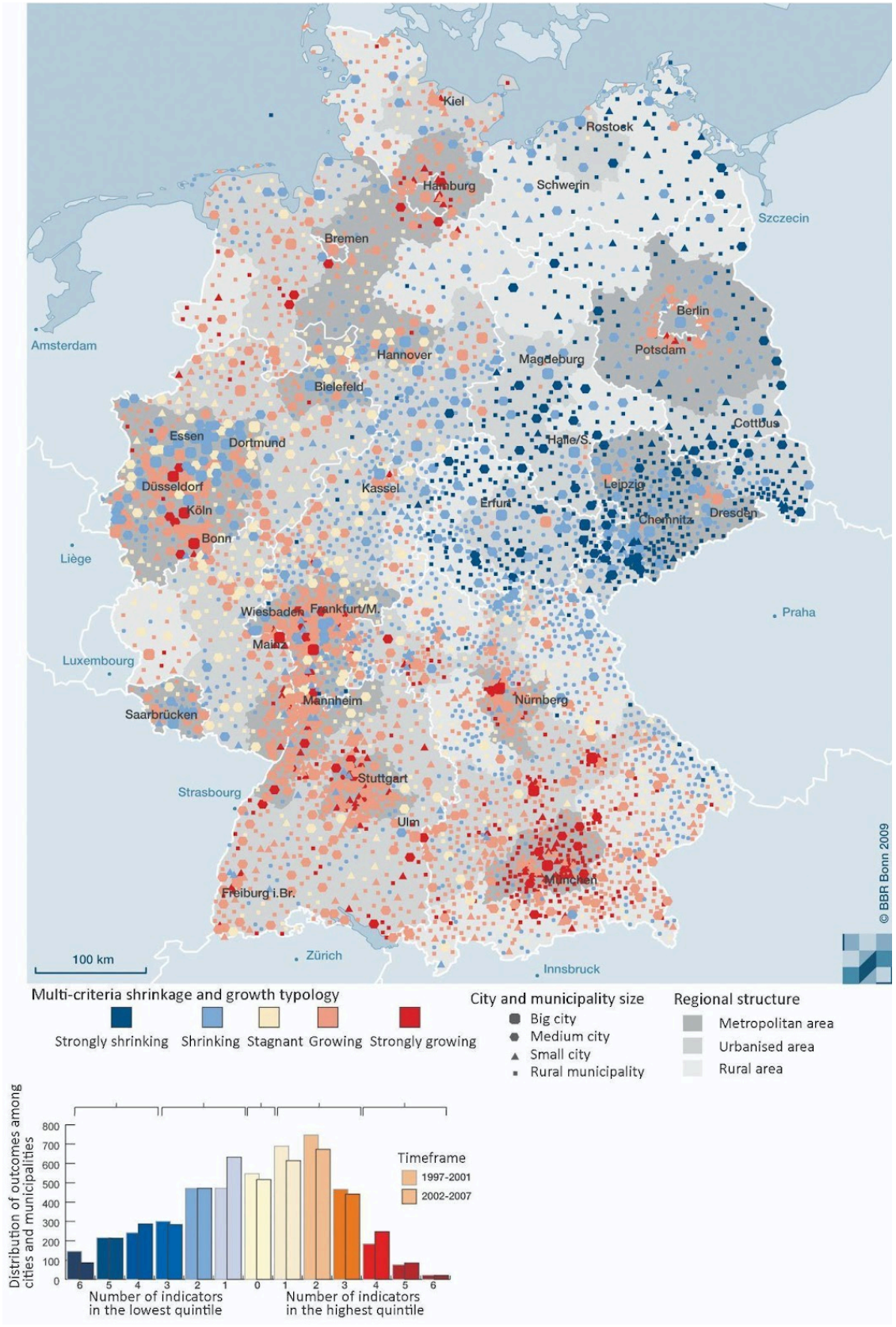


Figure 9. Multi-criteria shrinkage and growth assessment of German cities and municipalities 2003-2008. Source: Gatzweiler, Meyer and Milbert, Schrumpfende Städte in Deutschland? Fakten und Trends, 2003

An exception can be found in Germany, where the BBSR monitors urban growth and decline using a multi-criteria assessment method (Milbert, 2015, 2020). It has continuously monitored urban growth and shrinkage every five years since the early 2000s (see Figure 9). This supports the diagnosis of urbanisation processes, helps planning responses, and later assesses their effectiveness.

2.1.2. Context of urbanisation patterns in Poland

When analysing urbanisation processes in Polish cities, it is crucial to know its specificities. The urban settlement network in Poland, like in any other European area, is a result of an evolution that has taken place over centuries. "During this period, over 1,400 settlement complexes and units were established, either in the past or currently holding city status. These settlements have survived in various conditions, from minimal archaeological relics to fully preserved complexes with their original layouts and often intact building structures [...]. Poland's complex political, social, and economic history has influenced not only the diverse development of individual cities but also the structure of the settlement network. This network exhibits clear density in areas that developed intensively in the past (e.g., Silesia or Greater Poland), with noticeable sparsity in the northern part of the country and the border regions of the south and east. For other reasons, differences also emerged between various regions of Poland in the formation and architectural style of cities, which [...] appeared in the [...] late Middle Ages" (Kalinowski, 1986, p. 16, author's translation from Polish). Polish settlement network was a subject of study by numerous scholars (for example Chojnicki, 1970; Kalinowski, 1986; Kusiński, 1991, 1994; Liszewski, 1994; Parysek, 2004), including Jażdżewska (2006, 2008) who utilised mathematical methods to explore the development of urban networks. Jażdżewska argues that the historical development of urban settlement networks in Poland continues to influence urban areas' organisation and clustering today Jażdżewska (2008) (Figure 10).

Transformations of the Polish settlement network

When describing the context of the contemporary Polish urban settlement network, it is important to note that "Poland is an example of a country with the greatest territorial variability in European history. These changes did not only involve the temporary acquisition of some provinces and the loss of others, which were later regained. Rather, the country's expansion is far beyond its natural geographical boundaries, deeply into neighbouring regions, while losing its historical provinces. There were also periods when the Polish state disappeared from the map of Europe for a long time" (Koter and Kulesza, 2002, p. 165, author's translation from Polish). According to Jażdżewska (2008), the Polish urban settlement network was susceptible to the influence of various factors (including political, environmental, economic, and social) that altered its spatial arrangement over more than 1,000 years. Conversely, it displayed remarkable resilience and is regarded as one of

the most stable components of the country's physical landscape (Jażdżewska, 2008), with the primary urban centres today mirroring those from the mediaeval period. This observation aligns with Liszewski's (1994) perspective, which characterises the urban settlement network as "the cultural heritage of Poland."

Figure 10. Distribution of urban clusters in relation to the administrative division of Poland in 2002 (k-means method, k=16). Source: Jażdżewska, 2006

Post-WWII urbanisation patterns

The analysis of urbanisation patterns cannot be separated from the political context. The devastation of Polish cities during World War II was severe, with about 30-40% of the urban population lost (GUS, 2015). According to Lubocka-Hoffmann (2004), out of roughly 700 historic cities in post-war Poland, the average destruction in 177 centres exceeded 50%, with most of this damage occurring in the densely built Old Towns of cities located in the Recovered Territories (Lubocka-Hoffmann, 2004). Various researchers, including Johnson (2000), Racoń-Leja (2019), and Lorens (2023), have studied the impact of the war and reconstruction efforts on today's urban fabric in Poland.

After WWII, industrialisation was “the primary force driving urbanisation” (Kusiński, 1991, p. 277). While industrial investments were localised mainly in big and medium-sized cities, the main migration direction was from small towns and villages. Processes that significantly influenced the shape of the post-war urban settlement network stemmed from the six-year plan (1950–1955) assumptions, known as the plan for building the foundations of socialism in Poland. This plan aimed to initiate a long-term transformation of reducing disparities in the country's previously uneven distribution of productive forces. Over 85% of investment funds were allocated to heavy industry during this period (Jażdżewska, 2008). This stage was followed by the five-year plan (1956-1960), an extension of the former, which also focused on heavy industry, including mining and energy infrastructure and production. This industrialisation phase shaped urban centres and transformed Poland from “a country of great coal” to a country “of great sulphur and copper”. Consequently, by the end of 1978, the number of cities in Poland grew to 803 from only 603 in 1936 (Jażdżewska, 2008).

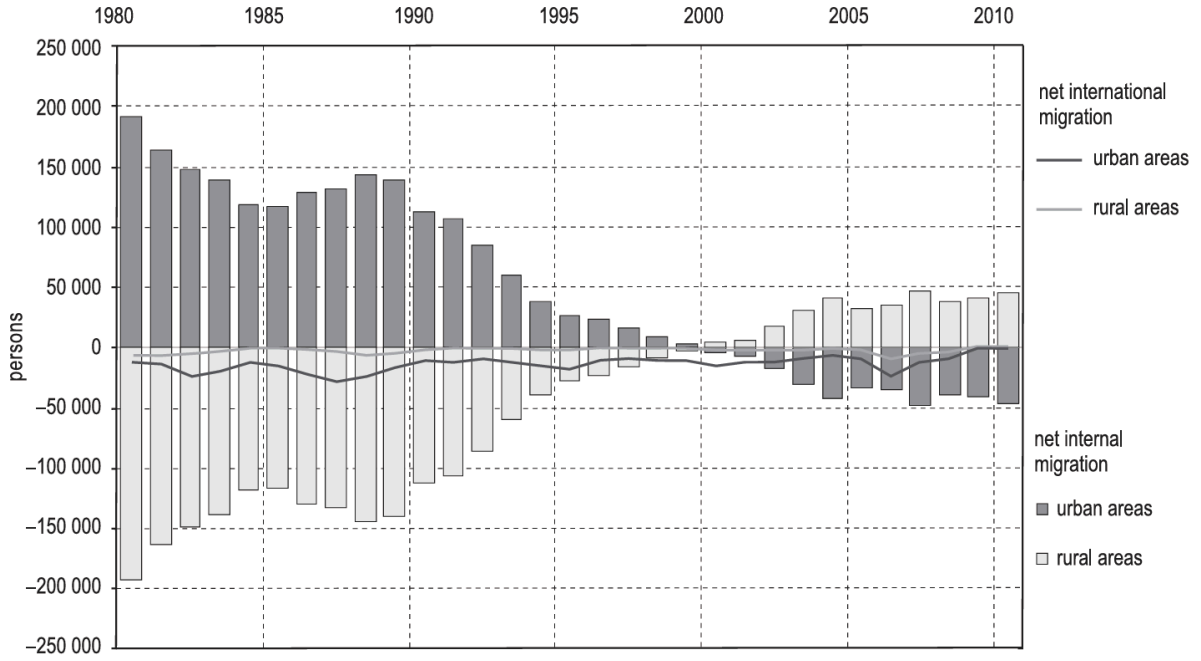


Figure 11. Migration of permanent residents in Poland in 1980–2010. Source: Zborowski et al., 2012

The 1989 political shift significantly altered the trajectory of urbanisation patterns (Parysek, 2004). During the transformation period, an unprecedented number of urban areas were granted city status, with an additional 63 cities, most of which were degraded. As a result, the urbanisation index saw an increase. The 1950s-1980s also marked a clear migration trend from rural areas to cities, culminating in a peak urbanisation level of 61.68% in 2003, a bit lower than the European average of 68.78% then. However, significant changes to the urban settlement network were caused by the 1999 administrative reforms and the ongoing deindustrialisation of cities. They resulted in changing the hierarchy in the system of cities, reshaping voivodeship boundaries, and

downgrading many cities from their leading regional functions (Zborowski et al., 2012). The de-urbanisation trends that started then continue until today (see Figure 11). In 2021, partially due to COVID-19-related dynamics, the urbanisation level had further declined by 1.8%, settling at 59.8% (GUS, 2024), with more people migrating from cities to rural areas. Despite the influx of migrants (also from war-torn Ukraine), the urbanisation forecasts are showing a decline (GUS, 2023).

Polish settlement network characteristics

One of the central qualities described in European urban policies is the urban network polycentricity, seen as more sustainable, able to contain sprawl, and leads to more efficient economies (ESPON, 2007). As a parameter describing urbanisation – the polycentricity index – indicates the settlement network diversity. It was studied under the ESPON 1.4.3 (2007) program and was high for Poland — 85.6 (in Germany – 93.4, the second highest index in Europe). In other words, Poland's urban settlement network is diverse in the number of big, medium, and small cities and equally distributed within the borders (see Figure 12).

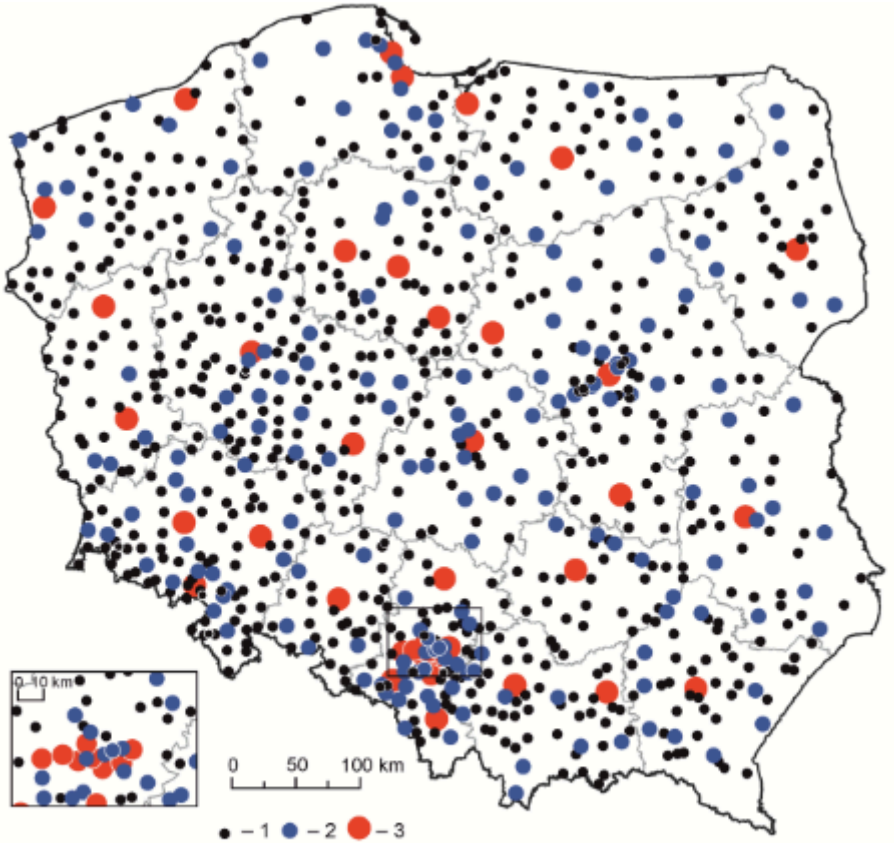


Figure 12. Cities in Poland in 2008 divided into small (1), medium (2) and large urban centres (3). Source: Runge, 2012

Urban challenges in Poland

As mentioned above, despite Poland's historically well-distributed network of cities, the settlement system has faced increasing imbalance since the late 1990s. According to Śleszyński (2017, 2019), who conducted an extensive study on the medium-sized cities role in the urbanisation of Poland, polarising trends, particularly resource concentration in major centres like Warsaw and the breakdown of functional linkages, have led to growing disparities in capital and human resources especially in peripheral areas. Moreover, urban sprawl and suburbanisation around the big cities pose challenges to harmonised and sustainable development (see Figure 13). The increasing depopulation of the country will further deepen socio-economic problems for most small urban centres (Runge, 2012; Stryjakiewicz, 2014; Krzysztofik and Szmytkie, 2018). According to Śleszyński (2017, 2019), medium-sized towns are vital to organising socio-economic structures in regions beyond large agglomerations and are crucial in supporting rural and marginalised areas. Strengthening city networks and linking them to degraded areas could foster stability and growth, helping revive struggling regions (Śleszyński, 2019).

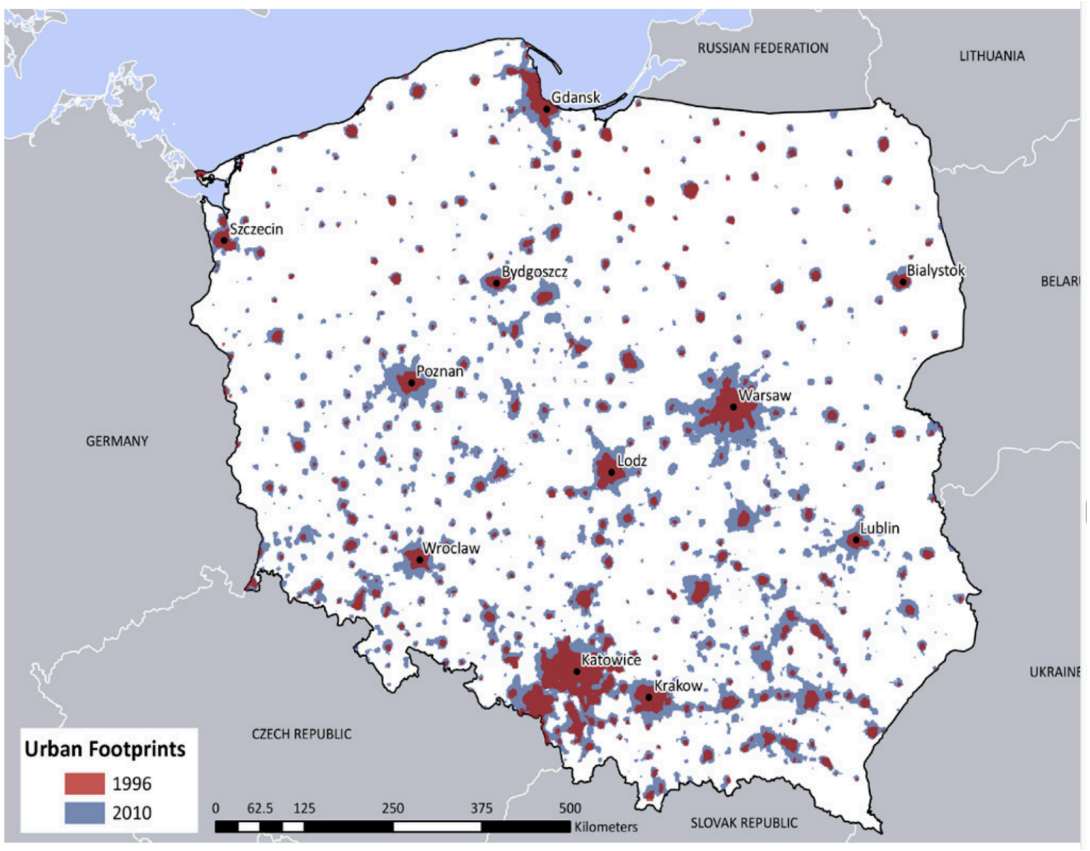


Figure 13. Nightlights change over time used to define urban footprints, showing how Poland has experienced an increased growth rate in built-up areas, especially around the major cities. Source: World Bank, 2010

2.1.3. Medium-sized cities

In recent decades, the academic discourse surrounding urban studies has predominantly concentrated on large urban agglomerations. This shift in focus is mainly attributable to the increasing globalisation and socio-economic transformations that have significantly augmented the prominence of the megacities and growing metropolitan areas. However, as stated by Audriac (2010), globalisation exposes all cities to both the "benefits and risks of global economic integration" (Audirac, 2010, p. 69). The forces of modern capitalism have established a global network that predominantly benefits large urban centres, leaving small ones at risk of being marginalised and unable to compete with major economic hubs.

Some scholars see urban decline as a peripheralisation process, which pushes certain cities out of global competition and distances them from metropolitan winners that can attract social capital. Theories coming from urban political economy describe this process as follows: “The flow and accumulation of capital tend to produce temporary ‘fixes’ in space and time (Harvey, 2006; Smith, 2010) and how geographical inequalities are shaped by the ownership and control of the means of production and the built environment as well as by corporate decisions (Massey, 1995).” (see Großmann et al., 2013). These inequalities especially affect cities lower in the hierarchy, such as *secondary cities*, which struggle to compete with metropolitan-level centres. Over time, many of them have diminished in vitality and significance, thereby becoming emblematic of broader issues such as "shrinking cities" and "urban decline" (SMESTO, 2005). For them, the question of their fate depending on location and position in a wider urban hierarchy must be addressed.

Consequently, scholars are progressively examining the challenges and vulnerabilities associated with the secondary position of urban centres in the settlement hierarchy to understand and address the multifaceted dynamics of urban decline. Kunzmann (2010) argues that small urban centres bear the negative consequences of overarching policies shaped by globalisation and regional competition. Excessive metropolisation leads, in his view, to a dangerous rise in polarisation between large urban agglomerations and local centres. The author highlights the increasing significance of small and medium-sized towns in contemporary discourse (Kunzmann, 2010).

Polish medium-sized cities

In her comprehensive analysis of medium-sized towns' role in shaping Poland's settlement system, Runge (2012) critically examines existing research while identifying significant gaps that warrant further exploration. She posits that the prevailing neglect of medium-sized cities in research can be attributed to entrenched post-war stereotypes and the relative accessibility of studies focusing on local, small urban centres. Furthermore, studying medium-sized cities necessitates more robust methodologies, diverse analytical tools, and well-established theoretical frameworks to foster a

deeper understanding of their dynamics and contributions to regional development (Runge, 2012). As argued by Runge (2012), compared to large urban centres, medium-sized cities often have less data available or are harder to access.

According to German BBSR research conducted in 1997-2001, a steep decline in population and employment was most prominent among medium-sized cities in East Germany (Gatzweiler, Meyer and Milbert, 2003). Compared to big and small urban centres, the medium ones were the most affected. Population predictions in Poland show a similar pattern, with medium-sized cities among those experiencing the most severe drops, e.g., Konin (predicted to lose 39% of its population in 2050), Tarnobrzeg (predicted 35,4% loss) and Sosnowiec (predicted 35,3% loss) (GUS, 2023). Due to a lower concentration of potential (social capital), technological changes are slower than in the buzzing metropolitan hubs. Despite these drawbacks, medium-sized cities still play key roles in the peripheral regions (Śleszyński, 2017,2019; Runge, 2012), serving as functional centres for surrounding rural areas and small towns. Thus, their performance affects the quality of life of a much greater population than the one inhabiting them and influences the stability of the entire settlement network.

2.1.4. Challenges of urban planning in Poland

The effectiveness of planning policies implemented thus far requires substantial enhancement to adequately address the above-mentioned challenges. According to the audit conducted between 2019-2022 by the Supreme Audit Office (orig. Najwyższa Izba Kontrol, NIK) (NIK, 2022), the local governments in Poland did not take advantage of the existing planning tools to steer their development sustainably (NIK, 2022). Not only were the local plans outdated in most of the 173 cases analysed, but they also greatly ignored the demographic statistics. The Study of conditions and spatial development directions (later called SCSDD) indicated that the area designated for residential development (single-family and multi-family housing) totalled over 6 million hectares, covering approximately 19% of Poland's total area. According to calculations by the Institute of Geography and Spatial Planning of the Polish Academy of Sciences, such an area could accommodate up to 200 million people. In contrast, Poland’s population is only 38 million (see Figure 14) (NIK, 2022).

Furthermore, as highlighted by the NIK report, in the period from 2019–2022, the inspected municipalities issued 1,664 Individual land development decisions (Warunnki Zabudowy i Zagospodarowania Terenu in Polish, WZiZT) instead of relying on local spatial plans. More than 36% of all WZiZT pertained to areas designated as greenfields, such as agricultural use or forests. This significant mismatch between the actual needs and the supply exacerbated by the ongoing urbanisation and depopulation poses a significant environmental challenge and creates additional

maintenance costs. It is estimated that spatial chaos generates a yearly loss of around 18.48 billion EUR (83 billion PLN) (NIK, 2022). Consequently, this puts local governments under even greater fiscal pressure.

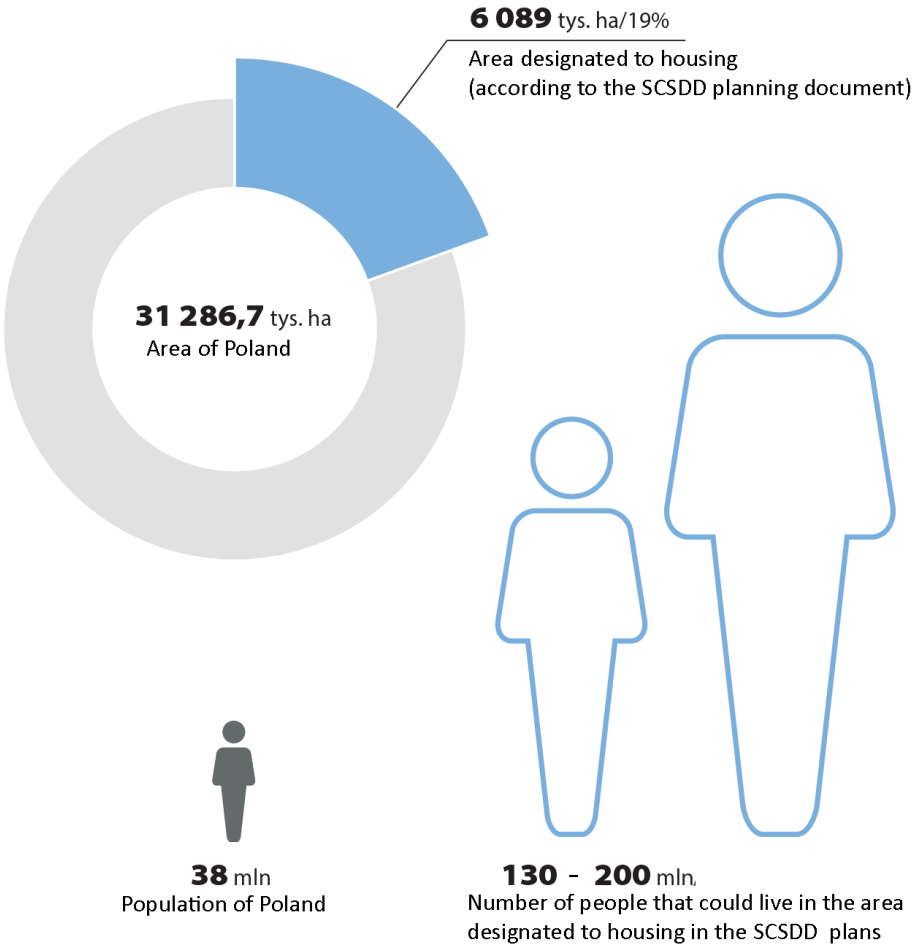


Figure 14. Oversupply of land designated for housing in local SCSDD plans and the actual population number on the 31st of December 2021. Source: NIK, 2022

New planning regulations

The 2023 planning law reform, effective in September 2023, introduces major changes to Poland's land-use planning system (Ustawa z dnia 7 lipca 2023 r., Dz.U. 2023, poz. 1688). A key aspect of this amendment is the introduction of a standardised General Plan (orig. Plan ogólny), which all 2,477 municipalities must adopt by the end of 2025 (!). This document replaces the zoning study (orig. Studium Uwarunkowań i Kierunków Zagospodarowania) and organises municipal areas into zoning classes. However, detailed zoning plans and building permits will still be required for development. As opposed to previous planning, individual land development decisions (WZiZT), after January 2026, can only be issued for projects in areas designated within the General Plan, with a validity of five years, ensuring a gradual phase-out of the old system while protecting investors' rights for decisions finalised by the end of 2025.

While the reform, tied to EU funding, mandates that existing zoning studies cannot be reused in creating new General plans, it also presents an opportunity to rethink the future spatial development of Polish cities. This is particularly significant given the introduction of new parameters that limit the provision of development areas based on demographic forecasts for municipalities, as derived from Polish Statistics data. For the first time, planning instruments have a chance to shape denser and more compact cities in Poland. However, effective use will always depend on local authorities' implementation and ability to see beyond the growth paradigm.

Model Urban Renewal (MRM)

When traditional planning instruments are not sufficient, experimental urban governance instruments such as urban renewal programmes can provide an alternative to business as usual. They can help innovate, raise awareness and build the capacities of the professionals and communities involved. An example in Poland is the Model Urban Renewal program (orig. Modelowa Rewitalizacja Miast, MRM), executed from 2015–2018 by the Polish Ministry of Development Funds and Regional Policy. The national government acknowledged the necessity for a more holistic approach to urban governance, particularly within small and medium-sized municipalities. The overarching planning framework underscored integrating social, economic, and urban development dimensions. The primary objective of this initiative was to facilitate the emergence of flagship projects and innovative initiatives. While urban development policies did not directly address the issues of shrinking cities, most beneficiaries identified depopulation as a critical concern in their project proposals. The approach adopted by the MRM program closely mirrored the concept of *urban restructuring*, a strategy widely applied in German urban development initiatives.

Both the IBA Saxony-Anhalt, mentioned in the introduction section of this dissertation and the MRM program were employed as complementary tools to support cities in managing urban challenges. However, while the IBA explicitly targeted selected medium-sized cities in the Saxony-Anhalt region, which had previously been identified as facing substantial challenges, MRM's competition was open to all cities in Poland dealing with various issues. Initially, there were no clearly defined guidelines or criteria for using indicators to benchmark the participating cities. This complexity was further intensified by the inclusive approach to city selection, which involved a diverse array of municipalities, including major cities with high growth rates and budgets. Understanding medium-sized cities' particular characteristics is essential in developing appropriate planning programs to address their challenging position. Suppose planning tools are to be efficiently designed. In that case, there is a pressing need for a better comprehension of Polish medium-sized cities in relationship to urban form and establishing guidelines for effective urban shrinkage management.

2.1.5. Research on the urban form patterns of growth and shrinkage

In contrast to other regions in Europe, the case of IBA Saxony Anhalt showed a bold step asserting that shrinkage opposes growth (IBA, 2011). Significant progress was made for small to medium-sized towns facing similar issues throughout the eight years of the IBA International Building Exhibition. A primary goal was to promote compact city principles, encouraging a shift from housing estates on the outskirts to urban centres (IBA, 2011). Over a decade later, most participating cities reported improvements, showcasing stable de-growth or re-growth and a change of perception among its citizens. While attributing the success of urban renewal solely to the Stadtumbau and IBA programs would be an overstatement, national and global economic factors contributed to this process. However, by enhancing spatial qualities and containing urban sprawl, shrinking cities in East Germany have effectively navigated their futures without depending on growth and developed new identities and ways forward (IBA, 2011).

The question of how urban form can enhance resilience and promote sustainable development in other shrinking cities is complex. Existing planning theories primarily focus on growth, prompting calls for tools specifically designed to address urban shrinkage (Reis et al., 2016). Resilience theories suggest that cities can adapt, transform, or resist challenges while maintaining essential functions (Alves et al., 2016). However, research on urban metrics related to urban shrinkage remains limited. In a study conducted in China, researchers found that urban shrinkage correlates with lower compactness and reduced land use efficiency (Wang et al., 2022). In Germany, Siedentop and Fina (2008) examined urban areas from 1996 to 2006, finding that suburban sprawl increased even as core city populations declined. This “shrinkage-sprawl” pattern mirrors sprawl in growing areas, leading to fragmented, low-density developments, rising vacancies, and deteriorating inner-city areas (see Figure 15). Research done by Sroka (2021) evidenced similar patterns occurring in Polish urban areas.

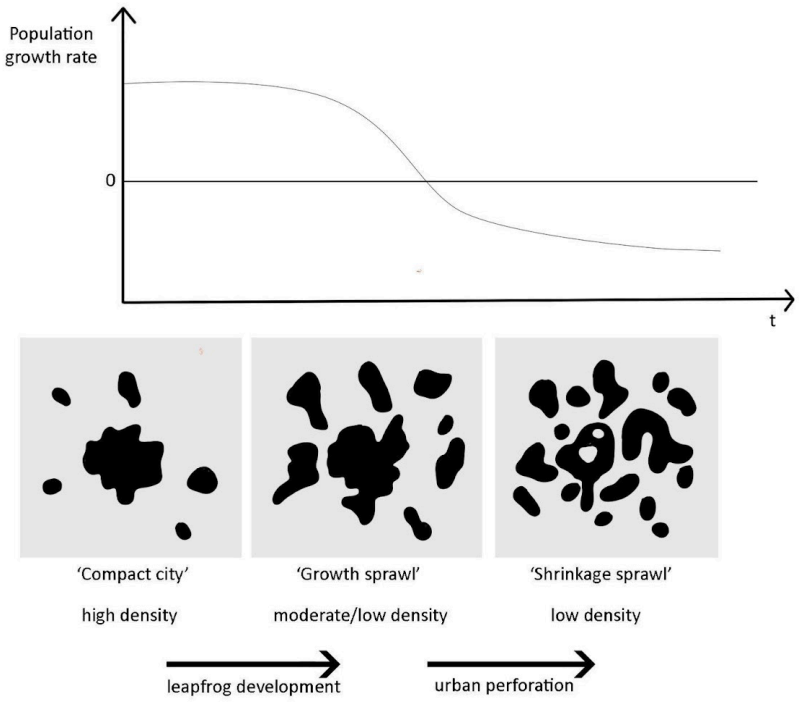


Figure 15. Pattern dimension of "shrinkage sprawl". Source: Author's own elaboration based on Siedentop and Fina, 2008.

Research shows that compact, contiguous urban areas have significantly lower infrastructure costs than dispersed ones (Carruthers and Ulfarsson, 2003; Miyauchi and Setoguchi, 2023). While in dispersed service areas, the length of inter-neighbourhood service components that connect them is higher than average (Burchell et al., 1998, p. 46), infrastructure costs can be a few times higher than in more compact urban areas. In shrinking cities, there is "too much town for too small a population" (IBA, 2011, p.19). Such disbalance often leads to a weakened fiscal base, disrupted infrastructure maintenance, and a diminished quality of life. As a result, many shrinking cities face challenges to sustain themselves (Hollander, 2009).

Schmidt et al. (2014) found that urban sprawl in post-socialist cities is driven not only by demographic and economic shifts but also by public policy and unregulated, market-driven growth. According to Schmidt et al. (2014), densities have been "exacerbated by public policy and unregulated market-induced growth in the case of the other CEE countries." (p.17). Authors argue that the ongoing demographic transition across Eastern Europe demands a comprehensive research agenda to examine how shrinkage impacts urban spatial patterns in more detail (Schmidt et al., 2014).

Urban form encompasses the historical context, economic conditions, well-being, spatial efficiency, and environmental impact of a city, making it a crucial indicator for understanding urban systems (Grimm et al., 2015; Wentz et al., 2018). Physical form is an empirical foundation for comparative

analysis of complex urban patterns across different cities (McPhearson et al., 2016). While historically, research on urban morphology has faced limitations due to data and computational constraints, recent advancements in geospatial tools and computing power have expanded analytical possibilities. However, studies examining urban metrics and shrinkage across entire urban networks must be advanced, necessitating computational resources.

2.2. State of research

Urban shrinkage is a complex phenomenon characterised by intricate cause-and-effect relationships. This process is closely tied to the post-transformation boom, deindustrialisation and spatial dependencies in CEE countries. Disruption, lack of or neglected city centres, and urban sprawl exacerbated by lack of effective planning policies influence shrinkage. Despite its significance, the relationship between a city's physical form and urban shrinkage is seldom analysed due to the substantial empirical challenges in capturing data on large spatial and longitudinal scales.

2.2.1. Urban shrinkage research in Poland

In contemporary Poland, urban shrinkage began to manifest in the early 2000s as the initial effects of the economic "shock therapy" became evident. While urban demographics have been a focal point of Polish researchers for several decades, the concept of urban shrinkage was first diagnosed by Zborowski (2002), Parysek (2004), and Jędraszko (2005). It was then followed by broader comparative studies such as CIRES and Shrink Smart (Krzysztofik et al., 2011, 2012a) and later Krzysztofik and Szmytkie (2011), Krzysztofik et al. (2011, 2012, 2014), Stryjakiewicz et al. (2012a, b), Zborowski et al. (2012), Stryjakiewicz et al. (2014, 2016), Kantor-Pietraga (2014), Jaroszewska (2019), Śleszyński (2017, 2019), Musiał-Malagó (2018a, b) and Sroka (2021). A study on the resilience of peripheral cities was conducted in a 3S RECIPE project (Ogrodowczyk et al., 2021).

As presented in the above sections, urban shrinkage is particularly pressing for medium-sized cities, which tend to have fewer resources and less planning capacity, making them more vulnerable to population loss (Runge, 2012; Śleszyński, 2017, 2019). Despite these cities being more susceptible to shrinkage, research on their experiences is limited. Most studies focus on case studies, for example of Wałbrzych (Jaroszewska, 2019), Bytom and Sosnowiec (Krzysztofik et al., 2011), Łódź (Kazimierczak and Szafrańska, 2019).

According to Śleszyński (2019), this complex phenomenon should be monitored and analysed across a broader set of urban units and from various thematic and problem-oriented perspectives. While much of the Polish discourse on urban shrinkage centres around socio-economic, demographic, and spatial dimensions, relatively few studies have approached this issue using a comprehensive, nationwide multi-criteria analysis. Studies by Jaroszewska (2019), Śleszyński (2017, 2019), Jopek and Musiał-Małago (2021) and Sroka (2021) are examples of this approach. However, no recent studies were conducted to assess how the process evolves. Therefore, there

is a need to regularly monitor and assess these trends, particularly focusing on all medium-sized cities which face challenges different from those of their larger counterparts.

2.2.2. Urban form research in Poland

There is no universally accepted or objective method for assessing urban form (Venerandi et al., 2016). In Poland, urban form patterns have been extensively studied, particularly in relation to urban sprawl (e.g., Gibas and Heffner, 2018; Lityński, 2021). The analysis of urban form within the context of urban shrinkage has been explored by Sroka (2021), who investigated the relationship between suburban sprawl and shrinkage. Research on the morphology of selected Polish cities includes studies of Łódź by Koter (1990) and Hanzl and Kowalski (2021), as well as analyses of Kraków's urban morphology by Kantarek (2010). However, to the best of the author's knowledge, there is limited literature on urban compactness, particularly from a nationwide perspective encompassing all cities in Poland.

An international literature review on urban shrinkage suggests that compactness is crucial in how cities manage challenges. Research shows that more compact cities tend to have stronger fiscal bases (Carruthers and Ulfarsson, 2003; Miyauchi and Setoguchi, 2023) and resilience to socio-economic decline (Haase et al., 2021). Planning practices in Germany have demonstrated that urban form can influence how cities cope with shrinkage. Right-sized, compact, and dense urban form enhances a city's resilience and mitigate the effects of decline (IBA, 2011). However, the relationship between shrinkage and form might be relevant for Germany but not necessarily in the Polish context. According to the authors' knowledge, such studies were never conducted in Poland, leaving an empirical and methodological gap to explore.

The central challenge guiding this research is effectively supporting medium-sized cities in Poland in effective urban shrinkage planning. While urban shrinkage poses complex issues, a nuanced understanding of its spatial, social, and economic impacts is required. Two types of research gaps have been identified: empirical and methodological. These gaps highlight the limitations in existing knowledge and the lack of tools for studying urban shrinkage, particularly in Poland, where such phenomena still need to be understood.

2.2.3. Summary of research gaps

This research addresses the need for a comprehensive, national-scale study of urban shrinkage in Poland that incorporates spatial, statistical and longitudinal data. It aims to bridge the field's empirical and methodological gaps identified in the research on medium-sized, shrinking cities in Poland. The following research gaps were defined in this study:

Empirical Gaps

- **Measuring Urban Shrinkage with multi-criteria indicators in Poland:** Current research struggles to measure the entire scope of urban shrinkage using multi-criteria indicators. This is due to the availability and management of appropriate datasets.
- **Long-Term Urban Shrinkage Measurement:** Another challenge is capturing long-term trends in urban shrinkage. Studies examining shrinkage over an extended period across all Polish cities are lacking.
- **Absence of Recent Shrinkage Assessments:** No national-scale assessment of urban shrinkage after 2018 has been conducted in Poland to the author's knowledge.
- **Absence of Recent Compactness Assessments:** No national-scale comprehensive evaluation of urban compactness across all Polish cities has been conducted to the author's knowledge.
- **Shrinkage and Compactness Relationship in Poland:** Little is known about whether urban shrinkage correlates with urban compactness in cities, a key factor in planning for sustainability and resilience. No such study has been conducted for Poland to the author's knowledge.

Methodological Gaps

- **Developing Multi-criteria Indicators for Shrinkage:** A method for measuring urban shrinkage on a national scale using multi-criteria indicator is lacking. Existing methodologies are either using demographic indicators, are outdated or adapted to selected cities. A method that captures socio-economic aspects of urban shrinkage relative to all municipalities is lacking to the author’s knowledge.
- **Compactness Measurement Methodology:** A method for comprehensive measuring urban compactness on a national scale using broadly available data was not developed to author’s knowledge.

3. Research description

The identified gaps in the literature guided the formulation of the research strategy. These gaps suggest that assisting medium-sized Polish cities in addressing urban shrinkage through urban planning requires both measuring urban shrinkage and assessing the compactness of urban forms and understanding the interplay between these two factors. Consequently, the study is structured into several stages to address methodological and empirical gaps, aligning with its specific objectives. This section outlines the main aims, objectives and specific research questions that guide this work and lead to verification of the hypothesis.

Moreover, this study recognises the potential relevance of the above concepts to other national contexts facing similar challenges and the benefits of sharing the outcomes in line with the principles of open science. Therefore, the selection of research aims, objectives, methods and data was made to enable their application in various European contexts and facilitate comparative studies to expand the scope of the research. The following chapters will outline the primary research concept.

3.1. Aims and objectives

Guided by the need to address urban shrinkage challenges through an urban planning lens, this research aims to expand knowledge in the field, establish tools to monitor socio-spatial phenomena and formulate practical planning guidelines. **The main aim is to examine if there is a relationship between urban form and shrinkage in medium-sized Polish cities**. To achieve it, analysis of recent trends in urban shrinkage and urban form compactness has to be conducted. Consequently, this research plans to address the four operational objectives, which are divided into two categories, **methodological** and **empirical**, listed below:

Methodological	*Objective 1*	**To identify methods to evaluate the urban shrinkage and urban form compactness using broadly available datasets.**
Empirical	*Objective 2*	**To assess shrinkage and growth trends in Polish cities.**
	Objective 3	**To assess compactness and dispersion trends in Polish cities.**
	Objective 4	**To find out if there is a relationship between urban shrinkage and urban compactness trends.**

The four objectives are connected to six operational research questions. The methodological objectives, listed as Objective 1, are guided by three questions. Answering them is necessary to

develop appropriate methods to investigate urban shrinkage and urban form compactness and answer the questions of empirical objectives.

Objective 1	*Question 1.1.*	**What are the methods utilisable in identifying shrinking and growing cities?**
	Question 1.2.	**How can existing multi-criterion methods for such identification of shrinking and growing cities be adapted to fit the Polish context?**
	Question 1.3.	**What are the methods for analysing compactness?**

The empirical objectives aim to find the relationship between urban shrinkage and urban form compactness. The Objective 2 is operationalised by a question that leads to understanding urban shrinkage in Polish cities. The Objective 3 is operationalised by two questions that lead to understanding urban from compactness in Polish cities. The Objective 4 is operationalised by three research hypotheses. Testing these hypotheses, aim to find if there is a relationship between the compactness of urban areas and urban shrinkage in medium-sized Polish cities in the researched period.

Objective 2	*Question 2*	**What are the trends and patterns of urban shrinkage, and how do these differ in cities of different sizes across Poland?**
Objective 3	*Question 3.1*	**What is the relationship between city size and city compactness in Poland?**
	Question 3.2	**How does the compactness of Polish cities change over time?**
Objective 4	*Hypothesis I*	**There is a statistically significant correlation between urban compactness and shrinkage of medium-sized Polish cities.**
	Hypothesis II	**There is a statistically significant correlation between urban population density and shrinkage.**
	Hypothesis III	**The trend persists within the analysed time frame.**

Figure 16 presents how the objectives are connected to specific research questions, leading to answering the research hypotheses, which are tested at the end. In other words, the answer to each question leads to the answer to the three hypotheses, which aim to find the relationship between the compactness of urban areas and urban shrinkage in medium-sized Polish cities in the specified period.

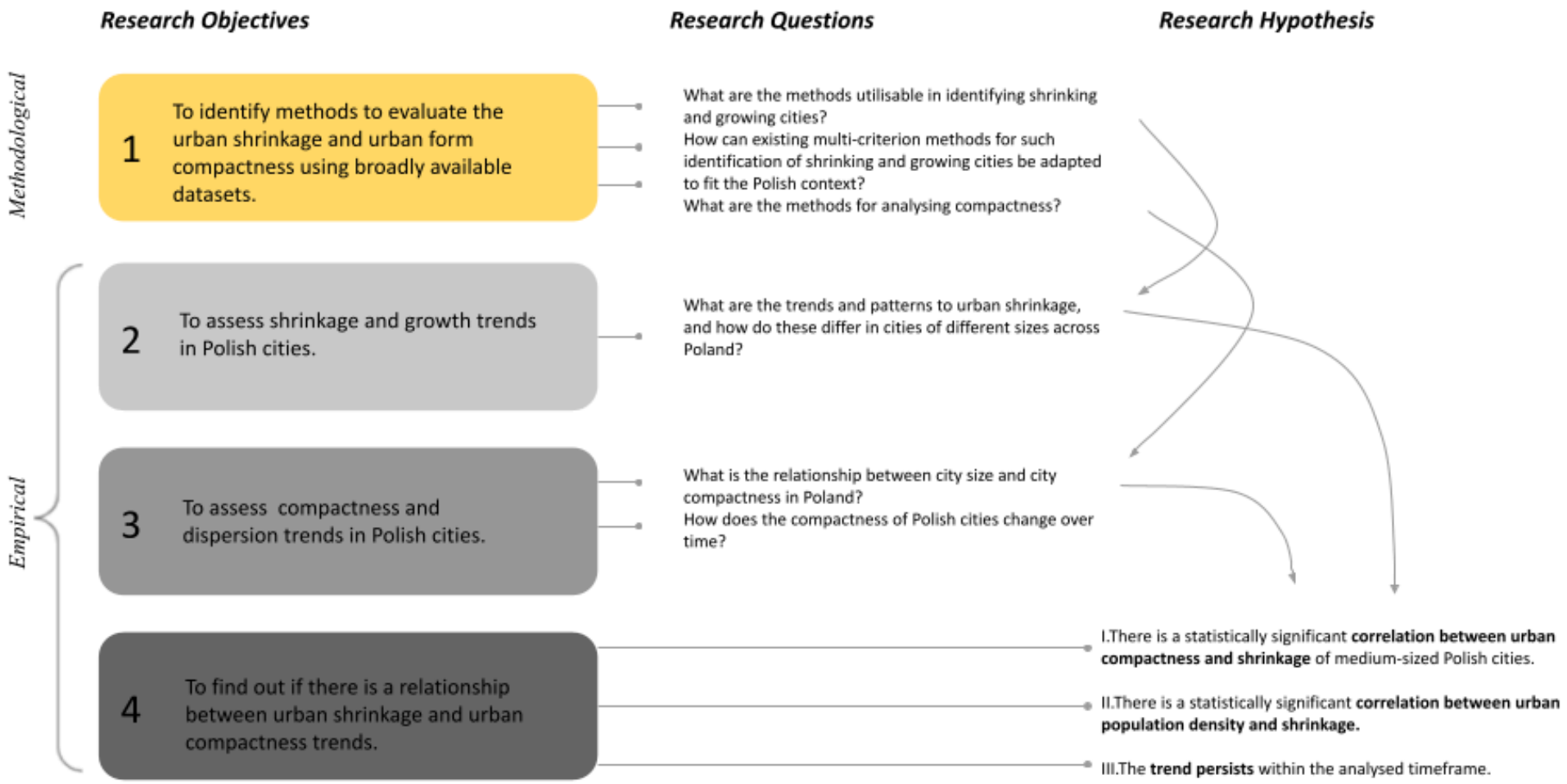


Figure 16. Diagram of research design including the aim, objectives, research questions and hypothesis. Source: Author

3.2. Scope and time frame

This study analyses the relationship between urban form and shrinkage in all medium-sized Polish cities. The question of spatial scale is particularly challenging because different definitions of a city (administrative, morphological, functional) can provide different research outcomes. UN-Habitat counted 104 definitions for *city* using criteria such as administrative function, population size/density or urban characteristics (UN-Habitat, 2020). In this study, the administrative city units are used for the statistical data research part. Thus, the definition of a city for this research is the following the administrative division in Poland (see Figure 17). For spatial research, a combination of administrative and morphological definitions are used to define the urban area (see section 4.1.2).

At first, the relative assessment of urban shrinkage and urban form necessitates considering all municipalities in Poland. Given the variability in their number and classification of cities, reassessment was necessary for each measurement period. As of 2021, Poland had 2,477 municipalities (gminas), comprising 302 urban municipalities, 662 urban-rural municipalities, and 1,513 rural ones (Statistic Poland, 2023). All of these are considered for calculation purposes. However, the study omits rural municipalities for the analysis and conclusion-drawing phases. It focuses on cities represented by urban municipalities (orig. *miasto*, level 6, kind 1 in Statistics Poland, Local Data Bank) or those in the urban-rural category (orig. *gmina miejsko-wiejska*, level 6, kind 3). The changing number of spatial units that Poland was divided into over the years is accounted for in the analysis. To ensure data consistency, 964 cities were selected, for which relevant data was extracted during the research period, enabling accurate comparison and analysis without discrepancies.

In the final stage of the analysis, the focus is narrowed to medium-sized cities. The definition of a medium-sized city poses another challenge of simplification, widely discussed by Runge (2013), Gaczek et al. (2019) and Śleszyński (2017). This study's classification follows a simplified Polish Statistics framework, categorising cities as follows: those with fewer than 20,000 inhabitants are classified as small cities, those between 20,000 and 100,000 as medium-sized cities, and those with more than 100,000 inhabitants as large cities (according to Statistics Poland). The author decided to give no margins. Thus, the city with 19,999 inhabitants will be considered small in this study. When examining urban population data, it is crucial to establish a consistent reference point for size classification. Here, the categories were defined at the beginning of each five years despite the potential fluctuations in population over time. This decision helped ensure accuracy and consistency in the analysis.

Time frame

The time frame for this research has been selected to provide the most relevant insights into urban shrinkage in Poland at the time this research was conducted. The period from 2006 to 2021 has been chosen for several reasons. Firstly, this time frame allows for examining the latest trends in urban shrinkage, particularly as doctoral research is being conducted between 2020 and 2024. Secondly, it is essential to situate the empirical study of urban phenomena within a specific socio-political and historical context. Given the notable spatial changes resulting from Poland's political and economic transformation and the country's accession to the EU in May 2004, this analysis focuses on the period following Poland's entry into the Union to avoid the complexities of a before-and-after comparison.

This study incorporates two types of data – spatial and statistical. While statistical data could be obtained on an annual basis, the selected spatial datasets are updated every six years, with the most recent update in 2018 for when this research was conducted. Therefore, three corresponding data sets were selected for this analysis. For 2006-2011, a CLC2006; for 2011-2016, a CLC2012; and for 2016-2021, a CLC2018 (see Figure 17).

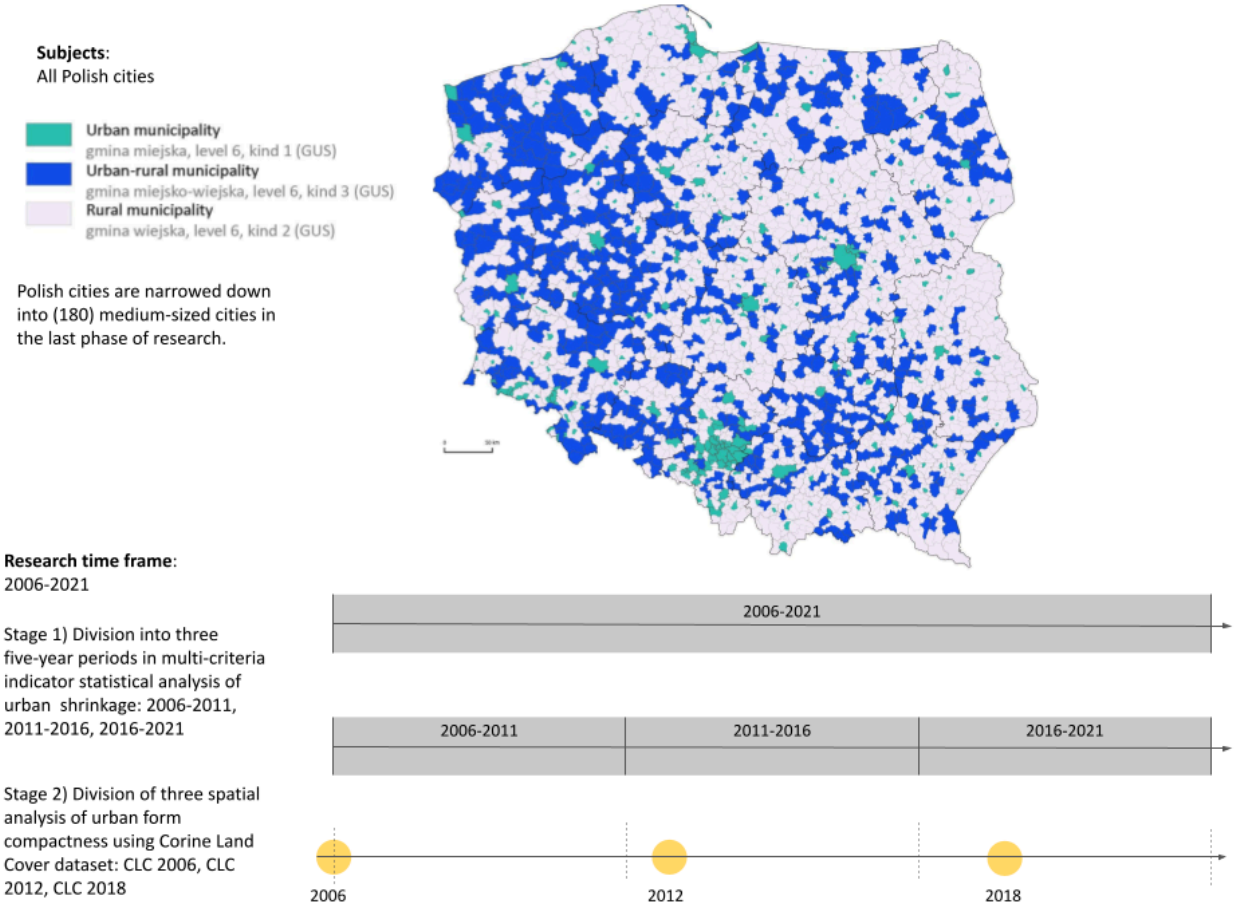


Figure 17. Diagram of research design including subjects and time frame. Source: Author

3.3. Data and tools

The statistical data utilised in the analysis is sourced from the Statistics Poland database (GUS BDL). Given the extensive spatial scope, lengthy time frame, and numerous indicators, the dataset comprises over 235,000 records (6 variables across 2,477 municipalities over 15 years) only for Stage 1. This enormous scope (size) requires using tools such as Python programming language and analytical libraries like Pandas, NumPy, and Visual Studio Code for operations on big data volumes. Such an extensive calculation could not be performed within the time of this doctoral research by the author and required the support of a data analyst. Thus, it must be acknowledged that the calculations in each of the research stages of this PhD were performed by IT engineer Mateusz Bukowski, who was developing data analysis according to the guidelines given by the author of this research.

The spatial study relies on widely available land-use data to analyse metrics related to medium-sized cities. Since comprehensive spatial data on a global scale is unavailable, the dataset for European countries is drawn from CORINE Land Cover (referred to as CLC), specifically for Poland. The CLC data is a significant resource for understanding land use and landscape dynamics from a European perspective and stands as the only consistent and harmonised multinational collection of land-use information at a continental scale. It employs a standardised methodology for producing comprehensive continent-wide land cover data. This part of the research used an open-source QGIS program for spatial analysis and data visualisation (see Figure 18).

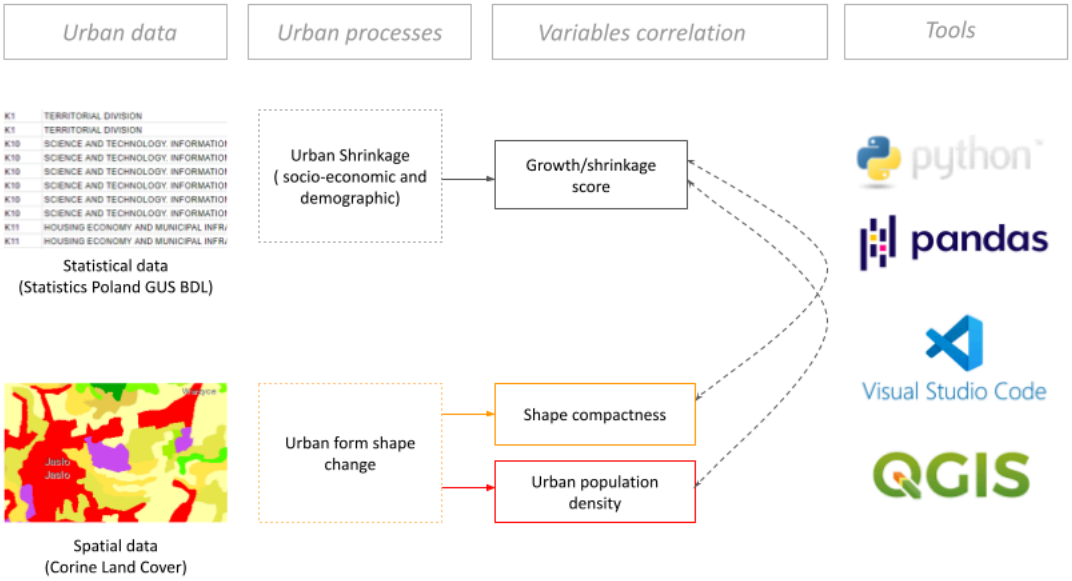


Figure 18. Diagram of research design, including data sources and tools. Source: Author

3.4. Methodology

This research utilises interdisciplinary methods and uses diverse datasets, which aligns with the model proposed by Chojnicki (1970). Chojnicki advocated for a departure from an overly fragmented and superficial approach. He identified "three new methodological trends characterised by a shift from:

- the study of simple relationships to the investigation of increasingly complex structural entities, i.e., systems.
- qualitative approaches to quantitative and mathematical ones, and
- a detailed focus to a more generalised perspective aimed at explanation and prediction" (Chojnicki, 1970, p. 201).

By looking at the entire urban network of Polish cities, using quantitative approaches to analyse shrinkage and urban form measures, and looking at general trends in a longitudinal study, this methodology follows Chojnicki's model. Furthermore, this research aimed to adhere to the principles of open science, an approach centred on collaborative progress in science and emphasises the early and broad sharing of knowledge, results, and tools. Open access to research data refers to the right to access and reuse digital research data, which should be FAIR: Findable, Accessible, Interoperable, and Reusable (NCN, 2024). In practice, this meant that the output data and algorithms were shared in public repositories, allowing other researchers to build on these research outcomes progressively. The above concepts guided the formation of this research methodology, which is explained in detail below.

Given the complexity of this research, for each research question, conceptual-methodological aspects such as scale and data and theoretical-empirical challenges like cause-and-effect relations are addressed through analyses using existing models and/or their adaptation. **Stage 1** of the research aims to assess all Polish cities with a multi-criteria indicator. It analyses statistical data from the Polish Statistics (GUS) for all Polish cities. In **Stage 2**, the two aspects of the urban spatial form are being researched: urban form compactness and actual urban population density. Analysis of urban spatial metrics of Polish cities is based on the data obtained from Corine Land Cover and GUS statistical data on the urban population. In the last step – **Stage 3,** the outcomes of the first two stages are used. In this stage, the urban spatial measures (Stage 2) are related to the outcomes of the first analysis (Stage 1) to seek correlation using statistical Pearson's correlation model. The last research stage concludes the relations between the two spatial approaches and compares the outcomes from the three analysed periods in search of trends. Figure 19 presents an overview of the research stages, describing the objectives, data and methods, and expected outputs.

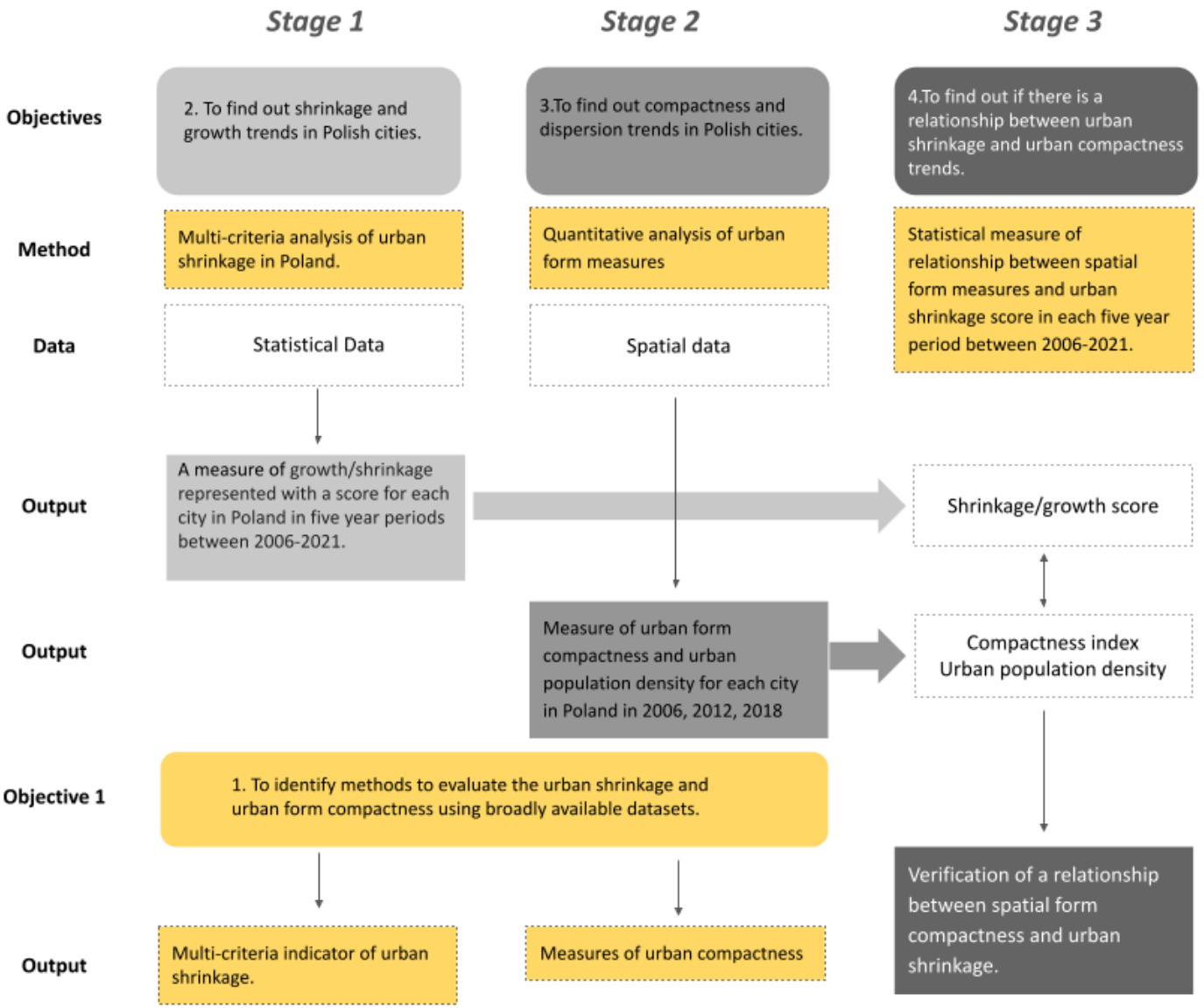


Figure 19. Diagram of research stages sequence. Source: Author

3.4.1. Stage 1 – Urban shrinkage assessment

This phase analyses Poland's shrinkage and growth patterns over the past fifteen years (2006–2021). It involves identifying appropriate methods for evaluating socio-economic and demographic trends following a comprehensive urban shrinkage definition followed by an adaptation of a selected one and its application in Poland. Unlike demographic shrinkage, a comprehensive definition considers multiple indicators to determine which cities in the national urban network are experiencing growth and which are declining. The output must allow for future correlation with the data from stage 2 of the research, meeting the criteria of a range (ordinal, discrete data) and the same time frame. Additionally, the chosen method must be capable of differentiating medium-sized cities from the overall calculations.

This phase begins with reviewing the literature on methods to analyse urban shrinkage. In total, 13 methods were reviewed (including 7 used for assessment in Poland). It was concluded that classifying urban shrinkage in Poland required a multi-criteria approach, with a division into shorter periods within the 15-year time frame and coverage of possibly all national spatial units (Statistics Poland, 2023; TERYT, 2023). An existing multi-criteria indicator method, developed by Milbert (2003, 2015, 2020), was selected due to its scope of socio-economic variables and proposed classification. To meet these criteria, it was adapted to fit Poland's territorial divisions and statistical data (see section 4.1.1 for details). The objective of analysing shrinkage patterns across the urban settlement network provided the basis for choosing a five-level typology, from growing to shrinking cities, applied to each municipality every five years.

A selected multi-criteria indicator analysis, based on Milbert (2015, 2020), measures urban shrinkage in Poland from 2006 to 2021 divided into the following five-year periods: 2006-2011, 2011-2016, and 2016-2021. As the diagram in Figure 20 shows, this method incorporates six socio-economic variables (P1-P6) divided into quintiles translated into scores ranging from 0–4. The outcome of this stage is a shrinkage/growth score (0–24) for each city in three five-year periods and is assigned to one of five categories. The output data was divided into small, medium-sized and large cities. This allows for further research that selects medium-sized cities and relates urban shrinkage to urban form measures (stage 3).

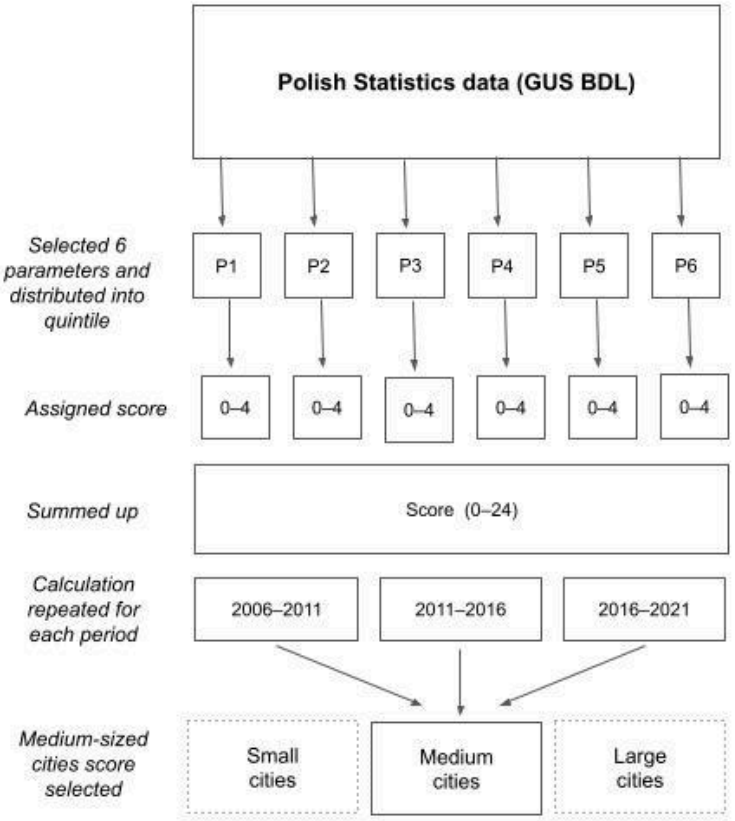


Figure 20. Diagram of stage 1 analysis sequence. Source: Author

The outcomes of this stage, including a detailed review of the state of research, methodology, results and discussion, were published in a peer-reviewed journal in the paper titled “Identification of shrinking cities in Poland using a multi-criterion indicator”, Szymczyk and Bukowski (2023) (see Attachments section).

3.4.2. Stage 2 – Urban form compactness assessment

This stage analyses Poland's compactness and dispersion patterns over the past fifteen years (2006–2021). It involves identifying appropriate methods for evaluating urban form measures following a comprehensive definition of urban compactness. This stage aims to identify compactness and dispersion patterns in all Polish cities and develop a method that can utilise a widely available dataset to monitor these trends on a large scale and regularly. Thus, establishing a method suitable for application across the broader European context was a prerequisite for designing the methodology. Moreover, the output of this phase was required to enable future correlation with the data from stage 1 of this research, meeting the requirement for continuous data that can be mapped to the stage 1 dataset. In addition, the chosen method had to be capable of distinguishing medium-sized cities from the overall calculations.

This phase begins with reviewing the literature on methods to analyse urban form. The review of methods demonstrated various ways physical urban areas can be measured, depending on the specific focus of the research (Ottensmann, 2021). While the *compact city* definition encompasses different meanings, it implies different evaluation approaches. Given the reviewed definitions of a *compact city* (see Table 1), the scope of this study, the available data, and the prerequisites mentioned above, it was concluded that the compactness index and urban population density measures will be used. The first one is quantifying the compactness of shapes' irregularity. The latter considers the urban area and the municipality population in the corresponding year to calculate the urban population density. Compared to the simplified population density found in Polish Statistics, this method of selecting urban areas excludes agricultural land, forests and water bodies, among others, giving a more accurate picture of density.

Table 1. Compact cities characteristics. Source: Ahlfeldt and Pietrostefani (2017).

Index	*Characteristic*	*Summary*
A	Economic density	Refers to the number of economic agents living or working within a spatial unit and is typically measured as population or employment density (Thomas and Cousins 1996; Churchman 1999; Burton 2002; Neuman 2005, cited in Ahlfeldt and Pietrostefani, 2017).
B	Morphological density	Refers to the density of the built environment and captures aspects of the compact city such as compact urban land cover, demarcated limits (demarcated urban/rural land borders), street connectivity, impervious surface coverage, and a high building footprint to parcel size ratio (OECD 2012; Wolsink 2016; Neuman 2005; Burton 2002; Churchman 1999, cited in Ahlfeldt and Pietrostefani, 2017).
C	Mixed land use	Captures the co-location of employment, residential, retail and leisure opportunities (Churchman 1999; Burton 2002; Neuman 2005, cited in Ahlfeldt and Pietrostefani, 2017), both horizontally across buildings and vertically within buildings (Burton, 2002)

As described previously, the Corine Land Cover (CLC) standardised methodology for producing continent-scale land cover, biotope, and air quality maps, including 44 land-use classes, was selected. The outcomes of this stage - a compactness index and urban population density, are

calculated for each city in each of the three datasets (CLC2006, CLC2012, CLC2018). The output data was divided into small, medium-sized, and large cities (see Figure 21). This allows for further research that relates medium-sized urban shrinkage to urban form measures.

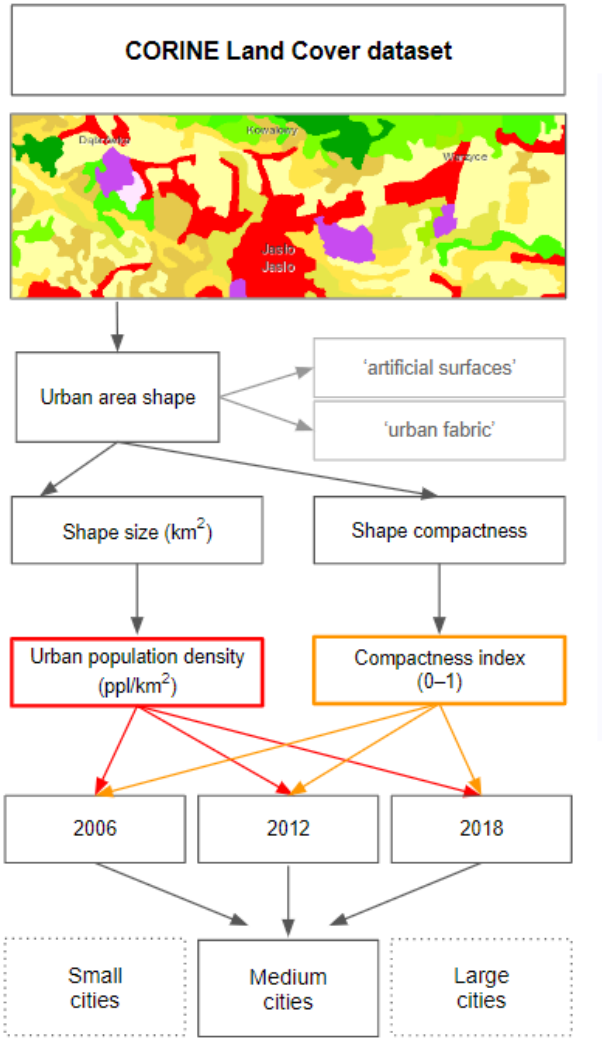


Figure 21. Diagram of Stage 2 analysis sequence. Source: Author

The outcomes of this stage were accepted for publication (in November 2024) in a peer-reviewed journal, Architects, in a paper titled "Compactness of Polish urban areas—methodologies and analysis based on CLC dataset", Szymczyk and Bukowski (see Attachments).

4.4.3. Stage 3 – Relationship analysis

Stage 3 represents the final analytical phase of the research, aiming at assessing the validity of the three research hypotheses. The goal is to establish whether a relationship exists between urban shrinkage trends and measures of urban form compactness among medium-sized cities during the analysed periods. A statistical model is constructed in this stage to test the correlation hypothesis between stage 1 and 2 findings. The outcome is the correlation coefficient values for each

research period on the relationship between the medium-sized city growth/shrinkage score and the two measures of urban compactness (see Figure 22).

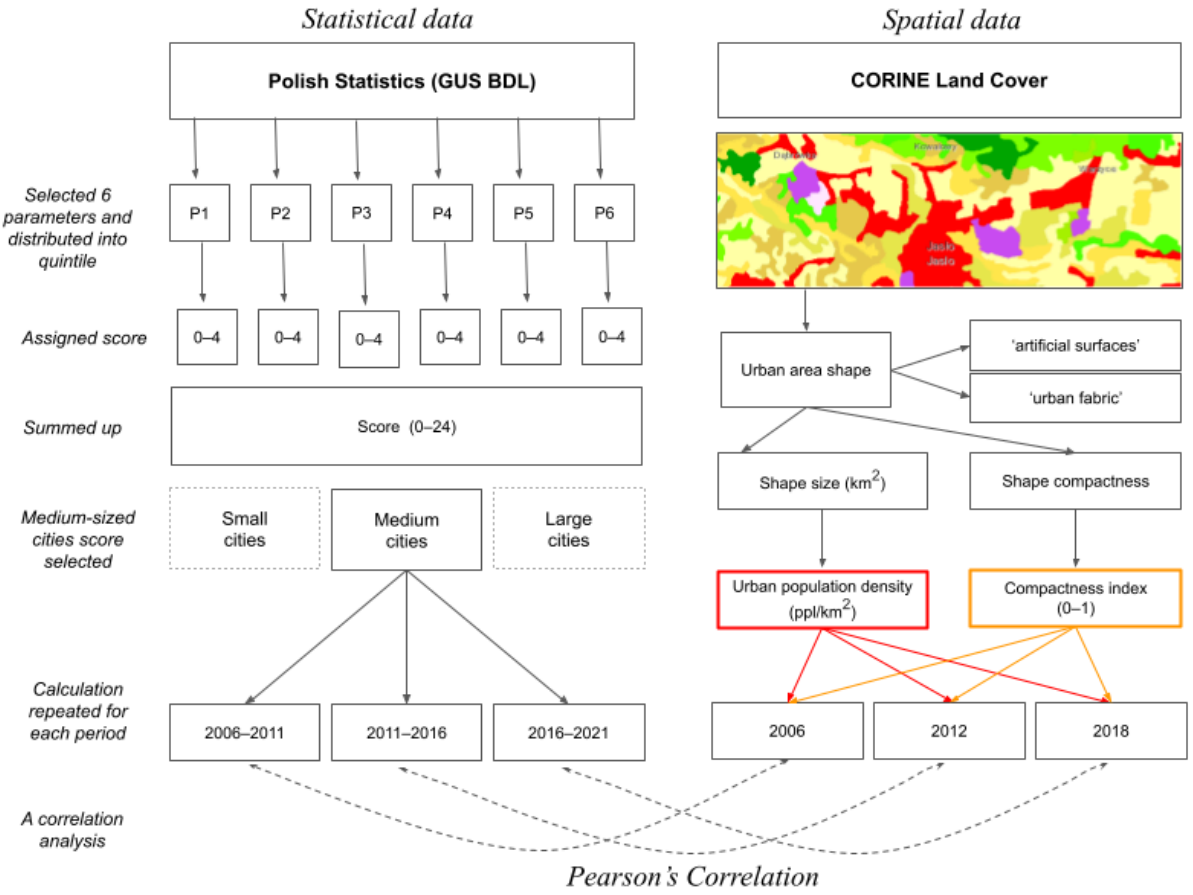


Figure 22. Diagram of stage 3 research design. Source: Author

A correlational analysis was conducted using Pearson's correlation. A coefficient (r) is used to assess the relationships among several variables of interest. The coefficient, calculated from the normalised values of two variables across a sample of n values, ranges from +1 (maximum positive correlation) to -1 (maximum negative correlation), with values near 0 indicating no correlation. The statistical significance index (p-value) was employed, confirming a significant correlation when p is below 0.05, which allowed the author to test the research hypotheses.

The outcomes of this stage were published in a peer-reviewed journal, Sustainability MDPI, in a paper titled "Understanding the Relationship between Urban Form and Urban Shrinkage among Medium-Sized Cities in Poland and its Implications for Sustainability", Szymczyk et al. 2024, (see Attachments).

4.4.4. Interdisciplinary research

This research integrates theories, methods, and practices from multiple disciplines to address questions that cannot be fully understood within a single framework. Unlike multidisciplinary

approaches, which maintain separate disciplinary contributions, interdisciplinary research blends insights to create new frameworks and methodologies (Repko, 2011). Architecture and urban planning inform the spatial dimensions of compactness analysis, while regional planning provides systemic perspectives on social, economic, and policy dynamics. Geographic studies, GIS, and data analysis enhance the quantitative and spatial depth, enabling comprehensive examination of urban form and socio-spatial relationships.

This dissertation engages with three interdisciplinary domains to explore the implications of urban shrinkage on urban form. It first examines urban shrinkage, identifying gaps and challenges. Next, it delves into the literature on urban compactness, focusing on methods to quantify and compare physical spaces across scales. Lastly, it explores the relationship between urban form and socio-economic patterns, analysing interactions between land-use changes and economic, demographic, and socio-cultural processes.

3.5. Research design summary

This doctoral thesis's main aim is to examine if there is a relationship between urban form and shrinkage in medium-sized Polish cities. While the first two articles, corresponding to stage 1 and stage 2 of this research, assess urban shrinkage and urban form compactness in Poland, the last article uses their outcomes to test the research hypothesis. The description below presents how articles form a coherent work designed to meet the goal of this study.

Article 1

This article aims to address the three research questions:

- What are the methods utilisable in identifying shrinking and growing cities?
- How can existing multi-criterion methods for such identification of shrinking and growing cities be adapted to fit the Polish context?
- What are the trends and patterns of urban shrinkage, and how do these differ in cities of different sizes across Poland?

It was published in a peer-reviewed journal, *Przegląd Geograficzny*, in the paper titled "Identification of shrinking cities in Poland using a multi-criterion indicator" (Szymczyk and Bukowski, 2023). The first author is the author of this PhD dissertation, who was responsible for the following roles:

- Conceptualization of the research topic, including the analysis of relevant literature and existing studies, the creation of a theoretical foundation, and the identification of the research gap, as well as the determination of the aim and scope of the study.
- Development of the overall methodology and its adaptation to the available databases.
- Design of specific research methods for each stage of the study.
- Selection of research tools in collaboration with Mr. Bukowski.
- Analysis of results and consultations with supervisors, experts, including statisticians.
- Drafting the initial text of the publication.
- Editing and revising the text following consultations and feedback from the editorial team.
- Development of visualisations, diagrams, tables, and graphics.
- Management of the research project.

This article is co-authored with Eng. Mateusz Bukowski who had the following roles in this work:

- Selection of tools, programming language, and necessary libraries for data processing as per the guidelines: Visual Studio Code, Python, Pandas, Matplotlib, etc.
- Creation of the computational environment and implementation of algorithms for the methodology.
- Harmonisation of statistical data to align it with spatial data.
- Visualisation of statistical data using Excel and Matplotlib.

- Processing of spatial data and visualisation using QGIS.
- Statistical calculations were performed according to the researcher's guidelines.

(see Attachments for research paper and author's statements).

Article 2

This article aims to address the three research questions:

- What are the methods for analysing compactness?
- What is the relationship between city size and city compactness in Poland?
- How does the compactness of Polish cities change over time?

It was submitted after a conference ArchReSci (ArchReSci, 2024) to a peer-reviewed journal, Architectus, with a paper titled "Compactness of Polish urban areas—methodologies and analysis based on CLC dataset" *(accepted for publication).* The first author is the author of this PhD dissertation, co-authored with Eng. Mateusz Bukowski. The roles are the same as above. The article was accepted for publication in November 2024 (see Attachments for research paper, journal declaration and author's statements).

Article 3

The last article is testing the research hypotheses:

I. There is a statistically significant correlation between urban compactness and shrinkage of medium-sized Polish cities.
II. There is a statistically significant correlation between urban population density and shrinkage.
III. The trend persists within the analysed time frame.

It was published in a peer-reviewed journal, Sustainability MDPI, in a paper titled "Understanding the Relationship between Urban Form and Urban Shrinkage among Medium-Sized Cities in Poland and its Implications for Sustainability" (Szymczyk et al., 2024). This article is co-authored with Eng. Mateusz Bukowski and prof. Jeffrey Kenworthy (see Attachments for research paper and author's statements). The first author is the author of this PhD dissertation and was responsible for the same roles as stated above. Eng. Mateusz Bukowski was responsible for the data analysis (same roles as described above). Prof. Kenworthy was responsible for the following roles:

- Supervision of research
- Validation to ensure the quality
- Review and editing

Figure 23 below shows how the three research papers correspond to different research questions and hypothesis of this thesis.

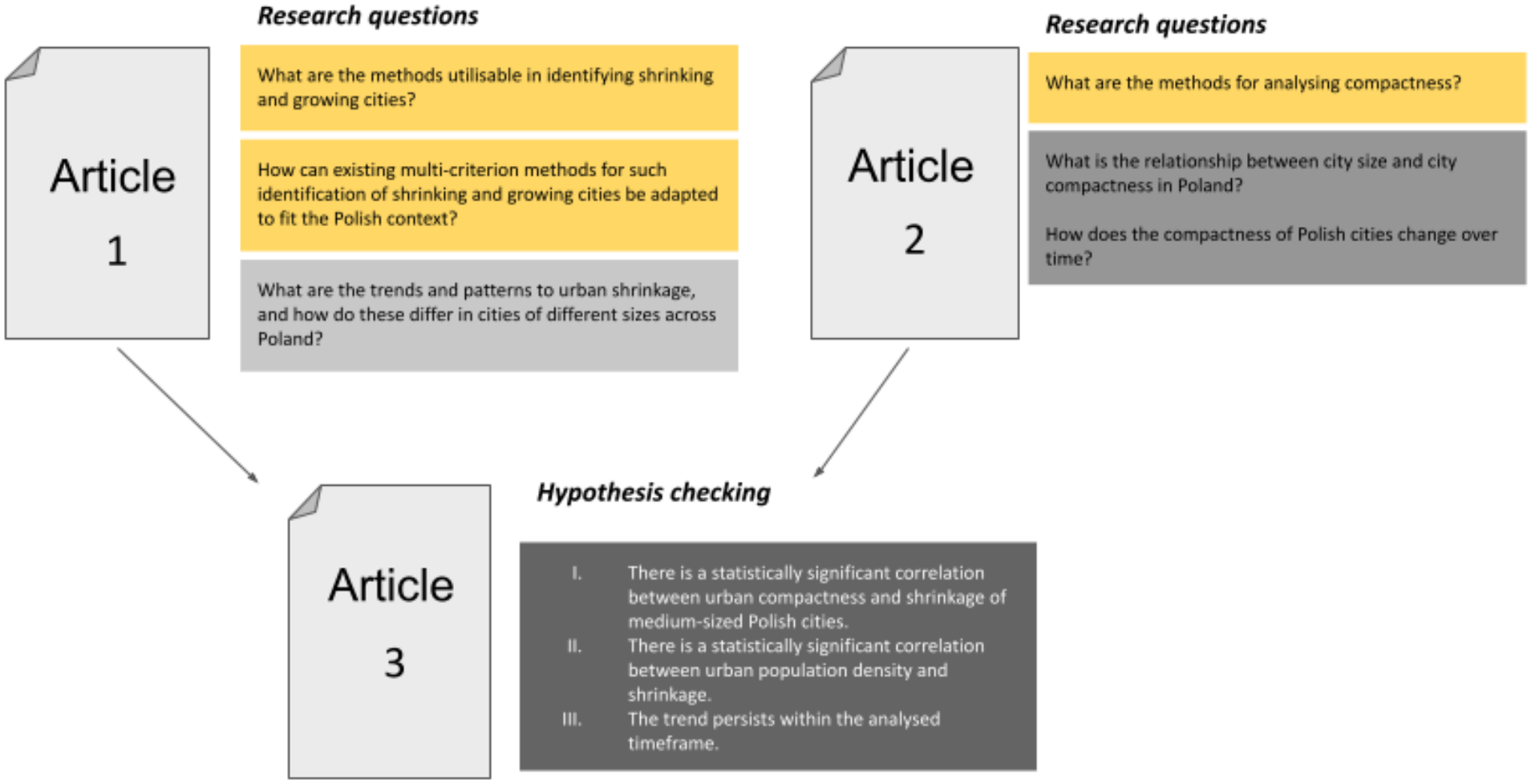


Figure 23. Paper publication strategy. Source: Author

4. Summary of results

This section provides a summary of the findings that were explained in more detail in the research papers. The summary below presents how the main objectives are met by answering the corresponding research questions and by checking the hypotheses. Ultimately, addressing these questions enables the evaluation of the relationship between urban area compactness and shrinkage in medium-sized cities across Poland in 2006-2021. It also facilitates the development of tools for ongoing monitoring and assessment. Furthermore, because the methodology employs pan-European datasets, it can be applied in various urban contexts where shrinkage presents challenges.

4.1. Methods to evaluate the urban form and shrinkage

The overall methodological objective for this part of the research was to identify **methods to evaluate urban shrinkage and form compactness using broadly available datasets**. In both cases, the literature review allowed suitable methods to be identified and adapted to fit the study requirements, scope and data.

4.1.1. Review of methods to analyse urban shrinkage

This part of the research was guided by the following research question:
What are the methods utilisable in identifying shrinking and growing cities?

In urban shrinkage studies, the population has commonly served as the primary indicator of city trajectories, largely due to data availability and alignment with prior research (Van den Berg et al., 1982; Cheshire and Hay, 1989; Turok and Mykhnenko, 2007). However, demographic trends and economic development do not always align, as cities with declining populations can maintain strong economic bases and continue developing (Wolff and Wiechmann, 2014). Therefore, there is a need to measure urban shrinkage using multiple variables.

Urban shrinkage can be seen as a complex interplay of demographic, social, economic, and spatial factors best understood through various indicators. Wolff and Wiechmann (2014) categorise these factors into five thematic areas, with indicator selection often guided by study scope and data comparability. Studies typically prioritise demographic and economic indicators and classify shrinkage based on severity, duration, and speed (Haase et al., 2017). Table 11 below reviews selected urban shrinkage classifications used in global, European and Polish research.

This review of methods shows numerous studies that considered population criteria. Only a few studies have employed multi-criteria approaches to evaluate urban shrinkage, and none of them, according to the author's knowledge, was done for the whole of Poland using the most recent data when this dissertation was being prepared. Jaroszewska (2019) analysed data from 2003 and 2013, while Sroka's (2021) analysis, inspired by the Milbert method, examined data from 1995 to 2018. Śleszyński developed multi-criteria assessments covering ten-year periods in 2004-2014 and 2008-2018 (Śleszyński, 2017, 2019).

Table 11. A review of selected urban shrinkage classification methods.

Scope	Analysed time frame	Project name (Source)	Method description	Variables	Proposed classification
World	1950-2000	Shrinking Cities (Oswalt and Rieniets, 2006; Bernt, 2018)	Subject: Selected world cities with over 100,000 inhabitants; Definition: a densely populated urban area, min. 10,000 inh., population losses in large parts for more than 2 years, undergoing economic transformations with structural crisis symptoms. Population losses are considered to be significant if they amount to a total of at least 10% or more than 1% annually.	Population change	Classified shrinking cities
Europe	N/A	SCIRN (Wiechmann, 2008; Pallagst, 2009)	Subject: Selected world cities over 10 000 inh.; Definition: depopulation of a minimum of 1% in 2 years or over 10% in the whole period.	Population change	N/A
Europe	1990-2010	CIRES (Stryjakiewicz 2014a; Stryjakiewicz and Jaroszewska 2016; Wiechmann, Wolff 2013)	Subject: 7,035 European cities with over 5,000 inh. - criteria of a minimum of 50% of the population living in an urban density over 1000 inh. /km2, built-up area of a minimum of 50% of all municipality area; Definition: depopulation in a period of minimum 5 years, with more than 0.15% of population loss each year.	Population change	The division into three types: a) permanently shrinking, b) short-term shrinking, c) episodic shrinking
Europe	1960-2005	Turok and Mykhnenko (Mykhnenko and Turok, 2007)	Subject: 310 European cities with over 200,000 inh.; Definition: Absolute change in population in successive five-year periods. Additionally, a relative to national change was included to illustrate shrinkage in the country.	Population change	The division into three types: a) recently shrinking, b) shrinking in mid-term, c) long-time shrinking

World	2000-2015	Urban Audit (Florczyk et al., 2019)	Subject: World FUA (with more than 50,000 inhabitants); Definition: Annual rate of population change between 2000 and 2015 at the FUA (Functional Urban Area) level at the global scale.	Population change	Classified into five levels: a) (∞, -0.50%), b) (-0.50%, -0.15%), c) (-0.15%, 0.15%), d) (0.15%, 0.50%), e) (0.50%, ∞)
Germany	1998-2020 continuously in a five-year periods division	BBSR (Milbert, 2015, 2020)	Subject: 4507 German communes (Gemeinde) including cities (Stadt); Definition: Shrinkage is defined as relative to the national levels regarding six demographic and socio-economic variables (see detailed explanation in chapter 4).	Average annual population development in %; Average annual total migration balance per 1000 inhabitants; Average annual development of the working-age population (20 to 64 years) in %; Average annual development of socially insured employees at the workplace in %; Average annual change in the unemployment rate in percentage points; Average annual development of business tax base per inhabitant in %	The division into five types: a) growing above average, b) growing, c) stable, d) shrinking, e) shrinking above average
Poland	1990-2010	Jaroszewksa (Jaroszewska, 2019)	Subject: 829 Polish cities (2948 administrative boundaries of communes and cities); Definition: Along with CIRES definition (see above).	Population change	Classification for the entire period: a) growing, b) stable, c) shrinking; In 5-year periods: a) permanently shrinking, b) short-term shrinking, c) episodic shrinking, d) no shrinkage
Poland	2003, 2013	Jaroszewksa (Jaroszewska, 2019)	Subject: 279 Polish cities; Definition: Shrinkage is defined as relative to the national levels regarding ten selected demographic, socio-economic and life quality variables. Values for two years (2003 and 2013) were compared to create a 9-level typology (A-I), which reflects economic and demographic development levels.	Number of individuals in post-productive age per 100 individuals of working age; Natural growth per 1000 inhabitants; Migration balance per 1000 individuals; % of registered unemployed in the population of working age; Employed per 1000 inhabitants; Municipal own revenues per capita; Amount of housing allowances paid per capita; % of dwellings equipped with central heating; Dwellings per 1000 inhabitants; % of homes from municipal resources with arrears in housing payments	The division into nine levels of development: A-D - shows a high level of economic and demographic development, E - the average level, F-I - shows a low level of economic and demographic development
Poland	2004-2014	Śleszynski (Śleszynski, 2017)	Subject: 913 Polish cities (urban and urban-rural communes); Definition: A multicriteria method defines medium-sized cities losing their socio-economic functions. It	Population changes; Forecast of the population number; Change in the number of unemployed; Change in the share of own income in municipal budgets; Change in the number of nights spent;	Classified into four levels: a) crisis cities, b) decreasing potential cities, c) stagnating cities,

			includes a combination of 7 variables analysed in ten years. Each variable was counted as a change relative to the national average during the same time.	Changes in the number of registered economic entities; Changes in the number of headquarters of the largest companies. All relative to the country's average change during the same period.	d) at the risk of marginalisation
Poland	2008-2018	Śleszynski (Śleszynski, 2019)	As above	As above	As above
Poland	1995-2018	Sroka (Sroka, 2021)	Subject: 853 Polish cities; Definition: Inspired by the Milbert method (see above) with the difference in the indicators used (selected six demographic and socio-economic variables) and the classification method (instead of quintile, mean and standard deviation proportion was used).	Population changes supplemented by an indicator describing the number of years with a population decrease; Average annual net internal migration rate per 1000 inhabitants; The ratio of the population aged 65 and over to the total population; The proportion of the population of working age; Number of private sector economic entities per 1000 inhabitants; The number of newly constructed dwellings per 1000 inhabitants	The division into size types (large, medium, and small cities) and shrinkage level for the entire period: a) symptoms of structural crisis, b) shrinking
Poland	2000-2016	Musial-Malago (Musiał-Malago, 2018a,b)	Subject: 39 Polish cities (over 100,000 inh.); Definition: According to SCIRN (CIRES) definition, 30/39 were shrinking for at least 5 years in a row. Next, selected 30 shrinking cities were classified using ten demographic and socio-economic variables.	Population change (primarily); Population density of cities; The proportion of the population of post-productive age; Natural growth per 1000 inhabitants; Migration balance per 1000 inhabitants; Deregistration from cities per 1000 inhabitants; Entities registered in the REGON system; Employed per 1000 inhabitants; Unemployment rate; Number of apartments for which building permits were issued per 10 000 inhabitants; Vacant properties per 1000 dwellings	The division into four types of shrinkage: a) moderate level of shrinkage, b) medium level of shrinkage, c) strong level of shrinkage, d) the highest level of shrinkage
Poland	2006-2016	The Institute of Urban and Regional Development - IRMiR (Janas et al., 2019)	Subject: Polish communes and cities; Definition: Studies show the relationship of shrinking cities with the surrounding cities, surrounding communes, flows between cities and metropolitan areas, migration trends to and from Poland, etc.	Population change; Natural growth rate; Migrations rates; Age structure and ageing processes of the population; Proportion of the population in pre-productive age; The burden on the population by individuals in post-productive age	Shrinkage is analysed in a broad spectrum of aspects: a) natural population trends, b) age structure, c) internal migrations, d) external migrations

Multi-criteria indicator method adaptation

This part of research was guided by the following research question:
How can existing multi-criterion methods for such identification of shrinking and growing cities be adapted to fit the Polish context?

Following the review of methods in the previous section, the author determined that a classification of urban shrinkage, particularly for Poland, required a multi-criteria approach over a long period (in intervals), covering all Polish cities. Building on Milbert's framework (2015, 2020), the author adapted the method to align with Polish territorial divisions and statistical data, creating five-level typology categorising cities from growing to shrinking based on socio-economic and demographic trends across Poland's municipalities.

The statistical data from Statistics Poland resulted in over 235,000 records, covering six variables across 2,477 municipalities over 15 years. Data preparation required extensive manipulation, which was conducted using Python programming and analytical libraries (Pandas, NumPy, etc.). Indicators, derived from Milbert's six-variable model (2015), included social, demographic, and economic factors selected from Statistics Poland (2023) databases, with adjustments made to accommodate differences in tax and reporting systems between Germany and Poland (see Table 12).

Table 12. Multi-criteria variables selection based on Milbert (2015). Source: Author

Original German criteria (Milbert, 2015)	Polish equivalents in GUS BDL data (Author's choice)	Subject ID in GUS	Variable ID in GUS
Durchschnittliche jährliche Bevölkerungsentwicklung in %, English: Annual average population development in %	annual average population development in %	'P2137'	72305
Durchsch. jährliches Gesamtwanderungssaldo je 1000 Einw. Eng. Annual av. total migration balance per 1000 inhabitants	net migration per 1000 inhabitants	'P1350'	1365234
Durchsch. jährliche Entwicklung der nach Alter Erwerbsfähigen (20 bis 64 Jahre) in % Eng. Annual av. development of the working-age population (20 to 64 years) in %).	annual average change in working age population (18 to 59/64) in %	'P1342'	152
Durchsch. jährliche Entwicklung der sozialversicherungspflichtig Beschäftigten am Arbeitsort in % Eng. Annual av. development of socially insured employees at the workplace in %.	annual average change of employed persons in %	'P2172'	54821
Durchsch. jährliche Veränderung der Arbeitslosenquote in %-Punkten Eng. Annual av. change in the unemployment rate in percentage points.	annual average change of unemployed persons in % points	'P1944'	10514
Durchsch. jährliche Entwicklung des Gewerbesteuergrundaufkommens je Einwohner in % *Eng.* Annual av. development of business tax base per inhabitant in %.	annual average change of the municipality's own income per inhabitant in %	'P2622'	76070

Data processing involved downloading and transforming the raw datasets, connecting statistical identifiers with spatial identifiers (TERYT, 2023), and exporting the final data in CSV format. Each spatial unit underwent a completeness check, with some units merged due to boundary changes to ensure continuity. Urban units were then classified by population size according to the Statistics Poland (2023) classification, using the initial year of each period as a reference. Depending on the administrative structure, this classification applied to either the entire urban municipality (6,1) or the urban portion (6,2) within a urban-rural municipality (6,3).

Table 13 shows the outcomes for an example city, with each criterion (p1-p6) resulting in the final shrinkage/growth score checked. Each spatial unit has its identifier (Teryt_id), allowing statistical data to be visualised as a map in the GIS tool. The data processing algorithm was shared publicly in a data repository to allow for open access and replicability with the newest datasets.

Table 13. An example of shrinkage/growth score calculation outcome.

Teryt_id	Start	End	p1	p2	p3	p4	p5	p6	Total	Type
1261011	2006	2011	3	3	0	2	2	2	12	C
1261011	2007	2012	3	3	0	2	0	2	10	D
1261011	2008	2013	3	3	0	2	0	2	10	D
1261011	2009	2014	3	3	0	2	0	2	10	D
1261011	2010	2015	3	3	0	2	0	2	10	D
1261011	2011	2016	3	3	1	3	0	2	12	C
1261011	2012	2017	3	4	1	3	1	2	14	B
1261011	2013	2018	3	4	1	3	1	2	14	B
1261011	2014	2019	4	4	2	3	2	2	17	B
1261011	2015	2020	4	4	3	3	1	2	17	B
1261011	2016	2021	4	4	3	3	0	2	16	B

4.1.2. Review of methods to analyse urban form compactness

This part of research was guided by the following research question:
What are the methods for analysing compactness?

Urban compactness is often conceptualised as the opposite of urban sprawl, a concept tied to critical social and environmental implications in planning (Burgess, 2000). Although definitions of the “compact city” vary, the OECD identifies several key features: dense, connected development, public transport integration, and access to local services and employment (OECD, 2012, p. 15). Dantzig and Saaty (1973) originally introduced the term to advocate for efficient urban resource use, while Ahlfeldt and Pietrostefani (2019) categorise compactness into economic, morphological, and mixed-use densities, each with measures such as population density, employment density, and land-use boundaries.

The most widely recognised measure of compactness is closely related to density (Burton, 2002; Siedentop and Fina, 2010). Much of the existing research focuses on urban population density, as demonstrated by the work of Newman and Kenworthy (1989), Siedentop and Fina (2010) and others. However, population density in Polish statistics is calculated using administrative areas, which can lead to inaccuracies. These areas often encompass forests and water bodies, thereby distorting the results. Research on urban densities should focus on populations residing within clearly defined urban boundaries (Ahlfeldt and Pietrostefani, 2019).

Regarding spatial measures, the concept of a compact city typically pertains to the two-dimensional expansion patterns of urbanised areas. An area is more compact when its development is more clustered around a central point, exhibiting less sprawl, leap-frogging, or branching (Mubareka et al., 2011). Compactness is also viewed as a relative and context-dependent concept shaped by regional norms rather than in absolute terms. Angel et al. (2011) explored the relationship between compactness and climate change, indicating that both population density and geometric shape can help mitigate greenhouse gas emissions and reduce infrastructure demands. In China, Wang et al. (2021) utilised a multi-criteria approach, while Guo et al. (2020) and He et al. (2020) assessed compactness in the context of urban shrinkage through spatial indicators, including population density, land use, and fragmentation.

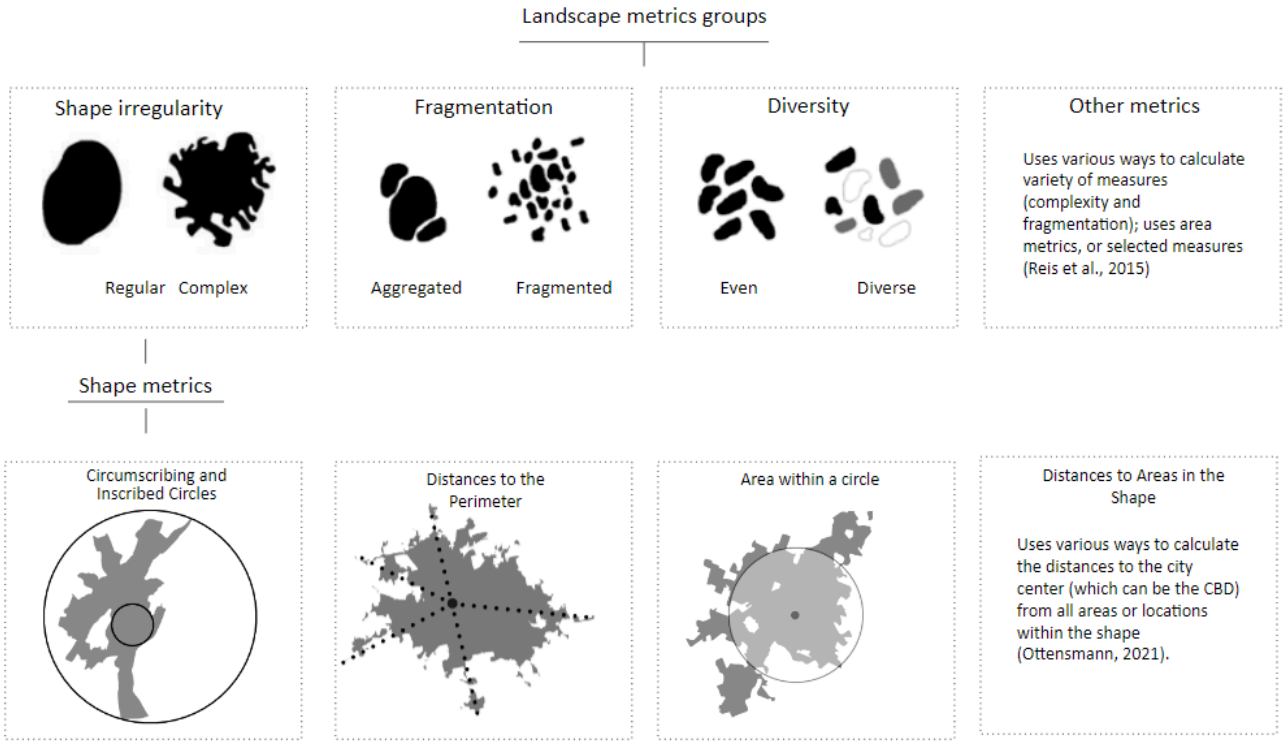


Figure 35. Landscape metrics groups and shape metrics categories based on Reis et al. (2015) and Ottensmann (2021). Source: Author's own elaboration based on Reis et al. (2015) and Ottensmann (2021).

As per Reis et al. (2016), the suggested landscape shape metrics ″evaluate how urban developments are either more continuous and concentrated or more dispersed (fragmented)″ (Reis et al., 2016, p. 13) see Figure 35. While there are various measures of shape (Altman et al., 1998; Chambers and Miller, 2010; Niemi et al., 1990), Barnes and Solomon (2021) noted several most frequently used. Given the large scope and the spatial data characteristics, the authors chose a single compactness metric named after its creator, the Schwartzberg (1966) compactness index see Figure 36.

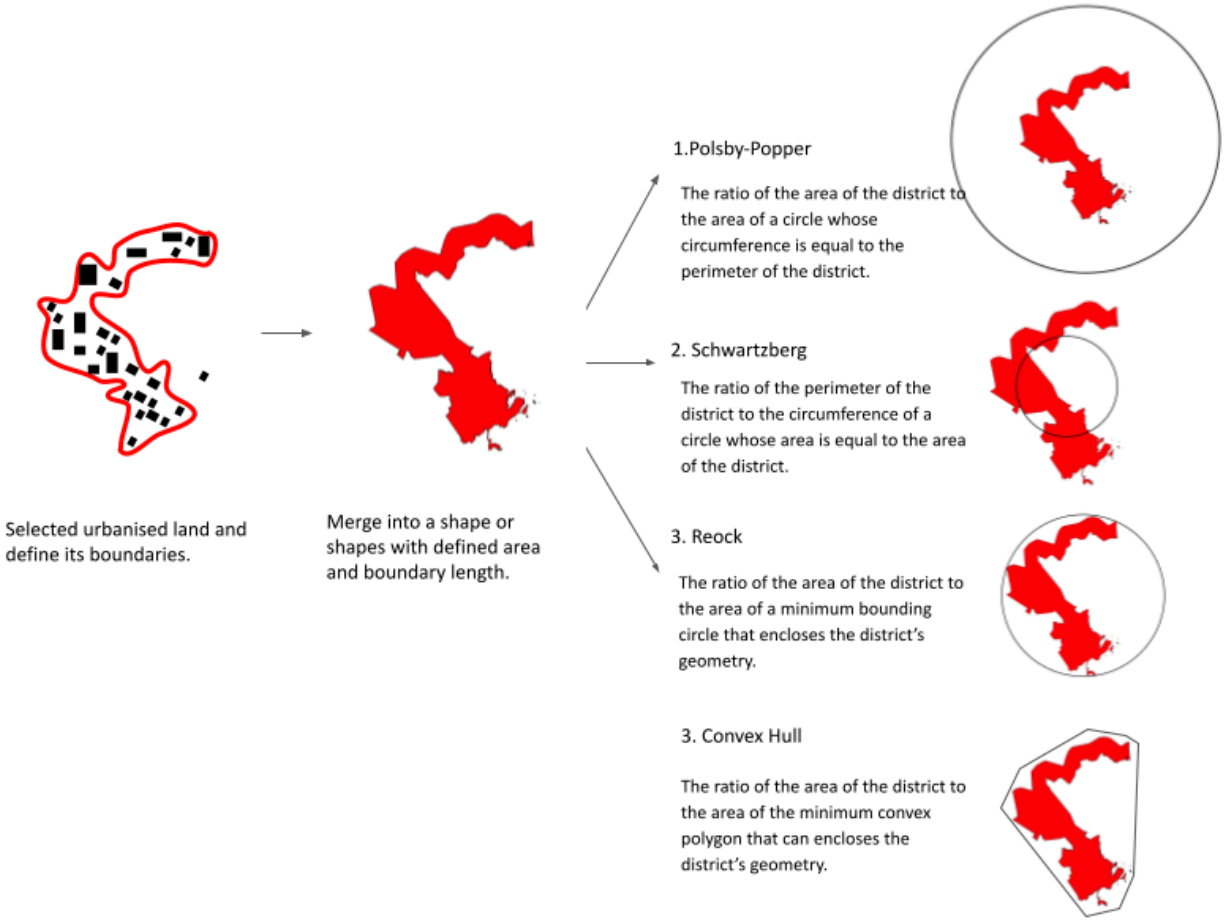


Figure 36. Diagram presenting common compactness index calculation methods. Source: Author's own elaboration based on (Altman et al., 1998; Chambers and Miller, 2010; Niemi et al., 1990; Schwartzberg, 1966).

The review of methods allowed the author to select two measures that combine urban population density metrics with a shape-based measure of compactness, leveraging Corine Land Cover (CLC) data and population statistics from Polish datasets (Statistics Poland, 2023). Adapted to Polish urban contexts, the shape measure provides new insights by capturing urban form more precisely than population density alone, particularly by excluding non-urban land from the calculations. The adapted method selected urban areas and cut them to the municipality's boundaries. Next, the two measures were calculated. The calculation consists of the following operations (presented in Figure 37) for each selected year:

A. Isolation of selected land use classes;
B. A cut of land use polygons with city administrative boundaries;
C. Merge polygons into continuous shapes;
D. Delete polygons below a set threshold - for a given shape;
E. Calculate the shape's area and perimeter;
F. Calculate the compactness index;
G. Calculate the urban population density.

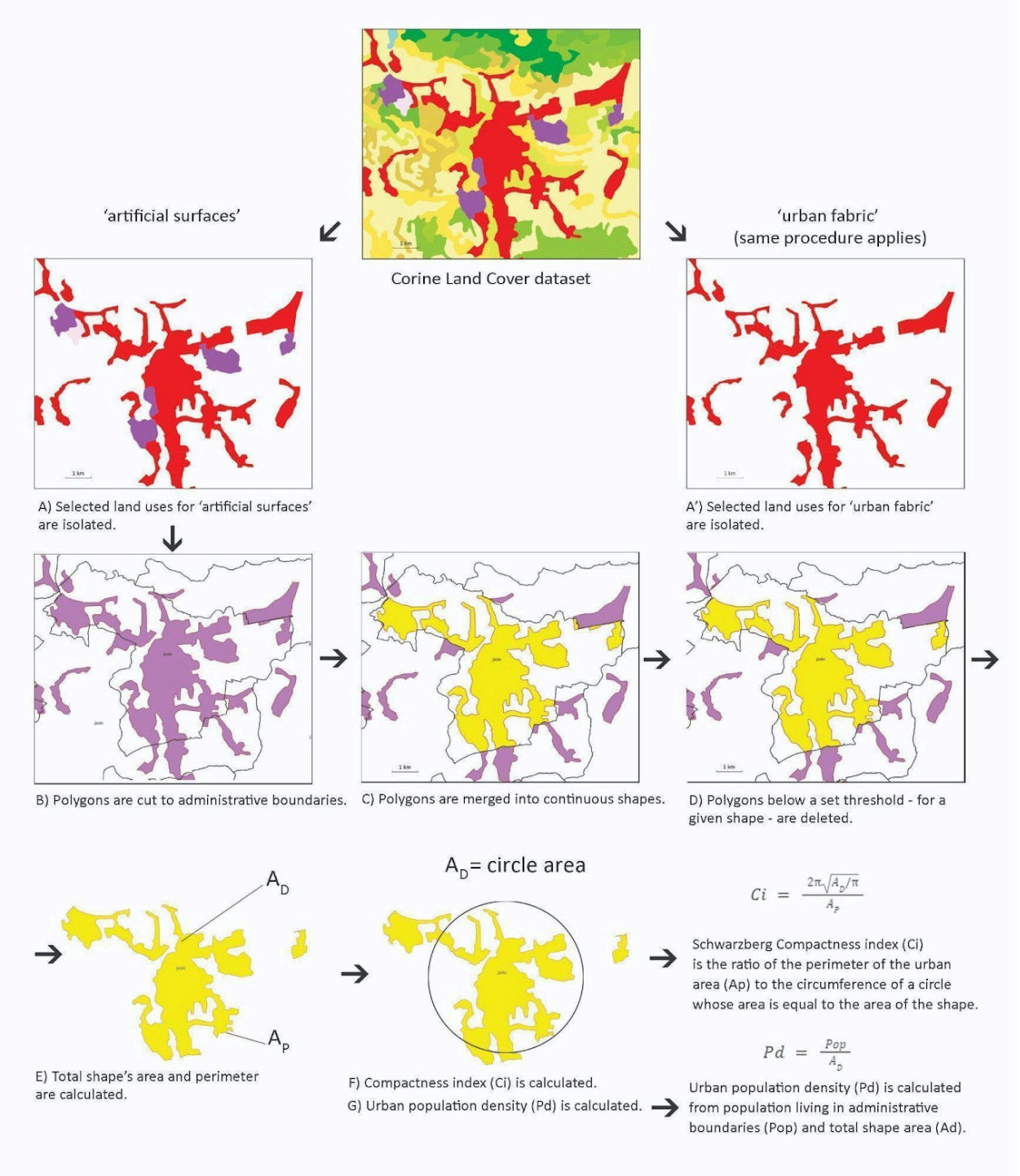


Figure 37. Urban compactness analysis diagram based on the Jasło urban municipality example. Source: Szymczyk et al., 2024

The results of the selected method

Tables 15 and 16 show the example of the outcome for the selected city. They were prepared to match the growth/shrinkage score outcomes from stage 1. Each spatial unit has its identifier (Teryt_id), allowing statistical data to be mapped and visualised as a map in the GIS tool. The data

processing algorithm was shared publicly in a data repository to allow for open access and replicability with the newest datasets.

Table 14. An example of a municipality's Urban population density (Pd) calculation based on CLC.

Teryt_id	Start	End	Population	CLC Year	District Area (km²)	Density (people/km²)
1261011	2003	2008	757,685	2006	151,538,462	4999.95
1261011	2004	2009	757,430	2006	151,538,462	4998.26
1261011	2005	2010	756,629	2006	151,538,462	4992.98
1261011	2006	2011	756,267	2006	151,538,462	4990.59
1261011	2007	2012	756,583	2012	167,952,975	4504.73
1261011	2008	2013	754,624	2012	167,952,975	4493.06
1261011	2009	2014	755,000	2012	167,952,975	4495.30
1261011	2010	2015	757,740	2012	167,952,975	4511.62
1261011	2011	2016	759,137	2012	167,952,975	4519.93
1261011	2012	2017	758,334	2012	167,952,975	4515.15
1261011	2013	2018	758,992	2018	169,016,958	4490.62
1261011	2014	2019	761,873	2018	169,016,958.1	4507.672
1261011	2015	2020	761,069	2018	169,016,958.1	4502.915
1261011	2016	2021	765,320	2018	169,016,958.1	4528.066

Table 15. An example of a municipality's Compactness index (Ci) outcomes based on CLC.

Teryt_id	Year	Ci (Schwartzberg)
1261011	2006	0.120702
1261011	2012	0.144760
1261011	2018	0.145119

The relationship between the two urban shape measures, Pd and Ci, was checked using Pearson's correlation, which revealed a sound coefficient and statistical significance. The results for all urban municipalities (urban and urban-rural) for data in 2006 indicated a r-value of 0.45 correlation with a statistically significant p-value. In the years 2012 and 2018, the correlation value increased to 0.48. This moderate/strong relationship is related to both measures having the same

component of the urban area (Ad in compactness index and Ua in urban population density). Still, it also proves that measures depict the same urban phenomenon.

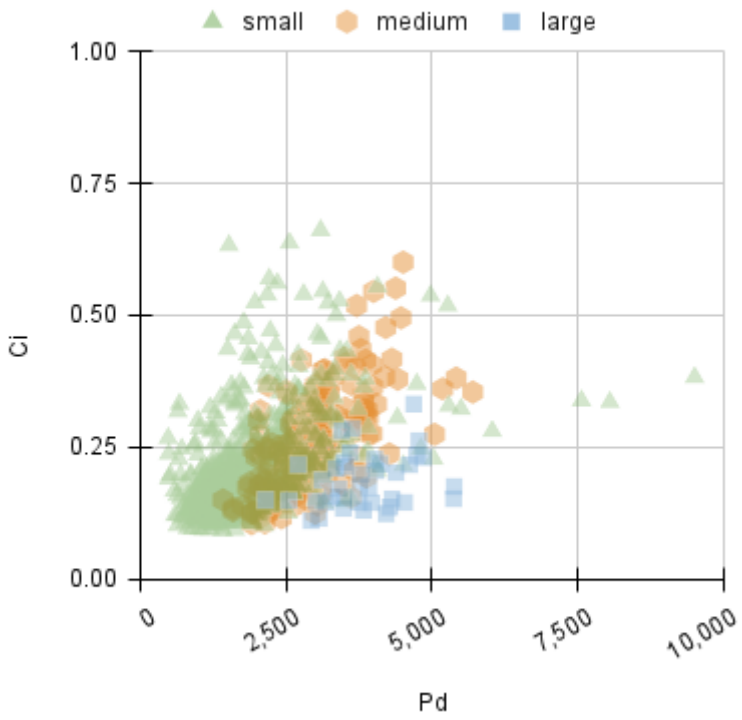


Figure 38. A scatter plot shows the large, medium-sized, and small Polish cities' urban population density (Pd) and compactness index (Ci) calculation based on CLC2018. Source: Author

Additionally, Figure 38 divided cities into different size groups based on their compactness and density. While small cities have numerous dense and compact outliers, they are mostly less dense and less compact than medium-sized ones. Large cities, on the other hand, are rarely as compact as small and medium-sized cities, fitting mostly under the Ci 0.25 threshold. Most medium-sized cities can be found in Ci 0.4 and Pd, around 3,100 people/km².

4.2. Stage 1 – assessment of urban shrinkage in Poland

The following research question guided this part of the research:
What are the trends and patterns of urban shrinkage, and how do these differ in cities of different sizes across Poland?

As outlined in the methodology section above, the initial phase of the analysis considers all Polish urban centres, aiming to explore recent trends and patterns relative to the country's statistics. It aims to measure urban shrinkage and identify how these measures vary across cities of different sizes. This section summarises the research findings on urban shrinkage from 2006 to 2021, utilising a multi-criteria approach (see section 3.1.4 for method selection rationale) adapted from Milbert (2015, 2020). The study examines three five-year periods, providing insights into the number and types of cities impacted, population sizes, and spatial distribution. The analysis facilitates comparison and pattern identification by categorising municipalities into different size types and five-year intervals. Each municipality can receive a maximum score of 24 points and a minimum of 0, with the resulting scores assigned to five distinct types of cities:
(A) growing by an above-average amount (24-19 points),
(B) growing (18-14 points),
(C) stagnating (13-11 points),
(D) shrinking (10-6 points),
(E) shrinking by an above-average amount (5-0 points)

Period 2006–2011
In the 2006-2011 period, 53% of Poland's urban population lived in shrinking cities. Of the 964 cities analysed, 311 were classified as shrinking (types D and E), accounting for nearly one-third of all Polish cities. Large cities, with populations over 100,000, were the most affected, with 77% of these cities experiencing shrinkage. Notably, 61% of the population in large urban areas resided in shrinking cities, with Tarnów and Włocławek most severely affected. In contrast, medium-sized cities (20,000 to 100,000 inhabitants) also saw significant shrinkage, with 95 out of 180 cities (53%) declining, although their overall population impact was smaller than in large cities. Small cities (under 20,000 inhabitants) were the least affected, with 24.5% of their population residing in shrinking cities, even though the absolute number of shrinking small cities was considerable. They also had the biggest share of the population living in the growing type cities (Figure 24).

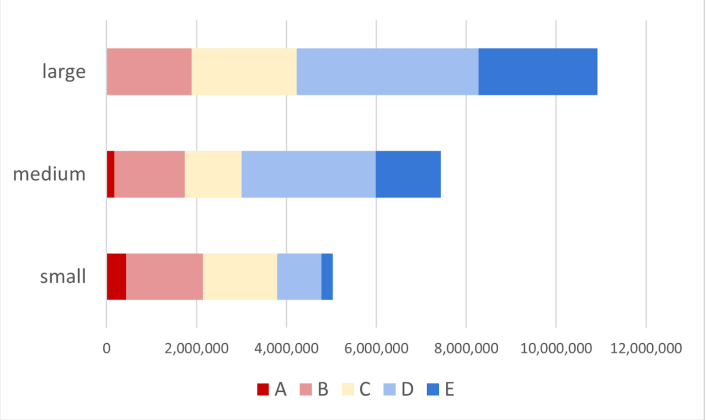


Figure 24. Urban population in Poland in 2006-2011 period, divided by growth and shrinkage type (A-E) and city size (large, medium, small). Source: Author based on GUS data

Period 2011–2016

During the 2011-2016 period, the percentage of the urban population living in shrinking cities increased to 57%. The number of shrinking cities rose significantly, from 311 in the previous period to 504, indicating that more than half of all Polish cities were now affected by shrinkage. This was caused by increased shrinkage in medium-sized and small cities. While the number of large cities experiencing shrinkage dropped to 27 out of 39, medium-sized cities saw an increase, with 65% (119 out of 184 cities) classified as shrinking. Of these, 41 medium-sized cities were experiencing strong shrinkage (type E). The situation deteriorated further for small cities, with 48% of their urban centres shrinking compared to 24.5% in the previous period. The absolute number of shrinking small cities nearly doubled, reflecting the growing severity of the shrinkage phenomenon across all sizes of cities. At the same time, small cities held the biggest share of the population living in the growing by above-average amount type of cities (Figure 25).

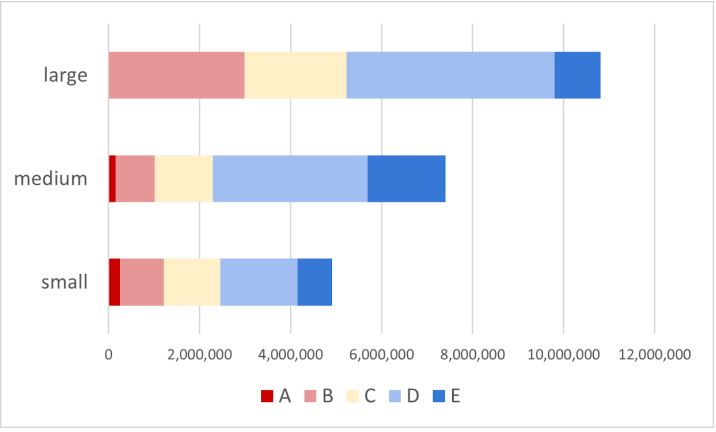


Figure 25. Urban population in Poland in 2011-2016 period, divided by growth and shrinkage type (A-E), and city size (large, medium, small). Source: Author based on GUS data

Period 2016–2021

In the 2016-2021 period, the share of the Polish urban population residing in shrinking cities slightly decreased to 53%. However, the number of cities affected by shrinkage remained high,

with 508 urban centres shrinking, indicating that over half of all Polish cities continued to experience shrinkage. The large urban centres (over 100,000 inhabitants) fared better than in the previous period, with only 2 of the 27 shrinking cities experiencing strong shrinkage (type E). Nevertheless, 69% of large cities continued to shrink, indicating that while the intensity of shrinkage lessened, it was still a widespread issue. For the first time, the highest amount of population living at an above-average rate was in large urban locations (Figure 26). This is a significant change compared to previous periods. A slight increase in the population living in growing medium-sized cities can be observed. However, they remained the most affected by urban shrinkage, with 119 out of 184 cities (65%) in decline, mirroring the challenges observed in earlier periods. Small cities saw the highest percentage increase in shrinking localities, with nearly half of their population residing in cities classified as shrinking. Despite this, small cities continued to experience less severe shrinkage than their larger counterparts.

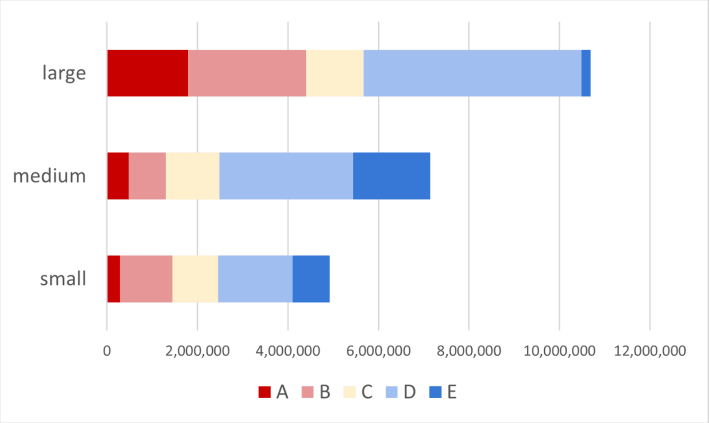


Figure 26. Urban population in Poland in 2016-2021 period, divided by growth and shrinkage type (A-E), and city size (large, medium, small). Source: Author based on GUS data

Spatial distribution of shrinking and growing cities

The spatial distribution of urban growth during the first five-year period shows it was concentrated around the largest metropolitan regions, particularly in Wielkopolskie, Mazowieckie, and Małopolskie Voivodeships (Figure 27). Shrinking cities, however, were more dispersed across the country, with post-industrial Silesia and regions like Lower Silesia (Sudety Mountains), Warmińsko-Mazurskie, Kujawsko-Pomorskie, and Łódzkie seeing significant shrinkage.

In 2011-2016, shrinkage increased and spread, particularly in small and medium cities, while growth remained concentrated around the same metropolitan areas. The 2016-2021 period saw these trends of growth and shrinkage intensified, with more growth in southern regions and less around Warsaw. Shrinkage intensified in the peripheries and post-industrial areas, while growth was concentrated around Warsaw, Poznań, Tri-City and Kraków metropolitan areas. However, some urban centres in Śląskie grew amidst ongoing shrinkage in nearby towns.

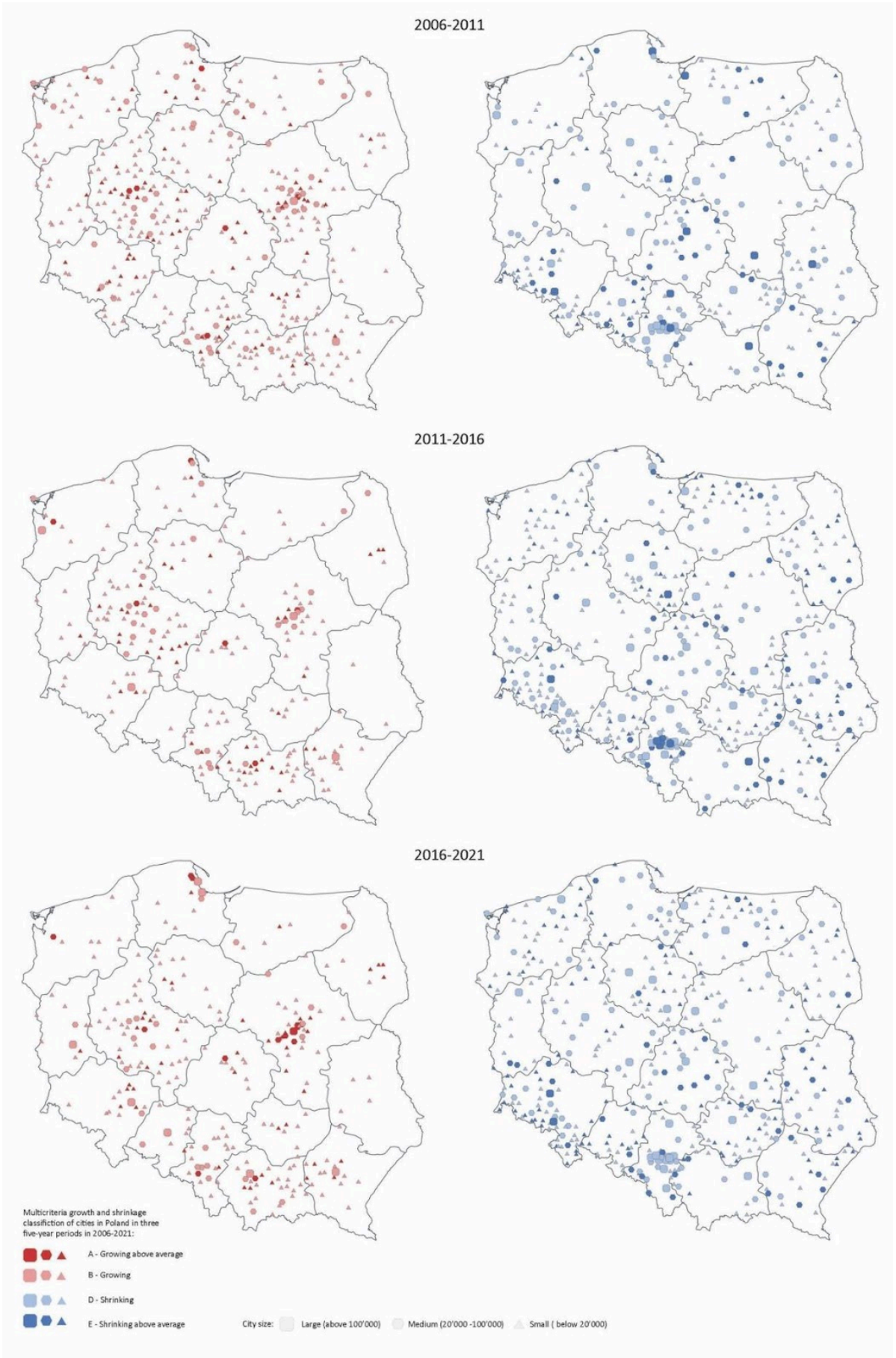


Figure 27. Multi-criteria assessment of growth and shrinkage in Polish urban areas in 2006-2021. Source: Author

In summary, Poland's shrinking urban centres increased from 311 in 2006-2011 to 504 in 2011-2016 and stabilised at 508 in 2016-2021. While large cities were most affected by this phenomenon initially, the trend moved to medium-sized ones later. The approach focuses not on absolute growth or decline but on analysing national statistics encompassing all municipalities in the country, thereby reflecting relative growth and decline. The primary outcomes of this multi-criterion indicator analysis for Polish cities from 2006 to 2021 are as follows:

1. It is uncommon for urban centres to return to a growth trajectory after experiencing shrinkage. While some exceptions exist, only five localities achieved a form of re-growth during the 15 years. Most urban centres showing shrinkage do not revert to a growth path.
2. The cities that exhibited significant shrinkage during all three five-year periods mostly fall within the medium-size category (20,000–100,000 inhabitants). Overall, the shrinkage phenomenon in Poland can mainly be attributed to these medium-sized cities.
3. Growing urban centres tend to be around Poland’s five major metropolitan areas.
4. While growth is concentrated around metropolitan areas, shrinking localities have been relatively widespread throughout Poland across all periods. However, they tend to be located on the edges of the country’s administrative voivodeships or on the outskirts of the nation itself.

Table 2 below indicates a comparison that grouped all cities according to their type in all three periods to see the extremes in the following five categories:

1. Cities that were always strongly growing [AAA],
2. Cities that changed from shrinkage to growth [EEB | EEA | EDA | DEA | DDA | EDB | DEB | DDBDDB, EDB],
3. Cities that were always stable [CCC],
4. Cities that changed from growth to shrinkage [AAD | AAE | BAE | ABE | BBE | BAD | ABD | BBDABD, BBD, BBE],
5. Cities that were always strongly shrinking [EEE],

Table 2. Classification status groups for all cities in three periods from 2006 to 2021, Source: Author

1. Always strongly growing	2. Changed from shrinking to growing	3. Always stable	4. Changed from growing to shrinking	5. Always strongly shrinking
Aleksandrów Łódzki [M], Choroszcz [S], Kąty Wrocławskie [S], Nekla [S], Niepołomice [S], Ożarów Mazowiecki [S], Siechnice [S], Szubin [S], Wieliczka [M], Zduny [S], Żukowo [S]	Gdynia [L], Nowy Sącz [M], Opole [L], Ostrów Lubelski [S], Tarnowskie Góry [M]	Drezdenko [S], Kępno [S], Międzybórz [S], Międzyrzecz [S], Milicz [S], Nowa Dęba [S], Oleśnica [M], Pyrzyce [S], Sompolno [S], Szlichtyngowa [S], Trzciel [S], Trzebinia [M], Ujście [S], Wołów [S]	Chełmek [S], Czaplinek [S], Dobra [S], Jabłonowo Pomorskie [S], Kamień Krajeński [S], Kłecko [S], Opalenica [S], Pilawa [S], Suchań [S], Świnoujście [M]	Bartoszyce [M], Bogatynia [S], Chodzież [S], Duszniki-Zdrój [S], Jarosław [M], Jasło [M], Kędzierzyn-Koźle [M], Łowicz [M], Piekary Śląskie [M], Przemyśl [M], Skarżysko-Kamienna [M], Zdzieszowice [S], Żychlin [S]

The research determines that 13 cities experienced continuous, severe shrinkage during the 15 years from 2006 to 2021. Among these, eight that fall into the medium-size category are Bartoszyce, Jarosław, Jasło, Kędzierzyn-Koźle, Łowicz, Piekary Śląskie, Przemyśl, and Skarżysko-Kamienna. At the same time, five (Bogatynia, Chodzież, Duszniki-Zdrój, Zdzieszowice, and Żychlin) are classified as “small”(see Table 2).

4.3. Stage 2 – assessment of urban form compactness

This part of the research was guided by the following research questions:

What is the relationship between city size and city compactness in Poland?

How does the compactness of Polish cities change over time?

In the second phase of the analysis (stage 2), the focus shifted to examining urban compactness and dispersion trends. The analysis aimed to explore the relationship between city size and compactness in Poland and how compactness has changed over time. Two key urban shape measures to quantify compactness were selected (see section 3.1.4 for selection rationale):

- the compactness index (Ci) and
- urban population density (Pd).

The compactness index quantifies the irregularity of a city's shape, assuming the circle is the most compact 2d form. The Schwartzberg compactness index was selected among the measures that Bernes and Solomon (2021) identified. It calculates the ratio of a city's perimeter (Pd) to the circumference of a circle with an area equal to the city's urban area. The second measure, urban population density, on the other hand, factors in the urban area (Ua) and the municipality population (Pop) for a given year, offering a more precise representation than the standard population density. This provides a clearer picture of urbanised boundaries in Polish cities. The author developed the methodology to suit research objectives, scale and the broadly available land use data from the CORINE Land Cover (later called CLC). Moreover, the calculation defines urban areas as "artificial surfaces" according to the CLC. This definition encompasses infrastructure and green urban spaces, represented by 11 categories (see Table 3).

Table 3. CLC codes indicate classes considered for calculation and their respective colours. Source: CLC, 2022.

	CLC Code	Name
	111	Continuous urban fabric
	112	Discontinuous urban fabric
	121	Industrial or commercial units
	122	Road and rail networks and associated land
	123	Port areas
	124	Airports
	131	Mineral-extraction sites
	132	Dump sites

	133	Construction sites
	141	Green urban areas
	142	Sport and leisure facilities

This section presents the analysis outcomes for all municipalities (2,477) and specifically for urban municipalities (964) across three periods based on the CLC datasets. The findings are categorised into patterns in time and trends concerning city size and location.

Compactness index

The Schwartzberg compactness index is expressed in numbers ranging from 0–1, with one being the most compact. Initially, the compactness index (Ci) of urbanised areas in Polish municipalities demonstrates a decreasing trend over time. It shows a normal distribution in all years. This observation holds true for all municipalities, specifically for urban municipalities (including urban, kind 1 and urban-rural, kind 3 in Statistics Poland) (Figure 28). On average, urban municipalities exhibit greater compactness compared to urbanised areas in rural municipalities. The most compact Polish urban municipalities in 2006 were Ząbki, Podkowa Leśna, and Wysokie Mazowieckie; by 2012 and 2018, the top municipalities were Zawidów, Wysokie Mazowieckie, and Podkowa Leśna, each with a Ci exceeding 0.6. Notably, all the highest-scoring municipalities are small, except Ząbki, a medium-sized city located within the Warsaw functional urban area.

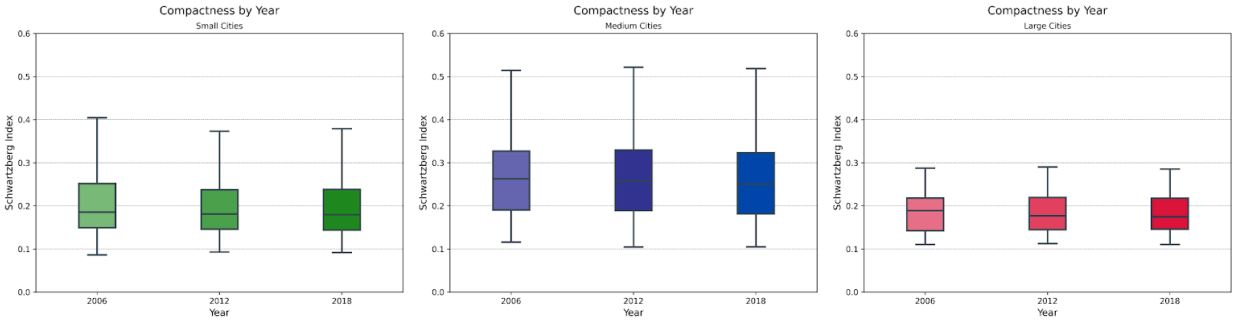


Figure 28. The urban compactness trend for all urban municipalities in 2006, 2012, and 2018 was divided into city sizes (large, medium, and small). Source: Author

The results of the compactness analysis for medium-sized and large cities (all urban municipalities with a population over 20,000) were found to be associated with the urban municipality's population size. Figure 29 depicts a clear logarithmic relationship, indicating that medium-sized cities (20,000–100,000 inhabitants) tend to be more compact than larger ones.

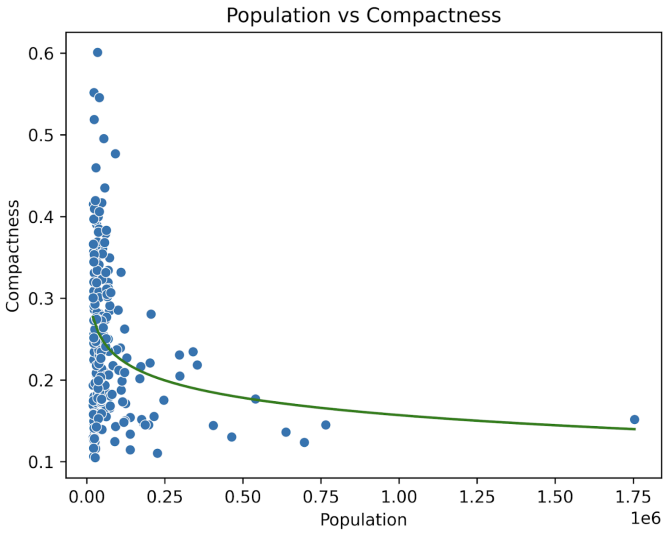


Figure 29. Urban compactness trend for medium-sized (0.02-0.1 $\times 10^6$) and big urban municipalities (0.1 –1.75 $\times 10^6$) in 2018. Source: Author

The compactness analysis results for medium-sized cities across three periods reveal consistent findings. Although the maximum values declined over time, the minimum values slightly increased from 2006 to 2012 and 2018. This indicates a general light dispersion pattern in small- and medium-sized cities, while large cities maintained their compactness index without significant changes. The medium-sized cities that consistently ranked among the top 10 in terms of compactness during all analysed periods include Ząbki, Piastów, Żyrardów, Legionowo, Słupsk, Giżycko, Świdnica, and Rumia. Conversely, the cities with the least compactness were Wyszków, Świebodzin, Opoczno, Jastrzębie-Zdrój, and Pszczyna.

Urban population density

Further, the study examined changes in urban density (Pd) in urbanised areas across Polish municipalities over time. Like compactness, there was a noticeable decline in urban population densities for all municipalities and urban municipalities over the years (refer to Figure 30). There are clear differences between urban population density, which is, on average, higher among large cities.

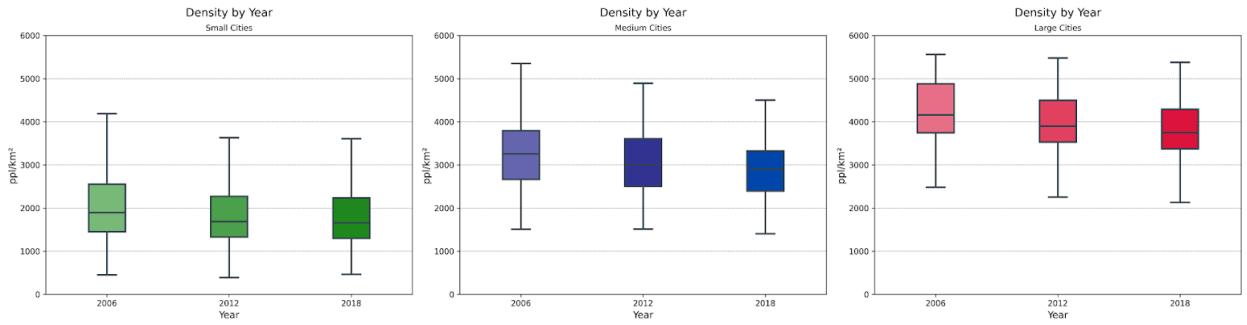


Figure 30. Urban population density trend for all urban municipalities in 2006, 2012 and 2018 divided into city size (large, medium, small). Source: Author

This was confirmed in Figure 31, where larger cities exhibit higher urban population density, indicating a distinct logarithmic pattern.

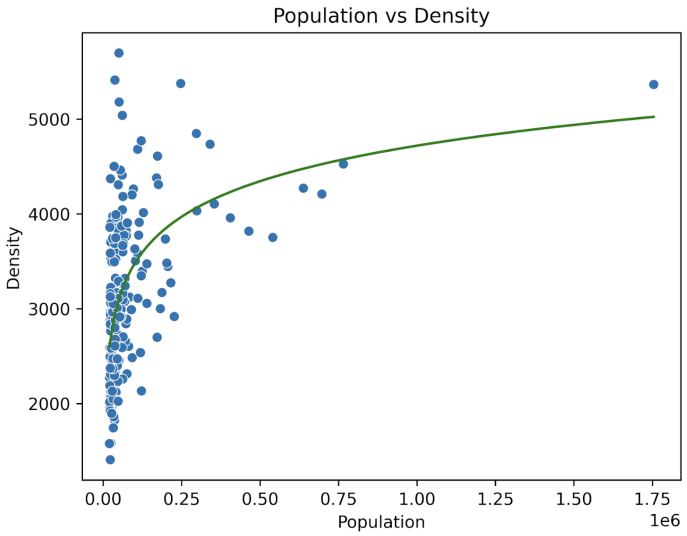


Figure 31. Urban population density trend for medium-sized (0.02-0.1 $\times 10^6$) and big urban municipalities (0.1 –1.75 $\times 10^6$) in 2018. Source: Author

The analysis of urban population density in medium-sized cities across three periods demonstrates a normal distribution and a significant downward trend for all city sizes. Although the maximum values declined over time, the minimum densities varied, indicating that medium cities become less dense as time progresses. This reflects a general tendency towards dispersion in medium-sized urban areas. Among the medium-sized cities with the highest density throughout the examined periods (consistently ranking in the top 10) were Wejherowo, Sopot, Świętochłowice, Ełk, and Grudziądz. Conversely, Polkowice, Trzebinia, Skawina, Czechowice–Dziedzice, Wyszków, and Pszczyna had the lowest densities.

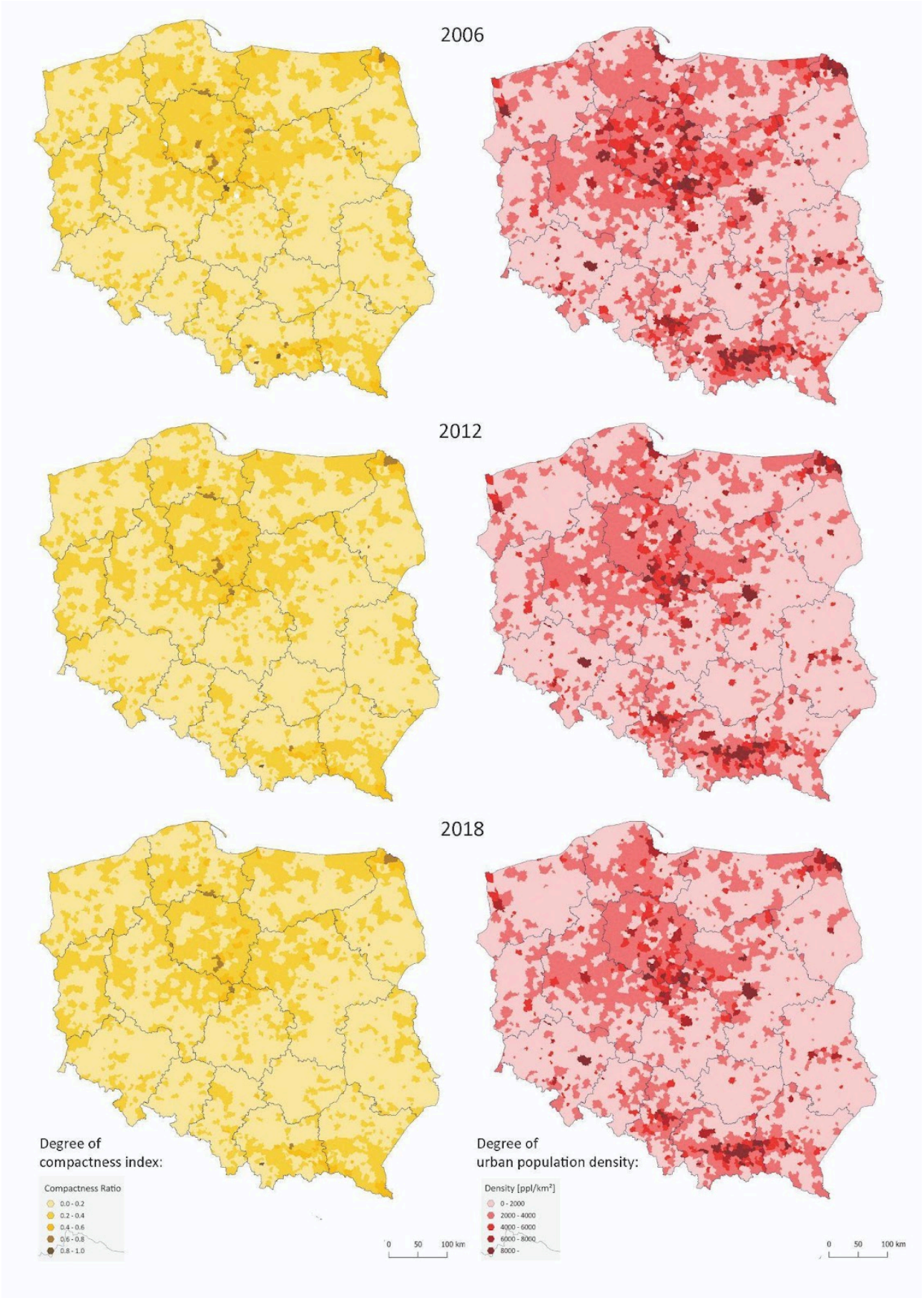


Figure 32. The compactness index (left) and urban population density calculation (right) for all Polish municipalities in three periods are based on CLC datasets and Polish Statistics (2023). Source: Author

Spatial distribution of results

As shown in Figure 32, cities with high scores in both the compactness index and urban population density tend to cluster in the same regions of Poland. Specifically, the country's southern edge and north-central areas feature a notable concentration of densely populated, compact cities, with the Kujawsko-Pomorskie voivodeship having the most compact municipalities. Neighbouring regions like Mazowieckie, Pomorskie, and northern Lodzkie also show a similar pattern. While the mountainous southern regions and lakelands exhibit a denser presence of compact cities, they are rare and sparsely spread across the lowland areas in the centre of the country. Notably, although the Silesian region maintains high population density, it consistently shows lower levels of compactness over time.

4.4. Stage 3 – identifying the relationships between urban compactness and shrinkage

The following research hypotheses guided this part of the research:

I. **There is a statistically significant correlation between urban compactness and shrinkage of medium-sized Polish cities.**
II. **There is a statistically significant correlation between urban population density and shrinkage.**
III. **The trend persists within the analysed time frame.**

In the third phase of the analysis (stage 3), the focus was to determine whether there is a relationship between urban shrinkage and urban compactness among medium-sized cities. In this final step, the author analysed the correlations between the urban growth/shrinkage score, the urban shape compactness measure (Ci), and the urban population density measure (Pd). A correlational analysis was conducted using Pearson's correlation coefficient (r) to assess the relationships among several variables of interest. The coefficient, calculated from the normalised values of two variables across a sample of n values (ranges from +1 to -1, with values near 0 indicates no correlation). The statistical significance index (p-value) was employed, confirming a significant correlation when p is below 0.05, which allowed the author to test the research hypotheses.

It is important to note that the author opted to modify the method used to define the shape of an urban area. In stage 2, the urban area considered for calculating the two measures was based on a broadly defined concept of urban area, referred to as 'artificial surfaces' (see Table 4). The modification incorporated calculations based on the 'urban fabric' layers (only CLC Class Numbers 111 and 112). While this area represents where most of the population resides, it does not capture the entire city landscape, as shown in the example of Jasło (Figure 33). Examining both definitions aimed to mitigate potential errors associated with an inadequate representation of urban form.

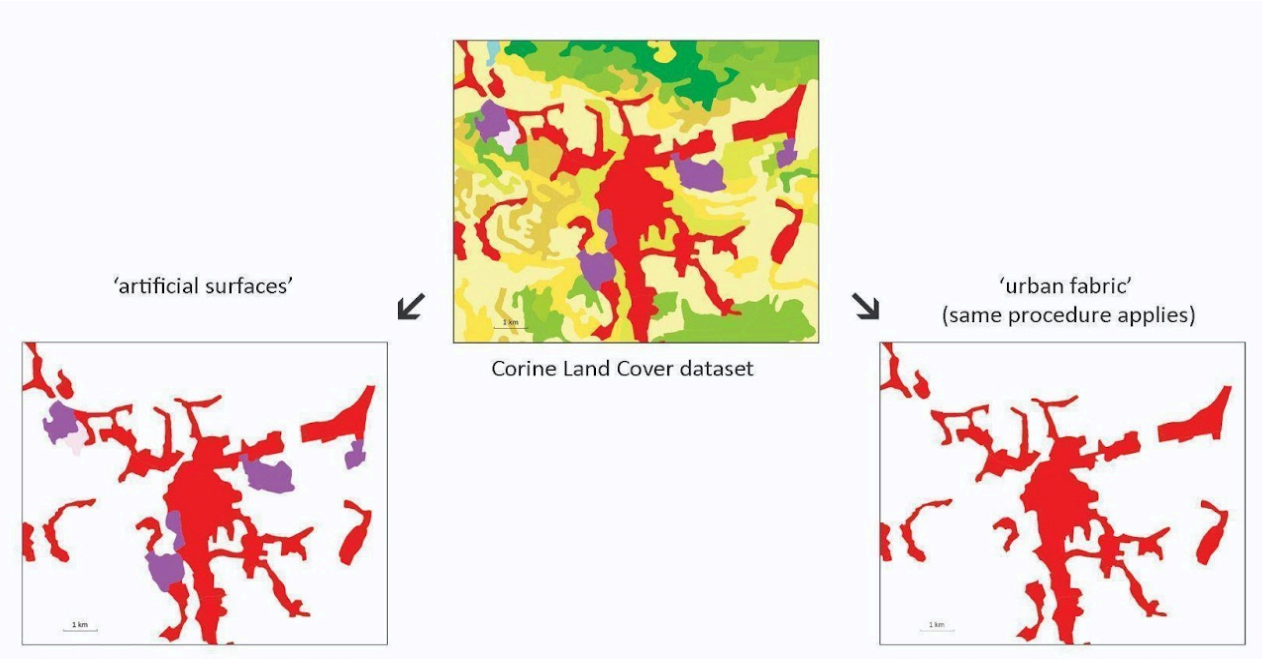


Figure 33. Urban shape-analysis diagram based on the Jasło urban municipality example. Source: Author

Moreover, in this analysis stage, the author found a need to distinguish the results for urban municipalities and urban-rural municipalities. In 2021, Poland comprised 2,477 municipalities: 302 urban, 662 urban-rural, and 1,513 rural. This research concentrates on medium-sized cities and towns. Data from "urban" municipalities and those classified as "urban-rural" were utilised for the study. An "urban municipality" (level 6, kind 1 in Statistics Poland) is a municipality consisting of a single city with administrative boundaries closely surrounding its urban areas. In contrast, an "urban-rural municipality" (6, 3) includes a city with various urban areas, such as villages and small towns, that are more loosely interconnected. Due to the difference between these two types, as exhibited in Figure 34, the analysis is divided into these two categories.

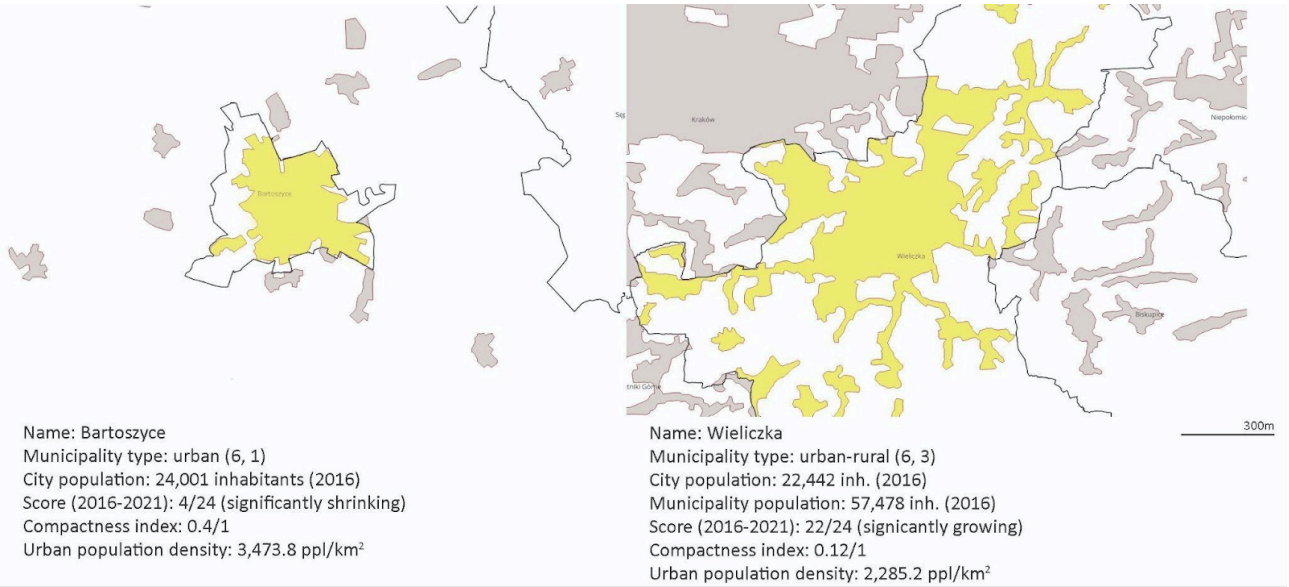


Figure 34. An example of an urban area defined I CLC as 'artificial surfaces' (in yellow) of an urban municipality (6, 1) and an urban-rural municipality (6, 3) showing different spatial patterns. Source: Author

Correlation between the shrinkage/growth score and compactness index

This examination explored the relationship between the compactness index and urban shrinkage and growth scores over three distinct periods. All statistically significant results are presented in bold in the tables below. For medium-sized cities, the results shifted over time from a modest positive correlation in the first period to a slight negative correlation in the subsequent periods. However, since the p-value exceeded 0.05, all findings are statistically insignificant (see Table 4).

When analysing the correlation separately for urban municipalities (6, 1) and the score index, a positive correlation with strong statistical significance was identified across all periods (refer to Table 5). This positive correlation shows that growing cities (with higher scores) are more compact. Although the strongest correlation coefficient of 0.34 was observed in the first analysed period and weakened over time, it was true for both ways of looking at urban areas. In the case of urban-rural municipalities (6, 3), the correlation was close to 0 and shifted from negative to positive; however, the p-value remained insignificant across all periods (see Table 6). According to the criteria outlined by Cohen et al. (2002), a correlation r value of 0.3 can be considered moderate. While strong correlations (r>0.5) are relatively rare in social science due to the complexity and variability of social systems, weak correlations can have practical significance if analysed on a large dataset (Cohen et al., 2002).

Table 4. Correlation outcomes between the shrinkage/growth score and urban compactness for all medium-sized cities.

	Periods		
	2006–2011	2011–2016	2016–2021
Number of observations	180	184	180
Correlation for "urban fabric"	0.09 (p = 0.21)	−0.07 (p = 0.32)	−0.06 (p = 0.4)
Correlation for "artificial surfaces"	0.05 (p = 0.44)	−0.08 (p = 0.235)	−0.08 (p = 0.252)

Table 5. Correlation outcomes between the shrinkage/growth score and urban compactness for all medium-sized urban municipalities (6, 1).

	Periods		
	2006–2011	2011–2016	2016–2021
Number of observations	147	149	147
Correlation for "urban fabric"	**0.34 (p = 0.00)**	**0.23 (p = 0.00)**	**0.22 (p = 0.005)**
Correlation for "artificial surfaces"	**0.29 (p = 0.0002)**	**0.19 (p = 0.014)**	**0.18 (p = 0.024)**

Table 6. Correlation outcomes between the shrinkage/growth score and urban compactness for all medium-sized urban-rural municipalities (6, 3).

	Periods		
	2006	2012	2018
Number of observations	33	35	33
Correlation for "urban fabric"	0.02 (p = 0.9)	−0.12 (p = 0.47)	0.02 (p = 0.89)
Correlation for "artificial surfaces"	−0.017 (p = 0.923)	−0.074 (p = 0.67)	0.064 (p = 0.72)

Correlation between the shrinkage/growth score and urban population density

The correlation between urban population density and shrinkage and growth scores was analysed over three periods. For medium-sized cities, the results from the first two periods indicated a slight negative correlation, supported by a statistically significant p-value (see Table 7). However, during the last period, specifically for "artificial surfaces," this correlation diminished. In the earlier periods analysed, a lower score (indicating higher shrinkage) was associated with greater urban density, but this trend no longer held true for 2016–2021.

Additionally, when examining the separate correlations for urban municipalities (6, 1), a shift to a positive correlation trend was observed in the last period (refer to Table 8). Although the high p-values indicate that these correlations are statistically insignificant, the analysis for urban municipalities in this latter period confirms a change in trend. For urban-rural municipalities, the correlation values were also weaker (see Table 9). Nevertheless, akin to compactness, a

correlation value of -0.2 is classified as a weak relationship. As the trend evolves throughout the analysed periods, it suggests a potential positive correlation in the future. As urban density increases, the shrinkage score may increase as well, indicating that higher densities could be beginning to be associated with reduced shrinkage levels.

Table 7. Correlation outcomes between the shrinkage/growth score and urban density for all medium-sized cities.

	Periods		
	2006–2011	2011–2016	2016–2021
Number of observations	180	184	180
Correlation for "urban fabric"	**–0.29 (*p* = 0.000)**	**–0.27 (*p* = 0.000)**	**–0.20 (*p* = 0.005)**
Correlation for "artificial surfaces"	**–0.222 (*p* = 0.002)**	**–0.231 (*p* = 0.001)**	–0.105 (*p* = 0.157)

Table 8. Correlation outcomes between the shrinkage/growth score and urban density for medium-sized urban municipalities (6, 1).

	Periods		
	2006–2011	2011–2016	2016–2021
Number of observations	147	149	147
Correlation for "urban fabric"	**–0.18 (*p* = 0.022)**	–0.11 (*p* = 0.15)	–0.03 (*p* = 0.71)
Correlation for "artificial surfaces"	–0.081 (*p* = 0.32)	–0.016 (*p* = 0.83)	0.12 (*p* = 0.14)

Table 9. Correlation outcomes between the shrinkage/growth score and urban density for medium-sized urban–rural municipalities (6, 3).

	Periods		
	2006–2011	2011–2016	2016–2021
Number of observations	33	35	33
Correlation for "urban fabric"	–0.24 (p = 0.16)	–0.26 (p = 0.11)	–0.18 (p = 0.31)
Correlation for "artificial surfaces"	–0.242 (p = 0.17)	–0.28 (p = 0.103)	–0.073 (p = 0.68)

Summary of hypothesis testing

Due to the different outcomes of testing the research hypothesis when different urban areas or types of municipalities were considered, this summary combines them in Table 10 below. When examining all types of medium-sized urban municipalities (6, 1 and 6, 3), Hypothesis 1 (H1) is false since no statistically significant correlation was found between urban shape compactness and shrinkage. However, the hypothesis is true in the case of urban municipalities (6,1), where a statistically significant, positive, moderate correlation exists between urban compactness and the shrinkage/growth score. In other words, the results indicate that a more compact urban municipality tends to experience less shrinkage. This connection remains consistent throughout the analysed period from 2006 to 2021 for both urban areas definitions. Therefore, one can say that

there is a significant negative correlation between urban compactness and shrinkage among medium-sized urban municipalities.

The correlation analysis between density and the shrinkage/growth score among medium-sized cities shows that urban areas with higher density were more prone to shrinkage between 2006 and 2016 than those with lower density. Though the correlation results demonstrate a significant spread, they retain statistical significance during that time frame, indicating a trend that lessened and ultimately disappeared in 2016–2021. Therefore, Hypothesis 2 (H2) is supported when looking at all medium-sized cities, as denser urban areas from 2006–2016 exhibited greater shrinkage. Therefore, one can say that there is a statistically significant, weak, positive correlation between urban population density and shrinkage among all medium-sized municipalities and a temporary one for medium-sized urban municipalities.

The third hypothesis (H3) is true: the relationship between shrinkage and compactness, specifically for urban municipalities. It also holds true for the connection between shrinkage and density across all medium-sized municipalities when urban density is assessed using "urban fabric" as the basis. However, when "artificial surfaces" are used for calculating urban density, this trend does not continue throughout all analysed periods and disappears in the final one.

Table 10. Summary of hypothesis confirmation.

Hypothesis	Selected Urban areas (CLC Classes)	All Medium-Sized Municipalities (6, 1 and 6, 3)	Medium-Sized Urban Municipalities (6, 1)	Medium-Sized Urban-Rural Municipalities (6, 3)
H1: There is a statistically significant correlation between urban compactness and shrinkage.	"Urban fabric"	NO	YES	NO
	"Artificial surfaces"	NO	YES	NO
H2: There is a statistically significant correlation between urban population density and shrinkage.	"Urban fabric"	YES	Yes, for 2006–2011	NO
	"Artificial surfaces"	YES for 2006–2016	NO	NO
H3: The trend persists within the analysed time frame.	"Urban fabric"	YES	YES (for compactness relationship only)	NO
	"Artificial surfaces"	NO	YES (for compactness relationship only)	NO

Considering the above outcomes, the research hypothesis could be answered as follows:
H1. A statistically significant, negative correlation exists between compactness and shrinkage of medium-sized Polish cities.

H2. A statistically significant, positive correlation exists between urban population density and shrinkage of medium-sized Polish cities.

H3. Some trends persist within the analysed time frame.

While the correlation results are significant, with the coefficient for compactness being positive and for population density negative, identifying the relationship between urban form and urban shrinkage is not straightforward. Correlation indicates an association, not causation, and should be juxtaposed with other potential factors.

5. Discussion of results

The list below outlines how the empirical and methodological research objectives of this study, were achieved:

Methodological objective

1. To identify methods to evaluate the urban shrinkage and urban form compactness using broadly available datasets.

Accomplishments:

Choosing a multi-criteria indicator developed by Milbert (203, 2015, 2020) that allows the assessment of growth and shrinkage using six, socio-economic variables in five-year periods (presented in section 4.1.1).

Adopting multi-criteria indicator method to Polish statistical data to allow for continuous monitoring of growth and shrinkage patterns in 2006-2021 (section 4.1.1).

Choosing and developing a compactness assessment method suitable for analysing big, national scope of urban areas based on Corine Land Cover datasets (section 4.1.2)

Empirical objectives

2. To assess shrinkage and growth trends in Polish cities.
3. To assess compactness and dispersion trends in Polish cities.
4. To find out if there is a relationship between urban shrinkage and urban compactness trends.

Accomplishments:

Assessing urban shrinkage in Poland using statistical data from 2006-2021 for all the municipalities to see the outcomes relative to the national perspective (section 4.2).

Verifying if urban shrinkage is related to city size types (section 4.2).

Measuring urban shrinkage in the fifteen-year term in five-year intervals to allow for observation of trends and changes in time (section 4.2).

Assessing urban compactness in Poland in 2006-2018 to provide an overview of urban form trends over the long term (section 4.3).

Verifying if urban compactness measures are related to city size types (section 4.3).

A relationship between urban shape compactness and the shrinkage in medium-sized Polish cities was testes through Person's correlation in three periods (section 4.4).

5.1. Methodological findings discussion

The methodological findings presented in Section 4.1 of this dissertation were confronted with existing literature, providing a comprehensive discussion on two main areas: urban shrinkage and urban form compactness assessment. The primary aim of this phase to explore approaches for measuring urban shrinkage and compactness using widely accessible datasets was achieved, offering insights that contribute to national and European urban studies.

5.1.1. Urban shrinkage measure

The multi-criteria indicator approach to measuring urban shrinkage offers a valuable lens for understanding the broader socio-economic transformations in Poland, in contrast to population only and other multi-criteria approaches. By leveraging widely available statistical data across the years, the methodology provided robust, scalable insights, aligning with prior findings on Poland's urbanisation challenges but adding temporal aspects. The method can be applied to other European contexts, reflecting the commonality of selected variables across Europe. However, due to differences in tax systems, the last variable (the Municipality's own income) might have to be changed into another similar one.

Furthermore, the multi-criteria method allows for temporal monitoring of Polish cities' growth and shrinkage trends. As shown by the example of German shrinking cities, monitoring urbanisation trends allows for better diagnosis of arising problems and more accurate responses. The division into five-year periods makes it a useful tool for national and local governments to observe changes over time, while the typologies (from A to E) provide straightforward information on the city's status. It is worth noting that a multicriteria method allows for country-specific observations as the calculation is not absolute but relative to the country's statistics. In Germany, this method made it possible to assess the effectiveness of planning responses.

Different approaches exist for selecting the indicators that most effectively explain the phenomenon of urban shrinkage. This study utilised six indicators, comprising an equal balance of demographic

and economic factors. In a multi-criteria method outlined by Śleszyński (2019), seven indicators were chosen, with only two being demographic in nature. Economic indicators, such as the number of registered companies and the presence of company headquarters, highlighted a strong emphasis on functional and economic performance, thus changing the results compared to this study. The final classification of this study from shrinkage to growth (A-E) is different from that used in Śleszyński's (2019) (e.g. "cities in crisis" or "marginalised cities"), leaving space for establishing new meanings to the term "shrinkage".

5.1.2. Urban form compactness measure

The developed methodology combines two primary measures: urban population density and shape, utilising the Corine Land Cover (CLC) database and population data from Polish Statistics. The combined use of density and shape measures revealed moderate correlation, a high degree of overlap, particularly in areas with the most compact and dense urban forms, and a consistent decrease over time, underscoring the measures' relevance in evaluating spatial distribution and urban form.

The study's approach to measuring urban compactness highlights notable dispersion in Polish urban forms. For instance, Sopot, identified as Poland's densest municipality in 2006, saw its population density decline from over 5,894 people/km² to 5,413 people/km² by 2018. Other municipalities with high density, such as Świętochłowice and Chełmno, also showed a gradual decline, though they retained relatively high-density levels overall. The observed relationship between city size and density corroborates research by Śleszyński (2014), which established a strong correlation between a city's central area density and overall size. This consistency with past findings confirms that density and shape measures provide comparable insights, reinforcing the validity of the other. Moreover, the methodology underscores a persistent trend of decreasing density across urban municipalities (Cortinovis et al., 2022), adding to the discourse on urban dispersion in Poland and providing a useful monitoring tool for national and local governments.

Comparative perspective and pan-European context

Many European countries experience similar patterns of urban dispersion, where smaller cities lose residents while larger cities densify and expand (Angel et al., 2020). By employing a combination of density and shape measures, this methodology provided insights into the socio-spatial characteristics of medium-sized cities in Poland, validating previous literature and aligning with established European urban studies. Moreover, these measures provide a potential foundation for pan-European comparisons and can be combined with other functional and morphological compactness measures.

In conclusion, this study establishes a solid framework for assessing urban compactness across Europe. It sheds light on the spatial dynamics of urban areas, including the effects of planning policies and economic trends. Given that CLC datasets span the entire EU, this method is adaptable across member states, enabling further comparative research.

5.2. Urban shrinkage in Poland

The empirical findings presented in Section 4.2 of this dissertation were confronted with existing literature, providing a comprehensive discussion on urban shrinkage assessment. The primary aim of this phase to assess urban shrinkage in Poland in 2006-2021 was achieved. While much of the Polish discourse on urban shrinkage centres around socio-economic, demographic, and spatial dimensions, relatively few studies have approached this issue using a comprehensive, nationwide multi-criteria analysis. Studies by Jaroszewska (2019), Śleszyński (2017, 2019), Jopek and Musiał-Małago (2021) and Sroka (2021) are examples of this approach. The chapters below reflect on the findings of this study an juxtaposes it with research conducted by the authors listed above.

Medium-sized cities shrinkage

This study reveals a broader trend of urban shrinkage in Poland, which has intensified over time, aligning with demographic foresight made by Statistics Poland (2023b). While the early 2000s posed significant challenges for larger cities, subsequent years have enabled these cities to recover economically, gradually attracting capital and residents from more peripheral regions of the country. Statistics Poland (2023b) forecasts that medium-sized cities will continue to experience considerably higher demographic decline rates than other urban areas, with projected population losses of up to 39% in Konin and 35.4% in Tarnobrzeg by 2050. Although the author focuses on the period between 2006-2021 with no attempts to present a forecast, this research underscores the notable trend of shrinking medium-sized cities throughout the study's time frame, thus supporting alarming projections made by Statistics Poland (2023b).

When putting together all analysed periods, this study reveals that of the 13 cities experiencing severe shrinkage in every five years, eight are medium-sized — namely Bartoszyce, Jarosław, Jasło, Kędzierzyn-Koźle, Łowicz, Piekary Śląskie, Przemyśl, Skarżysko-Kamienna — and five are small-sized — namely Bogatynia, Chodzież, Duszniki-Zdrój, Zdzieszowice and Żychlin. These findings partially correspond with Śleszyński's multicriteria research conducted between 2004-2014 and 2008-2018, which also highlighted medium cities such as Przemyśl, Jarosław, Bartoszyce, and Jasło being in crisis. Comparing the results of both studies is challenging due to differing time frames and selected indicators, which, considering urbanisation dynamics, influence the outcomes. However, Śleszyński (2019) underscored the challenges that medium-sized cities face, noting their declining economic significance and functionality—a trend that continues gaining traction in academic and policy discussions.

When considering Śleszyński's (2019) most recent delimitation in 2008-2018, it is notable that cities identified as most crisis-ridden — such as Kłodzko, Tomaszów Lubelski, Bolesławiec, Chełmno, and Gorlice — are also recognised as shrinking in this research (see Figure 39). A

noteworthy distinction is that while most of these cities are experiencing above-average shrinkage, Bolesławiec is classified in this study as shrinking (type D), and Gorlice temporarily faced above-average shrinkage (type E) before reverting to a trend of shrinking in the latest period studied. Thus, while the overall outcomes often align, there are instances where they diverge from Śleszyński's findings. This is related to the difference in time frame, the indicators selected, and the typology of both multi-criteria methods.

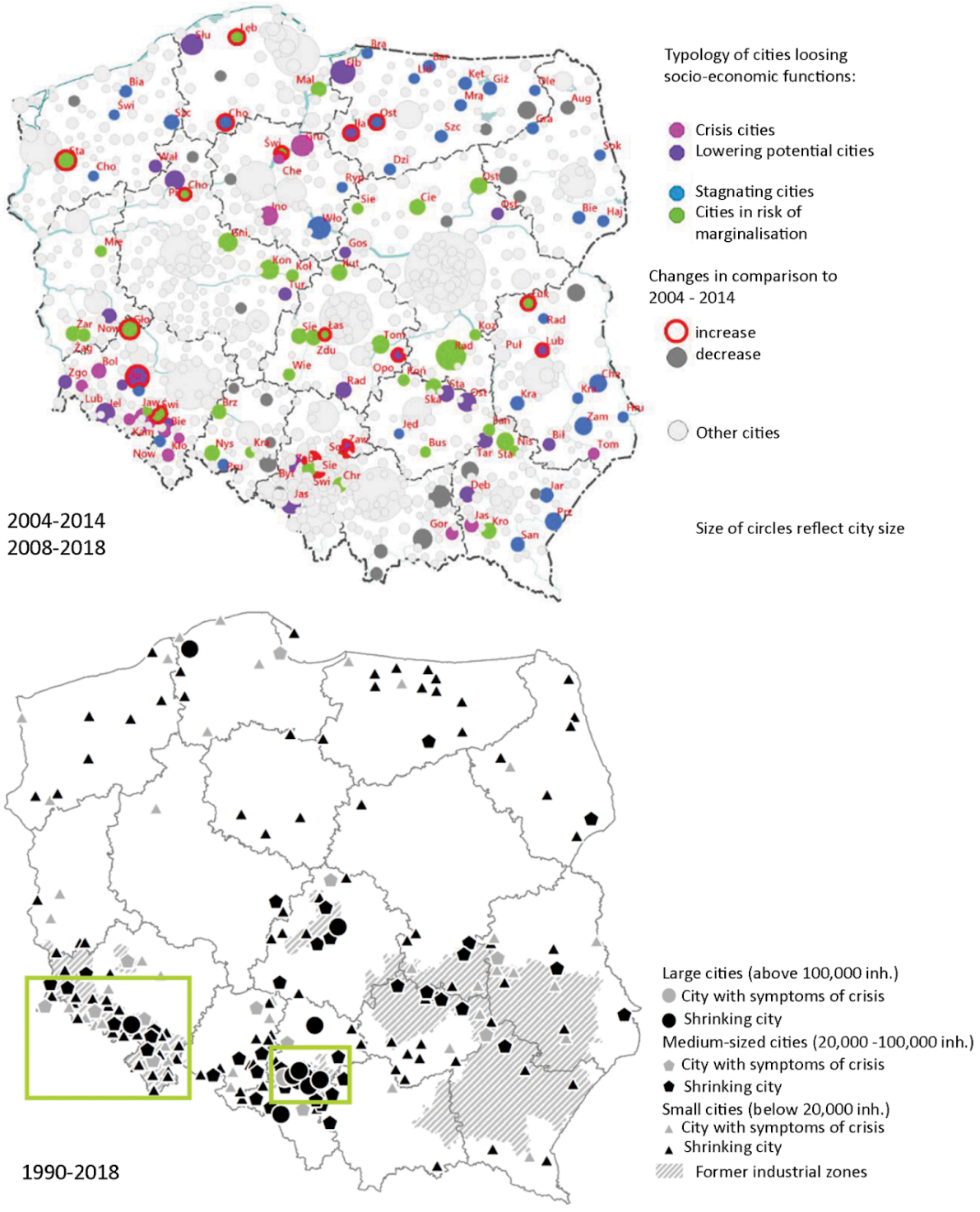


Figure 39. Outcomes of multi-criteria classifications presenting shrinking cities 1) Medium-sized urban areas in crisis in 2004-2014 and 2008-2018 (top); 2) All cities in 1990-2018 (bottom). Source: Author based on Śleszyński, 2019 (top) & Sroka, 2021 (bottom).

Spatial distribution

Examining the spatial distribution of classified cities during the initial five-year period reveals that most growth occurred in the metropolitan regions of Poland's largest cities. In contrast, the concentration of shrinking cities is less pronounced when analysed across all three periods.

Growth was most prevalent in the Greater Poland (Wielkopolskie), Masovian (Mazowieckie), and Lesser Poland (Małopolskie) voivodeships, whereas the occurrence of shrinking cities is more widespread throughout the country. Shrinkage is particularly evident in the post-industrial regions of western Lower Silesia and the Sudety Mountains and in areas that housed industries during the socialist era. Additionally, there is a notable concentration of shrinking small and medium-sized cities in the northeastern Varmian-Masurian (Warmińsko-Mazurskie) voivodeship, the Kujavian-Pomeranian (Kujawsko-Pomorskie) voivodeship, and Łódź voivodeship in central Poland (Figure 40). These findings are corresponding with Śleszyński's (2017, 2019) as well as Jaroszewska's (2019) and Sroka's (2021) multi-criteria analysis.

In the subsequent period from 2011 to 2016, a significant shift became apparent, characterised by an increase in shrinking cities and a decrease in those experiencing growth. While growth remained concentrated around the same metropolitan areas, shrinkage broadened across the country, particularly impacting small and medium-sized cities. The last analysed period, from 2016 to 2021, showed a polarisation with an increase in both strongly shrinking and strongly growing cities accompanied by a decrease in the number of stagnant (stable) cities. Additional growing urban centres can be found among large and smaller cities around them (refer to Figure 40). The rise in shrinking cities is especially noticeable on the peripheries of various voivodeships, situated away from the major metropolitan growth zones and in certain post-industrial areas still grappling with the challenges following the transformation.

Conversely, some cities in the Upper Silesian region displayed growth, indicating dynamic shifts within the agglomeration. A similar pattern of overlapping dynamics is observed around the Tricity agglomeration in the Pomeranian voivodeship, where medium and small shrinking cities surround growth poles. Jaroszewska (2019) and Krzysztofik et al. (2011), among others, have conducted detailed studies on those agglomerations.

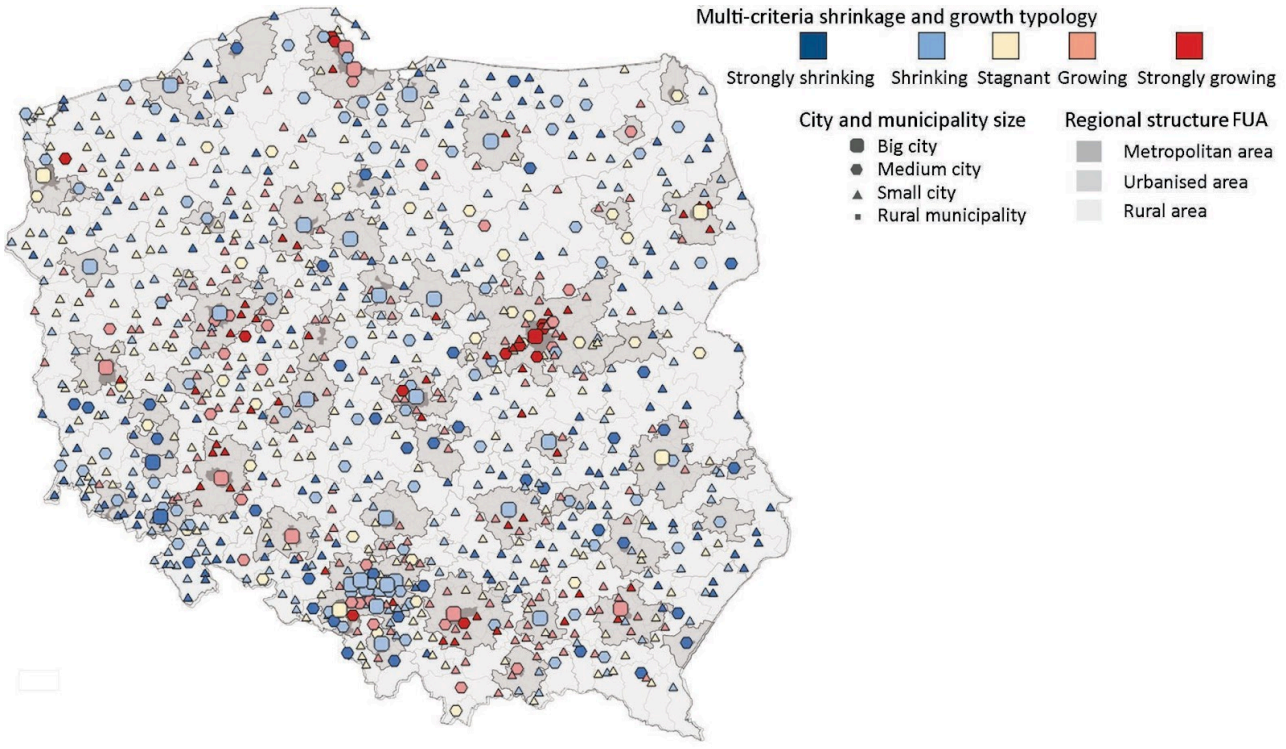


Figure 40. Multi-criteria assessment of growing and shrinking cities in Poland in 2016-2021 overlapped with FUA (Functional Urban Areas) for 2022 (Statistics Poland, 2024). Source: Author based on Statistics Poland

Summary

In summary, comparing the results with other multi-criteria analyses proved challenging. For example, Sroka (2021), inspired by Milbert's (2015) multicriteria method, examined urban shrinkage using different indicators and a different time frame (1995-2018) without subdivision into specific five-year periods. Sroka's analysis identified 53 of 190 medium-sized cities as severely shrinking. Compared to Sroka (2021), this study offers a more granular view, detailing trends and fluctuations in shrinking cities across five-year intervals. Similarly, due to methodological differences, it is hard to compare the outcomes to Jaroszewska's (2019) analysis of shrinkage trends. She analysed demographic shrinkage in 829 cities between 1990-2010 but considered socioeconomic data only from 2003 and 2013, which makes direct comparisons difficult. Nonetheless, both studies reveal similarities in shrinking and growing cities across voivodeships.

Furthermore, differences emerge when comparing this study's results to Jopek and Musiał-Małago's (2021) multi-criteria analysis of urban shrinkage from 2018-2020. First, Jopek and Musiał-Małago analysed selected cities with over 100,000 inhabitants, meaning their study omits the medium-sized group. Nevertheless, some large cities identified in their study can be compared with the author's outcomes. For example, Bytom and Wałbrzych were identified by Jopek and Musiał-Małago (2021) as the most severely shrinking cities. In this multi-criteria analysis, Wałbrzych indeed displayed above-average shrinkage in 2006-2011 and 2016-2021 (type E) but ranked higher in 2011-2016 (type D) due to favourable employment conditions despite population

loss. Bytom's ranking similarly improved in 2016-2021 (type D) due to low unemployment rates. This example comparison demonstrates the differences between the two classifications and their impact on shrinkage assessments.

The author identifies several convergences when comparing the outcomes of recent multi-criteria research. However, due to differences in methodology, it is evident that these studies cannot be considered directly comparable. Nonetheless, the issues of functional decline, status within the settlement hierarchy, and the broader economic challenges facing medium-sized cities in Poland are increasingly significant problems that demand careful attention in both practical and academic contexts. Until recently, these centres have been undervalued in development policy, yet as pointed out by Śleszyński (2017, 2019), they play a vital role in stabilising the polycentric settlement system and fostering balanced development in areas where, for various natural reasons, growth stimuli from major metropolises do not extend.

5.3. Relationship between urban form and shrinkage in medium-sized cities

The empirical findings presented in section 4.4 of this dissertation were confronted with existing literature, providing a comprehensive discussion on the urban shrinkage and from relationship. The primary aim of this phase to find out if there is a relationship between urban shrinkage and urban compactness trends among medium-sized cities in Poland was achieved.

5.3.1. Relationship between compactness and shrinkage

The empirical analysis of urbanised areas in Polish municipalities reveals a minor but clear downward trend in the compactness index over time. The compactness of medium-sized cities is the highest compared to small and large urban units. No statistically significant relationship was found when compactness was correlated with urban growth/shrinkage score in all medium-sized cities (categories 6, 1 and 6, 3). However, in the case of urban municipalities (6,1), a moderately positive, statistically significant correlation exists between compactness and the shrinkage/growth score (for both urban fabric" and "artificial surfaces"). This indicates that more compact urban municipalities are less likely to experience shrinkage. Moreover, this trend remains consistent from 2006 to 2021, suggesting a solid relationship will hold.

Exploring the range of urban, economic, social, and demographic dynamics that impact sustainable development is crucial to fully understand this finding. In research, higher compactness is associated with greater resilience and sustainability (Squires, 2002; OECD, 2012; Angel, 2020), which is particularly beneficial for medium-sized cities with limited governance resources. In contrast, urban sprawl and outward expansion increase infrastructure operating costs (Schiller and Siedentop, 2006; Siedentop and Fina, 2010), putting local governments' budgets under greater

pressure. Compact cities can manage these challenges more effectively by concentrating activities within a smaller area, as they do not have underutilised infrastructure. This results in lower costs and the maintenance of clear urban-rural boundaries, reinforcing that cities with more compact urban forms are less prone to economic shrinkage (Haase et al., 2021). While demographic shrinkage might still occur in cities, their compact form allows them to maintain fiscal balance.

In the correlation between urban sprawl and economic performance in selected growing Polish cities, Lityński (2016) concluded that higher local economic indicators significantly correlate with a lower degree of urban sprawl. However, this study is analysing the relationship between the compactness index and the shrinkage/growth score, which comprises six indicators, of which only half are economic; these two analyses demonstrate similar spatial phenomena. Supporting this view, research by Wang et al. (2022) finds that shrinking cities in Northeast China have significantly lower compactness than those experiencing growth.

5.3.2. Relationship between urban population density and shrinkage

The analysis of urban population density shows a steady decline across all cities throughout the observation period, like the trend observed in urban compactness. Here, however, medium-sized cities are, on average, less dense than large urban areas and more dense than small ones. The analysis of the relationship between density and size aligns with the findings of Śleszyński (2014), who demonstrated a significant correlation between the density of a city's central region and the size of the city in Poland.

Correlation analysis of density and shrinkage/growth scores in all medium-sized cities (both urban and urban-rural municipalities) reveals that denser urban areas were more prone to shrinkage from 2006 to 2021 than less dense areas. Although there was substantial variability in the correlation data (different for “urban fabric” than for “artificial surfaces”), the results remained statistically significant for “urban fabric”, pointing to a trend. However, that correlation weakened for “artificial surfaces” and eventually showed no statistical significance between 2016 and 2021. In other words, denser medium-sized cities temporarily experienced higher shrinkage levels between 2006 and 2016 than the less dense ones. Figure 41 demonstrates the diversity of shrinking and growing medium-sized cities (expressed in A-E types) regarding their compactness and density values. While a moderate positive correlation was observed between Ci and growth/shrinkage score, there was a temporal negative correlation between Pd and score, thus making the overall conclusion challenging.

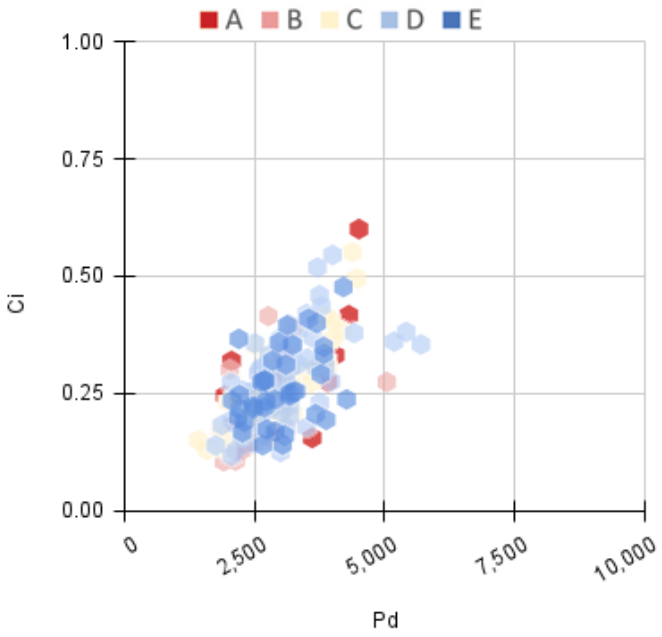


Figure 41. Compactness results (Ci and Pd) for all medium-sized Polish cities in 2018 divided by colour of shrinkage/growth types (A-E) in a corresponding period 2016-2021. Source: Author

Potential causes and future trends

Since demographic indicators are a part of the shrinkage/growth score, it is necessary to look at the possible causes of migration between cities. The increase in migration from denser, medium-sized cities to larger metropolitan areas was likely driven by metropolisation trends, limited job opportunities, and crowded housing conditions. While the housing situation improved over the last years, Poland consistently exhibits high overcrowding rates, an important factor in housing conditions that motivates migration to access better living standards at lower costs (EUROSTAT, 2023). Large Polish cities and their suburbs see significant new housing construction, attracting investment and employment. These factors, combined with economic liberalisation and land use policies that permit suburban sprawl (NIK, 2022) and market-driven growth, have led to declining densities in medium-sized cities from 2006 to 2021, while urban growth rates in the cores and suburbs of major cities have surged.

Finally, the findings of this study suggest that future development in the shrinking cities could follow a model Siedentop and Fina (2008, 2010) described as “shrinkage sprawl”. In their analysis of urban areas in Germany from 1996 to 2006, Siedentop and Fina (2008) noted an increase in “growth-sprawl” into suburban regions, which persisted even as the core cities experienced ongoing depopulation. The physical characteristics of this “shrinkage sprawl” are similar to those associated with urban sprawl in expanding cities. This phenomenon results in fragmented and perforated landscapes characterised by low-density development, rising vacancy rates, and a deteriorating urban fabric in inner-city locations.

The observation of a period between 2016 and 2021 suggests a shift towards this model. For all medium-sized cities (‘artificial surfaces’), low urban population density no longer correlates with higher shrinkage/growth scores. It revealed a positive yet statistically insignificant trend for urban municipalities (‘artificial surfaces’). This hints at the possible emergence of “shrinkage sprawl” (Siedentop and Fina, 2010), where a strong relationship between low density and shrinkage may develop over time.

5.4. Diversity of medium-sized cities

In addition to the above-described urbanisation patterns, this study revealed the diversity of medium-sized cities in Poland, both in growth and shrinkage and in urban form patterns, which substantially shape the outcomes of the correlation between the two. Firstly, the differences in urban density between urban (6,1) and urban-rural (6,3) municipalities greatly influence observed correlation trends. Secondly, the heterogeneous nature of medium-sized cities is underscored by their varied roles within the urban network system. This diversity is critical when interpreting the outcomes and considering planning implications, as policies must account for each city's unique structural and functional characteristics.

These findings highlight the diversity of medium-sized cities, as explained by Kunzmann (1992, 2000, 2010), who provides a valuable framework for understanding the typologies of medium-sized cities based on their positioning within broader urban networks (Figure 42). He identifies three main types of medium-sized cities:

1. **Within metropolitan regions**: These cities are integrated into major metropolitan areas' economy and transportation systems. They benefit from proximity to large urban centres, serving as commuter hubs or residential extensions of the metropolis.
2. **On the boundaries or between metropolitan areas**: Cities located at the intersection of metropolitan influences may experience competing dynamics, balancing the opportunities from multiple urban regions while maintaining local identity and function.
3. **On the geographic peripheries of Europe**: Cities on the outer edges of the European continent, or in isolated regions, often face unique challenges in attracting investment and retaining population due to their remote location. This underscores the importance of considering historical context, geographic location, and urban form in planning.

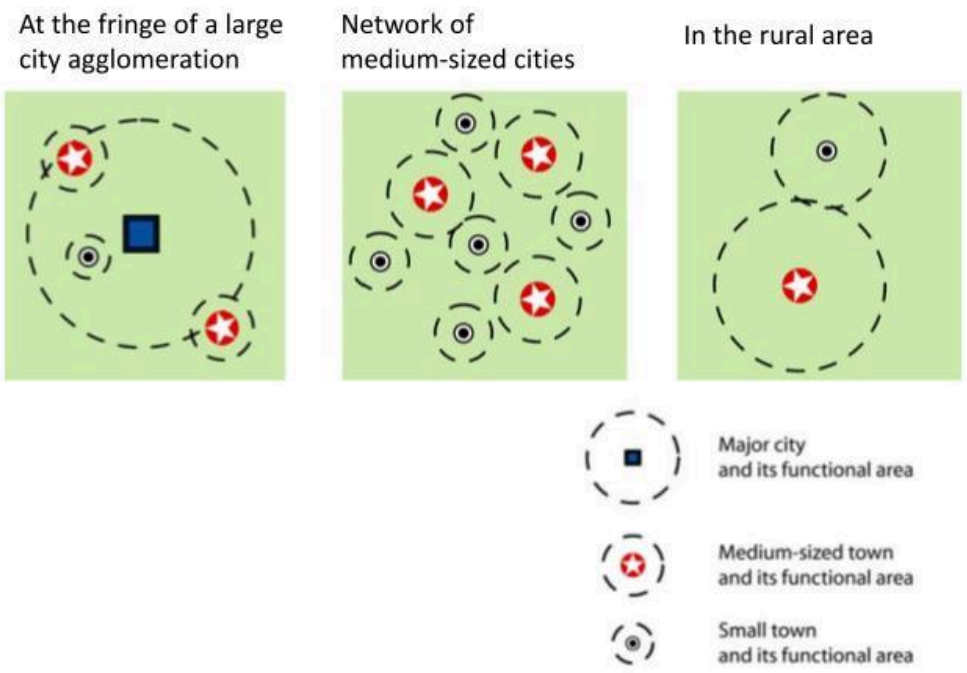


Figure 42. Typologies of medium-sized cities as defined by Kunzmann (2000, 2010). Source: SMESTO, 2005

The significant differences between the position of medium-sized cities in the urban settlement network help frame the variety in urban form, economic function, and demographic pressures, highlighting the role it plays in the urbanisation processes and the challenges they bring. Courtney and Errington (2003) note that growth pole theory in rural development often positions small towns as sub-poles, facilitating regional economic development and stabilising local economies. This is especially relevant for areas where small towns serve as focal points for essential functions, offering services that might not be accessible in larger metropolitan regions. In contrast, medium-sized towns close to large metropolitan areas often act as satellites, drawing residents who seek affordable housing within commuting distance of larger job markets. An observation of similar dependency was done in a study by Liu et al. (2022) in China, which identified different models based on the hierarchy and influence of nearby urban centres. The location within the urban network shapes their role in ways that differ markedly from their rural counterparts as they become integrated into the metropolitan labour market and regional economy. These typological differences are critical to consider when planning urban renewal strategies targeted to manage urban shrinkage in medium-sized urban areas.

5.4.1. Compact and dense cities

In Poland, most medium-sized cities located in metropolitan cities' functional urban areas (FUAs) areas—Ząbki and Legionowo near Warsaw and Rumia and Wejcherowo near Tricity—are growing and dense (see Figure 43). However, not all growing cities in a metropolitan hub's FUAs are dense.

For example, Wieliczka, near Kraków (see Figure 44), is characterised by strong growth accompanied by sprawling, low-density development patterns.

In cities like Sopot in northern Poland, a dense, compact urban form is maintained despite difficulties attracting new residents and investment. Similarly, despite shrinkage, the compact and dense Bartoszyce, Brzeg and Giżycko show high compactness and density, suggesting that the position of a city in the urban settlement network must be considered when analysing relationships between socio-economic and physical patterns.

Ząbki (see Figure 43), Piastów and Pruszków remain dense extensions of the growing capital city. Angel et al. (2020) describes the phenomenon of cities expanding by merging with nearby settlements. These satellite cities, often part of the metropolitan city, increase in density as they have no expansion areas. Ząbki is constrained by the forest, and Rumia (see Figure 44) by topography. Otherwise, they would have been merged entirely by the large urban agglomeration.

Słupsk (see Figure 45) is a historically important city that is currently shrinking due to demographic losses. Located on the Baltic coast, Sopot is far from other large cities. Its shrinkage is not associated with dispersion trends. Xu et al. (2020) emphasise that the historical development patterns of cities significantly shape their current densities. Their study on the 200 cities globally revealed that cities that developed historically as dense urban centres are likely to retain these characteristics, even if they face challenges of population decline and limited investment.

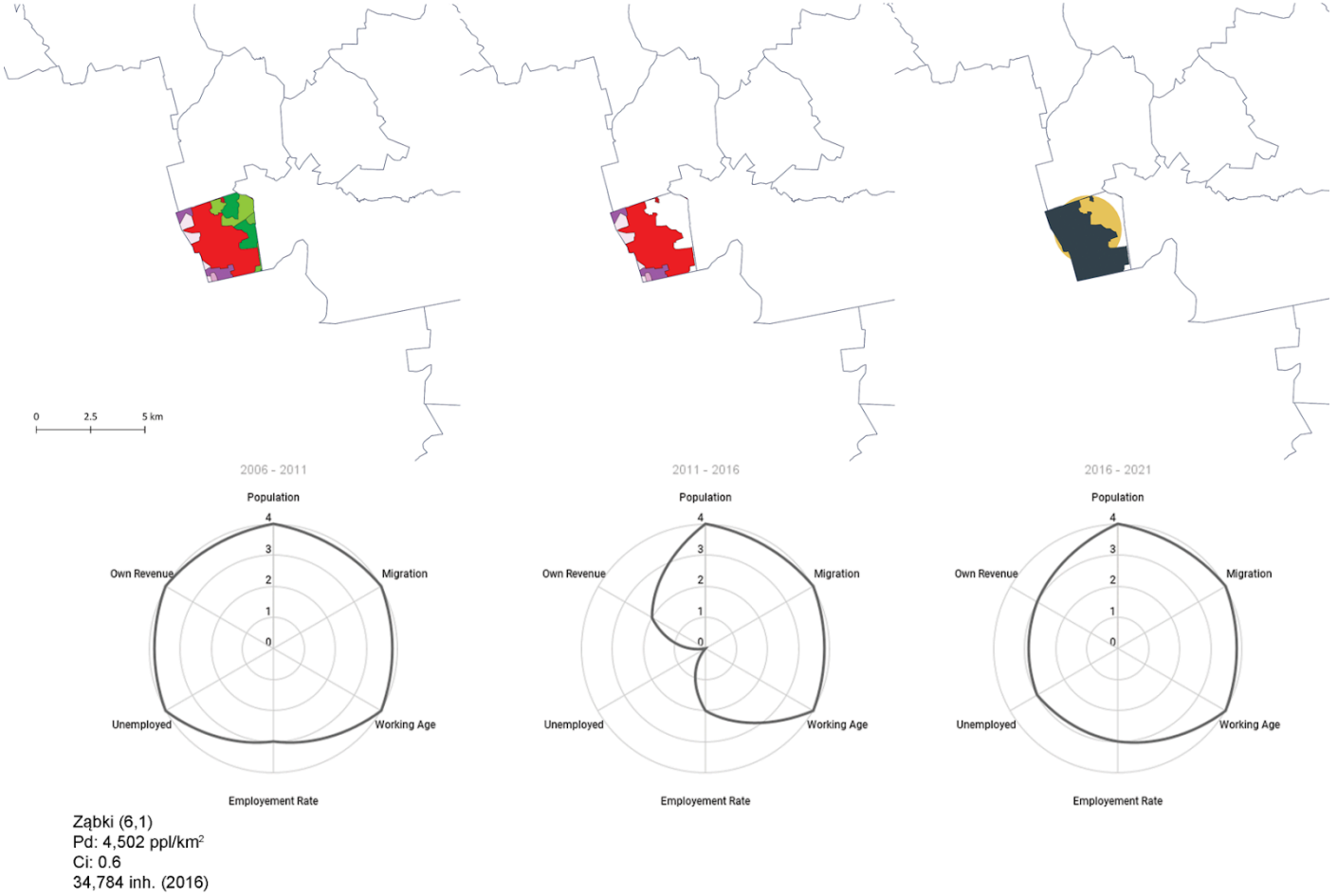


Figure 43. Ząbki - selected medium-sized dense and compact city. A municipality land use (left), urban areas (middle) and merged areas with a circle the size of an urban area (right). Below are the outcomes of growth/shrinkage score calculation in three five-year periods. Source: Author based on CLC2018 and Statistics Pol

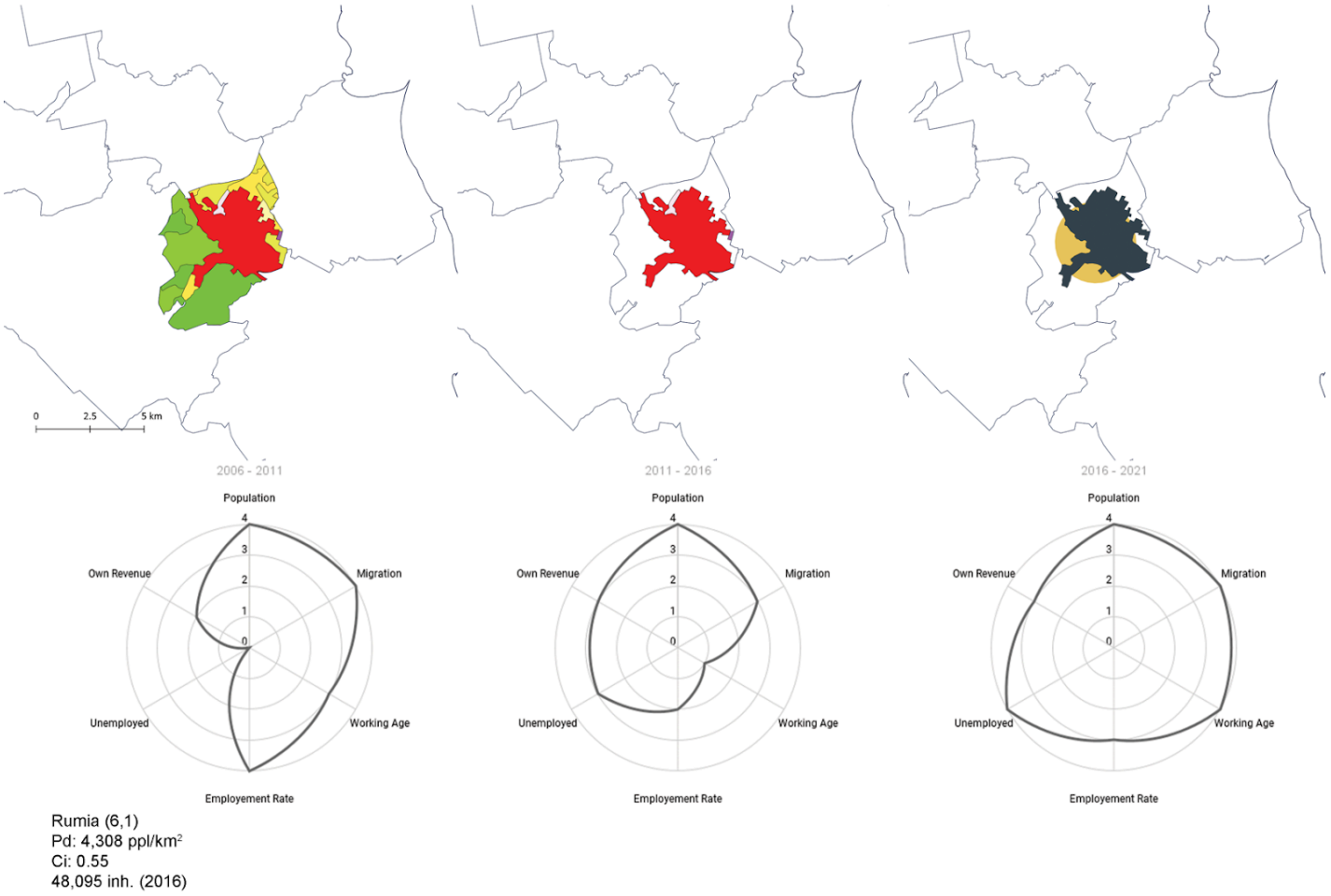


Figure 44. Rumia - selected medium-sized dense and compact city. A municipality land use (left), urban areas (middle) and merged areas with a circle the size of an urban area (right). Below are the outcomes of growth/shrinkage score calculation in three five-year periods. Source: Author based on CLC2018 and Statistics Poland

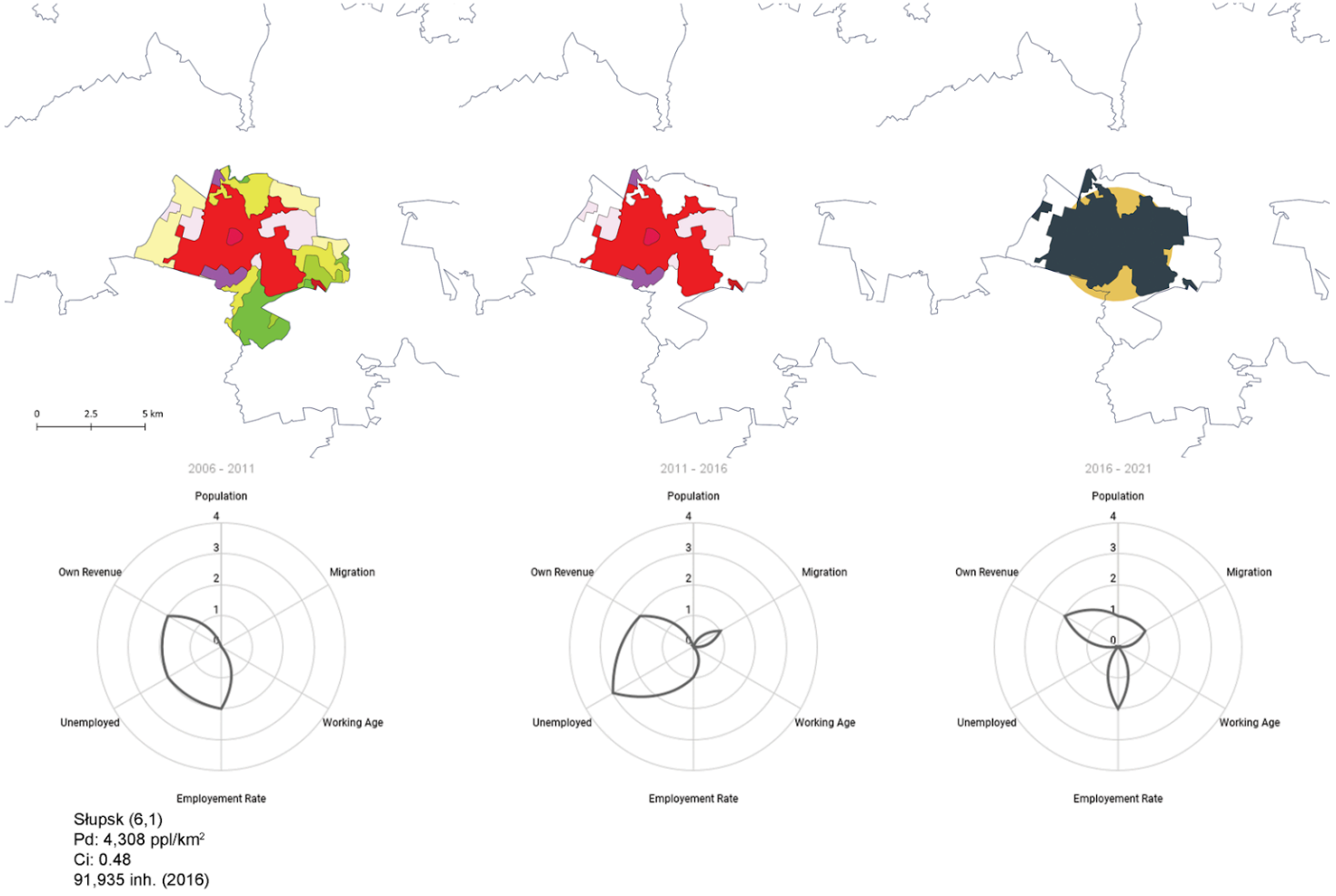


Figure 45. Słupsk - selected medium-sized dense and compact city. A municipality land use (left), urban areas (middle) and merged areas with a circle the size of an urban area (right). Below are the outcomes of growth/shrinkage score calculation in three five-year periods. Source: Author based on CLC2018 and Statistics Poland

5.4.2. Dispersed and low-density cities

An example of Wieliczka (see Figure 46) and Skawina, located in the metropolitan functional area (FUA) of Kraków, shows a sprawling growth pattern. While cities have experienced significant growth driven by their proximity to a large job market, it was often accompanied by physical expansion on the greenfields. While Wieliczka's city centre retains a historic, dense urban fabric, much of its new development is characterised by sprawling, low-density patterns across varied topography. Moreover, this municipality is surrounded by villages and small towns contributing to a more dispersed shape in this calculation.

Czechowice-Dziedzice (see Figure 47) is a municipality located in the close vicinity of a large Bielsko-Biała, a local growth pole. It is characterised by low density. For comparison, Rumia (Figure 44) has a bigger population and a significantly smaller urban area size (see a yellow circle size). Low density can be associated with historical development patterns. At the beginning of the 20th century, Czechowice and Dziedzice were two separate villages. The city was formally founded in the '50s, but its structures reflect its polycentric and dispersed village origins. The city struggled in the last period with low economic indicators, but its proximity to Bielsko-Biała could potentially change this in future.

Orzesze (see Figure 48) performs strongly in demographic indicators, but it lacks economic balance. This trend is common for Upper Silesian agglomerations, with many small and medium-sized cities experiencing challenges of post-mining transformation. Such urban systems require a holistic approach allowing them to grasp all urban complexities.

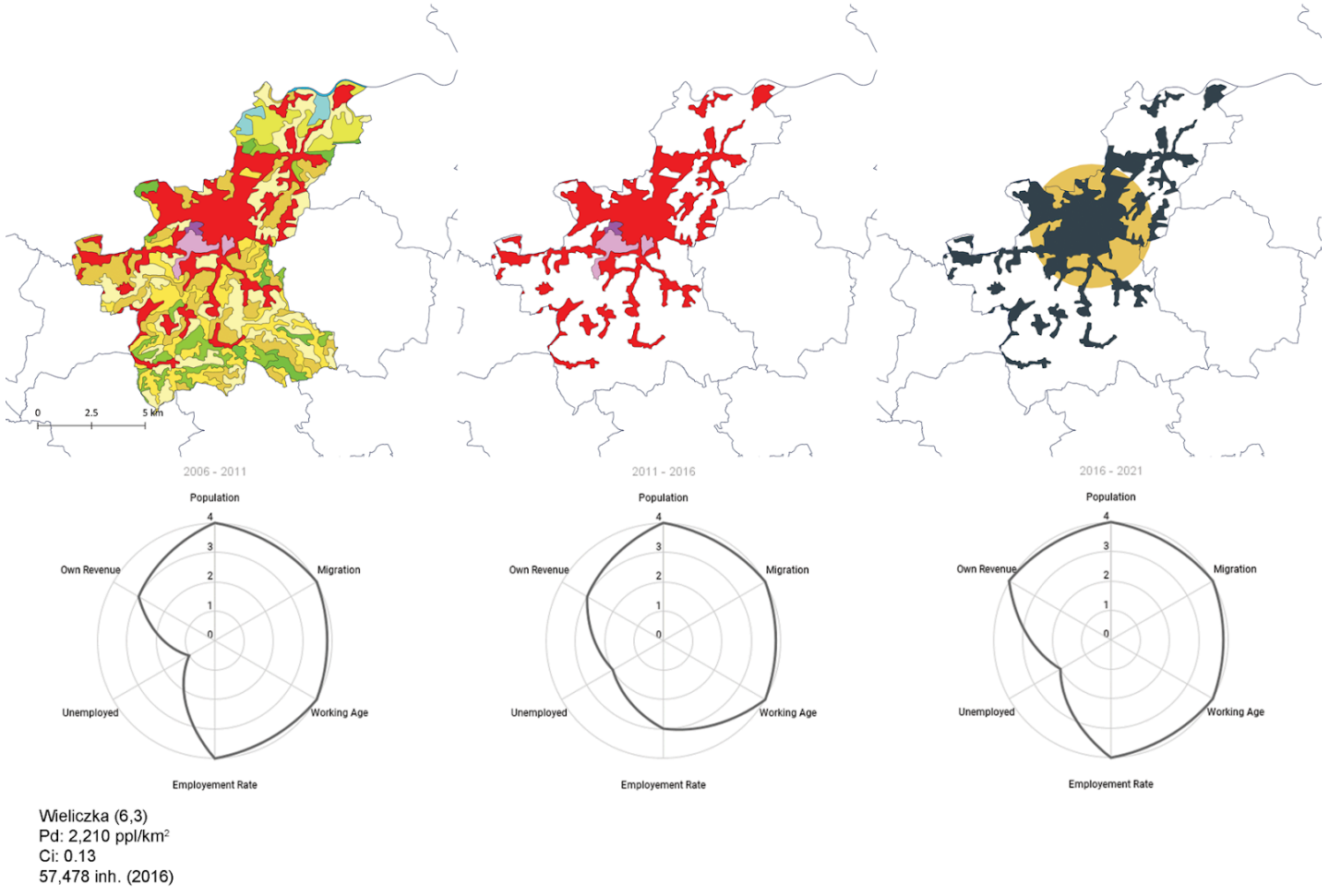


Figure 46. Wieliczka - selected medium-sized, dispersed, low-density city. A municipality land use (left), urban areas (middle) and merged areas with a circle the size of an urban area (right). Below are the outcomes of growth/shrinkage score calculation in three five-year periods. Source: Author based on CLC2018 and Statistics Poland

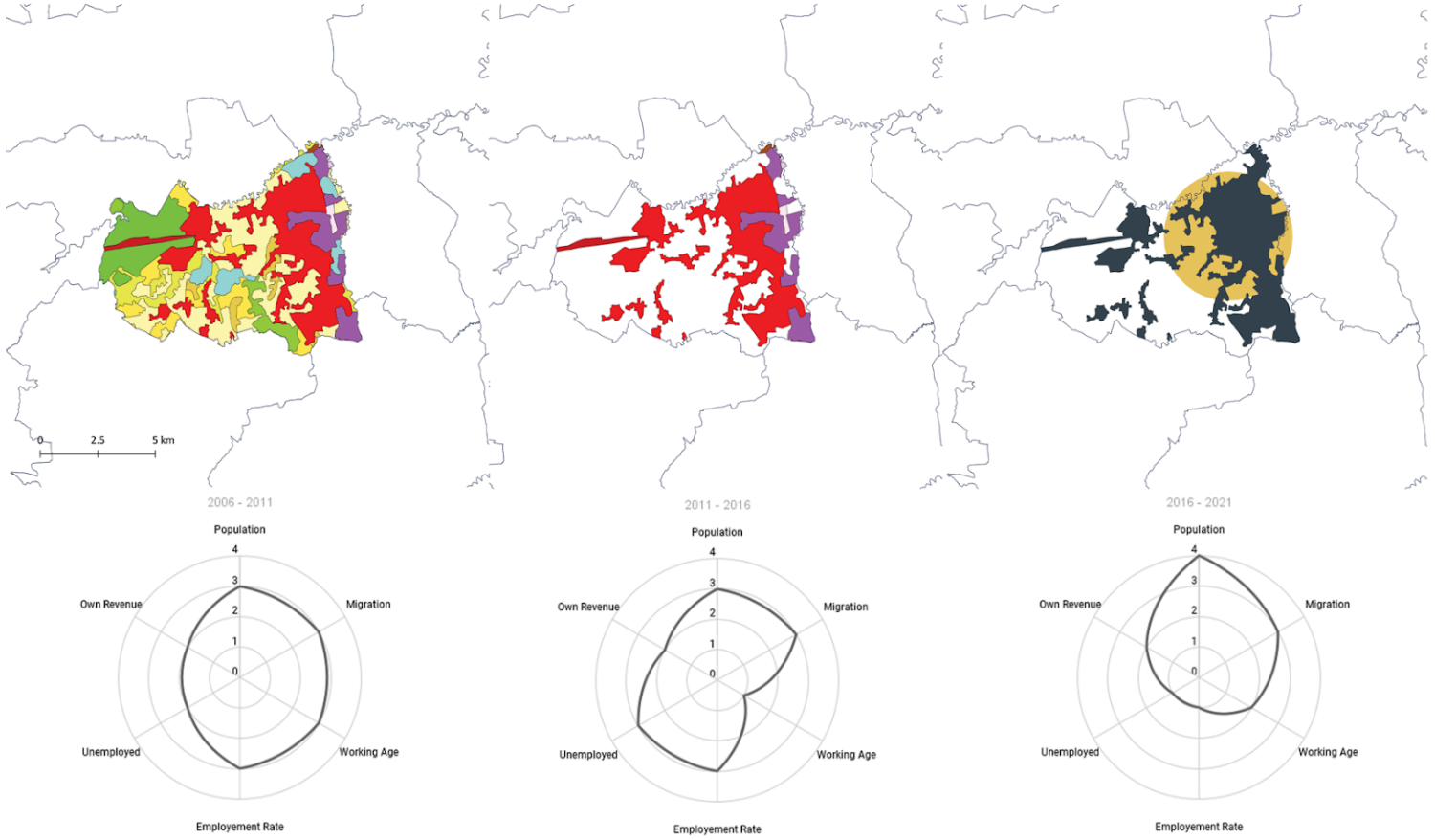


Figure 47. Czechowice-Dziedzice - selected medium-sized, dispersed, low-density city. A municipality land use (left), urban areas (middle) and merged areas with a circle the size of an urban area (right). Below are the outcomes of growth/shrinkage score calculation in three five-year periods. Source: Author based on CLC2018 and Statistics Poland

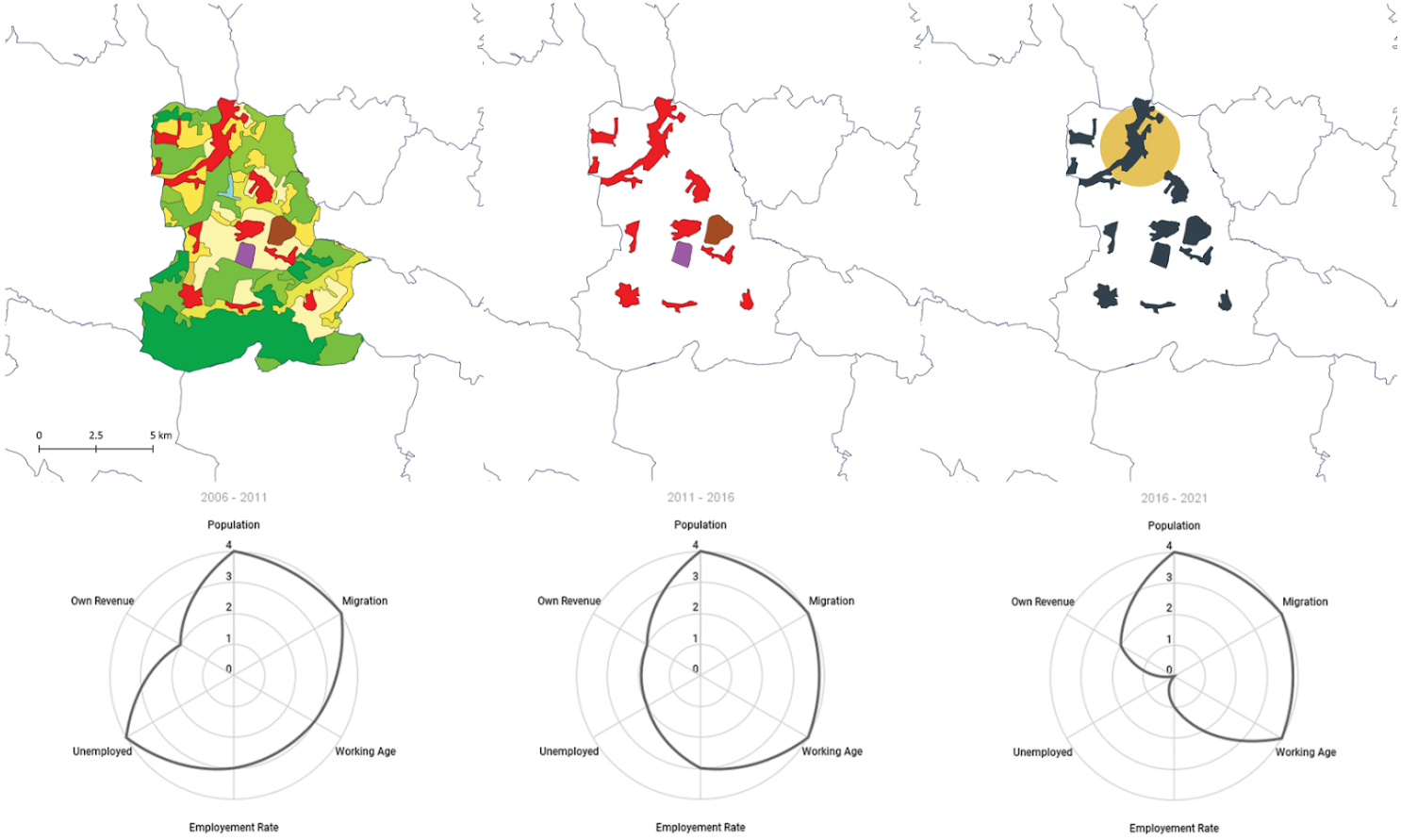


Figure 48. Orzesze - selected medium-sized, dispersed, low-density city. A municipality land use (left), urban areas (middle) and merged areas with a circle the size of an urban area (right). Below are the outcomes of growth/shrinkage score calculation in three five-year periods. Source: Author based on CLC2018 and Statistics Poland

5.5. Planning Implications

While it is not evident to pinpoint the relationship dynamics between urbanisation physical patterns and urban shrinkage among medium-sized cities, this research shows an intensifying trend of urban density loss and increase in urban shrinkage. Schiller and Kenworthy (2018) highlight the crucial role of urban density in promoting sustainable, transit-oriented cities that support walking and cycling. In Poland, Lytyński (2016) revealed that areas with lower population densities tend to have lower GDP, indicating a potential economic disadvantage for low-density municipalities. Additionally, Dong et al. (2019) research evidence that cities rarely shift from dispersed to compact forms. Given the dispersion trend in Poland presented in this research, reversing it will be challenging or impossible. Thus, containing dispersed development should be a key policy for all medium-sized cities.

In shrinking cities, reduced housing demand and lower housing costs could be an opportunity to stop sprawl by focusing on urban renewal of inner-city areas, which could, in turn, attract residents back to the urban core and help maintain or even increase density. Planning strategies should thus encourage this shift by investing in public transport, improving walking and cycling infrastructure, and enhancing public spaces, green areas, and social facilities (Schwaab, 2022). Reurbanization policies should target brownfields, former industrial sites, vacant lots, and oversized road infrastructure rather than undeveloped green spaces.

Newman et al. (2016) examined the distinct “urban fabrics” in cities, such as walking-oriented, public transit-oriented, and car-dependent areas. Their research traces how traditional walking and transit-based urban structures — common from the 1800s to the mid-20th century — have been disrupted by car-centric urban designs prioritising extensive road systems, parking areas, and single-family housing that encourage sprawl. They advocate for re-urbanizing these traditional areas, such as reclaiming roadways and parking lots for public spaces or residential projects and creating transit-oriented developments (TOD) near rail stations. They also advise limiting new car-dependent development. For shrinking cities, such measures could foster stable, sustainable economic growth by reducing excessive infrastructure (Schiller and Siedentorp, 2008) and car travel costs, enhancing the city's resilience (Newman and Kenworthy, 1999, 2015).

By containing urban dispersion and protecting surrounding green areas from development, cities can help reduce the urban heat island effect and optimise resource allocation to existing infrastructure rather than continuous outward expansion (Schwaab, 2022). This approach also supports a vibrant urban life and efficient asset management. Notably, cities often experience uneven patterns of growth and shrinkage (Kazimierczak and Szafrańska, 2019; Hollander et al.,

2019), making it essential for local governments to monitor these patterns closely and address emerging issues proactively.

Future national and regional policies on spatial planning, infrastructure and real estate must utilise parameters and instruments that focus on the driving forces of greenfield development. Demand-driven land consumption can predominantly be controlled with new planning instruments that aim at dense and compact urban forms and ensure that environmental norms are considered. This can be achieved with the following new planning instruments (Ustawa z dnia 7 lipca 2023 r., Dz.U. 2023, poz. 1688):

Instrument	*Use*	*Urban shrinkage planning goal*
General Plans (orig. Plan ogólny)	Parameters for allowed development based on the demographic forecast. Infill zones in the inner city.	Setting maximum development capacities in city and district plans. Constraints on areas of investment.
Municipality Development Strategy (orig. Strategia rozwoju gminy)	Strategy specifying trajectories and goals for future development.	Setting strict controlling mechanisms on local development, limiting suburbanisation by focusing on quality urban spaces in the inner city.
Zoning in General Plans (orig. Strefy planistyczne)	13 land uses each with specific parameters on building density and green areas provision	Defining minimum densities for new developments, providing parameters for green public spaces, and marking clear urban-rural boundaries.
Integrated Investment Plan (orig. Zintegrowany plan inwestycyjny)	Defining special investment zones with specific rules (depending on the local municipality's agreement with investors).	Setting price controls (tax, responsibilities) for settlement and building forms that use land extensively.
Participatory planning, Urban Register	Setting standards for transparency and inclusion in decision-making.	Making sure the decisions are made transparently and in a participatory approach, including all stakeholders.
-	No specific instrument exists.	Setting obligatory contributions to the costs of infrastructure to discourage expansion.

However, decisions on the exact shape of listed planning instruments depend on local municipalities and their ability to assess the risk that land-consuming developments pose to the city's future in the face of demographic decline.

The findings of this dissertation underscore the importance of an integrative analysis of urban shrinkage and urban form measures for achieving a more accurate understanding of the different realities of medium-sized cities. While there is no “one-size-fits-all” approach, the observations pave the way for formulating urban strategies designed to address urban shrinkage in a

contextualised way and promote development without spatial growth. it is crucial to recognise diverse developmental pathways and tailored plans that consider each city's historical evolution, position in the settlement hierarchy, urban form, and environmental context. Considering the obligation to design new General plans until the end of 2025, medium-sized cities can benefit from rethinking their current development strategies towards a more compact and resilient urban form.

5.6. Research limitations

This study acknowledges several limitations, suggesting pathways for future refinement and deeper analysis. First, the trends observed across this extensive sample of medium-sized Polish cities may be influenced by factors that interact in complex and locally specific ways. A comprehensive understanding of these dynamics would require in-depth local analyses and qualitative insights beyond the present study's scope. Methodological variations in measuring "urban compactness" and "urban density" also impact the observed correlations, as different data collection methods and definitions can yield varying outcomes. Although this research employs two approaches using Corine Land Cover (CLC) classifications to define urban areas, this method could be overly generalised. More precise results on urban density might require refined methods, such as population and urban land area data drawn from local statistical sources. However, gathering such detailed data for hundreds of cities would demand substantial time and resources, making it impractical within the scope of this study.

Further, there are potential data accuracy risks, particularly concerning census data in Poland. For example, population distribution data could be improved to address discrepancies between registered and actual residential addresses, especially among younger, mobile individuals who may not update their official addresses (there is no obligation in Poland to update home addresses). Such discrepancies can lead to overestimating populations in medium-sized cities, as younger age groups are more likely to migrate to larger centres for employment, education, and social opportunities.

While the approach presented here enables a broad, country-wide spatial analysis, it has limitations when applied to specific topographical contexts. Natural features such as hills or bodies of water can shape city boundaries in ways that affect the compactness index and urban density measures, potentially distorting results. This is especially relevant in cities where topographical constraints influence urban form. Consequently, caution is warranted when applying these metrics to such cases. Moreover, a broader approach to defining a city could bring different results. This study uses a combination of urban areas defined by land use and administrative borders. Such an approach does not show the sprawl in the neighbouring municipalities. Thus, applying a concept of functional urban areas could expose this phenomenon more accurately.

It should also be noted that while this approach is adequate for national-scale research, it lacks the granularity needed for more focused urban studies. There are discrepancies between CLC-defined land classes and actual land use patterns. For example, as highlighted by Śleszyński et al. (2020), the classification of urbanised areas sometimes diverges from on-the-ground land use realities. Although this method aligns with existing literature, it would benefit from integrating a broader range of compactness measures. Addressing these limitations could involve exploring alternative data sources and refining methodologies to minimise these discrepancies, offering a more nuanced picture of urban compactness and density in future research.

5.7. Suggestions for further research

This dissertation highlights various avenues for future research on urban shrinkage and compactness, particularly concerning medium-sized cities. While the current study has provided insights into urban density, shrinkage, and compactness patterns, further exploration is necessary to address the nuanced factors influencing these trends. This section outlines key areas for further investigation, emphasising capturing the spatial, socio-economic, and morphological dimensions of shrinking cities.

Compactness measures

The current study does not account for the nuanced impacts of topography on urban compactness. However, topographical settings may be critical in shaping urban form. Future research could employ qualitative methods to explore how factors like elevation, landscape type, and physical barriers influence population distribution, density, and urban sprawl in medium-sized cities. Examining cities within specific topographical contexts, such as coastal areas, valleys, or mountainous regions, could show how geographical features interact with urban dynamics. This line of inquiry may reveal localised patterns of shrinkage and growth, which can be instrumental for place-sensitive planning strategies. The observed discrepancies in urban population densities across medium-sized cities suggest a need for further research to explore the causes and implications of these variations. Future studies could conduct a more granular population density analysis by dissecting its distribution within inner-city districts. This approach could provide a clearer understanding of the spatial implications of shrinkage in inner-city areas versus suburban zones. Additionally, exploring these differences nationally could yield insights into the relationship between density and urban resilience, offering guidelines for enhancing city centres and containing sprawl in shrinking municipalities.

Functional aspects of compactness

Future research could adopt a functional lens to deepen understanding urban compactness. Researchers can gain a more dynamic view of compactness by examining how urban activities are spatially distributed, including factors like IoT data and nighttime patterns. Functional compactness may reveal areas of activity concentration, mobility patterns, and areas with underutilised potential. This approach could better illustrate how certain neighbourhoods within shrinking cities may still function as hubs, maintaining compact and lively urban life. Further investigation could involve comparing daytime and nighttime urban activity, offering insights into the vitality of different urban areas and informing interventions for enhancing local activity.

Morphological aspects of compactness

Future studies could also investigate morphological and urban quality characteristics, including building density, typology, floor area ratio, street connectivity, and urban expansion patterns, to enrich the concept of compactness of urban form. These characteristics influence urban areas' spatial efficiency and vibrancy and studying them in detail could help identify urban form elements that support compactness and resilience. Research that tracks these morphological elements over time would help understand the evolution of urban form in response to shrinkage, offering insights into which patterns promote or inhibit sustainable urban structures.

Context-specific studies

Socio-economic and cultural dimensions significantly impact the experience and implications of urban shrinkage, and examining these attributes could provide a more holistic view of the phenomenon. Future research could investigate the socio-economic conditions of shrinking cities, such as employment rates, housing affordability, and educational opportunities, which may reveal specific factors driving population decline. Additionally, exploring the cultural identity of these cities — particularly those with historical significance or unique local traditions — could uncover resilience factors and barriers. This analysis would enable a more comprehensive understanding of which areas face the most significant challenges and the root causes of urban decline, guiding targeted interventions.

Comparative studies

Given the unique development trajectories of cities within different countries, future studies could adopt a comparative approach by examining urban shrinkage across multiple national contexts. Comparative research that juxtaposes medium-sized cities in Poland with those in other European countries, for instance, could identify shared patterns and distinct drivers of shrinkage. Additionally, examining a broader range of city sizes — from small towns to large metropolitan areas — may reveal size-dependent patterns and adaptive strategies. This approach could also contribute to the

growing discourse on de-growth governance by offering cross-cultural perspectives on managing decline sustainably.

Longitudinal studies

A longer observational time frame could provide valuable insights into the long-term impacts of shrinkage and compactness on urban areas. Extending the study period would allow researchers to capture slower-moving processes, such as the effects of urban renewal policies, infrastructure investments, and demographic shifts. Furthermore, evaluating the outcomes of new planning regulations or specific urban renewal programs could offer empirical evidence on the effectiveness of planning interventions. By focusing on programs targeting brownfields, industrial zones, and road reclamation, such research could inform future policies to foster resilience in shrinking cities.

Typologies of medium-sized cities

Following Kunzmann's typology (1992, 2000, 2010), future research could analyse cities within categories based on their role within urban networks. This categorisation could include cities within metropolitan regions, those on the border or between metropolitan areas, and those on Europe's periphery. Additionally, cities can be analysed regarding their socio-economic positioning, as noted in studies by Runge (2012), which classified Polish medium-sized cities socio-economically over several decades. By segmenting cities based on their regional and network roles, researchers can better understand the interdependencies and unique challenges each type of city faces.

6. Conclusions

This research presents a comprehensive, interdisciplinary approach to analysing urban shrinkage from an urban planning perspective. Given that planning operates primarily within the physical realm, this study links spatial factors with social and economic dynamics, capturing the city both as a "physical place" and as "a mentality compiled from perceptions, behaviours, and beliefs" (Sennett, 2019, p.1). This is represented by the interdisciplinary approach of this doctoral thesis that links the domain of urban planning, architecture, data science and geography using contemporary GIS and analytical tools, enabling a multifaceted exploration of urban shrinkage.

This study first examined urban shrinkage trends across Poland from 2006 to 2021. Using a multi-criteria indicator analysis adapted from the German Federal Institute for Research on Building, Urban Affairs and Spatial Development (BBSR) provided a relative measure of urban shrinkage and growth based on a broad socio-economic definition. When adapted to Polish statistical data, this method revealed an increasing trend in urban shrinkage over the analysed period, affecting a growing number of predominantly medium-sized cities. Spatially, this shrinkage was concentrated on the peripheries of metropolitan areas, exposing a trend of metropolisation and polarisation in urbanisation processes.

Secondly, the research analysed urban compactness in Poland, examining spatial form changes over time across all Polish municipalities using compactness measures derived from the Corine Land Cover datasets for 2006, 2012, and 2018. The findings reveal a general decrease in urban compactness over time and a logarithmic relationship between population size, compactness index, and urban population density. While smaller cities tend to exhibit a more compact shape but lower density, larger cities demonstrate higher density alongside greater spatial dispersion. This nuanced understanding of compactness trends informs how urban form varies with city size and population density.

Finally, the study tested a hypothesis concerning the relationship between urban form and shrinkage among medium-sized cities. The data shows a positive correlation for urban municipalities (orig. gmina miejska): less compact urban areas tend to experience more shrinkage. Interestingly, the correlation between population density and shrinkage/growth scores was temporarily negative, shifting to positive from 2016 to 2021 for these urban areas (less dense urban municipalities show more shrinkage). This complexity underscores the dynamic nature of urban shrinkage and its potential links to urban form. Although a straightforward conclusion is elusive, these results reveal key interactions between urban form and shrinkage trends, inviting further exploration into their causal mechanisms.

This research underscores the urgent need for planning which addresses urban shrinkage, especially in medium-sized cities that may lack sufficient resources for sustainable futures. While current planning frameworks are growth-oriented and reliant on developing greenfield sites (NIK, 2022), the new planning reform (Ustawa z dnia 7 lipca 2023 r., Dz.U. 2023, poz. 1688) provides instruments that promote compact urban form and inward-focused growth based on demographic forecasts. This can lead to a shift towards enhanced quality of life, environmental sustainability, and biodiversity in medium-sized cities. Well-connected medium-sized urban centres have a chance to continue supporting rural areas and foster mutual resilience despite their peripheral locations and demographic trends.

While the trends identified in this analysis are subject to change, this study reveals that the path towards dispersion and urban shrinkage is usually one-way. This means that medium-sized cities should protect their compact and dense structure and maintain a stable socio-economic base during demographic decline. Urban planning instruments should be supported with targeted urban renewal programs developed to strengthen local government's capacities, encouraging resilient planning strategies that foster balanced, non-growth-dependent urban development.

This research contributes to a deeper understanding of urban shrinkage in Poland, particularly in medium-sized cities. Examining shrinkage's spatial, social, and economic dimensions laid a foundation for new methodologies and future studies. It informs policymakers, guiding the formulation of strategies tailored to the unique challenges posed by urban shrinkage. The findings advocate for continued, focused research on medium-sized cities, crucial yet often overlooked players in the broader urban landscape.

“Czasami w ten sposób rozpadały się na moich oczach nawet miasta. Domy, ulice, place - wszystko rozwarstwiało się i odklejało od widoku. Dziś myślę, że ona się kurczy. Pierwszy raz poczułem to w Karpaczu. Rozmawiałem z burmistrzem, który pozwolił by jego miasto kompletnie zmarniało. On widział ten proces inaczej. Był z siebie zadowolony, wręcz dumny. (...) Wypowiadał kolejne słowa: inwestorzy, harmonogram, modernizacja, promocja, a ja pod stopami czułem agonalne drgawki Krainy.”

Filip Springer, Mein Gott, jak pięknie, 2023.

"Sometimes, even cities seemed to fall apart before my eyes. Houses, streets, squares—everything would peel away and detach from view. Today, I think it’s shrinking. I first felt it in Karpacz. I was talking to the mayor, who had let his town completely wither. He saw the process differently. He was pleased with himself, even proud. (...) He uttered words like investors, schedule, modernisation, promotion, while I felt the dying tremors of the Land beneath my feet." –

Translated by author from Filip Springer, Mein Gott, jak pięknie, 2023.

7. Attachments

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Identification of shrinking cities in Poland using a multi-criterion indicator

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Abstract. Urban shrinkage, characterised by long-term demographic, socio-economic and spatial changes, has been studied extensively, including via research into causes, typologies, and planning responses. However, while understanding and measuring urban shrinkage processes is crucial if policymakers are to respond adequately to cities' challenges, multi-criterion studies on shrinkage trajectories are still required for the spatiotemporal complexity to be captured correctly. This study reviews methods by which urban shrinkage is studied and concludes with a selection of multi-criterion methods that offer more in-depth insight than population-based methods. Finally, a multicriteria analysis, adapted from Milbert (2015), is applied to measure urban shrinkage in Poland in the years 2006 to 2021. This incorporates six variables with a view to shrinking and growing cities being assessed and assigned to one of five categories.
The research provides insights into Poland's most recent urban shrinkage processes. Results show that, over the analysed period, urban shrinkage was a phenomenon that increased and intensified in Poland, affected a growing number of urban centres of medium size, and was to be noted on the peripheries of metropolitan areas. Such research outcomes contribute to a better understanding of urban shrinkage in Poland, provide a basis for further research, and inform policymakers as they seek to formulate more-targeted strategies to address the specific challenges that urban shrinkage raises.

Keywords: urban shrinkage, multi-criterion indicator, urbanisation trends, urban data analysis, Poland.

Introduction

The contemporary debate on urban population decline emerged in the second half of the 20th century, when urban shrinkage became a common transformation pathway for many large cities across Europe and North America. The term shrinking cities was first used by German researchers Hausermann and Siebel in the 1980s (originally as *Schrumpfende Stadt*) – with a view to a name being given to long-term demographic and economic changes taking place in urban areas of the Ruhr region (Haussermann & Siebel, 1988). Since then, the term has become a frame of reference for a wide range of topics (Haase et al., 2014), gaining wide use in urban-studies research, including within the fields of geography, social economics, urban planning, etc. The concept has been elaborated and reflected on in many research projects, such as COST Action TU 0803 'Cities Regrowing Smaller' (CIRES) and The Shrinking Cities International Research Network (SCiRN), as well as in global publications (Oswalt, 2005; Oswalt & Rieniets, 2007; Pallagst et al., 2009; Martinez-Fernandez et al., 2009, 2012, 2016; Großmann et al., 2013; Haase et al., 2013, 2014, 2021).

However, the challenge lies in defining this urban phenomenon (Bernt et al., 2014; Haase et al., 2014; Kantor-Pietraga, 2014; Sroka, 2022). Most research has been linked broadly to demographic aspects of shrinkage, with population change being the main indicator. CIRES, for example, defines shrinkage as a depopulation of more than 0.15% each year in a period of a minimum of five years. In contrast, Turok and Mykhnenko (2007) refer to it as a loss in population within consecutive five-year periods. Additionally, a population change relative to the national population was included to illustrate shrinkage in the country. However, researchers offer broad acknowledgment that urban shrinkage surpasses simple population decline and cannot be analysed adequately using a single indicator (Haase et al., 2013; Stryjakiewicz, 2014a). As noted by Wolff and Wiechmann (2014): "*there are many examples where the demographic and the economic development do not go hand in hand. Cities losing population can keep a strong economic structure and development*" (Wolff and Wiechmann, 2014, p. 1). Against this background, SCIRN has developed a definition that includes, aside from population loss, signs of economic transformation with some symptoms of a structural crisis (Bern, 2018). This approach implies that a variety of economic and social indicators should be considered when identifying shrinking cities.

However, a meta-analysis of the literature on urban shrinkage conducted by Döringer et al. (2019) indicates that it is rare for urban-studies research to explore multiple indicators. They found no universal definition of 'urban shrinkage', while: "*Two-thirds of the given definitions focus on population decline as the major dynamic. One-quarter of the articles also mention the dimension of economic decline. In contrast, multidimensional definitions are barely used*" (Döringer et al., 2019, p. 6). Moreover, research that grasps many dimensions of urban shrinkage is usually conducted as a case study (Döringer et al., 2019). Conversely, multi-criterion investigations are rarely shown in nationwide analyses as they pose a major challenge given the robustness and availability of data. Thus, with the different spatiotemporal aspects, trajectories and contexts of urban shrinkage being as they are, capturing it poses a challenge for theoretical and empirical studies (Haase et al., 2017). These are the reasons for the present article seeking to address this identified gap and focus on the methodological aspects of encapsulating the phenomenon of urban shrinkage in a broader, multi-criterion manner and on a national scale.

In contemporary Poland, urban shrinkage became apparent in the early 2000s, when the first symptoms of the economic 'shock therapy' became visible. Thus, while urban demographics were a common subject of Polish research over a number of decades, the first diagnosis under the heading of urban shrinkage was arrived at by Zborowski (2002), Parysek (2004) and Jędraszko (2005). As mentioned above, broader comparative studies then followed, with the above topic representing an element of international research incorporated into such projects as *CIRES* and *Shrink Smart* (Krzysztofik et al., 2011, 2012a; EU, 2023), in the period between 1990 and 2010. Furthermore, identification and analysis vis-à-vis Poland's shrinking cities was engaged in by Krzysztofik and Szmytkie (2011), Krzysztofik et al. (2011, 2012, 2014), Stryjakiewicz et al. (2012a, b), Zborowski et al. (2012), Stryjakiewicz et al. (2014, 2016), Kantor-Pietraga (2014), Jaroszewska (2019), Sroka (2021), Śleszyński (2017, 2019), and Musiał-Małago (2018a, b).

And notwithstanding recent influxes of migrants (notably from war-torn Ukraine), the forecasts for Poland's demographic future remain alarming. The most recent estimates in population predictions from *Statistics Poland* (GUS, 2023) still have the country

in an ongoing population decline, in cities in particular. The prediction for the rate of decline in some medium-sized cities is one of the estimates achieving the highest value (GUS, 2023). However, the up-to-date predictions are based on population statistics alone, thus failing to offer any more comprehensive or insightful understanding of the situation.

The research detailed here has proceeded on the assumption that urban-policy responses to processes of urban shrinkage (whether at state, regional or local levels) should be grounded in a more-nuanced assessment of the present circumstances. In line with the definition of urban shrinkage as a multifaceted phenomenon, a complementary study and prediction with a multi-factor approach would allow for a more-comprehensive picture of shrinkage processes. Consequently, future policy responses could consider the broader factors contributing to depopulation, with a crucial emphasis on understanding the dynamics of this phenomenon. This study, therefore, endeavours to offer a thorough exploration of urban shrinkage while encompassing a temporal perspective of fifteen years (2006-2021) with a spatial focus on cities across the territory of Poland.

Specifically, the two objectives addressed by the paper (one empirical and the other methodological) (Fig. 1) are guided by questions as follows:

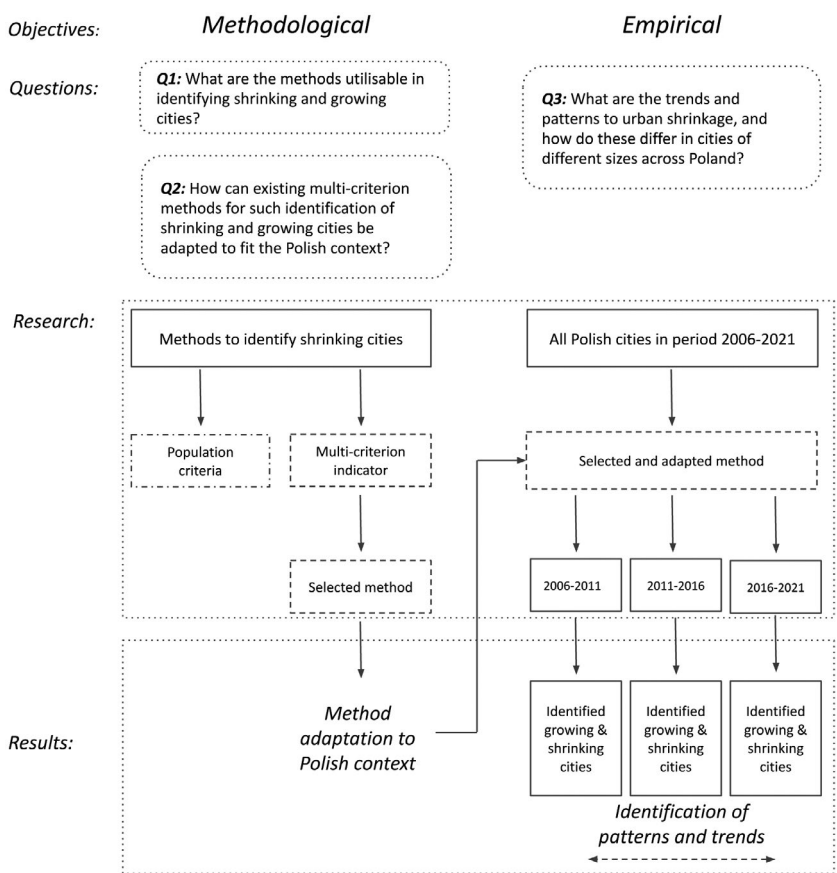

Fig. 1. Structure of research stages

Q1: What are the methods utilisable in identifying shrinking and growing cities?
Q2: How can existing multi-criterion methods for such identification of shrinking and growing cities be adapted to fit the Polish context?
Q3: What are the trends and patterns to urban shrinkage, and how do these differ in cities of different sizes across Poland?

In striving to answer these questions, our study focused on three key outcomes. Firstly, Section 2 provides a review of selected methods used in diagnosing and classifying urban shrinkage – above all with a view to a most suitable multi-criterion method being selected. Section 3 then seeks to present and explain methods used to conduct an empirical study of Polish cities through the years 2006-2021 inclusive. Section 4 then presents the results of the multi-criterion assessment of urban shrinkage actually made. In this way, the most recent statistical and geospatial data will be applied in offering a complete overview of the shrinkage process as it has been affecting today's Poland.

Review of Methods

This chapter presents a literature review of methods used to diagnose and classify the various types of urban shrinkage. It summarises the literature as to how the relevant processes have been defined, elaborates on commonly used variables and classification methodologies and alludes to research gaps remaining within the domain. The review extends to 44 papers in total, with 10 of global scope, 17 relating to Europe and a further 17 seen as explicitly focused on Poland.

Definitions

The first definition of urban shrinkage (*Schumpfungsprozess*) was developed in 1988 by Haussermann and Siebel, and summarised the problem as follows:

"… [it] does not lie in individual developments. Only the interaction of population losses with selective migration of qualified young workers, unsuccessful integration of immigrants, negative economic developments, high unemployment, declining municipal financial leeway, dissolution of the city structure and thinning out of the supply of goods and services results in an urban crisis in which negative developments can intensify into a vicious circle."(Haussermann & Siebel, 1988, p. 10).

The work of Haussermann and Siebel did not aim at quantifying the phenomenon, even as it represented a broad description of causes and effects that paved the way for further studies. Literature aiming to quantify the phenomenon of urban shrinkage can be viewed in at least two fundamental ways (Stryjakiewicz, 2014a). The older and more traditional approach regards this process as a progressive depopulation. However, a decrease in the number of residents does not *per se* equate to the decline of a city, and conceivably might even lead to an improvement in living standards and/or quality of life (Stryjakiewicz, 2014a). On that basis, a second, more multidimensional perspective was developed whereby shrinkage came to be viewed as a process linked to the social, spatial and economic restructuring of urban centres, as accompanied by or accompanying a steady decline in population (Zborowski, 2012).

A review of the methods used to classify urban shrinkage

In the study of the phenomenon of shrinking cities it is population that has been used as the main indicator of city trajectories, partly given the availability of data availability and consistency with previous research. Broadly speaking, all comparative studies have been based predominantly on indicators relating to population (Van den Berg et al., 1982; Cheshire & Hay, 1989; Cheshire, 1995; Turok & Mykhnenko, 2007). Yet, as has been noted already, there are many examples wherein demographic and economic development are not found to correlate. Cities with declining populations can retain strong economic structure and go on developing (Wolff & Wiechmann, 2014). Thus, as Section 2 indicates, there are many socio-economic factors shaping this urban phenomenon that will need to be included as processes of urban shrinkage receive proper study.

The shrinking of cities must therefore be regarded as being or involving a specific kind of interaction between matters of a demographic, social, economic and spatial nature discernible with the aid of indicators. Wolff and Wiechmann (2014) gave a comprehensive description of all potential factors underpinning shrinkage, as grouped in five thematic areas. It is then often the scope of a given study that seems to shape the selection of indicators. Indeed, the availability or comparability of data is a common concern, while the theoretical basis sees demographic and economic indicators treated as most important (Wolff and Wiechmann, 2014). Furthermore, classifications are most often ordered by reference to severity, temporality and speed of shrinkage (Haase et al., 2017). Research on causes of shrinkage is sometimes combined with classifications or typologies. A review of classifications arrived at for urban shrinkage is thus offered below, in Table 1.

Selection of a multi-criterion method

As previously mentioned, there have been only a limited number of studies that use a multi-criterion approach in the evaluation of urban shrinkage. One such study, conducted by Jaroszewska in 2019, focused solely on two specific years – 2003 and 2013. Another analysis, inspired by the Milbert method and undertaken by Sroka, spanned a 23-year period from 1995 to 2018. Finally, Śleszyński developed a multi-criterion assessment that covered two distinct 10-year periods – 2004 to 2014 and 2008 to 2018 – as documented in studies from 2017 and 2019.

We decided to focus on the method developed by Milbert (2015) from the Federal Office for Building and Regional Planning (later called *BBSR*) in Germany. According to research conducted by the *BBSR* in the years 1997-2001, a steep growth in shrinkage processes was most prominent among medium-sized cities in East Germany (Gatzweiler et al., 2003; Gatzweiler & Milbert, 2009). Consequently, the German government decided to step in and implement a bespoke urban-renewal strategy to stem further decline. The strategy included the Stadtumbau Ost Programme and the complementary IBA Saxony-Anhalt 2010 Programme and was oriented towards selected medium-sized cities facing the highest rates of urban shrinkage. Projects were implemented in the years 2002-2017, allowing many cities in eastern German states to embark upon a new path of stable de-growth despite the continuous depopulation trends present in the region (Bernt, 2019; Pallagst et al., 2021). The German approach shows that problem identification and monitoring are critical for informed planning but can lead to positive results.

Table 1. A review of selected methods used in the classification of urban shrinkage

Scope	Analysed timeframe	Project name (Source)	Method description	Variables	Proposed classification
World	1950-2000	*Shrinking Cities* (Oswalt & Rieniets 2006; Bernt, 2018)	Subject: Selected world cities over 100,000 inhabitants; Definition: a densely populated urban area, min. 10,000 inh., population losses over large parts for more than 2 years, undergoing economic transformations, with symptoms of structural crisis. Population losses are considered significant if they amount to at least 10% in total or are of more than 1% annually	Population change	Classified shrinking cities
Europe	N/A	*SCIRN* (Wiechmann, 2008; Pallagst, 2009)	Subject: Selected urban centres of over 10,000 inhabitants around the world; Definition: depopulation of 1% or more in a period of 2 years at minimum, or over 10% in the whole period	Population change	N/A
	1990-2010	*CIRES* (Stryjakiewicz 2014a; Stryjakiewicz & Jaroszewska, 2016; Wiechmann & Wolff, 2013)	Subject: 7,035 European cities with over 5,000 inh. – criteria of a minimum of 50% of the population living at an urban density over 1,000 inh./km^2, built-up area covering at least of 50% of an entire municipality; definition: depopulation over a period of 5 years minimum, with more than 0.15% of the population lost each year.	Population change	A division into types: a) permanently shrinking b) short-term shrinking c) episodic shrinking
	1960-2005	Mykhnenko and Turok (2007)	Subject: 310 European cities of 200,000+ inh.; definition: absolute change in population in successive five-year periods (a referencing of change nationally was also included to illustrate shrinkage in the country)	Population change	A division into 3 types: a) recently shrinking b) shrinking over the medium term c) long-term shrinking
World	2000-2015	Urban Audit (Florczyk et al., 2019)	Subject: World Functional Urban Areas (of more than 50,000 inhabitants); definition: annual rate of population changes between 2000 and 2015 at FUA level on the global scale	Population change	5-level classification: a) (∞,-0.50%⟩ b) (-0.50%,-0.15%) c) ⟨-0.15%, 0.15%⟩ d) (0.15%, 0.50%) e) ⟨0.50%, ∞)
Germany	1998-2020 continuously in relation to a division into 5-year periods	BBSR (Milbert, 2015, 2020)	Subject: 4,507 German communes (*Gemeinde*), including those with a city (*Stadt*) status; definition: shrinkage as relative to the situation nationally in respect of 6 demographic and socio-economic variables (for detailed explanation, see Chapter 4)	Average annual population development in %; average annual total migration balance per 1,000 inhabitants; average annual development of the working-age population (20 to 64 years) in %; average annual development of socially-insured employees at the workplace in %; average annual change in the unemployment rate in percentage points; average annual development of the business tax base per inhabitant in %	A division into 5 types: a) above-average growth b) growth c) stability d) shrinkage e) above-average shrinkage

Poland	1990-2010	Jaroszewksa (2019)	Subject: 829 Polish cities (2,948 administrative boundaries of local- (*gmina*- level) units of administration and cities); definition: in line with *CIRES* (see above)	Population change	Classification for the entire period as: a) growing, b) stable c) shrinking for 5-year sub-periods: a) shrinking permanently, b) short-term shrinking, c) episodic shrinking, d) no shrinkage
	2003, 2013	Jaroszewska (2019)	Subject: 279 Polish cities; definition: shrinkage defined by reference to national levels, as regards 10 selected demographic, socio-economic and life-quality variables. Values for two years (2003 and 2013) were compared to create a 9-level typology (A-I), which reflects levels of economic and demographic development	Number of individuals of post-productive age per 100 individuals of working age; natural growth per 1,000 inhabitants; migration balance per 1,000 individuals;% of registered unemployed in the population of working age; employed per 1,000 inhabitants; municipal own revenues per capita; amount of housing allowance paid per capita;% of dwellings equipped with central heating; dwellings per 1,000 inhabitants;% of homes from municipal resources with arrears in housing payments	Division into 9 levels of development: A-D – shows high level of economic and demographic development E – the average level F-I – shows a low level of economic and demographic development
	2004-2014	Śleszynski (2017)	Subject: 913 Polish cities (gmina-level units) enjoying urban or urban-rural status); definition: a multi-criterion method defines medium-sized cities losing their socio-economic functions. It includes a combination of 7 variables analysed over a ten-year period. Each variable is counted as a change relative to the national average over the same period of time	Population changes; forecast population size; changes in numbers unemployed; changes in share of own income within municipal budgets; changes in numbers of nights spent; changes in numbers of economic entities registered; changes in numbers of seats of largest companies. All relative to the average change for the country as a whole during the same period	Classified into 4 levels: a) crisis cities b) cities of declining potential c) stagnating cities d) at risk of marginalisation
	2008-2018	Śleszynski (2019)	As above	As above	As above
	1995-2018	Sroka (2021)	Subject: 853 Polish cities; definition: Inspired by the Milbert method (see above), with different indicators used (6 demographic and socio-economic variables selected), and a specific classification method (instead of quintile, mean and standard deviation proportionality was referred to). Counted for the entire period between 1995-2018	Population changes supplemented by an indicator describing the number of years with a population decrease; average annual net internal migration rate per 1,000 inhabitants; ratio of the population aged 65 and over to the total population; proportion of the population that is of working age; number of private-sector economic entities per 1,000 inhabitants; number of newly constructed dwellings per 1,000 inhabitants	The division into size types (large, medium, and small cities) and shrinkage level for the entire period: a) symptoms of structural crisis b) shrinking
	2000-2016	Musiał-Malago (2018)	Subject: 39 Polish cities (over 100,000 inh.); definition: under the *SCIRN* (*CIRES*) definition, 30/39 had been shrinking for at least 5 years in a row. 30 cities selected as shrinking were then classified using 10 demographic and socio-economic variables	Population change (primarily); population density in cities; proportion of the population of post-productive age; natural growth per 1,000 inhabitants; migration balance per 1,000 inhabitants; deregistration from cities per 1,000 inhabitants; entities registered in the REGON system; employed per 1,000 inhabitants; unemployment rate; number of apartments for which building permits were issued per 10,000 inhabitants; vacant properties per 1,000 dwellings	A division into 4 types of shrinkage: a) moderate-level, b) medium-level, c) strong-level, d) highest level
	2006-2016	Institute of Urban and Regional Development – *IRMiR* (Janas et al., 2019)	Subject: Polish gminas and cities; definition: studies show the relationship of shrinking cities with the surrounding cities, surrounding gminas, and flows between cities and metropolitan areas, migration trends to and from Poland, etc.	Population change; natural growth rate; migration rates; age structure and ageing processes of the population; proportion of the population of pre-productive age; burden on the population by individuals of post-productive age	Shrinkage analysed over a broad spectrum of aspects: a) natural population trends b) age structure 3) internal migrations, 4) external migrations

The Milbert multi-criterion method captures this multidimensionality with a selection of six demographic and socio-economic indicators based on the causal relationship as exemplified by Mayer and Knox (2010). While the *CIRES* methodology is based on the absolute measures defining shrinkage, the multi-criterion method of Milbert (2020) is based on measures relative to statistics for a country as a whole. A correlation and reliability analysis of the selected demographic and socio-economic indicators was conducted for all German municipalities (Gemeinden in German) for the observation periods 1997-2001 and 2003-2008. Cronbach's alpha reliability analysis conducted for 2008-2013 showed satisfactory results in alpha = 0.748 (Milbert, 2015). Moreover, the choice of indicators was selected in line with the availability of statistical information at the municipality level.

Milbert (2015) chose to focus on the encapsulation of short-term, current processes through study in relation to five-year periods. To track longer-term or structurally consolidating tendencies of growth or shrinkage, repeated short-term measures were taken. A follow-up analysis in 2009 (Gatzweiler & Milbert, 2009) confirmed the phases to the urbanisation trend and the effectiveness of shifting the constant time window instead of extending the period. This approach is favoured since it allows for better observation of the natural alternation of growth and shrinkage phases, over a sequence of several time windows.

It remains to be clarified whether decreases or increases in the individual six indicators should be viewed in absolute or in relative terms. In his research, Sroka (2021) modified the quintal division of each indicator into a division using mean and standard deviation. However, Milbert justifies the use of quintal division with the distribution of measures in five years representative of phases with economic peaks and drops. In such phases, the outer quintile (20%) can hardly be determined via clearly positive or negative developments. Therefore, all indicators are 'adjusted cyclically', i.e., corrected for the nationwide trend. Growth and shrinkage are then nothing more or less than a relatively more favourable or more negative development of cities and communities as compared with the national trend (Milbert, 2015, 2020).

Methodology

In line with our review of methods as documented in the previous section, we concluded that a classification of urban shrinkage in general, and ours for Poland in particular, had to be based on a multi-criterion approach, a timeframe divided into five-year periods, with calculation in relation to all nationally available spatial units and a maximum number of Polish cities covered (GUS, 2023; Geoportal, 2023). On that basis, the original method developed by Milbert (2003, 2015, 2020) was adapted to the Polish territorial division and statistical data in a manner made clear below in further parts of this paper. An overview of the socio-economic processes and patterns in the entire country's settlement network produced selected statistical data for each municipality area (*gmina* in Polish), with these then used to develop a five-level typology ranging from growing to shrinking cities.

Subjects

Poland's administrative system features the provincial/regional voivodship (*województwo*), the unit at county level (*powiat*), which can include individual cities, and the unit

at local-authority level (*gmina*). GUS data are fragmented and did not allow us to conduct a sound analysis based on individual-city data without omitting a portion of those for which data were not available. Indeed, due to far-reaching data fragmentation in the analysed period between 2006 and 2021 at the level of the city (or town) unit (known as *miasto* in Polish), an attempt at such a delimitation was discarded. One solution would be to estimate the missing data using computational methods. We decided to search for more continuous and robust data on a different administrative level. On that basis, given the availability of data, and for reasons of nationwide comparability, our method uses the smallest local-government unit, i.e. the *gmina*, which is on level 6 from the point of view of *Statistics Poland*. That unit is either a city (*miasto*, level 6, kind 1 in GUS), has a city part within an urban-rural municipality (*gmina miejsko-wiejska*, level 6, kind 3 in GUS) or is a rural municipality (*gmina wiejska*, level 6, kind 2 in GUS). In 2021, Poland had 2,477 municipalities: 302 cities, 662 urban-rural and 1,513 rural. For our research we utilised data for all the aforementioned municipality types. During the process of analysis and conclusion-drawing we narrowed the study area to cities represented by urban gminas (kind 1) or those in the urban-rural category (kind 3). We further had to consider the changing number of spatial units into which Poland was divided across different years. To ensure data consistency, we thus selected 964 cities, for which we were able to extract data during the research period. In this way, it was possible to achieve accurate comparison and analysis of our data without any discrepancies.

It is important to mention that the urban-rural gmina (level 6, kind 3) is deemed to consist of a part that is urban (level 6, kind 4) and a part that is rural (level 6, kind 5). However, because not all the datasets were available for both kinds 4 and 5, we used data from the 'parent' municipality to do our research. However, values for the urban part (level 6, kind 4) were used to identify the size type of a city (small, medium, or large). We followed the approach taken by Milbert (2020).

The fundamental criterion for categorising cities by size is naturally their number of inhabitants. When comparing the basic categories, namely the division of urban localities into small, medium-sized or large, certain questions arise regarding the criteria used (Runge, 2012). It is worth mentioning that in public statistics (including the *Demographic Yearbook*) and the subject literature, there are also seven size-classes identified for urban localities. These classes are as follows: below 5,000 inhabitants, 5,000-10,000 inhabitants, 10,000-20,000 inhabitants, 20,000-50,000 inhabitants, 50,000-100,000 inhabitants, 100,000-200,000 inhabitants, and above 200,000 inhabitants. For this research, we followed the simplified division and categorised as follows (after *GUS*): below 20,000 inhabitants – a small city, 20,000-100,000 – medium city, and above 100,000 inhabitants – large city. When analysing urban population data, it is important to establish a consistent reference point for size classification. We opted to base our categories on the beginning of each five-year period, even though populations may fluctuate in size over time. This helped us ensure accuracy and consistency in our analysis.

Research timeframe

There were a few reasons underpinning the selection of a timeframe between 2006 and 2021. Firstly, the selection aimed to capture the most-recent processes of urban shrinkage (data for the year 2022 were still not complete as of 10th July 2023, and employment

statistics were missing for a complete calculation), by reference to three five-year subperiods. Secondly, since shrinkage is a highly dynamic process, its empirical study needs to be located within a particular socio-political and historical context. Due to the significance of spatial changes following Poland's political and economic transformation, as well as in the wake of the May 2004 EU accession, the analysis captures after Poland joined the Union, so as to avoid a before-after comparison. It is worth adding that the absorption of EU funding was not commenced with immediately post-accession. As of the end of 2005, only 4.35% of funding allocated to Poland for the 2004-2006 period had been utilised (Żuber, 2005).

Data

Statistical data used in the analysis were obtained from the database of *Statistics Poland*. Due to the spatial scope, long timeframe, and multiple indicators, the volume of data extended to more than 235,000 data input records (6 variables, for 2,477 municipalities, for each of 15 years). Data manipulation required the use of tools such as *Python* programming language with analytics libraries (*Pandas*, *NumPy*, etc.). Six variables encompassing indicators of a social, demographic, and economic profile were defined after Milbet (2015) (Tab. 2). Equivalents of these factors were searched for among data available in GUS BDL statistics. Most of the variables were straightforward and were equivalent to German ones, though differences in the tax systems and data collected by the German and Polish statistical offices enforced changes as follows, with a view to the methodology being adapted successfully to Polish conditions (see Tab. 2).

Following downloading of the datasets, raw data were extracted and transformed with *Python* scripts, connecting the statistical ID with the spatial ID (called TERYT). Finally, results were loaded to output files – in our case in CSV (comma separated values) format[1]. Each spatial unit was checked in terms of the completeness of data. Due to changes in ad-

Table 2. Variables selection

Original German criteria (Milbert, 2015)	Polish equivalents in GUS BDL data (Author's choice)	Subject ID in GUS	Variable ID in GUS
average annual population development in %	annual average population development in %	'P2137'	72305
average annual total migration balance per 1,000 inhabitants	net migration per 1,000 inhabitants	'P1350'	1365234
average annual development of the working-age population (20 to 64 years) in %	annual average change in working age population in %	'P1342'	152
average annual development of socially insured employees at the workplace in %	annual average change of employed persons in %	'P2172'	54821
average annual change in the unemployment rate in percentage points	annual average change of unemployed persons in % points	'P1944'	10514
average annual development of business tax base per inhabitant in %	annual average change in *gminas* own income per inhabitant in %	'P2622'	76070

Source: Authors based on Milbert (2020).

[1] The detailed research results are available at: https://rcin.org.pl/dlibra/publication/276466

Table 3. Number of city size type in every analysed period

	2006-2011	2011-2016	2016-2021
Large cities	39	39	39
Medium-sized cities	180	184	180
Smal cities	745	741	745

ministrative boundaries, certain units had to be combined/unified to achieve continuity of data. The urban units were classified into one of three size types (under the GUS classification), by reference to the population in the first year of a period. The populations used in the size classification related to the city classified here as the urban gmina (kind 1), or else the urban part within a rural-urban gmina (kind 4).

Statistical and geospatial analysis

Analysis of statistical data was conducted in reference to the three five-year periods: (I) 2006-2011, (II) 2011-2016, and (III) 2016-2021. In the case of most variables, the calculation of the average development was achieved using the geometric mean of changes between years. In the case of the variable 'Unemployment', guidance from Milbert resulted in a different division being used to express the variety of cities and the changes they experienced as regards unemployment (see Milbert, 2020). After these corrections, a summary of the indicators with different units of measurement and a spread of the division into quintiles is made. Based on an assumed normal distribution, the limits of the outer quintiles are always such that the relative distance from extreme values and outliers does not play a role. The affiliation of units to a quintile is translated into points for each indicator. There are 0 points for being below the 1st or lowest quintile, 1 point for being in the range between the 1st and 2nd quintile, 2 points for being in the range between the 2nd and 3rd quintile, 3 points for being in the range between the 3rd and 4th quintile, and 4 points for being above the 4th or top quintile. Thus, the more favourable the developments are and the more often the indicators are in an upper quintile, the higher the overall score. A *gmina* can achieve a maximum of 24 points and a minimum of 0. Obtained results were then assigned to five types of cities:

(A) growing by an above average amount (24-19 points),
(B) growing (18-14 points),
(C) stagnating (13-11 points),
(D) shrinking (10-6 points),
(E) shrinking by an above average amount (5-0 points)

This classification was translated directly from Milbert (2020) and was repeated for each five-year period.

Further statistical analysis of the calculation outcomes includes a box plot of the types, various analyses of geographical distribution (of urban localities that ae large, medium, or small) by type (A-E), charts and tables with average score per city size type, and a summary on population per city size and type. The classifications were then moved to QGIS for visualisation. Additionally full data outcomes are provided in Appendix A.

Results

This section shares the findings of our research conducted on Polish cities from 2006 through to 2021 using our multi-criterion approach adapted from Milbert (2015, 2020). The results are presented for each five-year subperiod and include information on (I) the number and population of urban localities affected by urban shrinkage, (II) the types of cities most affected according to size, and (III) the spatial distribution of shrinking cities. Visual aids such as graphs and charts are included to facilitate understanding of the statistical and geospatial analysis. In addition to the detailed information shared in the previous section, the research also provides a comparative analysis for all the subperiods studied. This reveals spatiotemporal trends and patterns of urban shrinkage with respect to city size.

Urban centres in Poland shrinking or growing in the years 2006-2011

In the analysed period, 53% of Poland's urban population could be considered resident in urban centres that were shrinking. The number of cities affected by such shrinkage (in types D and E combined) is 311 out of a total of 964 under analysis. That means nearly one-third of all Polish cities experiencing shrinkage in the 2006-2011 period.

Cities of more than 100,000 inhabitants were among the centres most affected by shrinkage in 2006-2011, in terms of both number and population size (Fig. 2). Over 61% of the population resident in large urban localities could simultaneously be termed residents of localities of this kind that were shrinking (assigned to types D and E). This further shows that, out of 39 of Poland's largest urban centres at that time, 77% (or 30 cities) were in the shrinking categories. Localities affected most severely by this were: Tarnów and Włocławek (score 4), followed by Bytom, Elbląg, Łódź and Radom (score 5). However, the average score for the large city in the 2006-2011 period was 13.

Likewise, our medium-sized urban centres (of 20,000-100,000 inhabitants) had almost 60% of their total population living in localities that could be classed as shrinking in the 2006-2011 period, though the overall population involved was smaller than in the case of the largest urban centres. Within a total of 180 medium-sized cities in Poland, over half (95) were classified as shrinking. It is worth adding that there were 30 such localities in which the degree of shrinkage could be viewed as strong. Among all the shrinking

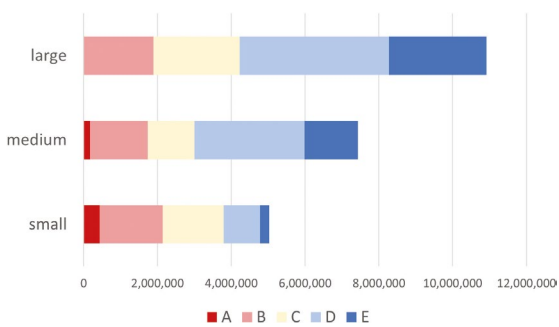

Fig. 2. Urban population in Poland in 2006-2011 period, in line with growth or shrinkage types (A-E), as well as size or urban locality (large, medium, small)
Source: The authors, on the basis of GUS data and their own calculations.

urban centres of medium size it was Konin, Kamienna Góra and Stalowa Wola whose scores were lowest (at 3). These were then followed by Prudnik, Kluczbork, Bartoszyce, Szczytno, Pabianice, Łowicz, Krosno, Jarosław and Przemyśl (score 4), while the average score for a medium-sized city as of 2006-2011 was 13 (meaning the same value as was noted for the group of large urban centres).

In general, the most optimistic situation could be said to characterise the last size group – involving the small urban centres of under 20,000 inhabitants. There, the percentage of cities that were growing was highest (at 45%), while the percentage that were shrinking was lowest. Thus only 24.5% of the inhabitants of localities in this category could be said to live in localities that were shrinking. Nevertheless, since the number of localities qualifying for this size category is large, that still leaves a large absolute number of urban centres in the shrinking category. Among 746 such localities, 39 were undergoing marked shrinkage (type E), while a further 186 were shrinking (type D). Among them was Zdzieszowice (Opole Voivodeship) achieving a 0 score in the period, followed by Ozimek and Żychlin on 2, and Olszyna, Stronie Śląskie, Dobrodzień and Gorzów Śląski all with a score of 3.

Urban centres in Poland shrinking or growing in the years 2011-2016

In the analysed period the percentage of the Polish urban population living in urban localities earning the description "shrinking cities" was greater than before, at 57%. Numbers of cities affected by shrinkage (in either type D or E) jumped from 311 in 2006-2011 to 504 in 2011-2016. That means that over a half of all Poland's urban centres were shrinking as of 2011-2016 – a considerable increase beyond what was noted in the first time period (Fig. 3).

By this period, the type of urban centre most likely to be shrinking was no longer a member of the grouping for the largest centres, but rather involved medium-sized or smaller localities. Indeed, the situation of the 39 Polish cities of the "large urban centre" category was better than before. While, in 2006-2011 these were among the centres most affected by shrinkage, by 2011-2016 only 27 remained in the relevant categories (types D and E), with only 7 experiencing above-average shrinkage. Among the most severely affected were again: Tarnów (score 3), and Włocławek and Bytom (score 4), followed by Zabrze and Sosnowiec (score 5), and Ruda Śląska and Legnica (score 6) which overall shows an in-

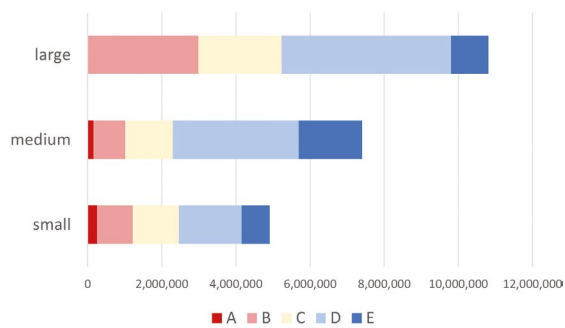

Fig. 3. Urban population in Poland in the 2011-2016 period, as assigned by growth or shrinkage type (A-E), and size of urban locality (large, medium, small)
Source: Authors based on GUS data and own calculations.

crease in score compared with 2006-2011. In this period 51% of the population in these cities overall could be deemed resident in a shrinking centre (assigned to types D and E).

In turn, the medium-sized urban centres then had 69% of their total population living in localities classed as shrinking, suggesting an issue of almost the same magnitude as with the "large" category of locality. Out of a total 184 urban localities of medium size, 119 could be classified as shrinking, i.e. 65% and indicative of a steep increase (major worsening) compared with the previous period. Furthermore, 41 of the shrinking localities could be seen as subject to a strong effect (assignment to type E). However, among the latter, only Przemyśl remained from the previous period, being joined by Chełm, Kraśnik, Jasło and Tarnobrzeg in the lowest-scoring group (score 3).

Once again in this period, it was the small localities that had the highest percentage (25%) of overall population residing in centres that could be termed growing. That said, the" shrinking" categories can be seen to have experienced a doubling to almost 50% compared with 2006-2011. Thus, among the 741 small centres identifiable during this period, 358 were shrinking and 101 subject to strong shrinkage (type E). Among these, Hel and Jastarnia in Pomorskie Voivodeship had 0 scores in that period, with Mirsk, Pieniężno, Drohiczyn and Szczuczyn scoring 2; as followed by a group of 12 small localities all scoring 3, i.e. Ciechanowiec, Dęblin, Frombork, Hrubieszów, Łeba, Lesko, Leżajsk, Lipiany, Przedecz, Przemków, Resko and Ustka.

Urban centres in Poland shrinking or growing in the years 2016-2021

In the most recent analysed period, the percentage of the Polish urban population living in shrinking cities decreased slightly to 53% comparing with the previous period. However, the number of urban centres affected by shrinkage (in both types D and E) was still higher – at 508 in relation to the 2016-2021 period. That means that over half of all Polish urban centres continued to shrink in the years 2016-2021, i.e. the same percentage as in the period before.

The situation for 39 large urban centres of Poland proved to be better than in the former period. While again, 27 of them experienced shrinkage (as previously), only 2 went through strong processes of shrinkage (type E). Where numbers of cities are concerned, 69% of the 39 of large size were found to be shrinking.

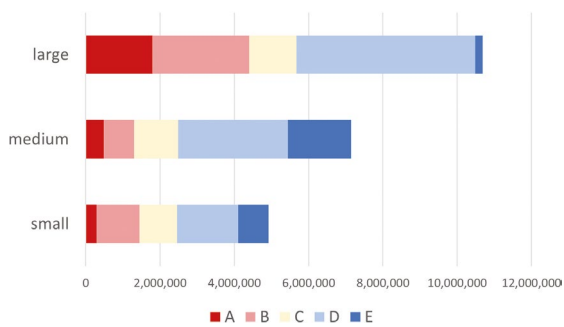

Fig. 4. Urban population in Poland in the 2016-2021 period, as categorised by growth and shrinkage type (A-E), and size or urban locality (large, medium, small)
Source: the authors, based on GUS data and own calculations.

This time, among the localities experiencing the most-severe shrinkage were Legnica and Wałbrzych (score 6) followed by Częstochowa, Sosnowiec, Kalisz and Łódź (score 7). Although, the average score for large centres undergoing shrinkage was again 13, the lowest-scoring examples were not so low anymore. In this period 47% of the population of large cities lived in shrinking cities (type D and E).

The medium-sized cities had 65% of their total population residing in the context of a situation of shrinkage as of 2016-2021. That was a more favourable circumstance than in 2011-2016, though only slightly so. Nevertheless, this was the second five-year period in a row wherein it was this group of localities that proved to be most affected by the phenomenon of shrinkage. Moreover, the numbers living in shrinking urban centres of medium size are almost as great as those in the large cities subject to shrinking. Out of a total of 180 medium-sized urban centres, 111 were classified as shrinking – a figure of 61% and a minor decrease compared with the previous period. Over the time in question, 38 of all the urban centres characterised by shrinkage were doing this at an above average rate. Among the cases in point were Stalowa Wola with the lowest score (of 3), followed by Olkusz, Oświęcim, Racibórz, Kędzieżyn-Koźle, Bartoszyce, Bełchatów, Piotrków Trybunalski, Puławy Sanok and Jarosław (score 4). The average score for the group of medium-sized shrinking localities is a mere 4, which stands in contrast to the score for the large urban centres – lowest Figure 6. There is a furthermore a highlighting of the difficulties these urban centres were facing, as revealed in all the previously classified indicators. At the same time, there was a slight increase from 6 in 2011-2016 to 13 in 2016-2021, in the number of medium-sized urban localities growing significantly, and thus assigned to type A).

The percentage of population residing in growing urban centres of small size rose from 25% to almost 30%, but the population of these centres remained at 50%. Thus, in the 2016-2021 period, among 745 such small cities and towns overall, 371 are seen to be shrinking, with 127 assignable to the strong shrinkage category. Among these localities, we find Chodzież, Recz, Łeba and Leżajsk, all with scores of 2. Equally, no longer was it possible to find small localities for which the score was actually zero. Moreover, most of the localities previously qualifying for the severe shrinkage category are now seen to have been "promoted" to type D. Among centres described as shrinking severely, there is a group of no fewer than 20 small ones scoring 4. These localities are Bierutów, Byczyna, Goraj, Hrubieszów, Kępice, Kock, Korfantów, Łaszczów, Lipiany, Lipsk, Lipsko, Lubowidz, Przemków, Radzyń Podlaski, Słupca, Świeradów-Zdrój, Tolkmicko, Wąsosz and Włodawa.

2006-2021 spatiotemporal changes characterising Polish urban centres that are shrinking or growing.

Comparison of the outcomes from the three subperiods shows spatiotemporal patterns of urban shrinkage within the spectrum of 15 years. While the urban population of Poland accounted for 61% of the national total in 2006, by the end of 2021 that had actually dropped to 59%, confirming a downward trend. In 2006 the urban centres under investigation here were inhabited by 23,346,297 people, with this number in steady decline through subsequent years, to reach 22,751,998 people at the end of 2021. To put urban shrinkage in the national context, the overall population of Poland can be noted to have dropped by 0.12% in 2021 – below the 38.1 million people noted in 2006. This confirms

tendencies for population transformations in cities and other urban areas to be more marked than in the country overall.

Within the broader context, the total number of Polish urban centres earning the description "shrinking" grew over the analysed period from 311 in 2006-2011, via 504 in 2011-2016, to 508 in 2016-2021 (Fig. 5). It confirms a trend that was signalled in population predictions from the Central Statistical Office (GUS, 2023), and by other researchers (Śleszyński, 2017, 2019,; Sroka, 2021; Jaroszewska, 2019). However, when size type is considered, shrinkage is not seen to be affecting urban centres equally but is rather most common in small and medium-sized localities cities and in later periods. The number thus rises over the years, even as there is a decline in cases of the largest cities shrinking. This proves that, while the early 2000s were challenging for the largest urban centres, later years have allowed them to bounce back economically, gradually attracting capital and people from the more peripheral areas of the country. A box plot analysis of the average score per type of urban locality in fact shows a growing difference (Fig. 6). Thus, while the score for large localities started on the lower level, it showed improvement later. At the same time, localities in the medium and small categories presented scores that have gone on declining gradually.

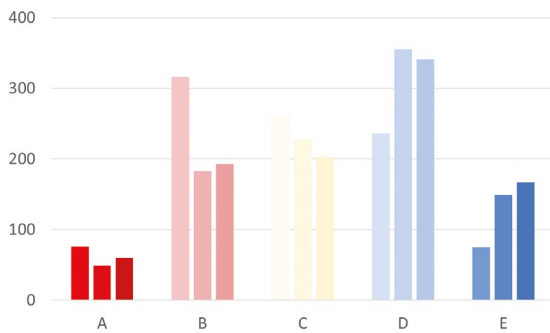

Fig. 5. Changes in the numbers of urban localities included in each group in the five-year periods between 2006 and 2021
Groups show the following types: A – above-average growth, B – growth, C – stability, D – shrinkage, E – above-average shrinkage

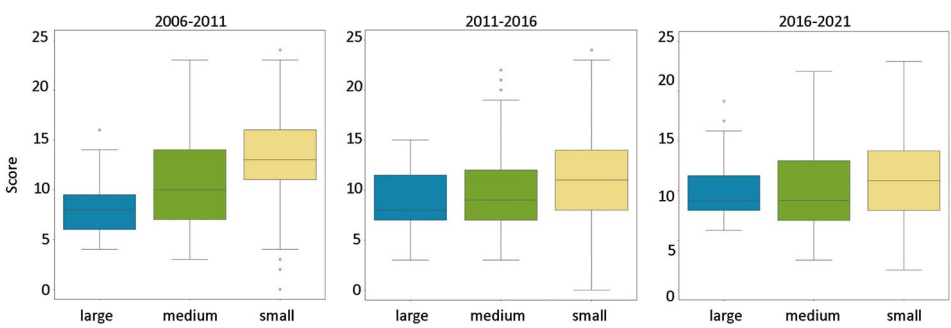

Fig. 6. Box plots of scores for urban centres in the different periods and as assigned to size-types of urban centres (large, medium or small)

A look at the spatial distribution of classified urban centres during the first five-year period makes it apparent that most growth occurred around the metropolitan regions of the largest Polish cities (Fig. 7). Conversely, the concentration of shrinkage is not as noticeable when all three periods are looked at. While a concentration of growing urban centres most often characterised Wielkopolskie, Mazowieckie and Małopolskie Voivodeships (the administrative divisions at regional/provincial level), the occurrence of localities that are shrinking is more dispersed across the entire country. However, post-industrial Silesia is one region in which shrinkage is evident, along with other areas where industries were located during the communist era. Additionally, there is a concentration of shrinking urban localities of small and medium size in Sudety Mountains region of Lower Silesia (Dolnośląskie Voivodeship) in SW Poland, as well as in the NE area of Warmińsko-Mazurskie and Kujawsko-Pomorskie Voivodeships, as well as in Central Poland's Voivodeship of Łódź (Łódzkie).

In the next period (of 2011-2016) an increase in numbers of shrinking localities and a decrease in numbers of those that are growing ones represents the first major visible change (Fig. 7). While growth then remained located around the same metropolitan areas as previously, shrinkage was a phenomenon spreading out across the country, especially among urban centres of small and medium size.

The last analysed period (of 2016-2021) saw these trends persist, albeit with more growth poles in the south, and fewer around Warsaw as capital of Poland (Fig. 7). Further intensification of the shrinkage phenomenon is evident on the peripheries of the voivodeships, away from the large metropolitan growth zones, and in certain post-industrial areas that continue struggling with the challenges post-transformation. At the same time, there are a few urban localities in the Silesian region (Śląskie Voivodeship) that are experiencing growth, and thus manifesting dynamics at play within the agglomeration there. Similarly, overlapping dynamics can be seen around the agglomeration in Pomorskie Voivodeship known as the Tri-City which mainly comprises Gdańsk, Gdynia and Sopot. There, we may find some strong growth poles in the vicinities of medium or small urban centres that go on shrinking.

Table 5 uses groupings of urban localities in line with their type, in each of the three periods, and thus allows us to note extremes. This classification shows the cities that retain their status in the classification (as groups 1, 3, 5), or which changed over the period (groups 2 and 4). The chart points to the existence of urban centres falling into the following five categories:

1. manifesting consistent strong growth [AAA],
2. changing over from shrinkage to growth [EEB |EEA |EDA |DEA |DDA |EDB |DEB |DDB],
3. manifesting stability throughout [CCC],
4. changing over from growth to shrinkage [AAD |AAE |BAE |ABE |BBE |BAD |ABD |BBD],
5. manifesting consistent strong shrinkage [EEE]

It is important to add that this list is not exhaustive, given its confinement to selected types considered of interest by the authors. Our aim was to show all urban localities capable of being regarded extreme in some ways. This leaves certain types not presented (e.g., BBB, DDD, CCB, etc.), as well as types potentially existing (in theory) but never exemplified in real-life cases (e.g., EEA, DDA, EDA, etc.). The outcomes expose the fact

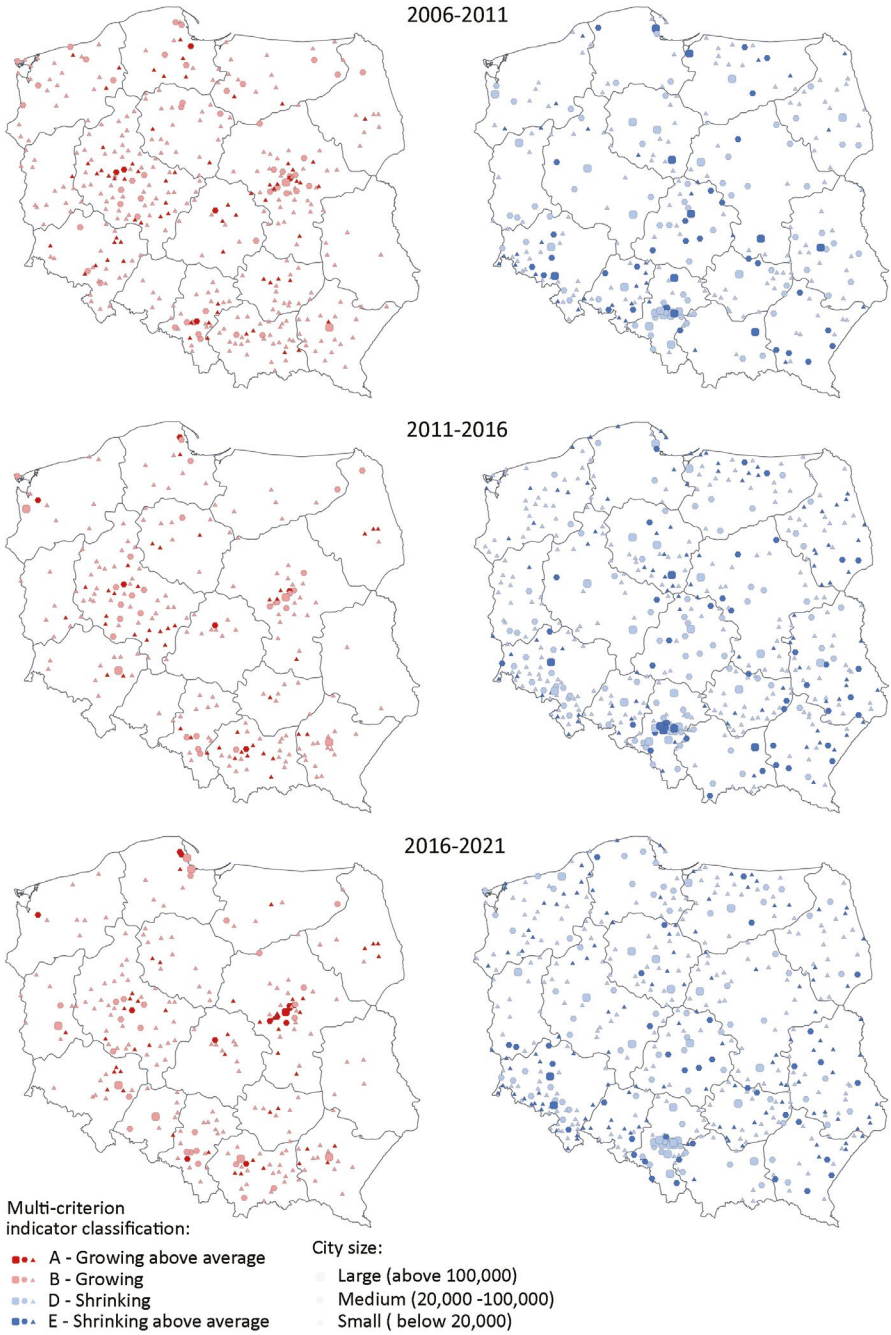

Fig. 7. Classification of Polish urban centres that grew or shrank in the 2006-2011, 2011-2016 or 2016-2021 periods, by reference to a multi-criterion indicator. The maps show localities in different size categories manifesting: A – above-average growth, or B – growth (left), or else D – shrinkage, E – above-average shrinkage (right)
Source: the authors, by reference to data from GUS as processed using the method from Milbert (2020).

of there being hardly any case in which an urban centre came back from a strongly shrinking path to one characterised by growth. Gdynia is here the exception, in that its unique case sees a change from strong shrinkage (type E) in the first period to type D, and then finally to growth (in type B). The other four centres represent cases of change from a categorisation of type D to type B. Ostrów Lubelski is the only small urban centre (sic!) that managed the switch from shrinkage to growth. On the other hand, there are nine small localities that changed in the opposite direction – from growth to shrinkage, with Kamień Krajeński being the only case of a recent move from type B in the first two periods to the strongly shrinking type E. Świnoujście is the only medium-sized urban centre in the group. The group of strongly growing localities mainly comprises those of small size, with only two in the medium-size category. Interestingly, Wieliczka only moved into the medium-sized category in 2009, when its population increased to reach the required threshold. The group of strongly shrinking centres is larger, with 13 cases, of which most are in the medium-sized category. This just confirms the challenges faced by this group that have been exposed earlier in this article.

When the spatial distribution of the classified extremes are looked at (Fig. 8), it is clear that urban centres that have gown consistently are always located in close proximity to the Voivodeship capitals. Conversely, localities that have remained assigned to the

Table 4. Numbers of Polish urban centres of different categories displaying growth or shrinkage in the three consecutive five-year periods between 2006 and 2021

Period	A	B	C	D	E
2006-2011	76	316	261	236	75
2011-2016	49	183	228	355	149
2016-2021	60	193	203	341	167

Table 5. Classification status groups for all three periods from 2006 to 2021

1. Always growing strongly	2. Changed over from shrinkage to growth	3. Always stable	4. Changed over from growth to shrinkage	5. Always shrinking strongly
Aleksandrów Łódzki [M]	Gdynia [L]	Drezdenko [S]	Chełmek [S]	Bartoszyce [M]
Choroszcz [S]	Nowy Sącz [M]	Kępno [S]	Czaplinek [S]	Bogatynia [S]
Kąty Wrocławskie [S]	Opole [L]	Międzybórz [S]	Dobra [S]	Chodzież [S]
Nekla [S]	Ostrów Lubelski [S]	Międzyrzecz [S]	Jabłonowo Pomorskie [S]	Duszniki-Zdrój [S]
Niepołomice [S]	Tarnowskie Góry [M]	Milicz [S]	Kamień Krajeński [S]	Jarosław [M]
Ożarów Mazowiecki [S]		Nowa Dęba [S]	Kłecko [S]	Jasło [M]
Siechnice [S]		Oleśnica [M]	Opalenica [S]	Kędzierzyn-Koźle [M]
Szubin [S]		Pyrzyce [S]	Pilawa [S]	Łowicz [M]
Wieliczka [M]		Sompolno [S]	Suchań [S]	Piekary Śląskie [M]
Zduny [S]		Szlichtyngowa [S]	Świnoujście [M]	Przemyśl [M]
Żukowo [S]		Trzciel [S]		Skarżysko-Kamienna [M]
		Trzebinia [M]		Zdzieszowice [S]
		Ujście [S]		Żychlin [S]
		Wołów [S]		

Fig. 8. Selected Polish urban centres classified in the five groups for the whole 2006-2021 period. The classification includes groups (1-5) of urban centres depending on their type (A-E) in each analysed five--year period

type of strong shrinkage (E) throughout the analysed period are peripheral. Bartoszyce, Duszniki-Zdrój, Łowicz, Przemyśl, Jasło, Skarżysko-Kamienna and Żychlin are located close to either Voivodeship boundaries or the state border. Similarly, the spatial distribution of urban centres that have consistently proved stable (assigned to type C) is characterised by peripherality. Most such localities are in western Poland, located on the perimeter of either Wielkopolskie or Dolnośląskie Voivodeships.

Discussion

An increasing number of cities in Poland have been experiencing the shrinkage processes understood as denoting social, spatial, and economic restructuring, as accompanied by population decline (Zborowski et al., 2012). The phenomenon has been the subject of ongoing research worldwide and still poses theoretical and empirical challenges. Scholars in Poland have done extensive work to analyse the extent of this phenomenon in recent years (Krzysztofik & Szmytkie, 2019; Janas et al., 2019; Jopek and Musiał-Małago,

2021; Sroka, 2021). While relevant Polish discourse on urban shrinkage revolves increasingly around its socio-economic, demographic and spatial aspects, very few studies have attempted to analyse the entire territory of Poland by reference to a single multi-criterion approach (Jaroszewska, 2019; Śleszyński, 2017, 2019; Sroka, 2021). The work detailed here has thus presented a spectrum of methods by which urban growth and shrinkage may be analysed. With the aim of providing a comprehensive and holistic overview of the shrinkage phenomenon in Poland, we decided to select and adapt a single multi-criterion method.

Germany's *BBSR* institute has engaged in the continuous monitoring of urban growth and shrinkage in that country since the early 2000s, when the eastern regions began to face unprecedented challenges. A multi-criterion method developed by Milbert (2008, 2015, 2020) was used to help diagnose and assess the effectiveness of planning responses. Given the potentially similar scope of challenges in Poland, we decided to adapt the above method to analyse the contemporary situation, with findings then set against the existing research. The approach pertains, not to absolute decline or growth, but to a processing of nationwide statistics involving all the country's local-authority areas, and thus indicating relative growth and decline. The main findings of such a multi-criterion indicator analysis for Polish cities over the 2006-2021 period are as follows:

1. It has been rare for urban centres to return to a growth path having once experienced shrinkage. Some exceptions exist, but over the 15 years only five localities achieved some kind of re-growth. Most urban centres manifesting shrinkage do not go back to a path of growth.
2. Most cities characterised by strong shrinkage across all three five-year periods were assigned to the medium size category (meaning 20,000-100,000 inhabitants). In general, the shrinkage phenomenon as manifested in Poland can mostly be ascribed to the medium-sized cities.
3. Urban centres manifesting growth are mostly located around Poland's five main metropolitan centres.
4. In all the periods, shrinking localities have proved to be rather dispersed across Poland, albeit with a tendency for them to be located on the peripheries of the country's constituent voivodeships (units of administration at regional/provincial level), or else on the peripheries of the country as a whole.

The research concludes that 13 cities experienced severe shrinkage throughout the 15 years from 2006-2021. Nine of these falling within this study's "medium" size category are Bartoszyce, Jarosław, Jasło, Kędzierzyn-Koźle, Łowicz, Piekary Śląskie, Przemyśl and Skarżysko-Kamienna, while five (Bogatynia, Chodzież, Duszniki-Zdrój, Zdzieszowice and Żychlin) are here categorised as "small". These findings offer partial overlap with the outcomes of a multi-criterion study conducted by Śleszyński (2017, 2019), in relation to the periods 2004-2014 and 2008-2018. In the former period, cities like Przemyśl, Jarosław, Bartoszyce and Jasło were identified by Śleszyński (2017). However, from 2008-2018, the study found that Bartoszyce and Przemyśl were in a better position. From the point of view of our study, they have to be viewed as remaining crisis-hit. Śleszyński concludes that the issues of loss of function, significance in the settlement hierarchy, and overall economic crisis affecting Poland's medium-sized urban centre seems to represent an increasingly serious problem, requiring careful consideration in both practical and scientific spheres (Śleszyński, 2019). Additionally, forecasts from *Statistics Poland* (GUS, 2023) have shrin-

kage exerting its most-severe effects in the coming years on medium-sized urban centres. Predictions for example include a 39% loss of population for Konin, and one of 35.4% in the case of Tarnobrzeg, by 2050. While the research presented here offers no long--term forecasts, it does demonstrate a growing trend for the analysed period whereby medium-sized urban centres undergo shrinkage.

Reference to the outcomes of other multi-criterion research does not suggest any easy identification of similarities. Sroka (2021) resembled ourselves in researching urban shrinkage and in drawing inspiration from the multi-criterion approach of Milbert (2015), yet that study revolved around different indicators (see Tab. 1) and a different timeframe (1995-2018); and it also eschewed the division into separate five-year periods. Instead, the work opted for a summary approach to the most severely shrinking cities. According to Sroka (2021) 53 of the 190 medium-sized cities analysed could be assigned to the severe shrinkage category.

Compared with Sroka (2021), the research presented here benefits from the approach involving sub-division of the overall period, in this way offering a more-detailed analysis of shrinkage trends, and changes in numbers of shrinking localities, over the years. Similarly, Jaroszewska (2019) deploys a method different enough to obstruct any making of comparisons. She conducted an extensive study on urban shrinkage involving 829 urban centres, over a period extending from 1990 to 2010, and with additional socio--economic data on offer for 2003 and 2013. While it is impossible to compare outcomes, some general voivodeship-oriented similarities can be identified as regards the proportionality between urban centres that are either shrinking or growing.

Finally, it is possible to observe discrepancy of outcome as the results of the present study are set against the analysis based on population criteria that was conducted for the 2000-2020 period by Jopek and Musial-Małago (2021). The latter authors identified Bytom and Wałbrzych as the urban centres showing the most severe shrinkage, though the multi-criterion approach used in this study reveals some differences. In the 2006-2011 and 2016-2021 period, Wałbrzych indeed scored relatively low (with the city assigned to type E). However, 2011-2016 brought a higher score due to low unemployment and high employment. Thus, despite its population decrease, this city ranked higher (being assigned to type D). Similarly, Bytom moved up the ranking due to low unemployment in the years 2016-2021 and is not even present among the urban centres found to be shrinking most. Such examples can be found as population-based analyses are compared with the multi-criterion approach, with this evidencing the difference in outcome attributable to the two methods of classification.

Summary

The work detailed here has first involved a review of selected approaches to measuring urban shrinkage, with this leading to our ultimate adoption of a multi-criterion method by which to run an assessment in Poland. Inspired by a German study from Milbert (2015, 2020), this method offers a nuanced understanding of shrinking cities, given that it extends to diversified socio-economic indicators in a position to reveal variations in the proportion of shrinking or severely shrinking municipalities, as compared with measures based solely on population. This underscores the importance of a multidimensional ap-

proach if we are to gain a more accurate representation of urban shrinkage dynamics, as well as the need for diverse measurement methods if an early warning system drawing on weaker signals is to be put in place.

Building on existing research in Poland, this study enhances our understanding of urban shrinkage, supporting informed decision-making in urban planning and development. The focus on a five-year period allows for a detailed investigation into the trajectories of individual urban centres, and the emphasis on those of medium size (here identified as the ones most affected by urban shrinkage) is notable, considering the role played in the stabilisation of polycentric settlement systems. Indeed, this study confirms previous findings to the effect that urban localities of medium size are in need of strategic support.

This study points to avenues for further research, for example encouraging the exploration of spatial associations relating to structure and networks in urban localities of medium size. An extension of this kind would serve to uncover patterns and offer valuable insights for planning practitioners and local governments working to develop more-informed planning strategies. Additionally, the study opens up the possibility of the results of implemented urban renewal programmes being reviewed and evaluated by reference to their outcomes. Overall, the study contributes to the ongoing discourse on urban shrinkage, emphasising the need for a holistic and multidimensional approach to the understanding and addressing of this complex phenomenon.

Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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[Wpłynęło: lipiec 2023; poprawiono: listopad 2023]

ARCHITECTUS

Research paper

Compactness of Polish urban areas - methodologies and analysis based on CLC dataset

Keywords
Poland, compactness, urban population density, CLC, urban form measures

Abstract
Introduction
This research delves into the dynamics of urban compactness in Poland, exploring methodologies for analysis and assessing changes over time. Three key research questions guiding the study revolve around methods for compactness analysis, the relationship between the size of urban municipalities and compactness, and temporal changes.

Subject and purpose / methodology
The research considers all Polish municipalities and analyses selected compactness measures in 2006, 2012 and 2018. By evaluating various analytical approaches and utilising land use data from CORINE Land Cover, the study provides a new methodology to monitor city compactness measures, thus contributing to evidence-based decision-making for sustainable urban planning.

Results / Conclusions
The outcomes unveil patterns and correlations across city sizes and temporal trends, showing the decrease in compactness over time. It reveals a logarithmic relation between population size, compactness index, and urban population density. While smaller cities tend to be more compact in shape, they are less dense. Conversely, larger cities tend to be more dense but also dispersed. This study contributes to the state of knowledge by introducing and testing a method to assess urban compactness across urban areas. Since the CLC datasets cover the entire EU, this method is replicable in every member state, allowing for further comparative studies.

Explanation letter
Dear Editorial Team,

Thank you for your email.
Please see the email for the response to the reviewers' comments and the new manuscript with highlighted revisions downloaded to the Architectus editorial system.

If something is missing, please let me know.

Kind regards,
Ewa Szymczyk

1. Introduction

There has been a growing interest in urban patterns in European and North American literature, specifically focusing on quantitative methods (Reis et al., 2016). The emphasis on sustainable development models, the advancement of GIS tools and information technology, and the increased availability and quality of spatial data have led to a rapid acceleration of data-driven spatial research across various domains. Geographers, environmental scientists, economists, and policymakers have all analysed the relationships with spatial patterns. Spatial indicators are crucial in examining the connections between the built environment and different urban processes. It is similar in urban science, where spatial measures are essential for monitoring the development of spatial organisation within cities over time, allowing for analysing and comparing spatial-temporal patterns. While numerous methods are available for such analyses, the choice of method is typically influenced by its relevance to the specific question.

Urban form measures have become a central focus in the study of urban compactness, an urban form characteristic strongly linked to sustainable development (OECD, 2012) and seen as the opposite of urban sprawl (Tsai, 2005). At the same time, urban sprawl is known to have high social costs in urban planning (Squires, 2002); recent research suggests that urban forms significantly impact commuting patterns (Song et al., 2017). According to Schiller and Kenworthy (2018), this development pattern also leads to increased costs, adverse effects on the city centre, higher energy and fuel consumption, and detrimental effects on household budgets and the environment. In a study on the relationship between urban sprawl and economic performance in growing Polish cities, Lityński (2021) found that stronger local economies are associated with less urban sprawl. Conversely, high urban compactness and high urban density are believed to benefit public transit systems (OECD, 2012; Schiller and Kenworthy, 2018).

The concept of the compact city is one of the most widely discussed in contemporary urban policy (OECD, 2012). The term compact city was first used by Dantzig and Saaty (1973), who were principally interested in a more efficient use of urban resources. It is recommended for urban development at all levels of planning guidelines, from global organisations like the UN-HABITAT to the European Union and in Polish national planning documents (KPM 2023). Compactness can be measured in various ways but generally relates to urban expansion and density patterns. The OECD defines the characteristics of the compact city as “dense and proximate development patterns (...) urban areas linked by public transport systems (...) accessibility to local services and jobs” (OECD, 2012, p.15). Understanding urban compactness is crucial for addressing urban sprawl and promoting and effectively planning sustainable urban development globally and locally. Since this concept in Poland was mainly analysed from the perspective of the opposite phenomenon of urban sprawl and never from a nationwide scale, this study fills this gap. It aims to achieve methodological and empirical objectives of assessing urban compactness in Poland. This aim is achieved by addressing three key research questions:

1. What are the methods for analysing compactness?
2. What is the relationship between city size and city compactness in Poland?
3. How does compactness change over time in Polish cities?

The research assesses various methods for analysing urban compactness, including morphological indices and computational models, and their relevance in the context of Poland. It suggests a methodology based on the CORINE Land Cover (later called CLC), a crucial data source on Europe's land use and landscape dynamics. The study applies two methods to assess the compactness of all municipalities in Poland. It uses historical CLC data to explore the evolution of urban compactness in all Polish urban areas (in all municipalities) and

separately only for urban areas in cities (urban and urban-rural municipalities) and its relationship to the municipality population size.

2. State of research on compactness measures

Ahlfeldt and Pietrostefani (2017) reviewed the theoretical literature and identified three main characteristics of compact cities: economic density, morphological density, and mixed land use. Each of these characteristics can be measured in various ways. Economic density, the number of people or jobs within a given area, is typically measured using population or employment density (Ahlfeldt & Pietrostefani, 2017). Morphological density focuses on the built environment and includes measures such as urban/rural boundaries, street connectivity, and building footprint-to-parcel ratio. Mixed land use captures the co-location of different functions, such as residential, employment, and retail. It can be measured in two dimensions (Ahlfeldt & Pietrostefani, 2017) or vertically (in three dimensions) (Burton, 2002). When considering the concept of a compact city, it is essential to select measures and methods based on their relevance to the specific question being addressed, available data and the scale of the analysis (Ottensmann, 2021).

A study on spatial metrics conducted by Reis et al. (2015) provides an extensive overview of all measures and methods to study patterns of urban growth and shrinkage. Authors subdivided patterns of growth into four main groups:

1) Expansion,
2) Urban sprawl,
3) Polycentrism,
4) Densification/Coalescence.

According to their review, urban sprawl is the most studied pattern in Planning and Geography. While the exact definition is ambiguous, it is commonly understood as characterised by scatter/fragmentation, low density (both population and building), single-use and poor accessibility (Reis et al., 2015). Compactness, seen as the opposite of urban sprawl, may be measured similarly.

The most commonly used measure of compactness is related to density (Burton, 2002). Most known research uses population density (for example, Newman & Kenworthy, 1989). When it comes to spatial measures, the compact city concept typically concerns the two-dimensional expansion pattern of an urbanised area, which is considered more compact if the pattern is more clustered towards a centre and with less sprawl, leap-frogging or branching (Mubareka et al.,2011). Referring to Reis et al. (2015) classification of metrics, the analysis can use one of three metrics groups depending on the area of knowledge and methodological approach to urban form. These groups are Landscape metrics, Geospatial metrics and Spatial metrics. Categories organise each of these groups and consist of numerous metrics to investigate them. Figure 1 shows how the selected shape metrics fit into the classification.

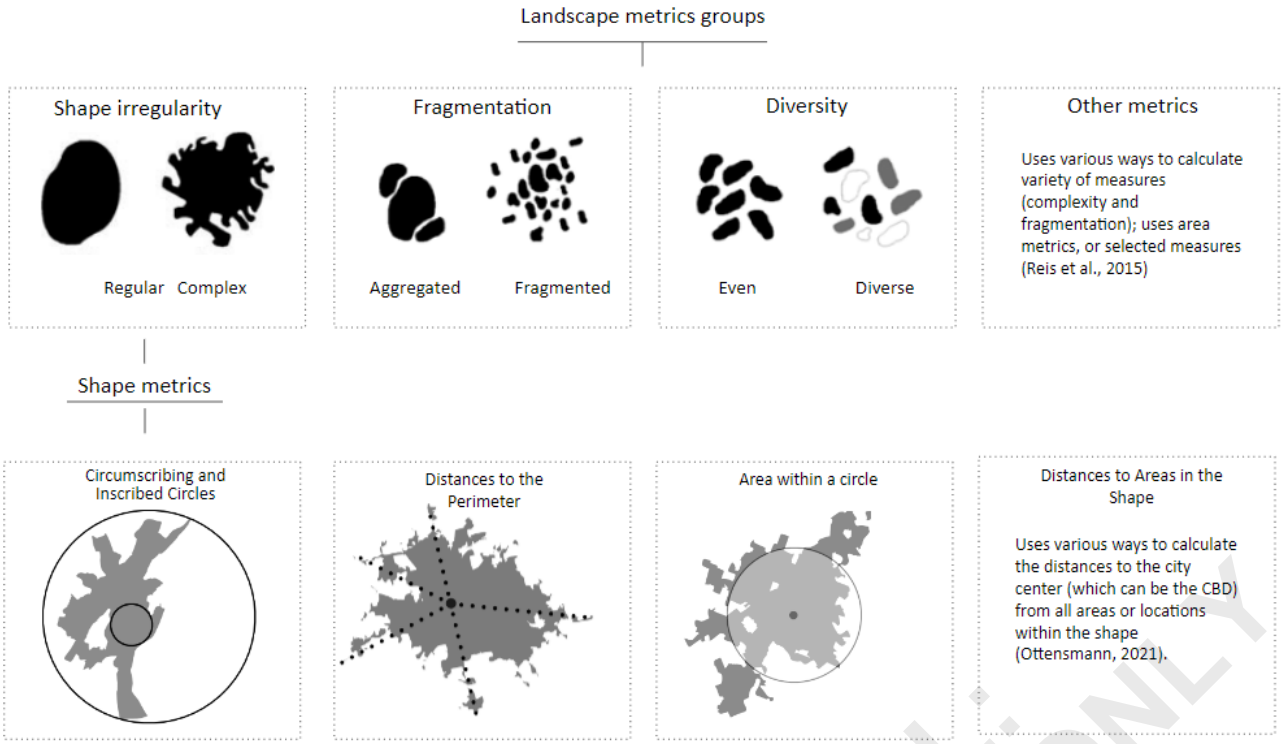


Figure 1. Landscape metrics groups and shape metrics categories. Source: Author based on Reis et al. (2015) and Ottensmann (2021).

Ottensmann (2021) conducted a study on the urban shape of 59 large cities in the US, evaluating measures based on specific criteria. The author identified three crucial aspects for determining the most suitable shape indices: the ability of metrics to measure the relation to the city centre (Central Business District in the US), the method of measuring holes and discontinuous areas, and the applicability to given urban area data. The study reviewed shape measures that assess the compactness of urban areas, assuming that the circle is the most compact 2D shape. In his research on large US cities, Ottensmann used the Proximity Index (belonging to the 'Distances to Areas in the Shape' category). This landscape metric measures shape irregularity by calculating the distance from all locations within the urban area to the CBD. The author points out that this method is suitable when only one centre can be identified but isn't useful for polycentric urban areas.

Similarly, Burton (2002) studied English compactness, selecting 25 towns, medium-sized, and big cities. However, Burton developed a multi-criteria indicator method. Indicators were organised into six groups: compactness, density, mixed-use, intensification, population intensification, and built-form intensification, each with four variables. While the measures of compactness objectively represented the phenomenon, the author concluded that they may not always accurately represent subjective compactness. This supports the idea that compactness is a socio-cultural construct rather than a purely objective one.

Thinh et al. (2002) research on the compactness of 116 German cities was driven by the question of how compact is a sustainable city. The authors used data from the CLC and the Digital Landscape Model (DLM) of Germany to establish and validate the degree of surface sealing (in percentage). They established a GIS raster analysis using a square raster (500/500m grid) and the gravitational approach (Thinh et al., 2002). Their research presented a connection between various socio-environmental indicators and the compactness of city form.

In the literature about Polish cities, there is a significant focus on urban sprawl. Urban compactness is primarily examined in terms of urban density. Śleszynski (2014) conducted the most extensive study on urban population density in 147 Polish cities. His analysis utilised data from the 2002 census, which divided cities with over 30'000 inhabitants into statistical districts, enabling more in-depth studies on population distribution within cities. The key findings are related to the distribution of density from the city centre, revealing a strong correlation between population density in the 0-2 km concentration zone from the city centre and the demographic sizes of towns or cities. Smaller cities and towns generally have less dense centres compared to larger ones. Lityński (2016) conducted a major study on urban sprawl in relation to economic performance. The Author analysed 4 big Polish cities and their neighbouring municipalities. The method used to assess urban sprawl is based on the following indicators: density, continuity, concentration, clustering and centrality. Higher ratios indicate less urban sprawl. Density, for example, is the number of housing units per hectare of urbanised land[1] and Centrality is the degree to which buildings are located in relation to the city centre. It calculates the distance from the village centre to the city centre. The measure is the inverse of the average sum of these distances weighted by the number of housing units in the village.

The methods listed above answer the first research question by demonstrating the various ways compactness can be measured, depending on the specific focus of the research. The next sections of this study add to the methodologies for measuring the compact city by offering a technique that utilises open-source spatial data (CLC) and statistical population data.

3. Data and methods description

This study adopts a quantitative approach to examine Poland's urban municipalities from the perspective of 12 years. The selection of subjects is based on Poland's administrative system. On the highest/regional level, there is a voivodeship (województwo), which consists of counties (powiat); counties are divided into individual local-authority municipalities (gmina); a municipality contains either an individual city (GUS level 6, kind 1), only villages - rural area (GUS level 6, kind 2), or a mix of a town and villages - urban-rural area (GUS level 6, kind 3). The selected method uses the smallest local government unit, i.e., the municipality (gmina). In 2021, Poland had 2,477 municipalities: 302 urban, 662 urban-rural and 1,513 rural. Therefore, the analysis is divided into three administrative categories:

- an urban area in the urban municipality (GUS level 6, kind 1),
- an urban area in the urban-rural municipality (GUS level 6, kind 3), including a city and small settlements.
- an urban area in a rural municipality (GUS level 6, kind 2), including towns and small settlements.

The varying spatial units over different years in Poland were carefully considered to maintain data consistency. Additionally, to see the possible linkage with the size of urban areas, this study relied on a simplified division based on Statistics Poland's categorisation:

- below 20,000 as a small city,
- 20,000-100,000 as a medium city and
- above 100,000 a big city.

The population was categorised based on the year of the spatial analysis data.

The timeframe of our study was chosen for two reasons: first, because the most recent data available at the time was provided for 2018, and second, to see urban areas for an extended amount of time after the EU accession (in 2004). The data for urban spatial metrics is based on land use data from the CORINE Land Cover

[1] Author calls it Developable land (DL) which is an area that is the difference between the total municipal area and the sum of land covered by water, forest, recreation areas, roads and land reserved for ecological purposes (Lityński, 2016).

(later called CLC) for the area of Poland. The CLC data is a standardised methodology for producing continent-scale land cover, biotope, and air quality maps, including 44 land-use classes. Since the product is updated every six years, with the most recent update being in 2018, the three data sets were selected: CLC2006, CLC2012, and CLC2018.

To define the shape of the urban area, the 44 classes of land used by the CLC were considered. Urban areas were broadly defined as 'artificial surfaces' (CLC), which include infrastructure and green urban areas, represented by 11 classes (Table 1). This method is similar to the one followed by the (GUGiK). While most of the population lives in the first two 'urban areas' classes (111, 112), the remaining nine classes represent urbanised areas, which are an integral part of the city.

	CLC Code	Name
	111	Continuous urban fabric
	112	Discontinuous urban fabric
	121	Industrial or commercial units
	122	Road and rail networks and associated land
	123	Port areas
	124	Airports
	131	Mineral extraction sites
	132	Dump sites
	133	Construction sites
	141	Green urban areas
	142	Sport and leisure facilities

Table 1. CLC Codes indicate classes taken under consideration and their respective colours. Source: CLC

The selected classes were cut to the municipality's boundaries and merged into one shape consisting of one or more polygons (Figure 2). Each shape received a unique identification number of a spatial unit, called the National Official Register of the Territorial Division of the Country (TERYT). Moreover, the development of the analytical method included some calibrations. Due to some discrepancies in the spatial data (such as imprecise land use demarcation), many cities had minor shapes left after cutting to the boundaries. After analysing possible thresholds to avoid distorting the calculation, a threshold of 2% of the total shape area was set. All the shapes that were below this value were deleted (step D).

The calculation consists of the following operations for each selected year:

A. Isolation of selected 11 land use classes;
B. A cut of land use polygons with city administrative boundaries;
C. Merge polygons into continuous shapes;
D. Delete polygons below a set threshold - for a given shape;
E. Calculate the shape's area and perimeter;
F. Calculate the compactness index;
G. Calculate the urban population density.

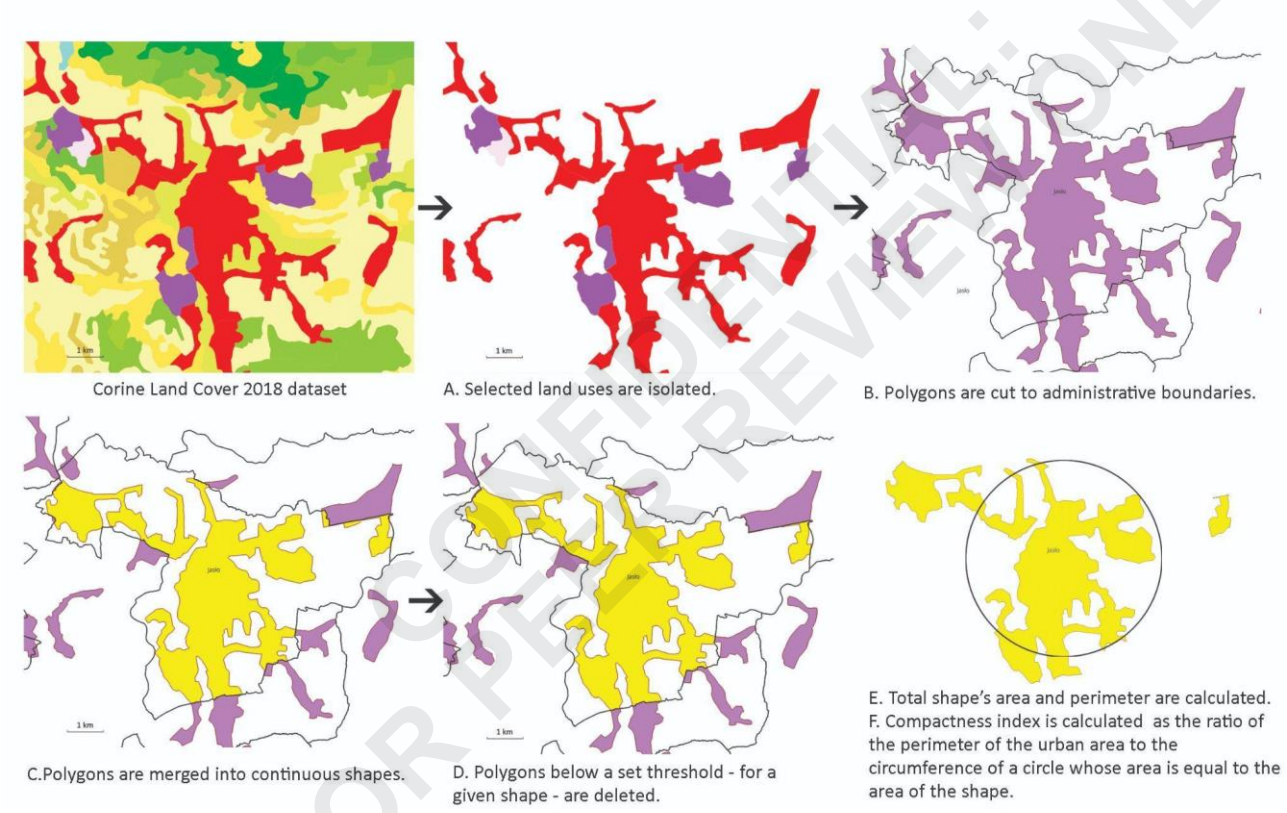


Figure 2. Diagram presenting a step-by-step spatial analysis method, defining compactness index (Ci) and Urban population density (Ud) based on Jasło.

As presented in Section 2, there are multiple ways to measure urban area compactness. This study uses the compactness index (Ci) and urban population density (Ud) measures with values in people per square kilometre.

The compactness index quantifies the compactness of shapes' irregularity. There are many measures of the compactness index (Niemi et al., 1990; Altman et al., 1998; Chambers & Miller, 2010). A few were identified by Bernes and Solomon (2021) as the most commonly used. Among these most common, the authors selected a single measure named Schwartzberg (1966). The Schwartzberg compactness index is determined

by comparing the perimeter (Pd) of an urban area (see Figure 2) to the circumference of a circle that has the same area (Ad) as the urban area. It can be expressed as follows:

$$Ci = \frac{1}{\frac{P_D}{2\pi\sqrt{A_D/\pi}}}$$

Index ranges from 0 to 1, where 0 is the least compact and 1 is the most compact. This index was calculated for each medium-sized city in each CLC year.

The second measure considers the urban area (Ua) and the municipality population (Pop) in the corresponding year to calculate the urban population density. Compared to the simplified population density found in Polish Statistics, this method of selecting urban areas excludes agricultural land, forests and water bodies, among others, giving a more accurate picture of where the city urbanised boundaries. The urban population density (Ud) can be formally written as:

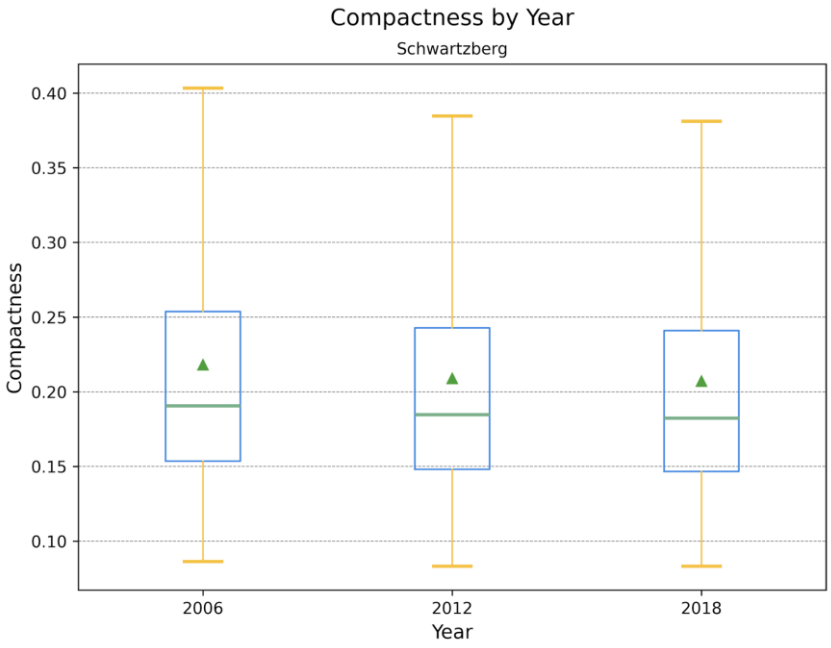
$$Ud = \frac{Pop}{U_A}$$

4. Results

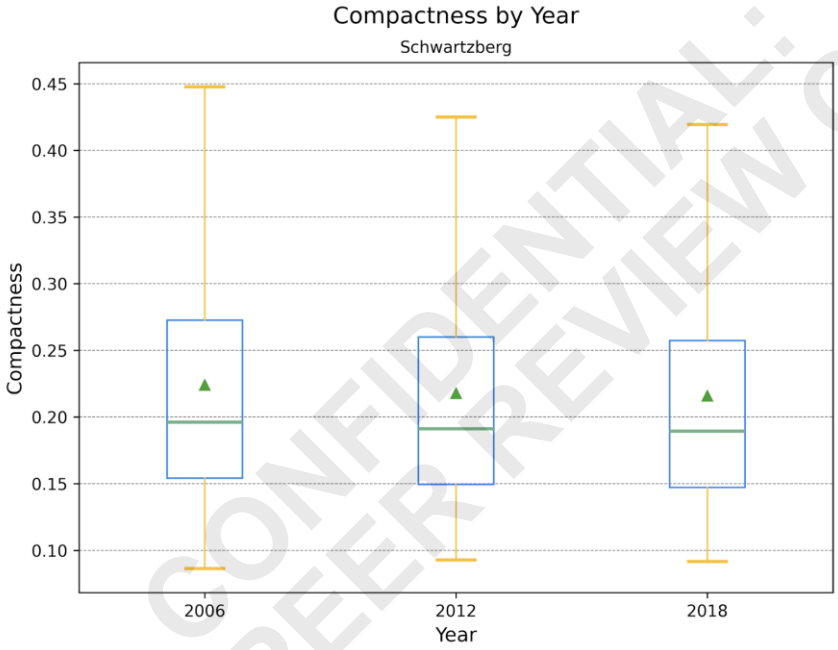
This section presents the analysis outcomes for all municipalities (2477) and separately only for urban municipalities (964) in three periods based on the CLC datasets. The outcomes are divided into three relations:

- Trends in time,
- Trends concerning city size,
- Trends concerning the location.

Firstly, the compactness index (Ci) of urbanised areas in Polish municipalities shows a decreasing trend over time. This is true when urban areas in all municipalities are considered (Figure 3) and when only the urban municipalities (Kind 1, Kind 3 in GUS) are taken into consideration (Figure 4). On average, Urban municipalities were more compact than rural ones. Table 3 shows detailed analysis outcomes, revealing the decrease in the Ci of urban areas in urban municipalities. The most compact Polish urban municipalities in 2006 were Ząbki, Podkowa Leśna and Wysokie Mazowieckie in 2012 and in 2018, it was Zawidów, Wysokie Mazowieckie and Podkowa Leśna with over 0,6 Ci. All the top-scoring cities are small (except for Ząbki, a medium-sized city), and all are adjacent to a big urban area.



214 Figure 3. Compactness index trend for all Polish municipalities.



215 Figure 4. Compactness index trend for all urban municipalities.

216

Years	2006	2012	2018
217 number of observations	964	964	964
218 median	0.1962	0.1912	0.1895
219 mean	0.2239	0.2177	0.2158
220 Lowest outcome	0.0864	0.0929	0.0917
221 Highest outcome	0.4478	0.4251	0.4195

222 Table 3. Outcomes of compactness index analysis of urban areas in all urban municipalities (kind 1, kind 3).

Secondly, the urban density (Ud) of urbanised areas in Polish municipalities over time was compared. Similarly to compactness, change over the years for all municipalities and urban municipalities shows a trend of significant decrease in urban population densities (Figure 5, Figure 6). Interestingly, the densest Polish urban municipality in 2006 - Sopot, with over 5894 people/km2 was decreasing its density to reach 5413 people/km2 in 2018. The densest urban municipalities in 2006 were Sopot, Świętochłowice and Chełmno. In 2012 and 2018, Wejcherowo, Chełmno and Sopot with over 5 thousand people/km2. For comparison, the densest European city and one of the densest in the world among mega cities - Paris, has an urban population density of 20641 people/km2. Table 4 shows detailed outcomes of the analysis, revealing the decrease in the urban population density in all urban municipalities.

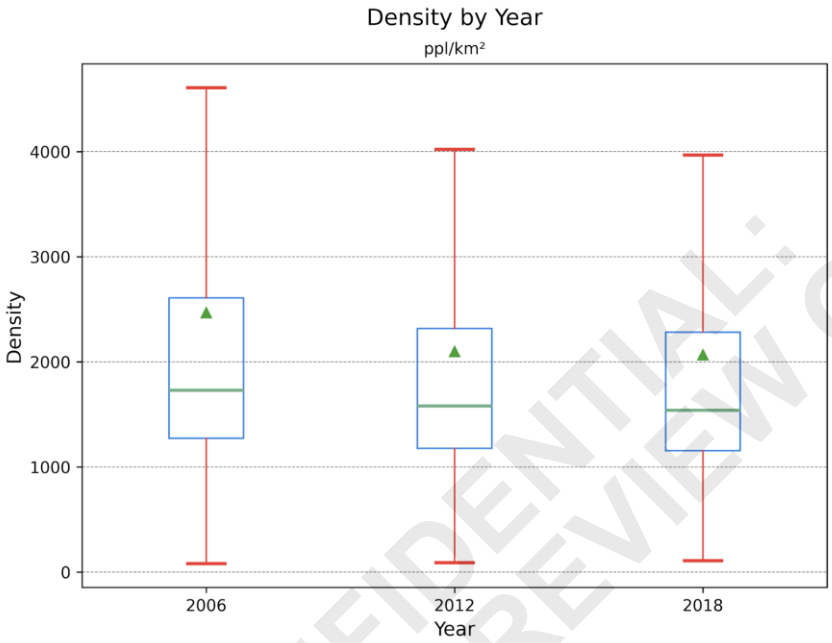


Figure 5. Urban population density trend for all municipalities.

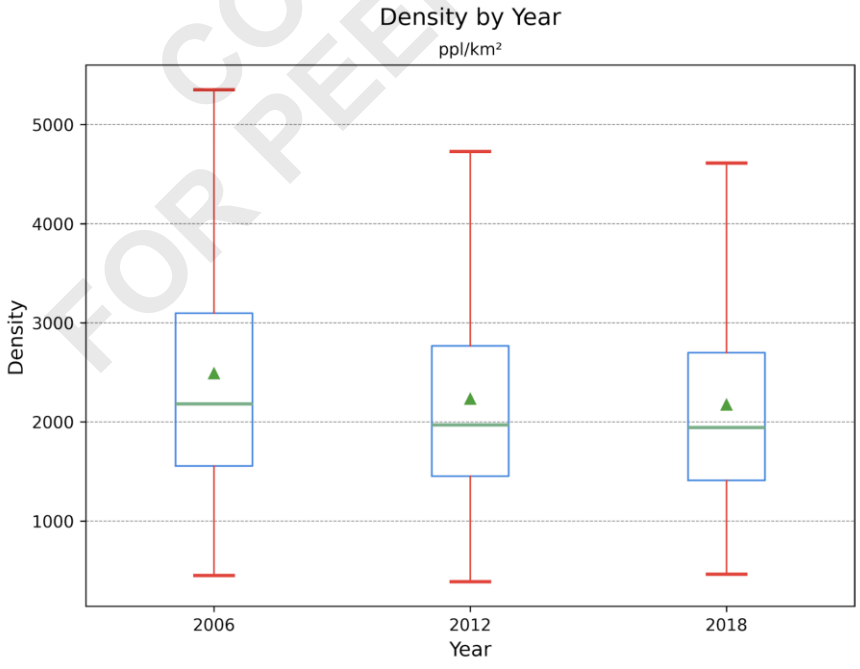


Figure 6. Urban population density trend for all urban municipalities.

Years	2006	2012	2018
number of observations	964	964	964
median (people/km2)	2183.1	1970.24	1945.08
Mean (people/km2)	2487.4	2232.33	2173.55
Lowest outcome (people/km2)	451.86	388.22	464.36
Highest outcome (people/km2)	5353.09	4730.06	4611.62

Table 4. Outcomes of urban population density analysis for all urban municipalities.

The outcomes of compactness analysis for medium-sized and large cities (population over 20,000) were related to the urban municipality's population size. Figure 7 shows a clear logarithmic relationship of medium-sized cities being more compact than the big ones.

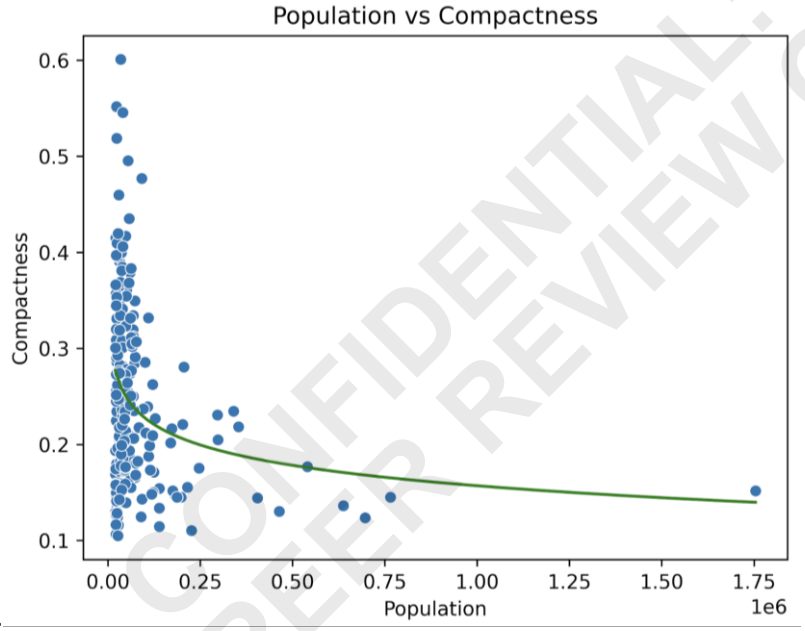
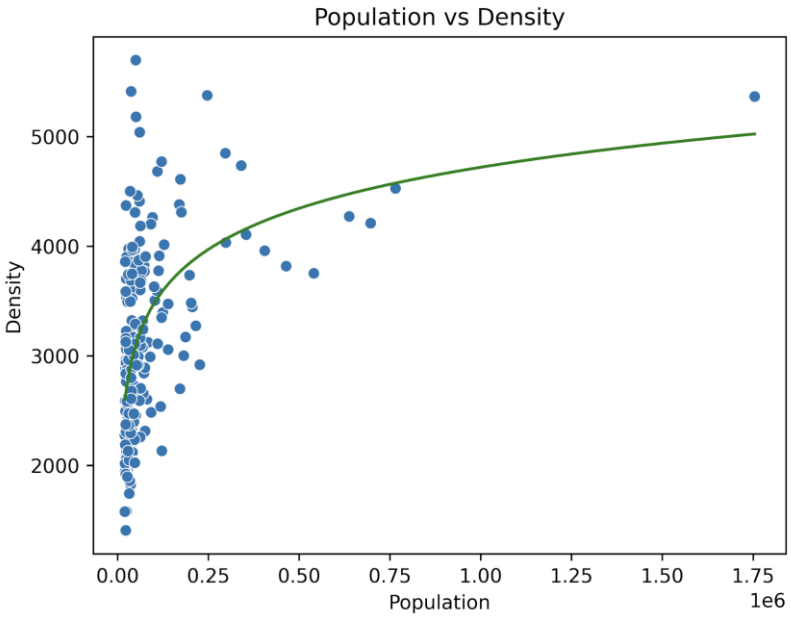


Figure 7. Urban compactness trend for medium-sized and big urban municipalities in 2018.

A similar relation analysis was conducted for the urban population density (Figure 8). Conversely, the urban population density of bigger cities is higher, showing a clear logarithmic trend.



248 Figure 8. Urban population density trend for medium-sized and big urban municipalities in 2018.

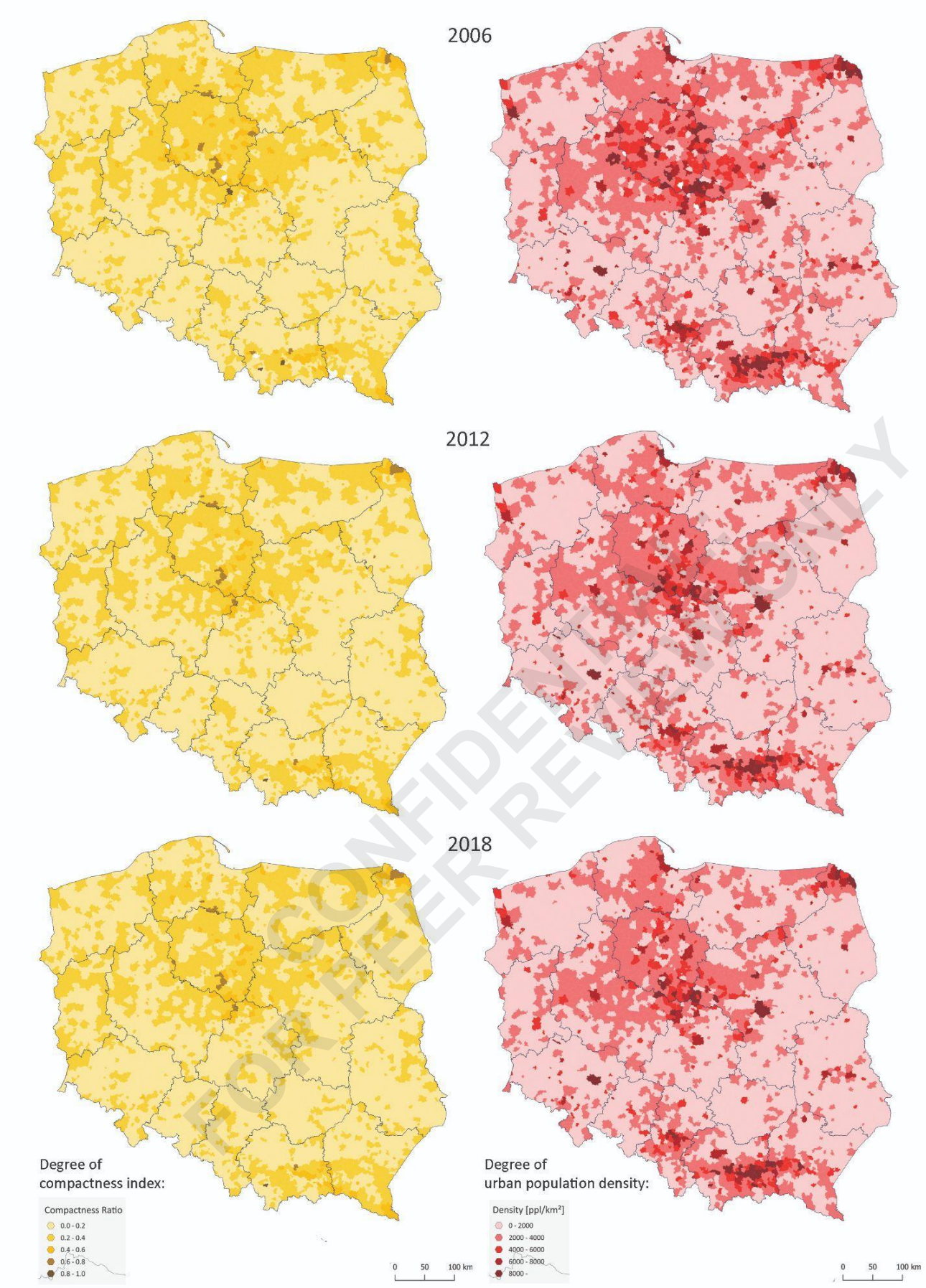


Figure 9. The compactness index (left) and urban population density calculation (right) for all Polish municipalities in three periods based on CLC datasets and Polish Statistics (GUS).

5. Discussion

This research contributes to the study of urban compactness in Poland, being the first to employ a shape measure to assess the compactness of all urban municipalities in the country. Previous studies have predominantly focused on urban sprawl, often limited to a smaller scope of cities (for example, Śleszyński, 2014; Lityński, 2021). Leveraging GIS and information technology tools enabled the management of extensive data sets across numerous municipalities, providing a comprehensive analysis of all urban areas over three distinct years for which spatial data was available in CLC. This chapter discusses the findings concerning the primary research questions.

5.1. Methods for analysing the compactness of Polish cities

The methodology utilised in this study combines the widely used measure of urban population density with an urban shape measure based on the assumption that a circle represents the most compact geometric shape. It uses CLC- an open-sourced pan-European land use database in combination with population data (Polish Statistics). The integration of these measures proved effective in analysing compactness at a national scale. The shape measure, in particular, offers a novel approach in the Polish context, allowing for a more nuanced understanding of urban form beyond simple population density metrics. There is a considerable overlap between compactness index (Ci) and urban population density (Ud) measures concerning the geographic concentration of the most compact and densest urban areas.

Additionally, when correlated between each other, measures show a strong relationship. The Pearson correlation between Ud and Ci was conducted for three datasets. The results for all urban municipalities (urban and urban-rural) for data in 2006 indicated a r value 0.45 correlation with a statistically significant p-value. In the year 2012 the correlation value increased to 0.48. In the last period the coefficient remained strong at 0.48. This strong relationship is related to both measures having the same component of urban area (Ad in compactness index and Ua in urban population density). This also proves that measures depict the same urban phenomenon.

Both measures exhibit a significant decrease over time. These observations confirm that these measures describe a similar concept. Moreover, the presented outcomes of density relation with size are in line with research conducted by Śleszyński (2014), which showed a strong correlation between the density of a city's central area and city size. However, it has to be noted that this measure, while sufficient for general nation-scale research, is not sufficiently detailed for detailed studies. This is because there are discrepancies between land classes identified by CLC and the actual land uses. For example, according to the study of Śleszyński et al. (2020), there is a mismatch, especially in the urbanised areas classification. While this method's alignment with existing literature supports its validity, future improvement is required. Further research should try to eliminate these discrepancies by reaching for different data.

5.2. Relationship between city size and compactness

The analysis reveals that compactness is more prevalent in medium-sized urban municipalities, whereas urban population density is higher in larger urban municipalities, with Warsaw being a notable outlier. However, there is a significant geographic overlap between the most compact and densest urban areas, particularly in the southern edge and above the central belt of Poland. The Kujawsko-Pomorskie voivodeship exhibits the most compact and densest municipalities, with neighbouring regions like Mazowieckie, Pomorskie, and northern parts of Lodzkie sharing this concentration. Conversely, lowland areas show a sparse distribution of compact and dense cities, while mountainous regions in the south and the lakelands have higher concentrations. Moreover, the voivodeship with sparse populations, such as the northeastern

corner of Poland, exhibits high-density urban areas. These findings suggest that historical context and topography play crucial roles in shaping urban compactness and pave the way for future research on the causes of compact urban patterns.

5.3. Changes in compactness over time

This study provides evidence that the compactness of Polish urban areas is declining over time. Both compactness and urban population density measures demonstrate significant decreases, suggesting an ongoing trend towards urban dispersion. This trend poses environmental and economic risks, as highlighted by Lityński (2021), Śleszyński (2014) and Schiller & Kenworthy (2018), among others, and challenges the sustainability of urban development. The implications are particularly concerning in the context of declining demographic rates and urban shrinkage in Poland (Szymczyk & Bukowski, 2023). Shrinking cities find it harder to maintain excess infrastructure in low-density areas. Research on shrinkage sprawl in the Polish context should follow to keep track of urbanisation patterns to effectively manage this phenomenon's negative effects.

5.4. Research limitations

It has to be noted that this study did not account for topographical features such as bodies of water or forests, which constrains urban area development (making it more compact), nor did it consider the relationship to the Central Business District (CBD) or historic city cores (Ottensmann, 2021). Moreover, this study shows that the most compact cities are part of a bigger urban area with administrative boundaries “cutting” the shape out. Such cities, e.g. Ząbki and Podkowa Leśna around Warsaw, can be seen around big metropolitan areas. It would not be fair to see them as separate compact entities in the same way as Kościan, a city which is not bordering any big urban area, nor is it shaped by natural features. This leads to a conclusion that delimitation of urban areas in future research could try to use the concept of functional areas instead of administrative boundaries. According to The OECD definition (Moreno-Monroy et al., 2021), functional urban areas (FUAs) allow to capture connections between cities and their surroundings. This can help grasping the suburban sprawl more accurately than presented in this research.

Moreover, this study acknowledges the discrepancies between land uses, which tend to be overly generalised in CLC. Future research could benefit from incorporating these factors and improving the accuracy. Exploring morphological aspects like street connectivity building density (Burton, 2002) and combining it with economic and functional aspects of compactness warrant further investigation. Moreover, population data coming from municipal data allowed for a generalised urban density calculation. This could be improved by using population data with more precise geolocation.

In conclusion, this study provides a robust framework for analysing urban compactness in the European context, offering valuable insights into the spatial dynamics of urban areas, such as the spatial implications of planning policies or economic processes. Since CLC datasets cover the entire EU, this method is replicable in every member state, allowing for further comparative studies. The findings underscore the need for tailored urban policies that address the challenges of urban dispersion and promote sustainable urban development.

6. Summary

This study contributes to the state of knowledge by introducing and testing a shape measure to assess urban compactness across urban areas, offering a general but comprehensive national analysis. The research reveals that compactness in Poland is falling over the analysed time between 2006 and 2018. It shows that

smaller urban municipalities are more compact in shape, whereas larger municipalities exhibit a logarithmic pattern of higher urban population density. Geographic patterns indicate that compact cities are more concentrated in Poland's southern and central regions.

Despite these advancements, the measure should have considered factors such as functional urban areas, topography, the location of a city in relation to other cities (free standing or adjacent) and the aspects of proximity of urban areas to city centres. Future research should also incorporate morphological factors like street connectivity, building density, building typologies, and economic and functional aspects of compactness. Addressing these limitations will enhance understanding of urban dynamics and inform more effective urban planning and policy-making, contributing to more sustainable development patterns in the context of climate change as well as in times of demographic and urban shrinkage.

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Review 1:
Authors may consider widering of aspect of sustainablility in context of the subject of the article.

Review 2:
The article and the research carried out are very interesting due to the analysis of the problem of spatial compactness of settlement structures within the administrative boundaries of municipalities - it is recommended to further develop research on this topic, paying even more attention to the depth of the relationships and processes occurring between selected phenomena hidden under the analyzed metrics. The review of the literature should be praised, carefully characterizing the current state of research on the subject.
The text lacks an explanation of the AD symbol when describing the formula for the compactness index.
From the substantive point of view, it seems that it would be good to expand the Results paragraph with an additional analysis, in this case examining the correlation between Ci and Ud (e.g. using the Pearson correlation coefficient), so that conclusions drawing attention to the relationships between population density and changes in the compactness of settlement structures are more objective.
It seems that ultimately, with an increased number of features determining the degree of compactness of cities, ranking methods (zero unitarization, Perkal and Hellwig) could be used to build a synthetic index. It also seems that it is worth focusing on cities, but not only within administrative boundaries, but above all on functional areas. Such a solution would allow for the inclusion of suburbanization areas in the analyses.

sustainability

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Understanding the Relationship between Urban Form and Urban Shrinkage among Medium-Sized Cities in Poland and Its Implications for Sustainability

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Abstract: Understanding the relationship between urban form and urban shrinkage is crucial for developing sustainable urban policies, particularly in medium-sized cities facing demographic and economic challenges. This study investigates the complex relationship between urban form and urban shrinkage in medium-sized Polish cities (population of 20,000 to 100,000), highlighting the implications for sustainability. Utilising a comprehensive multi-factor approach, it analyses the shrinkage and growth trends over 15 years (2006–2021) by establishing a shrinkage/growth score based on social, demographic, and economic factors for each city. It examines spatial aspects, particularly urban form compactness and population density, using Corine Land Cover (CLC) spatial data, making the methodology applicable to urban areas across Europe. The findings reveal no significant overall correlation between urban compactness and shrinkage/growth score across all cities. However, a positive correlation exists within "urban municipalities", indicating that less compact urban areas tend to experience more shrinkage. Additionally, a temporary negative correlation between population density and shrinkage/growth score was observed from 2006 to 2016, which shifted to a positive trend in "urban municipalities" from 2016 to 2021. These results highlight urban shrinkage's complex and dynamic nature and its potential ties to urban form. The study concludes with recommendations for urban policymakers and planners regarding compact and dense urban strategies to mitigate the adverse effects of shrinkage and enhance urban resilience and sustainability. While the trends change, the study highlights the need for further analysis of these relationships.

Keywords: Polish medium-sized cities; urban shrinkage; urban form; compactness; spatial measures; urban population density; CORINE Land Cover

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1. Introduction

The modern-day discussion on urban population decline began in the second half of the 20th century when so-called "urban shrinkage" became a common transformation for many large cities in Europe and North America. German researchers Hausermann and Siebel [1] first used the term "shrinking cities" to describe long-term demographic, socio-economic, and spatial changes in urban areas. Since then, research on urban shrinkage has been conducted around the globe. According to the most recent UN-Habitat—World Cities Report 2022, almost half of the developed countries' cities have experienced shrinkage processes since the 2000s, most based in Europe and North America [2]. Significant population losses have also been recorded in Japanese and Northeastern Chinese cities [3,4], as

well as in Australian small towns. Shrinkage is always linked to specific local and global forces. In Australia, it is linked to youth migration, fluctuation in global mineral markets, climate change, and policy change in the localisation of government services [5,6], while urban shrinkage in the Global South is additionally related to conflicts often exacerbated by climate change [2]. Because of its multidisciplinary nature and complexity, understanding this phenomenon still challenges researchers worldwide.

The first definition of urban shrinkage (Schumpfungsprozess) embraced the multidimensional aspects beyond the population decline problem and summarised it as follows: "... [it] does not lie in individual developments. Only the interaction of population losses with selective migration of qualified young workers, unsuccessful integration of immigrants, negative economic developments, high unemployment, declining municipal financial leeway, dissolution of the city structure, and thinning out of the supply of goods and services results in an urban crisis in which negative developments can intensify into a vicious circle" [1] (p. 10). In some shrinking cities, adverse developments are deteriorating the fiscal base and disturbing the maintenance of local infrastructure levels and quality of life. Consequently, many are suffering from problems related to vacant and underutilised housing, uncompetitive local business firms, and derelict transportation systems, including streets and other utility infrastructure [7]. Large amounts of housing vacancies or underutilised supply networks and facilities raise the question of whether such infrastructures can be sustained [8]. When prolonged, this state can lead to a decline spiral, deepening over time [9].

In general, it was observed that smaller cities near economically prosperous metropolitan areas benefit from urbanisation effects and can compensate for natural population development. In contrast, those in peripheral and structurally weak areas struggle to cope with the consequences of demographic change [10]. Due to limited resources, small- and medium-sized cities with less beneficial positions will have less time to react. The question of whether effective urban spatial strategies on a local level can influence resilience to the decline spiral and promote a sustainable path for shrinking medium-sized cities without growth is an important and complex one. Resilience theories suggest that cities can adapt, transform, or resist challenges and maintain their core functions [11]. However, it is essential to understand which spatial qualities impact urban resilience and sustainability. Reis, Silva, and Pinho [12] note the growing importance of understanding the relationship between spatial qualities and urban resilience to urban shrinkage. However, understanding how effective urban strategies can influence resilience and promote sustainability in shrinking cities requires a comprehensive and interdisciplinary approach.

Urban planning practices and how they relate resilience to urban decline have been widely debated among scholars [9,13,14]. According to Schwarz et al. [15], shrinkage has severe implications for all dimensions of sustainability and quality of life in cities. These implications force planners and policymakers to search for new concepts. Pallagst et al. [9] suggest that effective management of urban shrinkage requires shifting attitudes from growth to de-growth, reuse, and retrofit. In times of scarce external funding, inclusive governance and innovation in urban planning play a crucial role [9]. Haase et al. [14] point out that different external and internal drivers influence urban growth and development, and planning policies should focus on inward-oriented, right-sized, compact cities with revitalized dense urban centres. The Urban Renewal program in Eastern Germany successfully implemented this approach through the Stadtumbau Ost program and the complementary IBA Saxony–Anhalt 2010 program for medium-sized cities facing urban shrinkage. These projects provided valuable insights for research and planning for urban shrinkage. Despite criticism, they enabled many cities in Eastern German states to enter a new path of stable de-growth despite continuous depopulation trends in the region. The abovementioned approach emphasises urban compactness and density as the critical qualities that help redirect the decline path towards a more optimistic, stable de-growth path.

The concept of urban compactness has been widely linked with the sustainability of urban areas. In the context of shrinkage, it has been associated with improved outcomes of

sustainable shrinkage planning. However, the empirical literature on this subject is still lacking. A literature review conducted by Reis et al. [12] on spatial metrics used in urban shrinkage studies revealed that these metrics are insufficient to comprehensively assess spatial patterns.

In light of this, the present study aims to at least partly bridge this gap in empirical literature by testing the relationship between urban compactness, urban population density, and urban shrinkage processes. The objective is to assist urban governments in responding more precisely to the challenges of urban shrinkage in medium-sized cities by providing them with a methodology to monitor the urban shrinkage patterns with the use of available datasets. While more research on a wide, national scale is still needed to gain understanding, this study serves as a step in finding the relationship between urban form and urban shrinkage patterns in European medium-sized cities.

The conceptual framework for the study is based on the example of Poland. Possible connections between changes in urban form in all Polish medium-sized cities (population size of 20,000–100,000) and urban growth and shrinkage processes are investigated. These proposed connections reflect current planning knowledge regarding factors associated with urban shrinkage. Against the background of the identified research gaps, briefly summarised in the introduction and expanded in subsequent sections, together with reflection on the debate and theory of shrinking cities, the following hypotheses structure this work:

H1. *There is a statistically significant correlation between compactness and shrinkage of medium-sized Polish cities.*

H2. *There is a statistically significant correlation between urban population density and shrinkage of medium-sized Polish cities.*

H3. *The trend persists within the analysed timeframe.*

This study incorporates statistical and geospatial data to explore urban shrinkage and growth processes and the shape of each city in the analysed years. Geospatial tools evaluate urban form concerning its compactness and population density. By correlating the findings of both datasets, this study aims to test the hypothesis mentioned above. Figure 1 provides an overview of the study's structure and methodology. Within this diagram, a number of key tools have been used to execute the research. Briefly, these are as follows: QGIS for spatial analysis and Visual Studio Code to manage and write scripts in Python language with Pandas libraries.

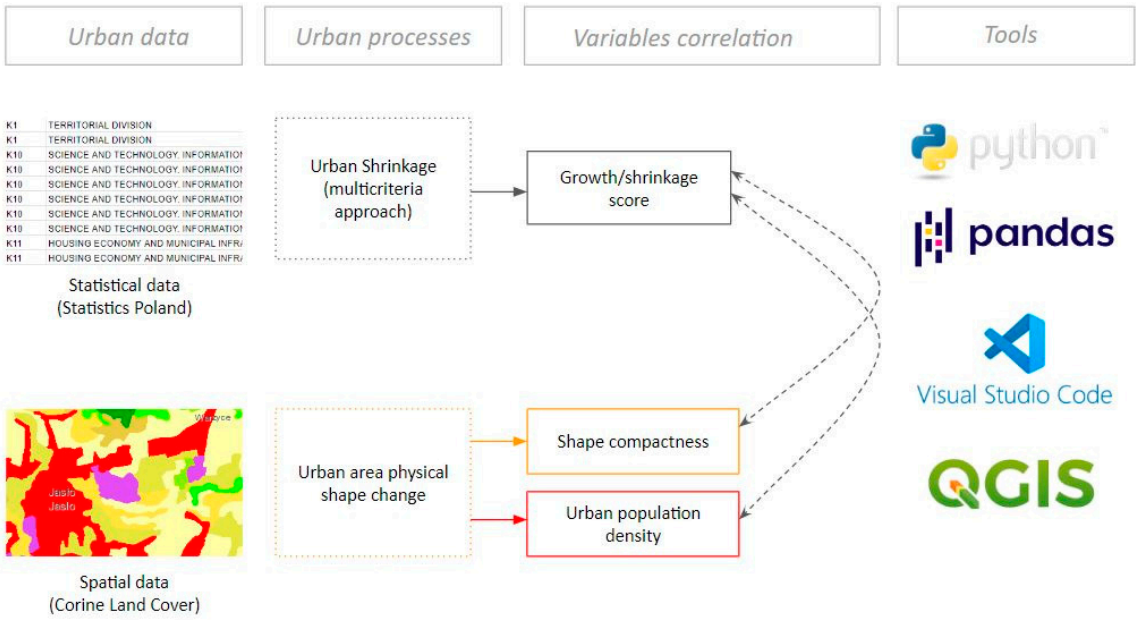

Figure 1. Research plan diagram. Source: Authors.

The article has six sections. After this general introduction, Section 2 addresses the changing spatial patterns of urban shrinkage, presenting an overview of the literature. A particular emphasis is set on the measures of urban form. This section concludes with identified research gaps and outlines the research proposal. Section 3 presents the materials and methods used in the research, along with the selected subjects and time frames of analysis. The outcomes of all measured variables are presented in Section 4, along with a statistical analysis of their relationships. Finally, Section 5 presents and compares the main findings with previous research. The article ends with Section 6., which summarises the conclusions and provides a list of references.

2. Spatial Patterns of Urban Shrinkage

Although analysing urban morphology and shape in urban research dates back to at least the early 20th century [16–18], data and computational limitations have prevented a more comprehensive implementation of these metrics beyond case studies. However, the field has significantly broadened with the advancement of geospatial tools and computing power. Nonetheless, little research has examined urban metrics and shrinkage across all cities in the national urban network, which necessitates significant computing capacities and sophisticated spatial data analysis. Recent research in this field highlights the importance of quantitative methods and emphasises the physical dimension of urban areas.

2.1. State of Research on Spatial Patterns of Urban Shrinkage

According to Kazimierczak and Szafrańska [19], there are three primary scales for analysing spatial patterns of urban shrinkage, as shown in Figure 2. Comparative studies at the national and regional levels can identify differences and similarities in the causes, progression, and consequences of depopulation among a specific group of cities, providing general and detailed conceptual and theoretical assumptions (e.g., Turok and Mykhnenko [20]). At a lower level, general urban studies (urban and supra-urban scale, according to Kazimierczak and Szafrańska [19]) can identify direct and indirect depopulation effects relevant to local growth and planning. Intra-urban scale studies, which focus on a city, its specific districts, urban zones, or housing estates, can be compared across the city to provide a comprehensive understanding of the dimensions of urban shrinkage [19]. It can also reveal shrinkage of certain areas despite overall growth processes when looking at the entire city. Thus, integrating studies at all three levels can provide a complete picture of urban shrinkage.

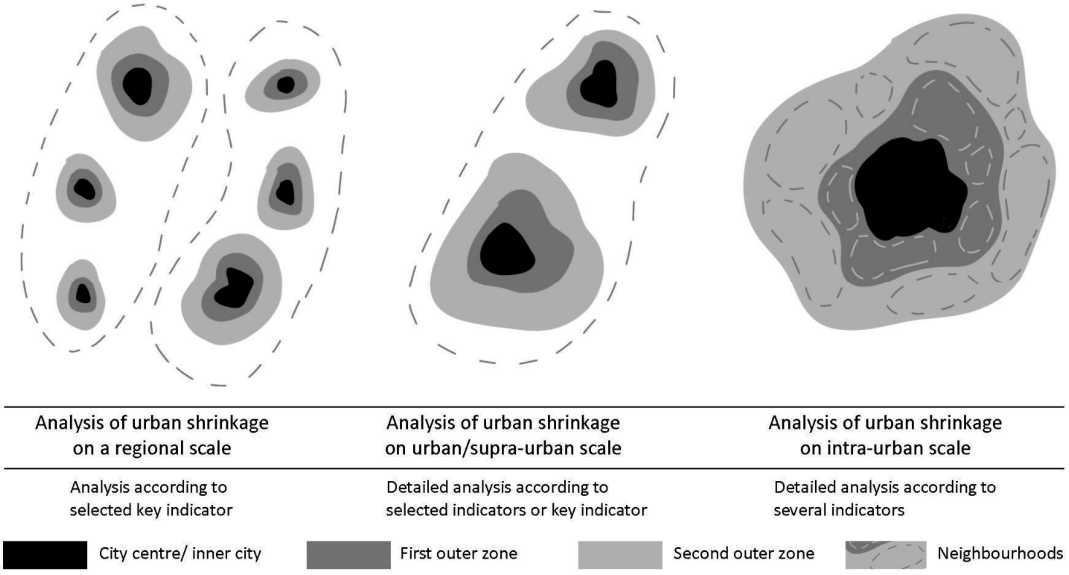

Figure 2. Scale of analysis of urban shrinkage process; Source: Authors based on Kazimierczak and Szafrańska [19].

A literature review on spatial patterns of urban shrinkage conducted by Reis, Silva, and Pinho [12] shows that it is less extensive than the literature on growth patterns. This is partially because spatial patterns of shrinkage tend to be less precise, as built-up areas do not disappear when people move out [12]. Großmann et al. [21] propose examining shared spatial characteristics across different scales that may indicate shrinking urban areas.

2.1.1. Regional or Inter-Urban Scale

Spatial patterns of urban shrinkage on a national scale often reveal entire regions undergoing structural changes such as deindustrialisation. Examples can be found in the Rust Belt in the USA, the old industrial regions of Northern Great Britain, the German Ruhr region [9], China's Northeastern regions of the Yangtze River Delta [22,23], and many more worldwide. These hot spots of urban shrinkage might be temporal or long term. Analysing large-scale associations involves looking at metropolisation processes and their effects on all cities in the urban hierarchy. Liu et al. [22] looked at inter-urban hierarchical dependencies to analyse patterns between different sizes of growing and shrinking cities in Northeast China from 2000 to 2020. Their study reveals five typical patterns, with small and medium towns experiencing more challenges than bigger, central ones. However, the growth of the central city might as well have a strong spillover effect on the region [22]. Tan et al. [23] used Nighttime Light Data to identify possible reasons for urban shrinkage in the Yangtze River Delta. The remotely sensed nighttime light (NTL) can accurately record the trajectory of human production and life, reflecting the integrated demographic, economic, and spatial changes of cities. Their study concluded that the mono-economic structure, the difficulty of industrial transformation, and the lack of linkage among bigger cities were the leading causes of shrinkage in that region [23]. Yu et al. [24] investigated the connection between urban shrinkage and urban resilience indicators. Their research pointed to various resilience indicators, including urbanisation and environmental indicators. The results showed no significant relation between shrinkage and these indicators. However, the nature of Chinese urbanisation and its hierarchical urban settlement model makes it difficult to relate the results to other urban contexts. Therefore, research conducted in the European context can show different relationships compared to those found in China.

2.1.2. Urban and Supra-Urban Scale

When analysing urban areas in Germany in the period from 1996–2006, Siedentop and Fina [25] observed increased suburban sprawl, which continued despite ongoing depopulation in the core city. The physical patterns of "shrinkage-sprawl" are similar to those of urban sprawl in a growing context, resulting in a fragmented and perforated territory with low-density development, increasing vacancy, and deteriorating urban fabric in inner city locations (Figure 3). On the other hand, research on "post-socialist sprawl" conducted by Schmidt et al. [26] demonstrates that declining densities and sprawling growth patterns are not only linked to demographic decline and economic change, but instead, they have been "exacerbated by public policy and unregulated market-induced growth in the case of the other CEE countries" [26] (p. 17). They conclude that the continuing demographic transition of much of Eastern Europe calls for a research agenda that analyses the impacts of shrinkage on urban development in much more detail [26].

Urban shrinkage often results in urban areas where fewer people and fewer activities are spread out across a more extensive territory [25,27]. This results, on the one hand, from low-density suburban sprawl and new land-intensive industrial enterprises, an automobile-oriented transport network, and, on the other hand, a deteriorating urban core that suffers from population loss, a lack of investment in public infrastructure, neighbourhood deterioration, and an overall image problem [26]. Consequently, this development pattern generates excessive costs, such as increased public expenditures for building and maintaining infrastructure and public services. It bears a commercially negative impact on the city centre, an increase in energy and fuel consumption, and a negative impact on household budgets and the environment [28]. In a study on the correlation between urban sprawl

and economic performance in selected growing Polish cities, Lityński [29] concluded that higher local economies significantly correlate with a more minor degree of urban sprawl.

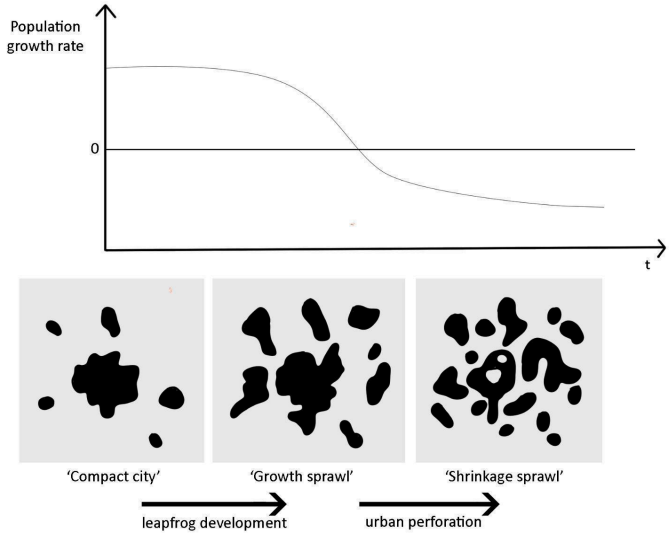

Figure 3. Pattern dimension of "shrinkage sprawl". Source: Authors based on Siedentop and Fina [25].

Consequently, the more compactly the houses in a particular municipality are built across its space, the higher the local economy level, regardless of the distance from the city [29]. On the other hand, a study of urban sprawl in two shrinking cities, Leipzig and Liverpool, shows that sprawl is not a challenge bounded by shrinkage [27]. The study concluded that declining cities' suburban zones are similar to those in thriving regions. However, some shrinking cities might have problems with urban sprawl, but they are often more burdened with the urban decline of the inner city [30].

2.1.3. Intra-Urban Scale

The growth and shrinkage of urban areas often co-occur, resulting in a growing geographic divide within and between cities and their surrounding regions. Various studies, including those by Hollander et al. [7], Pallagst et al. [3], and Wolff and Wiechmann [31], have examined this phenomenon. A study by Schwarz et al. [15] tested simulation models on urban land-use change to understand relations with shrinkage. The models were tested in selected US, European, and Japanese cities. The results show a very heterogeneous mechanism; no single model fulfils the criteria to explain the relations. Another study explored the morphological aspects of Łódź and found that patterns of intra-urban shrinkage were not uniform, with the downtown and historic areas being particularly affected, in line with Klaassen's [32] theoretical assumptions regarding the mismatch between urban and social subsystems [19]. However, while there are numerous case studies on the subject, large-scale and longitudinal studies on the spatial patterns of urban shrinkage are few. One such study by Wang et al. [4] analysed 15 cities in Northeastern China and found that shrinking cities had lower compactness and land-use efficiency than growing ones. As cities evolve and transform, industries that rely on resources may abandon significant amounts of industrial land, exacerbating the problem of lagged land-use efficiency in shrinking cities. Further research on this topic is necessary to identify spatial patterns of urban shrinkage in Europe and provide more evidence for informed planning decisions.

2.2. Polish Urban Shrinkage Context

The decline in the urban population in Poland is a significant challenge for the country's spatial policy, as projected by the Poland Statistics [33] forecasts for 2023–2060. According to the report, the population of Poland will experience a decline by 2060 of 25% in the low scenario and 40% in the high scenario [34]. This decline will primarily affect urban

areas as the progress of suburbanisation is expected, especially in rural areas around major urban centres [34]. This alarming trend has prompted numerous researchers to address the issue and propose strategies to counteract and eliminate its adverse effects in cities. The Institute of Geography and Spatial Organization of the Polish Academy of Sciences has conducted numerous analyses of this topic. Project manager prof. Śleszyński stated that, proportionally, it might be one of the most significant declines in the world.

Furthermore, medium-sized cities are the group most affected [35,36], and due to limited resources, they face challenges to manage it quickly and effectively [35–37]. A study by Szymczyk and Bukowski [38] confirmed that trend by investigating the patterns of urban shrinkage in all Polish cities through a multicriteria indicator approach. It highlights that medium-sized cities were the predominant size type among all shrinking cities between 2016 and 2021, with over half of medium-sized cities classified as shrinking, as shown in Figure 4. It is worth adding that the number of inhabitants of shrinking medium-sized cities (4.0 mil. in.) is almost the size of small and large shrinking cities together (4.7 mil. in.). The terms small, medium, and large cities in the Polish context are explained later in this paper.

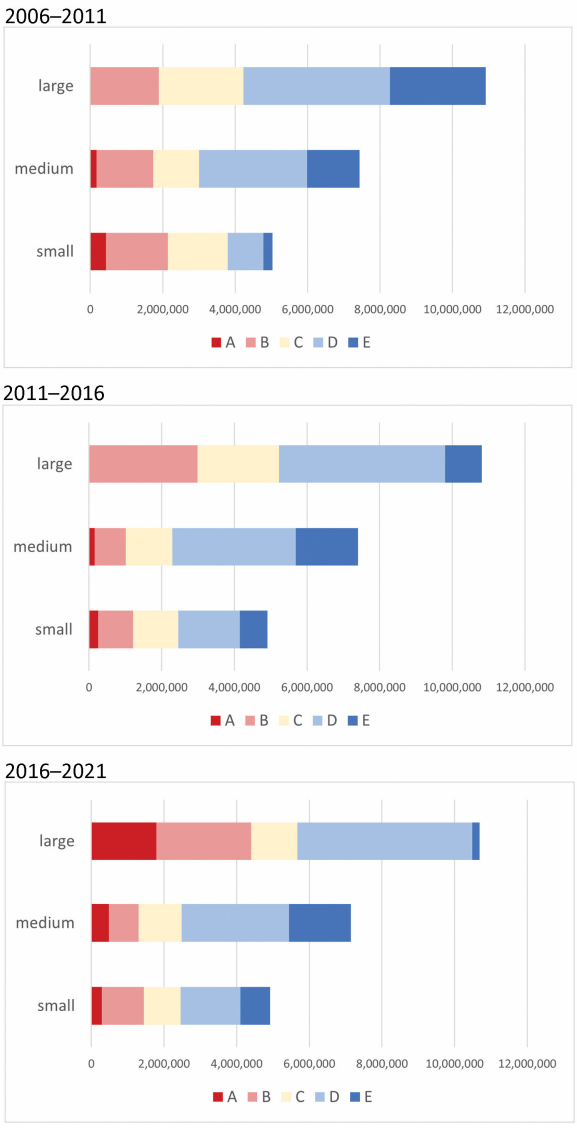

Figure 4. The number of inhabitants of small, medium-sized, and large cities in Poland in three 5-year periods divided by growth and shrinkage type (A growing significantly, B growing, C stagnant, D shrinking, E shrinking significantly). Source: Szymczyk and Bukowski [38] based on the multicriteria method [39].

In the European settlement network, medium-sized cities have a vital supply function for rural regions, providing goods and infrastructure for basic and more specified needs. They are essential elements of a sustainable polycentric urban network. These types of cities are especially endangered by demographic change and fiscal collapse. Their future significance and development depend on external circumstances and internal governance strategies. Due to the urgency and magnitude of the problem, the urban shrinkage of medium-sized cities in Poland challenges traditional, growth-oriented urban planning strategies and requires informed, innovative approaches. Thus, empirical studies on the relationship between shrinkage and urban space help find more adequate solutions.

While medium cities are the group most affected by shrinkage in Poland, many are in socio-economic balance or thriving. Understanding if there are common spatial patterns among growing and shrinking medium-sized cities can provide critical information about relations between spatial and socioeconomic factors. Since planning theories and tools were mainly developed for growth-oriented planning, researchers call for advancing shrinkage-oriented tools [12] to help shape more appropriate urban shrinkage governance.

2.3. Compactness

Urban compactness is typically viewed as the antithesis of urban sprawl [40], linked to high social and environmental costs in urban planning [41]. While the term "compact city" has different meanings, it implies different evaluation approaches. The OECD describes the characteristics of the compact city as "dense and proximate development patterns (...) urban areas linked by public transport systems (...) accessibility to local services and jobs" [42] (p. 15). The term "compact city" is often said to have first been used by Dantzig and Saaty [43], who were principally interested in a more efficient use of urban resources. According to Ahlfeldt and Pietrostefani [44], three concepts are commonly used in describing the compact city: economic, morphological, and mixed-use densities, each translating into different measures (Table 1). They include measures such as the population density of a spatial unit, employment density, and mix of uses or demarcated limits of urban and rural borders [44]. It is worth adding that compactness is regarded as a relative concept, not a concept of absolute material density. Thus, it must be analysed in a specific national or regional context.

Table 1. Compact cities characteristics. Source: Ahlfeldt and Pietrostefani [44].

Index	Characteristic	Summary
A	Economic density	Refers to the number of economic agents living or working within a spatial unit and is typically measured as population or employment density (Thomas and Cousins 1996; Churchman 1999; Burton 2002; Neuman 2005).
B	Morphological density	Refers to the density of the built environment and captures aspects of the compact city such as compact urban land cover, demarcated limits (demarcated urban/rural land borders), street connectivity, impervious surface coverage, and a high building footprint to parcel size ratio (OECD 2012; Wolsink 2016; Neuman 2005; Burton 2002; Churchman 1999).
C	Mixed land use	Captures the co-location of employment, residential, retail and leisure opportunities (Churchman 1999; Burton 2002; Neuman 2005), both horizontally across buildings and vertically within buildings Burton (2002).

An example of such a study can be found in Angel et al. [45], where the authors explore relationships between the compactness of urban form and climate change. They state: "Other things being equal, both population density and shape compactness help determine the average travel distances in cities, and, hence, affect their energy consumption and their greenhouse gas emissions. They also affect the length of infrastructure lines and the length of commutes. In principle, therefore, increasing either the shape compactness or the population density of cities can contribute—in different yet similar measures—to mitigating climate change" [45] (p. 1). Overall, the study not only demonstrates the importance of density and shape compactness as critical measures in the shrinkage discussion but also as

critical in helping to forge greater sustainability, especially in urban transport and climate change policy in cities.

Another example of measuring compactness comes from China. In their research on spatial relations of shrinking cities, Wang et al. [4] used a multicriteria assessment with multiple statistical indicators ranging from population, economic, land use, and public-service compactness [4]. Mouratidis [46], on the other hand, uses a combination of urban population density, building typologies, and functional mix in his study to assess the compactness of Oslo's neighbourhoods. In a study on the link between urban form and CO_2 emissions, Guo et al. [47] used four measures to analyse urban area compactness and complexity. He et al. [48] analysed 293 Chinese shrinking cities in search of relationships between shrinkage and urban form characteristics. Their research examined changes in morphological characteristics of urban expansion, such as fragmentation, compactness, urban sprawl, and city size.

Due to the scale of this study (a large number of analysed data), it uses selected key indicators and follows the "morphological density" characteristics Ahlfeldt and Pietrostefani [44] described. It aims to analyse the spatial urban form of all medium-sized municipalities in Poland, reflected by the urban–rural boundaries and measured with "shape irregularity" [12] (p. 11). The authors calculated compactness using a compactness index of demarcated urban borders and more precise urban population density, considering the actual urbanised land instead of administrative boundaries. Such politically drawn boundaries can arbitrarily include large areas of non-urbanised territory or, conversely, very little or no non-urban land, depending on where they are drawn. Densities so derived are, therefore, totally inconsistent with each other and non-comparable.

3. Materials and Methods

This study adopts a quantitative approach to examine the urban settlement network in Poland over a 15-year timeframe. It draws on classifying urban areas in Poland using a multicriteria indicator of urban growth and shrinkage. The results from the multicriteria analysis are then compared to spatial data expressed in compactness and density. The study checks if there is a correlation between urban growth and shrinkage and urban-form parameters. The following section provides a comprehensive overview of the study's subjects, time frame, data, and analysis methods.

3.1. Subjects

This study focuses on all medium-sized Polish cities. The selection of cities is based on Poland's administrative system. Expressed simply, on the highest/regional level, we have a voivodeship (województwo), which consists of counties (powiat); counties are divided into individual local-authority municipalities (gmina); a municipality contains either an individual city (GUS level 6, kind 1), only villages—rural area (GUS level 6, Kind 2), or a mix of a town and villages—urban-rural area (GUS level 6, Kind 3)(see Figure 5 for municipalities map). Due to data availability, continuity of research, and nationwide comparability, the selected method uses the smallest local government unit, i.e., the municipality (gmina).

In 2021, Poland had 2477 municipalities: 302 urban, 662 urban–rural, and 1513 rural. While this research focuses on medium-sized cities and towns (in Poland, both cities and towns are called "miasto", a city), we utilised data for "urban" municipalities and those in the "urban–rural" category. An "urban municipality" (6, 1) is a municipality with an individual city and has administrative boundaries tightly enclosing urban areas. An "urban–rural municipality" (6, 3), on the other hand, includes a city and various urban areas such as villages and small towns loosely connected to each other. Due to the difference between these two types of urban areas, the analysis is divided into two categories:

- urban area in the urban municipality (6, 1),
- an urban area in the urban-rural municipality (6, 3), including a city and small settlements.

To maintain data consistency, we carefully considered the varying number of spatial units in Poland over different years. After much consideration, we ultimately selected 964 cities to ensure accurate comparison and analysis of our data without discrepancies. We relied on a simplified division based on Statistics Poland's categorisation. Cities with a population of up to 20,000 are categorised as small, between 20,000 and 100,000 as medium, and above 100,000 as large. When analysing urban population data, it is crucial to establish a consistent reference point for size classification. Therefore, we chose to base our categories on the beginning of each analysed period despite potential population fluctuations over time. This approach allowed us to guarantee precision and consistency in our analysis. The population was categorised based on the 1st year for the 5-year periods. Figure 5 provides a map of the different spatial entities.

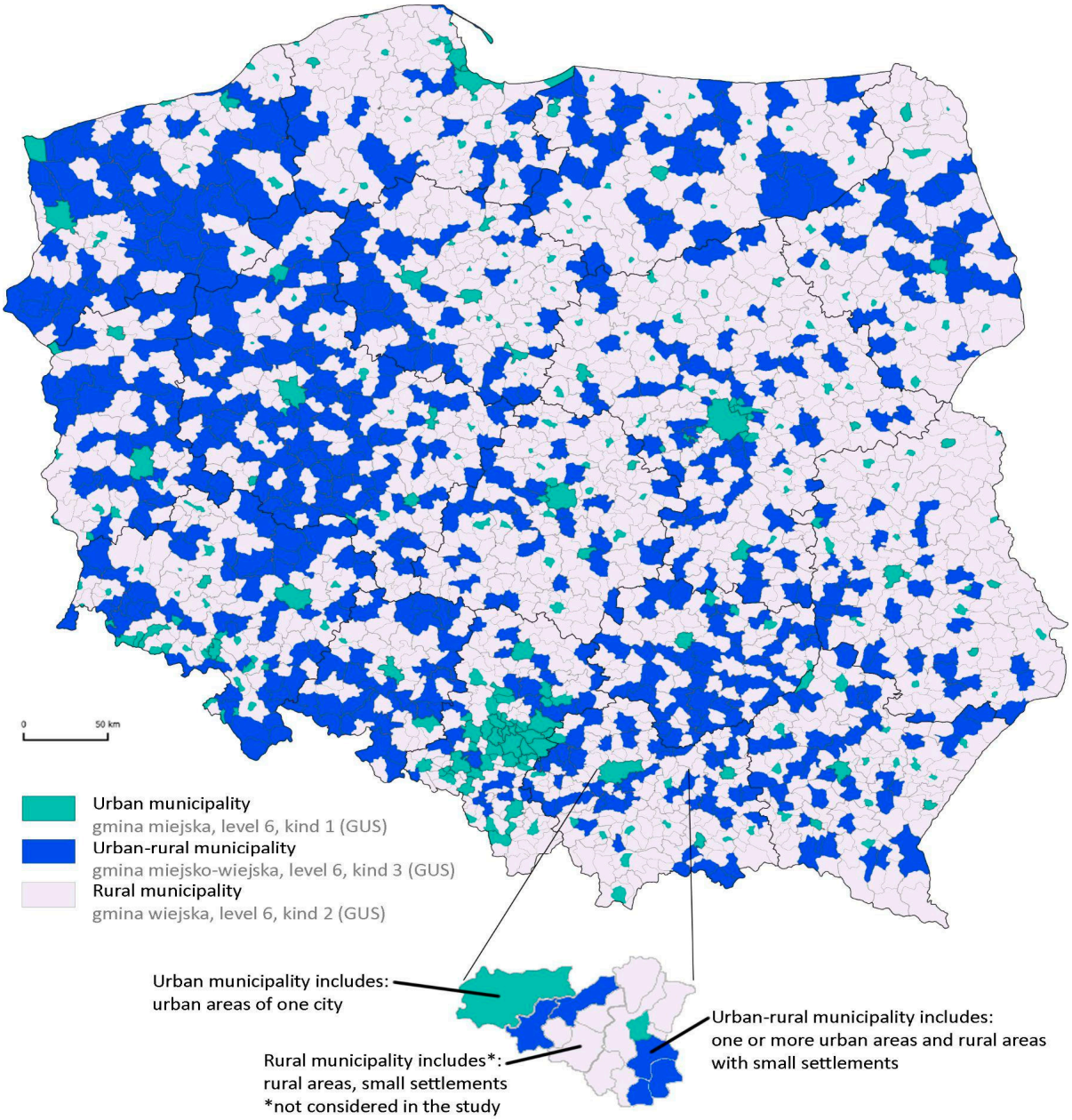

Figure 5. A map of Poland's urban and urban–rural spatial units according to the TERYT register as of 1 January 2022. Source: Authors based on Statistics Poland (TERYT) for 2022 [49].

3.2. Timeframe

Urban dynamics are inherently complex and can vary depending on the specific phenomena being studied. For instance, socio-economic factors tend to be more dynamic than physical changes to the built environment. To fully understand the relationships between these factors, it is necessary to conduct longitudinal studies. The timeframe of our study was chosen for two reasons: first, because of the availability of spatial data (as discussed in Section 3.4), and second, because our study builds on the multicriteria indicator assessment of shrinking cities in Poland conducted by Szymczyk and Bukowski [38]. The analysis was divided into three sub-periods: 2006–2011, 2011–2016, and 2016–2021 (Figure 6).

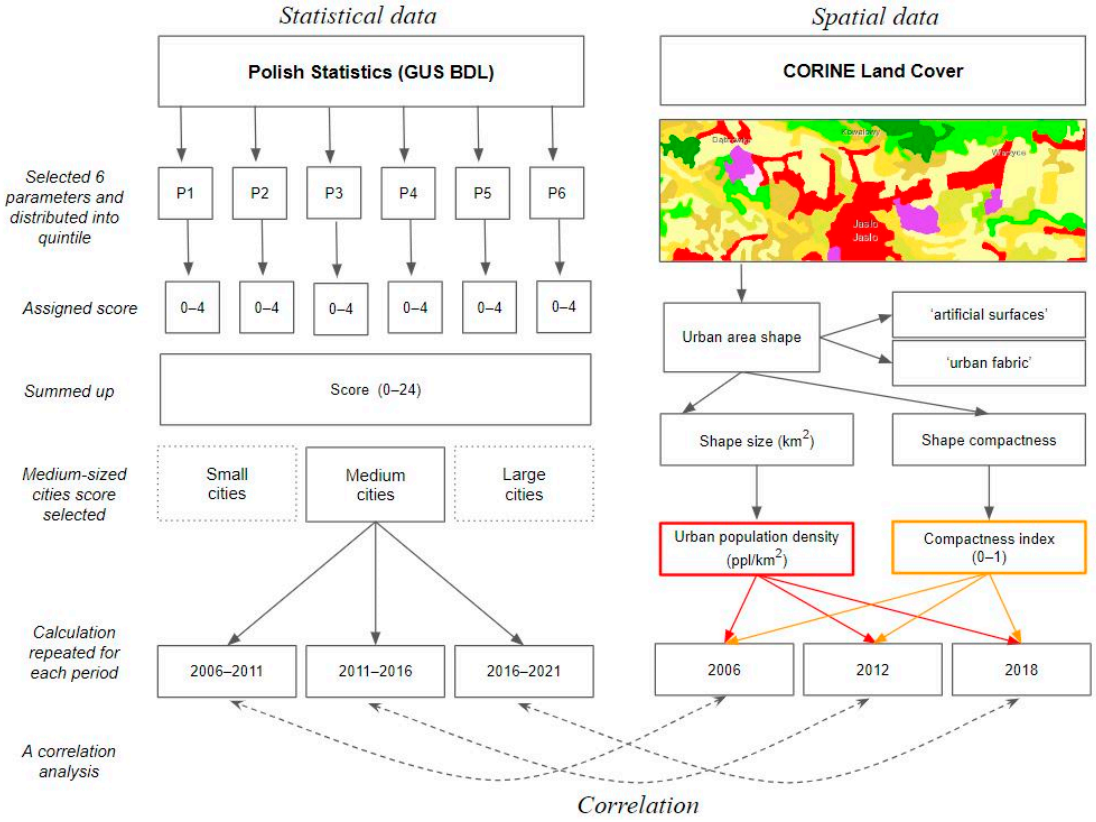

Figure 6. Correlation analysis between the shrinkage/growth score and corresponding spatial analysis. Source: Authors.

3.3. Statistical Data

The literature aiming to quantify the phenomenon of urban shrinkage can be divided into two fundamental approaches [50]. The traditional view sees urban shrinkage as a progressive depopulation, with studies primarily focusing on population-based indicators [20,51,52]. However, there are examples where demographic and economic development do not align. Cities with declining populations may still have robust economic structures and continue to thrive [31]. In Poland, a multi-criterion approach to assess urban shrinkage has been conducted by researchers such as Jaroszewska [53], Śleszyński [36], Sroka [54], and Szymczyk and Bukowski [38], among others. Of these, Szymczyk and Bukowski [38] focused on the method developed by Milbert [55] from the Federal Office for Building and Regional Planning in Germany (BBSR in German). The Milbert method captures this multidimensionality through six demographic and socio-economic indicators. This method was adapted to the Polish territorial division and statistical data. It considered the following equivalent indicators from Polish Statistics: annual average population development (in %), net migration per 1,000 inhabitants, annual average change in working-age

population (in %), annual average change of employed persons (in %), annual average change of unemployed persons in (% points), and annual average change in municipality own income per inhabitant (in %). A summary of the indicators with different units of measurement and a spread of the division into quintiles is made. Based on a tested normal distribution, the limits of the outer quintiles are always such that the relative distance from extreme values and outliers does not play a role. The affiliation of units to a quintile is translated into points for each indicator. Points are summed up into a numeric score ranging from 0–24 for each city in each research period. Cities scoring 0–10 are considered shrinking, 11–13 are stagnating, and 14–24 are growing (the calculation outcomes can be found here: https://rcin.org.pl/dlibra/publication/276466 (accessed on 13 May 2024). The outcomes for a group of medium-sized cities are selected to relate them with the spatial analysis results we conduct here. Figure 7 shows the distribution of different types of medium-sized cities in 2016–2021, with division from strongly growing to shrinking significantly. Consequently, we have analysed all 180 medium-sized cities in the first period, 184 cities in the second period, and 180 cities in the last period.

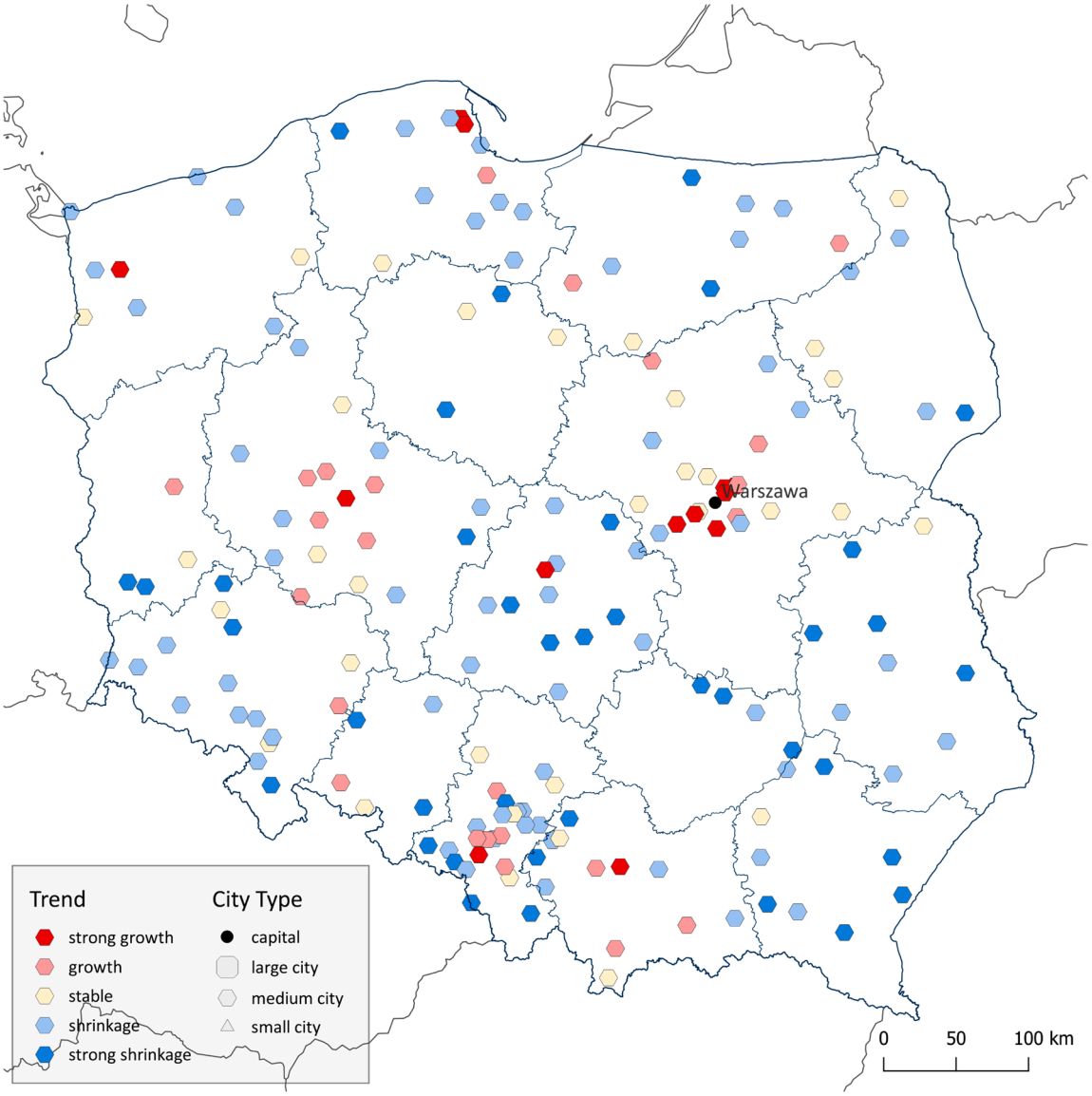

Figure 7. A multicriteria analysis of growth/shrinkage trend for all medium-sized Polish cities in 2016–2021. Source: Authors.

3.4. Spatial Data

The data for intra-urban spatial metrics of medium-sized cities is based on land-use data from the CORINE Land Cover (later called CLC) for the area of Poland. The CORINE Land Cover (CLC) data is one of the most important sources of land use and landscape dynamics data from a European perspective and the only consistent and harmonised multinational, continental-scale collection of land-use information in the world [56]. It is a standardised methodology for producing continent-scale land cover, biotope, and air-quality maps. CLC uses a hierarchical classification system to categorise land cover and land use into 44 classes grouped into the following five main categories:

1. Artificial surfaces—built-up areas, including residential areas, commercial and industrial areas, mines, and green urban spaces.
2. Agricultural areas—arable land, permanent crops, meadows, pastures, and land principally occupied by agriculture with significant areas of natural vegetation.
3. Forests and semi-natural areas—forests, shrubs, and open areas with little or no vegetation.
4. Wetlands—inland marshes, peat bogs, salt marshes, salines, and intertidal flats.
5. Water bodies—inland waters and marine waters.

The methodology involves the interpretation of satellite images combined with ancillary data and field surveys to ensure accuracy (see a detailed explanation of the CLC methodology in the European Environment Agency [57]). Furthermore, CLC classes can be associated with the concept of defining Production–Living–Ecological Space (PLES), which is commonly used in Chinese planning policies. PLES categorises land into spaces for production (industrial and commercial units in CLC), living (urban fabric in CLC), and ecological purposes (forest, wetlands, and water bodies in CLC). This alignment allows for the integration of PLES into the European context. Since the product is updated every 6 years, with the most recent update in 2018, the three corresponding datasets were selected for this analysis. For 2006–2011, a CLC2006; for 2011–2016, a CLC2012; and for 2016–2021, a CLC2018 (Figure 6). In their study of urban sprawl in Poland, Cieslak et al. [58] indicated that the CLC database is a reliable source of information about urbanisation processes. On the other hand, it has to be noted that there are some discrepancies between the CLC and the actual urbanised areas in Poland [59]. Consequently, the results were later compared with the data on urban population density calculated by the Head Office of Geodesy and Cartography (GUGiK) in Poland [60], which employs similar urban uses (see Table 2) but a different calculation method.

3.5. Defining Urban Compactness

To define the shape of the urban area, we considered the 44 classes of land uses provided by the CLC. We opted for two approaches. First, we consider an urban area a shape represented by only "urban fabric" layers (Class Number 111, 112). This is where most people live in the city. Secondly, we also analyse a more broadly defined urban area as "artificial surfaces", which includes infrastructure and green urban areas, represented by 11 classes (Table 2). The aim is to ensure that the two approaches allow us to control for potential errors related to inadequate urban form definition.

Built-up and urbanised areas, according to GUGiK, are shown below in Table 3.

The selected classes were isolated and cut to the boundaries of the municipality. Next, they were merged into one shape consisting of one or more polygons (Figure 8). Each shape received a unique identification number of a spatial unit, called the National Official Register of the Territorial Division of the Country (TERYT).TERYT functions on the basis of The Law of June 29th, 1995 on official statistics (Journal of Laws from 2018, item 997 with amendments) and the Regulation of the Council of Ministers of December 15th, 1998 on detailed principles of running, using and making available the territorial register and related to it, obligations towards the state administration agencies and the self-government entities (Journal of Laws from 1998 No 157, item 1031 with amendments). Moreover, the development of the analytical method included some calibrations. Due to

some discrepancies in the spatial data (such as imprecise land use demarcation), many cities had minor shapes left after cutting to the boundaries. We have analysed possible thresholds to avoid distorting the calculation by examining the histogram of shape sizes. Most small patches had a size below the 2% of the total shape area. Consequently, we have decided to set a threshold of 2% of the total shape area. All the shapes that were below this value were deleted.

Table 2. CLC codes indicate classes considered and their respective colours. Source: CLC [56].

	CLC Code	Name
	111	Continuous urban fabric
	112	Discontinuous urban fabric
	121	Industrial or commercial units
	122	Road and rail networks and associated land
	123	Port areas
	124	Airports
	131	Mineral-extraction sites
	132	Dump sites
	133	Construction sites
	141	Green urban areas
	142	Sport and leisure facilities

Table 3. Polish Statistics codes and classes indicating urbanised areas (in Polish, "grunty zabudowane i zurbanizowane"). Source: GUGiK [60].

Code	Class Name
B	Housing
Ba	Industrial
Bi	Other built-up areas
Bp	Urbanised areas with no buildings
Bz	Recreation areas
K	Mining areas
dr	Transport areas—Roads
Tk	Transport areas—Rail
Ti	Transport areas—other
Top	Areas designated for future infrastructure investments

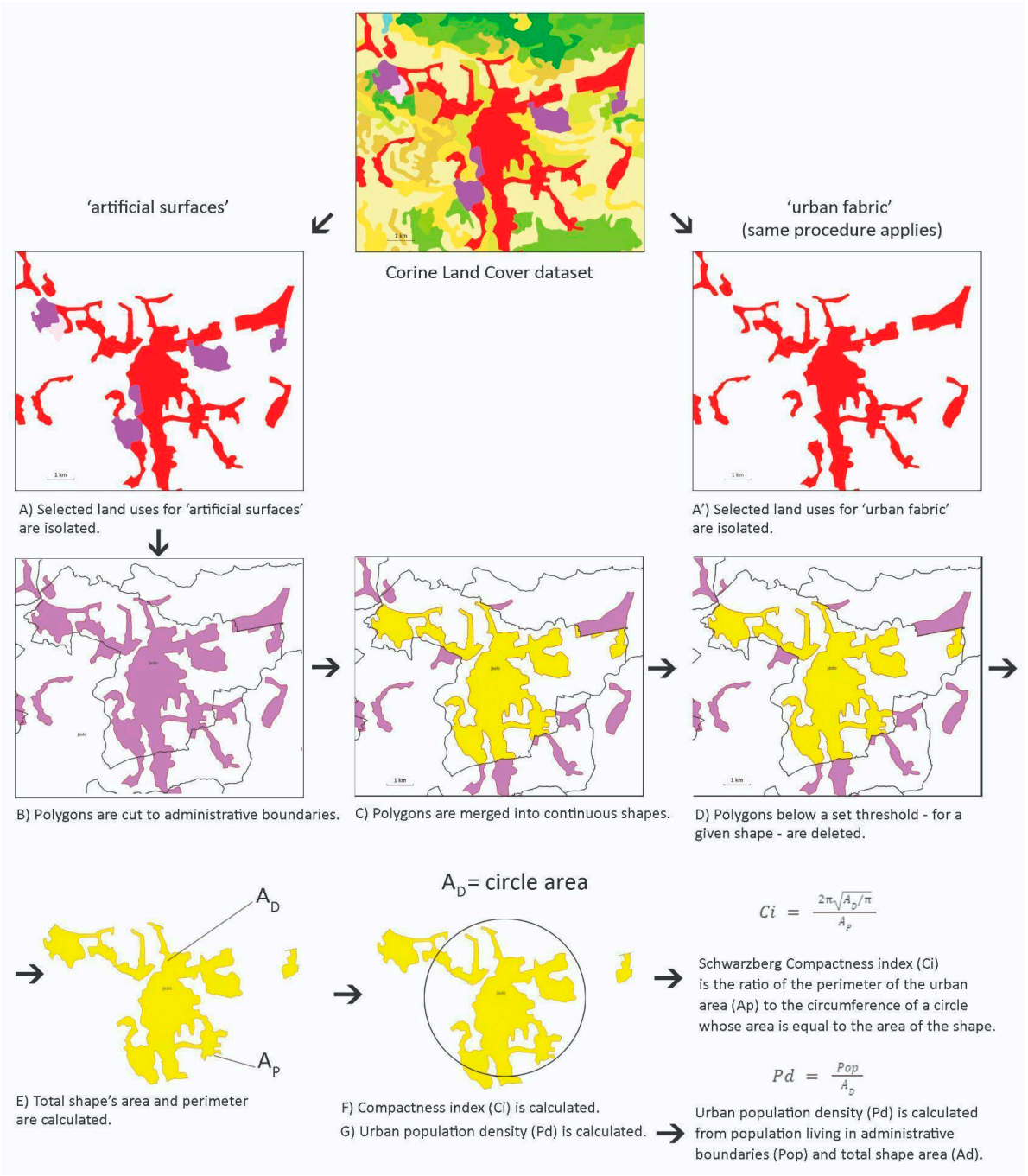

Figure 8. Urban shape-analysis diagram based on the Jasło urban municipality (6, 1) example. Source: Authors.

In summary, the calculation consists of the following operations (presented in Figure 8) for each selected year:

A. Isolation of selected land use classes;
B. A cut of land-use polygons with city administrative boundaries;
C. Merge polygons into continuous shapes;
D. Delete polygons below a set threshold for a particular shape;
E. Calculate the shape's area and perimeter;
F. Calculate the compactness index;
G. Calculate the urban population density.

3.5.1. Spatial Measures

Once the shape is extracted and its measures calculated, we calculate a measure of compactness and a measure of urban population density. For this research, the following definitions are used:

A_D	Urban area
A_P	Urban area perimeter length
Ci	Compactness index
Pop	Urban population
Pd	Urban population density

Compactness Index Calculation

As mentioned previously, there are multiple ways to measure compactness. This study uses the compactness index (Ci) measure, quantifying the compactness of shapes' irregularity. According to the classification by Reis et al. [12], the proposed metrics "measure the extent to which urban settlements are more continuous and concentrated or more scattered (fragmented)" [12] (p. 13). Thus, the fundamental idea primarily revolves around the two-dimensional expansion pattern of an urbanised area, which is deemed to be more compact if the pattern is more clustered towards a centre and with less sprawl, leapfrogging, or branching [61]. There are many measures of the compactness index [62–64]. Among them, a few were identified by Barnes and Solomon [65] as the most commonly used. Among these most common, the authors selected a single measure named after the name of its author, Schwartzberg [17].

Interestingly, both the Polsby–Popper and Schwartzberg Compactness indexes are mathematically equal (one score is the other score raised to a power) and based on comparing an urban area shape to a circle assumed to be a perfectly compact shape. Schwartzberg compactness index is calculated as the ratio of the perimeter of the urban area (A_D) to the circumference of a circle whose area is equal to the area of the urban area. It can be written as

$$Ci = \frac{2\pi\sqrt{A_D/\pi}}{A_P}$$

Scores range from 0 to 1, where 0 is the least compact and 1 is the most compact. This index was calculated for each medium-sized city in each CLC year.

Urban Population Density Calculation

The second measure considers the urban area (A_D) and the municipality population (Pop) in the corresponding period to calculate the urban population density. As opposed to the city population density provided in the national statistics, this method captures a more accurate density as it considers not the administrative boundaries but the actual urban area within them. Compared to the administrative boundaries, the urban area excludes agricultural land, forests, and water bodies, among others, providing a more accurate picture of the city boundaries and where people live. The urban population density (Pd) can be formally written as:

$$Pd = \frac{Pop}{A_D}$$

3.5.2. Statistical Correlation Analysis between Spatial Measures and Urban Shrinkage

In the last step, an analysis was undertaken, establishing the correlations between the urban growth and shrinkage score, the urban-shape-compactness measure (Ci), and the urban population-density measure (Pd). We conducted the correlational analysis, determining whether there is any relationship or association between several variables of interest [66]. A correlation analysis and Pearson's correlation coefficient (r) were used. Correlation r results from comparing two variables in their normalised form over the sample of n values in each case. One of its properties is that its value varies between +1 and −1, representing a maximum positive and inverse correlation. Values close to 0 show

there is no statistical correlation between the variables. In the social sciences, values above 0.5 can be considered a statistically significant, high correlational effect [67]. The analysis method used the statistical significance index or *p*-value. This indicator confirms that the correlation between two variables is significant if *p* is below 0.05. This enabled us to test our research hypotheses. It is worth mentioning that correlation results are cross-sectional and should be interpreted cautiously, as they point to associations but not necessarily causal relationships.

3.6. Tools

Due to the spatial scope, long timeframe, and volume of data (multiple variables, times all 2621 municipalities considered in this research, times three periods), any manipulation required data-analytic tools. Python 3.11 programming language and data analytics libraries (Pandas and NumPy) were used to harmonise and clean the data. After downloading, raw CLC data were converted into a dataset connecting the statistical ID with spatial ID (called TERYT). Each spatial unit was checked for completeness. Spatial analysis was conducted using QGIS 3.28 and Python scripts (see the Appendix A for detailed information).

4. Results

The results are divided into two stages. The first stage (Section 4.1) shows the outcomes of each variable analysis: compactness index (Ci) and urban population density (Pd). The second stage (Section 4.2) shows correlation analyses between the variables and urban growth and shrinkage score (Sc) (for more details on Sc, see Section 3.3).

4.1. Spatial Measures Calculation Outcomes

This section presents the outcomes of calculating compactness index (Ci) and urban population density (Pd) for three selected CLC datasets (2006, 2012, and 2018).

4.1.1. Compactness Index

The results of the compactness analysis for medium-sized cities in three periods show rather similar outcomes (Table 4). The Schwartzberg compactness index is expressed in numbers ranging from 0–1, with one being the most compact. It shows a normal distribution in all years. While the maximum values decreased in time, the minimum ones in 2006 increased slightly in 2012 and 2018. This shows an overall trend of light dispersion in small- and medium-sized cities, while large cities did not change their compactness index over time). Among the most compact medium-sized cities throughout the analysed timeframes (Holding top 10 position in all the analysed periods) were Ząbki, Piastów, Żyrardów, Legionowo, Słupsk, Giżycko, Świdnica, and Rumia. The least compact were Wyszków, Świebodzin, Opoczno, Jastrzębie-Zdrój, and Pszczyna (Figure 9).

Table 4. Outcomes of the compactness index analysis (Schwartzberg compactness index) for all medium-sized Polish cities in 2006, 2012, and 2018 considering urban areas as "artificial surfaces".

Schwartzberg Compactness Index Outcomes Per Year	2006	2012	2018
Number of observations	180	184	180
Min	0.1160	0.1047	0.1049
Median	0.2628	0.2577	0.2503
Max	0.5146	0.5221	0.5186

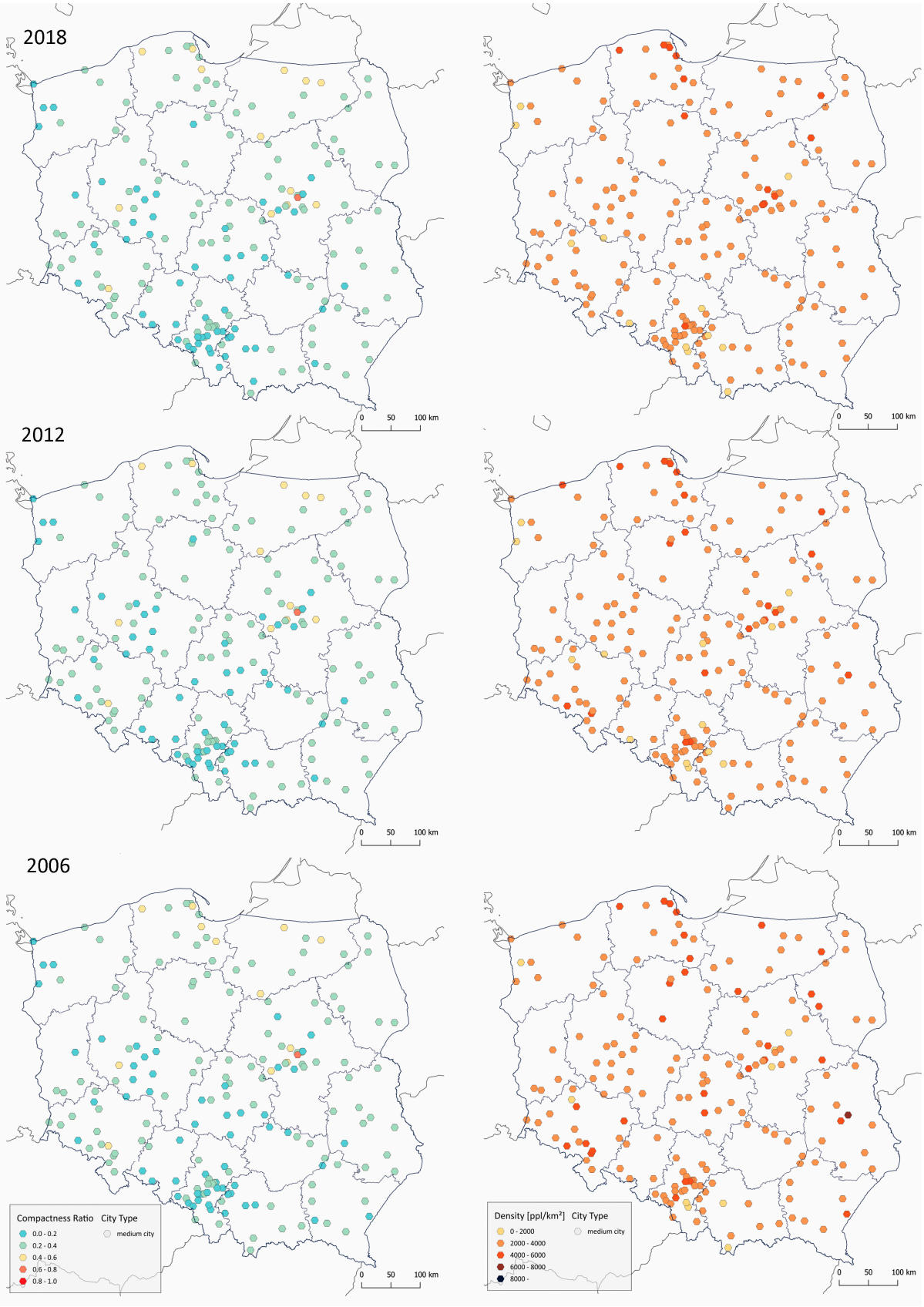

Figure 9. A map of Polish medium-sized cities showing a degree of urban compactness index (**left**) and urban population density (**right**) in different years (based on "artificial surface" area). Source: Authors.

4.1.2. Urban Population Density

The urban population density-analysis results for medium-sized cities in three periods show a normal distribution and a strongly decreasing trend for all city sizes (Table 5). While the maximum values decreased in time, the minimum densities fluctuated, showing a trend of medium cities becoming less dense over time. This shows an overall trend of dispersion in medium-sized cities. Among the densest cities throughout the analysed timeframes (Holding top 10 position in all analysed periods) were Wejherowo, Sopot, Świętochłowice, Ełk, and Grudziądz (Figure 9). Polkowice, Trzebinia, Skawina, Czechowice–Dziedzice, Wyszków, and Pszczyna were the least dense.

Table 5. Urban population density for medium-sized Polish cities in 2006, 2012, and 2018 considering urban areas as "artificial surfaces".

Urban Population Density Outcomes Per Year	2006	2012	2018
Number of observations	180	184	180
Min (ppl/km²)	1511	1512	1406
Median (ppl/km²)	3259	3000	2903
Max (ppl/km²)	5353	4893	4502

It is important to note a discrepancy between the results obtained from the 2012 CLC dataset calculation and the urban population density available in Polish Statistics (Table 6). However, the Polish Statistics data were only published for 2013, 2014, and 2015, with no new data available to date, making it difficult to compare. Based on the analysed sample of randomly selected cities, the Polish statistics appear to calculate fewer urban land areas than the "artificial surfaces" do (and more than "urban fabric"). As a result, density values are higher in Polish Statistics. There could be several reasons for this difference. While Tables 2 and 3 show that the principles of delimitation of urban areas are very similar, the method relying on CLC uses satellite images, which simplifies the contours of urbanised land, which leads to discrepancies. On the other hand, CLC 2018 dataset classes were compared with building address points data by Śleszyński, Gibas, and Sudra [59], showing an average of approximately 35% of buildings located in areas defined in CLC as agricultural, suggesting an underestimation of urbanised areas in CLC. Finally, since this study aims to establish a methodology that uses comparable, open-source, up-to-date, and Europe-wide land-use data, CLC data meet these requirements. While Polish Statistic data are not regularly updated, it does not provide a reliable source for the purpose of territorial monitoring.

Table 6. A comparison of selected cities' urban population density based on CLC and GUGiK data. Source: Author's research and GUS BDL [33].

Name of the City	Urban Population Density Based on the Authors' Calculation for 'Artificial Surfaces' for CLC2012 (people/km²)	Urban Population Density Sourced from GUS BDL for 2013 (people/km²)
Wieliczka (6, 3)	2134	3634
Jasło (6, 1)	2357	3568
Bartoszyce (6, 1)	3809	4295
Śrem (6, 3)	3156	2877
Leszno (6, 1)	3307	4164
Wejherowo (6, 1)	5735	5847
Sopot (6, 1)	5614	5582
Trzebinia (6, 3)	1617	2926
Polkowice (6, 3)	1513	1231

Figure 10 shows an overall trend of light dispersion in small—and medium-sized cities, while large cities did not change their compactness index over time. Similarly, Figure 11 shows that the urban population density analysis results show a strongly decreasing trend, but this time, it is for all city sizes. The two measures indicate an overall trend of dispersion, mostly among medium-sized cities. Figure 12 presents the outcomes of shrinkage/growth score for each city size type.

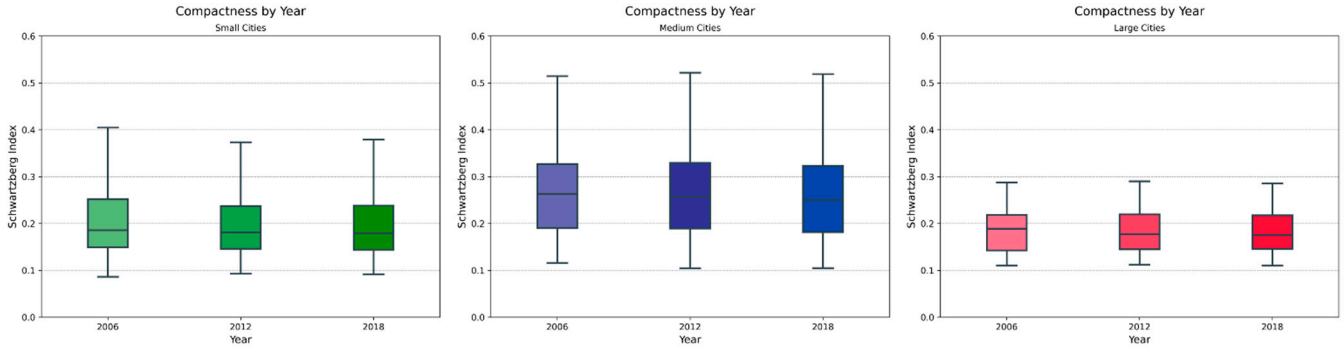

Figure 10. An overview of the distribution of outcomes for small-, medium-, and large-sized Polish cities in terms of urban compactness index in three analysed periods between 2006 and 2021. Source: Authors.

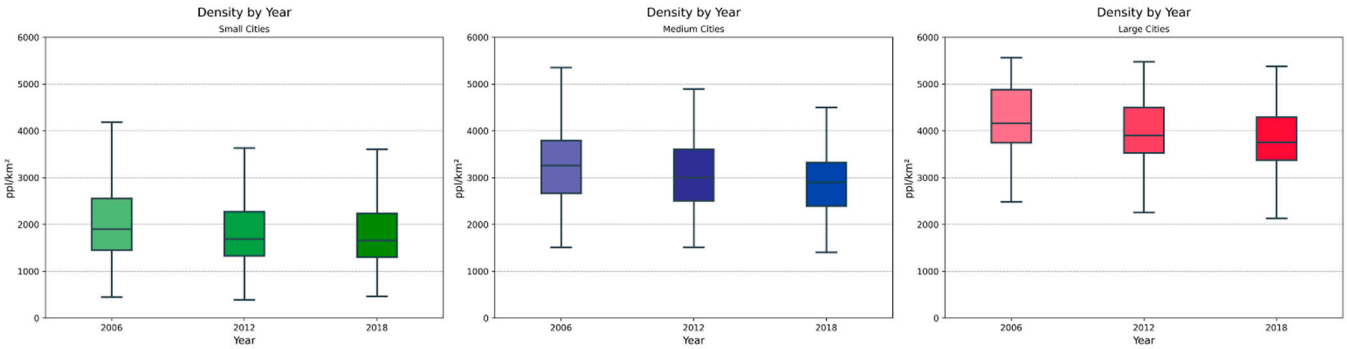

Figure 11. An overview of the distribution of outcomes for small-, medium-, and large-sized Polish cities in terms of urban population density in three analysed periods between 2006 and 2021. Source: Authors.

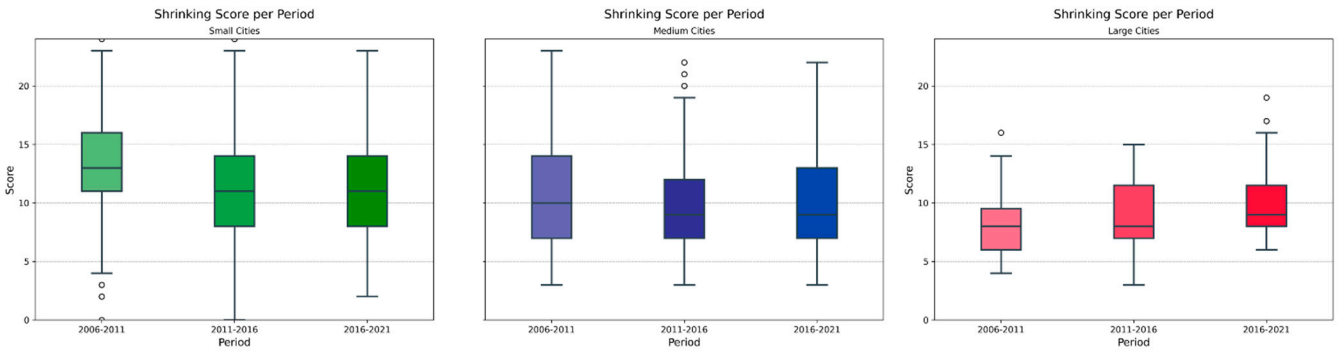

Figure 12. An overview of the distribution of outcomes for small-, medium-, and large-sized Polish cities in terms of urban growth/shrinkage score in three analysed periods between 2006 and 2021. Source: Authors.

4.2. Correlation Analysis

This section presents the outcomes of the correlation analysis between the score and spatial measures such as compactness index (Ci) and urban population density (Ud). They

are additionally broken down into more detailed analyses looking at these correlations for urban municipalities (6, 1) and urban–rural municipalities (6, 3). This was done because the characteristics of a single urban area differ from those of an urban-rural area, which considers a more diverse context with possible smaller settlements included in the calculation.

4.2.1. Correlation between the Shrinkage/Growth Score and Compactness Index

An examination was performed on the relation between compactness index and urban shrinkage and growth score for three periods. All statistically significant results are shown in greyscale in the tables. The results for all medium-sized cities changed over time from a minor positive in the first period to a slight negative correlation in the later periods. However, with a *p*-value above 0.05, all the results are statistically insignificant (Table 7 and Figure 13). When correlated separately between urban municipalities (6, 1) and the score index, there is a minor positive correlation with a strong statistical significance for all periods (Table 8). This positive correlation means that growing cities are typically more compact. While the strongest correlation was in the first analysed period, this relation weakened over time. The correlation analysis for urban–rural municipalities (6, 3) shows a change from a negative to a positive value. However, the *p*-value is insignificant for all the periods (Table 9), and, per the criteria described by Onwuegbuzie and Daniel [67], a correlation value dropping from 0.3 to 0.18 is not strong.

Table 7. Correlation outcomes between the shrinkage and growth score and urban compactness for all medium-sized cities.

	Periods		
	2006–2011	**2011–2016**	**2016–2021**
Number of observations	180	184	180
Correlation for "urban fabric"	0.09 (p = 0.21)	−0.07 (p = 0.32)	−0.06 (p = 0.4)
Correlation for "artificial surfaces"	0.05 (p = 0.44)	−0.08 (p = 0.235)	−0.08 (p = 0.252)

Table 8. Correlation outcomes between the shrinkage and growth score and urban compactness for all medium-sized urban municipalities (6, 1).

	Periods		
	2006–2011	**2011–2016**	**2016–2021**
Number of observations	147	149	147
Correlation for "urban fabric"	0.34 (p = 0.00)	0.23 (p = 0.00)	0.22 (p = 0.005)
Correlation for "artificial surfaces"	0.29 (p = 0.0002)	0.19 (p = 0.014)	0.18 (p = 0.024)

Table 9. Correlation outcomes between the shrinkage and growth score and urban compactness for all medium-sized urban–rural municipalities (6, 3).

	Periods		
	2006	**2012**	**2018**
Number of observations	33	35	33
Correlation for "urban fabric"	0.02 (p = 0.9)	−0.12 (p = 0.47)	0.02 (p = 0.89)
Correlation for "artificial surfaces"	−0.017 (p = 0.923)	−0.074 (p = 0.67)	0.064 (p = 0.72)

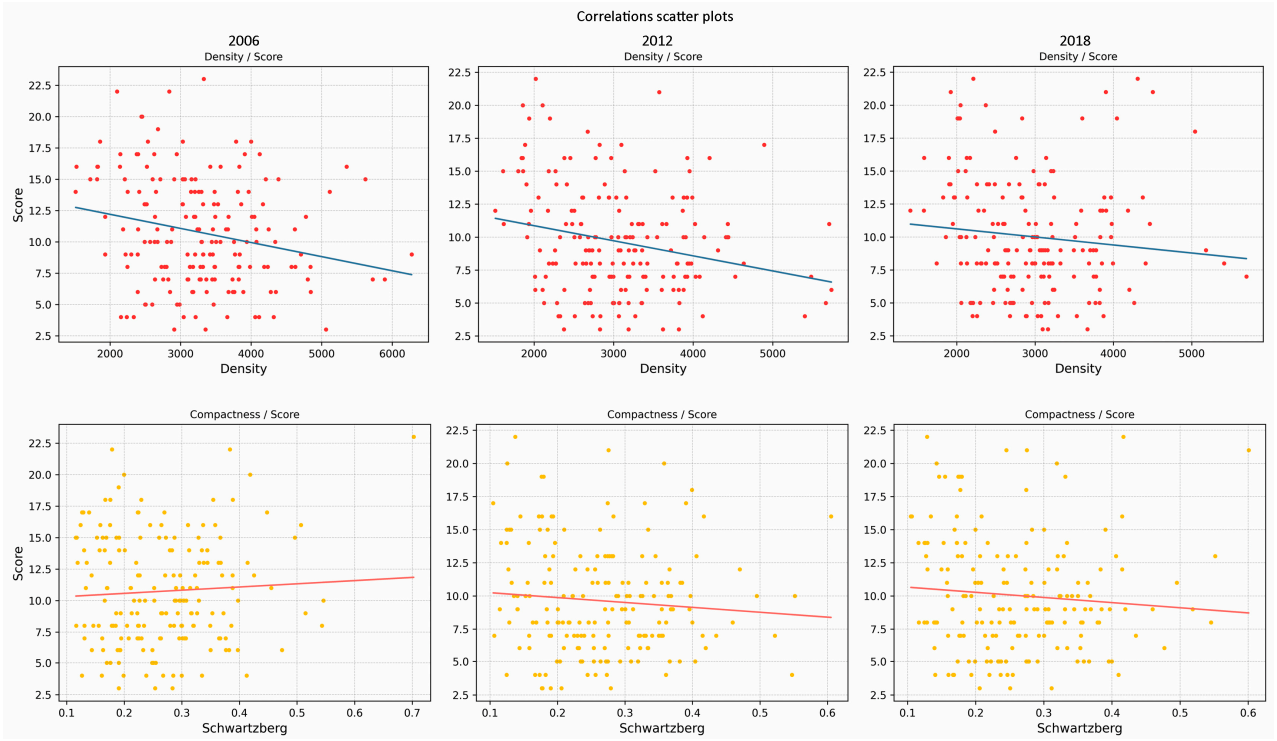

Figure 13. Scatter plots of Pearson's correlation analysis between urban population density ("artificial surface") and growth/shrinkage score and between compactness ("artificial surface") and growth/shrinkage score for all medium-sized Polish cities in three periods (2006–2011, 2011–2016, 2016–2021). Source: Authors.

4.2.2. Correlation between the Shrinkage/Growth Score and Urban Population Density

The correlation between urban population density (an independent variable) and urban shrinkage and growth score (a dependent variable) was conducted for three periods. The results for all medium-sized cities for the first two periods indicated a slight negative correlation with a statistically significant *p*-value (Table 10 and Figure 13). However, the results from the last period for "artificial surfaces" show that this correlation disappears. While in the first analysed periods, a lower score (high shrinkage) is related to higher urban density, this trend does not hold, and in 2016–2021, it is not true anymore. Moreover, when looking at the separate correlations conducted for the urban municipalities (6, 1), there is a switch to a positive correlation trend in the last period (Table 11). While due to high *p*-values, these correlations are statistically insignificant. The analysis for urban municipalities in the last period confirms a change in trend. For urban–rural municipalities, it also shows weaker values (Table 12). Nevertheless, similarly to compactness, a correlation value of −0.2 is considered a weak relation. As the trend changes over the analysed periods, it signals a possible positive correlation in the future. As urban density increases, the shrinkage score increases, meaning that higher densities appear to be beginning to be associated with *less shrinkage*.

Table 10. Correlation outcomes between the shrinkage and growth score and urban density for all medium-sized cities.

	Periods		
	2006–2011	**2011–2016**	**2016–2021**
Number of observations	180	184	180
Correlation for "urban fabric"	−0.29 (p = 0.000)	−0.27 (p = 0.000)	−0.20 (p = 0.005)
Correlation for "artificial surfaces"	−0.222 (p = 0.002)	−0.231 (p = 0.001)	−0.105 (p = 0.157)

Table 11. Correlation outcomes between the shrinkage and growth score and urban density for medium-sized urban municipalities (6, 1).

	Periods		
	2006–2011	**2011–2016**	**2016–2021**
Number of observations	147	149	147
Correlation for "urban fabric"	−0.18 (p = 0.022)	−0.11 (p = 0.15)	−0.03 (p = 0.71)
Correlation for "artificial surfaces"	−0.081 (p = 0.32)	−0.016 (p = 0.83)	0.12 (p = 0.14)

Table 12. Correlation outcomes between the shrinkage and growth score and urban density for medium-sized urban–rural municipalities (6, 3).

	Periods		
	2006–2011	**2011–2016**	**2016–2021**
Number of observations	33	35	33
Correlation for "urban fabric"	−0.24 (p = 0.16)	−0.26 (p = 0.11)	−0.18 (p = 0.31)
Correlation for "artificial surfaces"	−0.242 (p = 0.17)	−0.28 (p = 0.103)	−0.073 (p = 0.68)

5. Findings and Discussion

The decline in Poland's urban population presents a significant challenge to the country's spatial policy. The trend of urban shrinkage, understood in a multicriteria way as a socio-economic and demographic decline, is most noticeable in medium-sized cities. However, while some cities struggle to handle the process, others thrive. By understanding the patterns and interconnections between urban form and shrinkage, it is possible to gain insights into the spatial characteristics that influence this phenomenon. This can lead to informed management of the negative impacts and enable sustainable development. In this section of the paper, we seek to check three research hypotheses on relationships between medium-sized city urban form and shrinkage (Table 13):

Addressing H1. There is a statistically significant correlation between compactness and shrinkage of medium-sized Polish cities.
Addressing H2. There is a statistically significant correlation between urban population density and shrinkage of medium-sized Polish cities.
Addressing H3. The trend persists within the analysed timeframe.

Table 13. Summary of hypothesis confirmation.

Hypothesis	**Selected Urban Areas (CLC Classes)**	**All Medium-Sized Municipalities (6, 1 and 6, 3)**	**Medium-Sized Urban Municipalities (6, 1)**	**Medium-Sized Urban-Rural Municipalities (6, 3)**
H1: There is a statistically significant correlation between urban compactness and shrinkage.	"Urban fabric"	NO	YES	NO
	"Artificial surfaces"	NO	YES	NO
H2: There is a statistically significant correlation between urban population density and shrinkage.	"Urban fabric"	YES	Yes, for 2006–2011	NO
	"Artificial surfaces"	YES for 2006–2016	NO	NO
H3: The trend persists within the analysed timeframe.	"Urban fabric"	YES	YES (for compactness relationship only)	NO
	"Artificial surfaces"	NO	YES (for compactness relationship only)	NO

5.1. Urban Shape Compactness and Urban Shrinkage

The empirical analysis conducted on the urbanised areas in Polish municipalities indicates a discernible declining trend in the compactness index (Ci) over time. Notably, the reduction in compactness is more pronounced in small- and medium-sized cities. Upon considering all types of medium-sized cities (6, 1 and 6, 3), Hypothesis 1 (H1) is not true as no statistically significant correlation was observed between urban-shape compactness and shrinkage. However, this hypothesis only holds true in urban municipalities (6,1), where a statistically significant, positive, moderate correlation exists between urban compactness and the shrinkage/growth score. The findings suggest that a more compact urban municipality is less likely to experience shrinkage. This relationship persists throughout the analysed period from 2006 to 2021 and is attributable to various factors.

A comprehensive understanding of this phenomenon necessitates the examination of diverse urban, economic, social, and demographic dynamics and their influence on sustainable development. Compactness is intricately linked to heightened resilience and sustainability, rendering it beneficial for medium-sized cities with limited governance capacities. The sprawl of urban form and expansion patterns escalate the operational costs of infrastructures. Conversely, compact cities adeptly navigate challenging socio-economic trends by concentrating activities within a smaller area, thereby reducing costs and upholding clear urban–rural boundaries. Consequently, it is observed that the more compact the urbanised area of a city, the lower the likelihood of shrinkage.

Research by Wang et al. [4] underscores that the compactness of shrinking cities in Northeast China is notably lower than that of growing ones. Conversely, a global-scale study by Angel et al. [45] asserts that city-shape compactness is independent of city population, area, population density, and per-capita income but may be contingent on physical barriers, merging of adjacent settlements, inter-city roads and rail lines, land-use restrictions, beachfront preferences, and land-market distortions. Furthermore, Dong et al. [68] suggest that transitioning from a compact form to a dispersed one is common, while the reverse is rare and difficult to achieve. Therefore, prioritising the maintenance of existing urban compactness is imperative for cities contending with urban shrinkage processes.

5.2. Urban Population Density and Urban Shrinkage

The collected data indicate a consistent decrease in urban population densities across all urban municipalities over the observed period, paralleling the findings on urban compactness. Correlation analysis between the density and the shrinkage/growth score among medium-sized cities reveals that denser urban areas were more inclined to experience shrinkage between 2006 and 2016 than less dense ones. Although the correlation results exhibit a considerable scatter, they remain statistically significant throughout that period, suggesting a trend that diminished and eventually vanished in 2016–2021. Hence, Hypothesis 2 (H2) holds true when considering all medium-sized cities, whereby denser urban areas during 2006–2016 demonstrated higher degrees of shrinkage.

This pattern aligns with the broader global trends investigated by Angel et al. [45], demonstrating an overall decline in urban density between 1990 and 2014, particularly prominent in developed countries and associated with higher economic growth rates. While Schwarz et al. [15] linked low-density settlements with the urban landscape of shrinking cities, our study of medium-sized Polish cities does not fully support this view. Nonetheless, it suggests that future development in medium-sized cities might adhere to a pattern described as "growth sprawl" by Siedentop and Fina [25], characterised by initial growth, followed by an outflux of residents from the city centre to the outskirts and subsequent urban perforation and decreased densities. However, the latest analysed period indicates a departure from this trend, as low urban population density no longer correlates with higher shrinkage/growth scores, hinting at the potential emergence of "shrinkage sprawl" [25] with a robust statistical relationship between decreasing density and increasing shrinkage in cities in the near future.

In the context of Poland, the emigration of inhabitants from denser, medium-sized cities to larger metropolitan areas may be attributed to metropolization trends driven by limited job prospects and overcrowded housing conditions. Notably, Poland exhibits consistently high overcrowding rates, a key dimension in evaluating housing conditions [69]. This trend highlights one of the challenges posed by dense urban areas and contributes to migration decisions to access better living conditions at a reduced cost. Large cities in Poland witness substantial new housing construction, attracting increased investment and employment opportunities. These dynamics, coupled with economic liberalisation and land-use policies allowing for suburban sprawl and market-led growth, have resulted in declining densities in medium-sized urban centres from 2006 to 2021 and escalating urban growth rates within the inner areas and suburbs of major cities.

5.3. Changes in Time

The third hypothesis (H3) is valid for the first relationship between shrinkage and compactness and only for urban municipalities. It is also valid for the relationship between shrinkage and density for all medium-sized municipalities when measuring urban density using "urban fabric" as the denominator. When considering "artificial surfaces" for the urban-density calculation, the trend did not persist over all analysed periods but disappeared in the last.

Furthermore, the differences in urban density between the two types of municipalities substantially impact the correlation trend. The heterogeneous nature of medium-sized cities is emphasised, indicating variations in their functioning within the urban network system. These differences are crucial considerations when devising planning implications. According to Xu et al. [70], historical development patterns of cities play a significant role in their current density, with cities historically developed as dense urban centres likely to retain this characteristic even as they experience shrinkage. An example of such a city is Bartoszyce in Northern Poland, which exhibits dense and compact urban characteristics despite facing challenges in attracting capital and residents due to its location (Figure 14). Conversely, newer growing cities, particularly those near metropolitan areas, tend to develop in a sprawl-oriented, low-density pattern by merging with adjacent settlements, as described by Angel et al. [45]. Wieliczka, for instance, exemplifies this pattern, which is characterised by sprawling development in diverse topography. While the city centre retains a relatively dense, historic urban fabric, the predominant development consists of low-density urban sprawl patterns. The location, particularly its proximity to the metropolitan area of Krakow, serves as a significant driver of growth for Wieliczka, offering ample job opportunities. These findings align with the classification of Chinese cities by Liu et al. [22]. They identified five main types depending on the relationship between the hierarchy of cities in the network. Wieliczka exhibits a so-called "growth-driven" model, with Krakow being the growth pole for surrounding medium-sized and small cities. Consequently, these findings highlight the diverse nature of medium-sized cities and emphasise the need to consider their historical development and urban characteristics in urban planning and policymaking.

5.4. Planning Implications

Studies conducted by Schiller and Kenworthy [28] stress the importance of urban densities in creating sustainable cities oriented to public transport, walking, and cycling. Moreover, according to Lytyński's [29] research, a preponderance of low densities is accompanied by lower GDP in selected municipalities. In shrinking cities, lower housing demand and lower housing costs might be seen as an opportunity to contain the sprawl and focus on improving inner city areas. This can, in the future, attract residents to central areas, maintaining or increasing density. Planning strategies should stimulate it further through investment in public transport infrastructure, better conditions for walking and cycling and improvement of urban life, public spaces, green areas, and social infrastructure [71].

Reurbanisation policies should focus on brownfields, industrial areas, former car parks, and excessive road infrastructure rather than open green spaces.

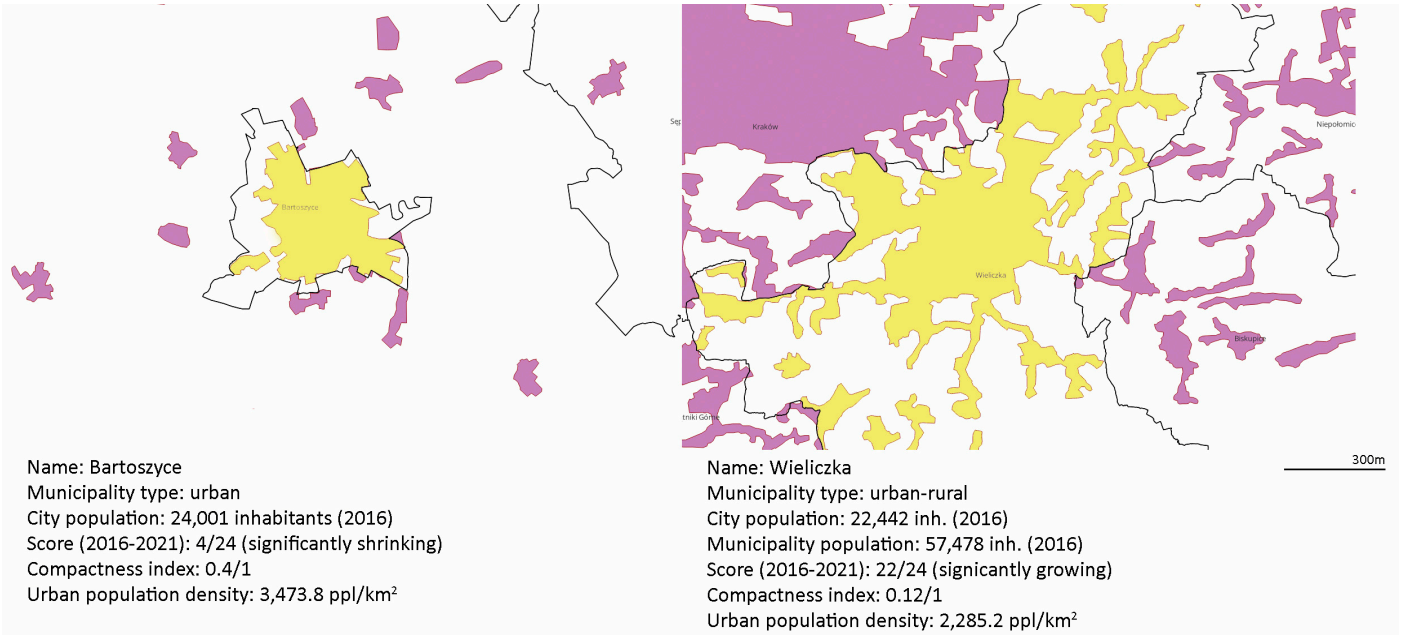

Figure 14. An example of an urban municipality (6, 1) and an urban–rural municipality (6, 3) showing different urban area-development patterns. Source: Authors.

Newman et al. [72] provide a detailed discussion of the different urban fabrics that exist in all cities today and portray these as walking fabrics, public transport fabrics, and automobile-based fabrics. They show how, over decades, traditional urban fabrics developed in the walking era (up to about 1850) and public transport fabrics (dominant in the period from 1850 to around the Second World War), have been negatively impacted and even destroyed by the imposition of automobile-based urban development, which stresses space-consuming parking, expansive road networks, and single-family, sprawling housing. Their analysis shows the critical need to stop and reverse this process by re-urbanising traditional walking and public transport fabrics, especially by reclaiming roads and parking spaces for public life and new residential development and developing TOD around rail stations. In parallel, they also emphasise the need to minimise further automobile-based urban development in most parts of the city.

Through such approaches, well-managed shrinking cities could re-grow or enter a stable and sustainable degrowth path with a balanced economic base and fewer expenses lost on excess infrastructure and excessive travel costs in cars. In essence, they have the potential to become more sustainable and resilient [73,74]. By containing its boundaries and avoiding destructive city sprawl into forested areas, thus reducing the urban heat island effect [71], an urban area can maintain lively urban life, manage assets efficiently, and allocate funds to enhance existing potential rather than further expanding built-up areas. It is worth adding that uneven growth and shrinkage patterns within one city are also common [19,75]. Therefore, it is essential that the local government monitors the situation and identifies problems early.

5.5. Research Limitations

Overall, it is essential to note that the factors mentioned above can interact in complex ways, and the specific reasons for the observed trends in this large sample of medium-sized Polish cities would require detailed local-scale analysis and additional qualitative studies. Data-collection methods and definitions for measuring "urban compactness" and "urban density" can significantly affect the observed correlations. Despite showing two approaches

to selecting different CLC land-use classes, the urban area defined in this study can be seen as overly generalised. Therefore, achieving conclusive urban-density results may require a different or refined method, perhaps collecting population and urban land-area data from local statistical databases. However, such an exercise for hundreds of cases would be highly time-consuming and beyond the scope of the present research.

Additionally, there are risks associated with data accuracy, particularly about census data in Poland. For instance, population distribution data in Poland could be improved, as there are discrepancies between actual and registered home addresses, especially among young mobile people who still need to update their addresses in the registry. This could result in overestimating the number of inhabitants in medium-sized cities, as younger population cohorts tend to relocate to larger centres for work, education, and social opportunities unavailable in smaller settlements.

Finally, while the method presented in this paper is general enough to allow for country-wide spatial analysis of all available cases, it may need to be revised to account for specific topographical conditions. For example, natural elements such as hills or bodies of water may define the boundaries of a city and render the compactness index of a city's shape and urban population density misleading. Therefore, caution should be exercised when applying the method to such cases.

5.6. Implications for Further Research

Although this study did not account for the nuances of cities within specific topographical settings, further research is necessary to explore these relationships through qualitative data. The discrepancies between the urban population densities identified in this article should be further investigated.

Additionally, a more nuanced understanding of compactness can be achieved by examining the compactness of selected cities through a functional lens and utilising data on activities such as the Internet of Things (IoT) and nighttime patterns. Further, analysing the socio-economic and cultural attributes of shrinking cities can provide a more holistic comprehension of which areas of the city face difficulties and the underlying causes.

Moreover, future studies could focus on morphological and urban qualities, such as building density, typology, floor-area ratio, street connectivity, and expansion pattern, which play a significant role in better understanding an area's compactness. Future studies could also benefit from a more extensive timeframe and a broader scope with a comparative view juxtaposing two or more national contexts and looking at different city sizes in search of patterns.

6. Conclusions

The present study provides empirical insights into the intricate relationship between urban form and shrinkage in medium-sized Polish cities. It delves into the pressing issue of urban shrinkage, examining the interplay between urban form, compactness, and population density. Spanning 2006 to 2021, our analysis aimed to test three hypotheses to grasp these relationships. The results revealed a nuanced and dynamic relationship between urban form and shrinkage. While no significant correlation was found between urban compactness and shrinkage across all medium-sized cities, a positive correlation was identified in urban municipalities. This suggests that more compact urban areas are less susceptible to shrinkage, underscoring the potential advantages of compact urban forms for resilience and sustainability. Conversely, denser urban areas showed a higher likelihood of shrinkage between 2006 and 2016. However, this trend weakened in the subsequent years, which may signal a reversal of the earlier relationship in medium-sized Polish cities.

The study emphasises the diverse nature of medium-sized cities and the need for tailored urban-planning strategies. Compactness and density, while not consistently linked to shrinkage, play roles that demand careful consideration in sustainable urban development. This is especially so in supporting global efforts to develop more sustainable urban

transport by reducing trip distances, making walking, cycling, and public transport more attractive and feasible, and minimising the need to use a car.

Based on Corine Land Cover (CLC) spatial data, our methodology extends to urban areas across Europe, providing a valuable framework for broader spatial analyses. However, the observed correlations warrant further investigation through detailed local-scale analyses and additional qualitative studies involving more diverse variables than urban density and compactness alone. Recognising limitations in data accuracy and methodological constraints, the study urges caution in interpreting observed correlations as causative, highlighting the multifaceted nature of urban-shrinkage determinants. Due to its widely recognised adverse sustainability implications, it also discourages viewing urban sprawl as a remedy to shrinkage.

Future research endeavours can benefit from refining compactness assessments to encompass morphological and functional dimensions and longer time spans, leveraging advancements in urban data analytics. In conclusion, the study underscores the need for further research, particularly in exploring the socio-economic and cultural dimensions of shrinking cities. It calls for nuanced housing policies and land-use regulations to manage urban density in shrinking cities without compromising their long-term development or sustainability objectives.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su16167030/s1, Datasets.

Author Contributions: Conceptualization, E.S.; Methodology, E.S.; Software, M.B.; Validation, M.B., J.R.K.; Formal Analysis, E.S.; Investigation, E.S. and M.B.; Data Curation, M.B.; Writing—Original Draft Preparation, E.S.; Writing—Review and Editing, E.S. and J.R.K.; Visualization, M.B. and E.S.; Supervision, J.R.K.; Project Administration, E.S. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Appendix A presents a simplified methodology for the research process. This section depicts the following aspects: shrinking city classification, compactness and density index calculation, and correlation analysis. In our example, we follow a cycle for the city of Kraków. All data were obtained either from Polish Statistics (GUS) or CORINE Land Cover (CLC).

Appendix A.1. Shrinking Score

All discrete data were obtained from BDL—Local Data Bank (in Polish Bank Danych Lokalnych) provided by GUS. These data can be either downloaded as spreadsheets https://bdl.stat.gov.pl (accessed on 13 May 2023) or via provided through REST API https://api.stat.gov.pl (accessed on 13 May 2023).

We download data for the whole research period for all unit municipalities from Level 6. The data are divided into specific subjects, which can be identified as parameters; in our case, we focus on the ones listed in Table A1. Each subject can be further divided by specific sex, age group, or additional parameters, but we focus only on total values in our case.

Table A1. BDL Subjects. Ordered shrinking parameters: P1–P6.

Parameter Id	Description
P1	Total population of municipality
P2	Inward and outward migration
P3	Population in working age
P4	Employed persons in municipality
P5	Registered unemployed persons
P6	Municipality's own revenue

After a set of queries, sample data for Kraków appear in Table A2. Teryt Id is a unique unit identifier derived from the Unit Id field. We use it as a primary ID in further computations. Level 6 indicates that a unit is a type of municipality, while Kind 1 indicates an urban municipality.

Table A2. Sample population data.

Unit Id	Teryt Id	Name	Level	Kind	Year	Population
011212161011	1261011	Kraków	6	1	2006	756,267
011212161011	1261011	Kraków	6	1	2007	756,583
011212161011	1261011	Kraków	6	1	2008	754,624
011212161011	1261011	Kraków	6	1	2009	755,000
011212161011	1261011	Kraków	6	1	2010	757,740
011212161011	1261011	Kraków	6	1	2011	759,137
011212161011	1261011	Kraków	6	1	2012	758,334
011212161011	1261011	Kraków	6	1	2013	758,992
011212161011	1261011	Kraków	6	1	2014	761,873
011212161011	1261011	Kraków	6	1	2015	761,069
011212161011	1261011	Kraków	6	1	2016	765,320
011212161011	1261011	Kraków	6	1	2017	767,348
011212161011	1261011	Kraków	6	1	2018	771,069
011212161011	1261011	Kraków	6	1	2019	779,115
011212161011	1261011	Kraków	6	1	2020	779,966
011212161011	1261011	Kraków	6	1	2021	782,137

Extracting subject-specific data is repeated independently for each parameter.

We follow the multicriteria methodology (Milbert, 2020) [39], and for each parameter, we calculate the changes year by year. We average them over 5-year periods and distribute results from each municipality in quantiles (five buckets). Based on the bucket, we assign a score from 0 to 4. If needed, a score is adjusted based on additional rules (see Table A3).

Table A3. Score assignment for the population parameter.

Teryt Id	Year	Population	Difference	Rate	Mean	Score
1261011	2006	756,267	−362	−0.000480	−0.000440	2
1261011	2007	756,583	316	0.000418	−0.000250	2
1261011	2008	754,624	−1959	−0.002590	−0.000810	2
1261011	2009	755,000	376	0.000498	−0.000640	2
1261011	2010	757,740	2740	0.003629	0.000293	3
1261011	2011	759,137	1397	0.001844	0.000758	3
1261011	2012	758,334	−803	−0.001060	0.000462	3
1261011	2013	758,992	658	0.000868	0.001155	3
1261011	2014	761,873	2881	0.003796	0.001814	3
1261011	2015	761,069	−804	−0.001060	0.000877	3
1261011	2016	765,320	4251	0.005586	0.001624	3
1261011	2017	767,348	2028	0.002650	0.002366	3
1261011	2018	771,069	3721	0.004849	0.003162	3
1261011	2019	779,115	8046	0.010435	0.004486	4
1261011	2020	779,966	851	0.001092	0.004917	4
1261011	2021	782,137	2171	0.002783	0.004357	4

Once the score for each parameter (P1: population, P2: migration, P3: working age, P4: employment, P5: unemployment rate, P6: municipality own revenue) is calculated, we sum them, and, based on the final outcome, we indicate if a municipality is growing (A, B), stagnating (C), or shrinking (D, E) type (see Table A4).

Table A4. Shrinking score calculation.

Teryt Id	Start	End	P1	P2	P3	P4	P5	P6	Total	Type
1261011	2006	2011	3	3	0	2	2	2	12	C
1261011	2007	2012	3	3	0	2	0	2	10	D
1261011	2008	2013	3	3	0	2	0	2	10	D
1261011	2009	2014	3	3	0	2	0	2	10	D
1261011	2010	2015	3	3	0	2	0	2	10	D
1261011	2011	2016	3	3	1	3	0	2	12	C
1261011	2012	2017	3	4	1	3	1	2	14	B
1261011	2013	2018	3	4	1	3	1	2	14	B
1261011	2014	2019	4	4	2	3	2	2	17	B
1261011	2015	2020	4	4	3	3	1	2	17	B
1261011	2016	2021	4	4	3	3	0	2	16	B

Appendix A.2. Spatial Indexes

Following a method described in Section 3.5, we calculate the properties of basic geometries (see Table A5). The district is the urban area indicated by the shapes of "artificial surface" codes. The calculations below are repeated for "urban area" codes.

Table A5. Municipality's geometries—based on CLC.U.

Teryt Id	Year	District	
		Area (km²)	Perimeter (km)
1261011	2006	151,538,463	361,537
1261011	2012	167,952,975	317,358
1261011	2018	169,016,958	317,574

Table A6 calculates the compactness index Ci (Schwartzberg) using the above geometries (Table A5).

Table A6. Municipality's compactness indexes.

Teryt Id	Year	Ci (Schwartzberg)
1261011	2006	0.120702
1261011	2012	0.144760
1261011	2018	0.145119

In parallel, we combine the municipality's population for a particular year and calculate the density of the district's area (see Table A7). We ensure that CLC calculations were included in the particular shrinking period.

Table A7. Municipality's density based on CLC.

Teryt Id	Start	End	Population	CLC Year	District Area (km²)	Density (people/km²)
1261011	2003	2008	757,685	2006	151,538,462	4999.95
1261011	2004	2009	757,430	2006	151,538,462	4998.26
1261011	2005	2010	756,629	2006	151,538,462	4992.98
1261011	2006	2011	756,267	2006	151,538,462	4990.59
1261011	2007	2012	756,583	2012	167,952,975	4504.73
1261011	2008	2013	754,624	2012	167,952,975	4493.06
1261011	2009	2014	755,000	2012	167,952,975	4495.30
1261011	2010	2015	757,740	2012	167,952,975	4511.62
1261011	2011	2016	759,137	2012	167,952,975	4519.93
1261011	2012	2017	758,334	2012	167,952,975	4515.15
1261011	2013	2018	758,992	2018	169,016,958	4490.62
1261011	2014	2019	761,873	2018	169,016,958.1	4507.672
1261011	2015	2020	761,069	2018	169,016,958.1	4502.915
1261011	2016	2021	765,320	2018	169,016,958.1	4528.066

Appendix A.3. Correlation Analysis

Finally, we combine spatial data with a growth/shrinkage score for each investigation period (see Table A8).

Table A8. Combined analysis data.

Teryt Id	Name	Start	End	Score	Density (People/km²)	Ci (Schwartzberg)
1261011	Kraków	2006	2011	12	4990.59	0.120702
1261011	Kraków	2011	2016	12	4519.93	0.144760
1261011	Kraków	2016	2021	16	4528.06	0.145119

After combining the data, we calculate the correlation described in Section 3.5.2. Because cities have multiple characteristics: population/size category, level/kind, and CLC codes, we run a correlation analysis between spatial parameters (compactness and density) and growth/shrinkage scores by grouping cities based on the aforementioned characteristics.

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Kraków, 11.12.2024

OŚWIADCZENIE

Oświadczam iż jako współautorka poniższych artykułów miałam następujący wkład w powstanie publikacji:

Publikacja nr.1
Tytuł: *"Identification of shrinking cities in Poland using a multi-criterion indicator"*
Autorzy: Ewa Szymczyk, Mateusz Bukowski
DOI: 10.7163/PrzG.2023.4.5
Wydawnictwo: Przegląd Geograficzny
Strona: https://przegladgeograficzny.igipz.pan.pl/article/item/13835.html
Rok: 2023
wkład w powstanie publikacji:

- Konceptualizacja publikacji badawczej w tym analiza literatury tematu, określenie celu i zakresu badań,
- Opracowanie metodologii w tym dobór danych statystycznych i przestrzennych, określenie zakresu pracy (czasowy, przestrzenny, tematyczny), dobór metod badawczych (multikryterialna metoda Milbert), dobór metod statystycznych (analiza box plot, etc.)
- Konsultacje specjalistyczne z promotorem oraz ekspertami (w tym z A.Milbert)
- Opis badań
- Nadzór nad pracami związanymi z analizą danych i analizą statystyczną opracowaną przez mgr. Bukowskiego.

Publikacja nr.2
Tytuł: *"Compactness of Polish urban areas - methodologies and analysis based on CLC dataset."*
Autorzy: Ewa Szymczyk, Mateusz Bukowski
Wydawnictwo: Architectus
wkład w powstanie publikacji:

- Konceptualizacja publikacji badawczej w tym analiza literatury tematu, określenie celu i zakresu badań,
- Opracowanie metodologii w tym dobór danych statystycznych (GUS BDL) i przestrzennych (CLC), określenie zakresu pracy (czasowy, przestrzenny, tematyczny), dobór metod badawczych (metody analizy przestrzennej obszarów zurbanizowanych), dobór metod statystycznych (analiza box plot, etc.).
- Opis badań.

Publikacja nr.3

Tytuł: *"Understanding the Relationship between Urban Form and Urban Shrinkage among Medium-Sized Cities in Poland and its Implications for Sustainability"*

Autorzy: Ewa Szymczyk, Mateusz Bukowski, Jeffrey Kenworthy

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- Opracowanie metodologii w tym dobór danych statystycznych i przestrzennych, określenie zakresu pracy (czasowy, przestrzenny, tematyczny), dobór metod badawczych (multikryterialna metoda Milbert oraz analizy przestrzennej kompaktowości), dobór metod statystycznych (korelacja Pearson'a, analiza box plot, etc.)
- Opis badań,
- Konsultacje specjalistyczne ze statystykami i demografami,
- Konsultacje i superwizja z prof. Jeffreyem Kenworthy,
- Korekta i edycja tekstu po recenzjach.

Kraków, 11.11.2024

OŚWIADCZENIE

Oświadczam iż jako współautor artykułów:

- *"Identification of shrinking cities in Poland using a multi-criterion indicator"* o numerze DOI /10.7163/PrzG.2023.4.5 wydanego przez Przegląd Geograficzny,
- *"Compactness of Polish urban areas - methodologies and analysis based on CLC dataset" wydanego przez Architectus,*
- *"Understanding the Relationship between the Urban Form and Urban Shrinkage among Medium-sized Cities in Poland and its Implications for Sustainability"* o numerze DOI */10.3390/su16167030* wydanego przez Sustainability MDPI.

miałem następujący wkład w powstanie publikacji:

- Dobór narzędzi, języka programowania oraz niezbędnych bibliotek do obróbki danych wg. wytycznych: Visual Studio Code, Python, Conda, Pandas, Matplotlib etc.,
- Stworzenie środowiska obliczeniowego oraz implementacja algorytmów na potrzeby metodologii,
- Harmonizacja danych statystycznych celem dostosowania do danych przestrzennych,
- Wizualizacja danych statystycznych w Excel i Matplotlib,
- Obróbka danych przestrzennych oraz wizualizacja danych w programie QGIS,
- Obliczenia statystyczne według wytycznych autorki badań.

Mgr. inż. Mateusz Bukowski

Frankfurt am Main, 11.08.2024

STATEMENT

I hereby declare that as a co-author of the article *"Understanding the Relationship between the Urban Form and Urban Shrinkage among medium-sized Cities in Poland and its Implications for Sustainability"*, published in 2024 by Sustainability MDPI,

I made the following contributions to the publications:

- Supervision of research
- Validation to ensure the quality
- Review and editing

Prof. Jeffrey Raymond Kenworthy

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9. List of tables and figures

Tables

Figures

Appendix

Date and Place	*Name of the conference*	*Authors input*
25.03.2021, Kraków	XVI International Conference - Urban Composition of a Resilient City	Presentation “Guidelines for creating public spaces in a resilient city.”
9-20.05.2022, Munich	Architecture Matters 2021	N/A
26-30.06.2022, Katowice	World Urban Forum UN-Habitat	N/A
30-2.07.2022, Gliwice	Co-operation Revisited by TRIALOG Journal	Research presentation “Bottom-Up Urban Planning Powers in the City of Krakow, Poland.”
24-27.10.2022, Valencia	XVIIIth International Conference on Urban Health	Paper presentation “Assessing participatory urban planning instruments in Krakow, Poland.”
12-13.05.2023, Kraków	XVII International Conference Wise City	Research presentation „Does urban form matter? Growth and shrinkage of Polish medium-sized cities from an urban planning perspective.”
28-29.09.2023, Wrocław	The International Conference "Centrality in The Age of Dispersion"	Paper presentation “Quantifying Urban Shrinkage Concentration and Dispersion in Medium-Sized Polish Cities”
20.11.2023, Frankfurt am Main	FUAS Conference on Urban Planning	Poster on the Shrinking Cities Research
15.12.2023, Dresden	Dresden Leibniz Graduate School -Winter School	Paper presentation “Quantifying Urban Shrinkage: Compactness of medium-sized Polish shrinking cities.”
18-20.04.2024, Wrocław	The International Conference Architecture-Research-Science 24	Paper presentation “Compactness of Polish Cities”
23-24.05.2024, Kraków	XVIII International Conference Wise City and a Polish Academy of Science (PAN) Urban Panel meeting.	N/A
5-7.09.2024, Goerlitz	Denksalon - Transformativer Stadtumbau	Panel discussions
25.09.2024, Dresden	Dresden Leibniz Graduate School -Summer School	N/A
26-27.09.2024, Dresden	IOER International Conference	Presentation “Bottom-Up Urban Planning Powers in the City of Krakow”