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External development potential of brownfield sites in the Czech–Polish cross-border post-industrial region: A network-based assessment

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Abstract

Brownfield transformation is not only a technical and environmental task, but increasingly a cross-scalar governance challenge, particularly in European cross-border regions where planning systems, legislation and development trajectories intersect. The study examines brownfield sites in the cross-border region of Moravian-Silesian Region (Czech Republic) and Silesian Voivodeship (Poland). It pursues two aims: to harmonise and characterise brownfields across contrasting planning contexts, and to assess how network-based accessibility zones relate to the socio-economic development potential of surrounding municipalities. The study introduces a harmonised method for delimiting brownfield sites, defined as post-mining and post-industrial areas that may be contaminated and partially reused, and develops a Composite Index of External Development Potential as a contextual screening tool integrating five external socio-economic indicators relevant to post-industrial redevelopment contexts and comparative spatial assessment. The 595 identified brownfield sites reveal pronounced cross-border differences in size structure and spatial concentration, with smaller, clustered sites in Moravian-Silesian Region and larger, more dispersed sites in Silesian Voivodeship. Accessibility-based analysis shows clear socio-economic gradients, with the weakest external development potential near brownfields and progressively more favourable conditions at greater network distances. K-means clustering distinguishes three municipal types, highlighting contrasting socio-economic contexts in which brownfields are embedded across the cross-border region.

Keywords: Spatial accessibility, socio-economic development potential, network-based analysis, post-industrial regions, Moravian-Silesian Region, Silesian Voivodeship

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1. Introduction

Brownfields remain a persistent challenge for post-industrial regions across Central Europe, where long-term mining, metallurgy and heavy industry have produced extensive landscapes of derelict or underused sites. Their presence affects surrounding municipalities by introducing environmental burdens, reducing land-use efficiency and contributing to socio-economic disadvantages. Although brownfield regeneration has been widely studied in Central Europe, several important knowledge gaps remain.

While most studies have examined brownfield sites within national settings, research on those located in cross-border regions is still limited, despite the fact that ecological processes, settlement structures and labour markets commonly extend beyond state boundaries. Definitions, classifications, and datasets differ considerably among EU member states, and the absence of harmonised approaches limits the possibility of comparative analyses, coordinated policymaking and the formulation of effective transformation strategies. Systematic, quantitative analyses of brownfields across national borders are particularly scarce. While governance-related challenges and just transition dilemmas have been documented for individual countries, it is unclear how these issues manifest in cross-border regions shaped by divergent planning systems, institutional practices and funding mechanisms.

A more detailed understanding of how brownfields are delimited, structured and spatially embedded, and how their accessibility interacts with local socio-economic performance, is essential for interpreting post-industrial transformation patterns. Addressing this gap requires improved definitions and delimitation procedures that ensure cross-border compatibility of brownfield inventories.

This study focuses on the cross-border region of Ostrava (Czech Republic) and Katowice (Poland) – one of the most complex and largest post-industrial environments in Europe. Although both sides share a long history of coal mining and heavy manufacturing, their restructuring trajectories since 1990 have diverged due to differences in planning systems, institutional conditions and governance frameworks. The study examines brownfields in

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a quantitative and cross-border context, aiming to make data, definitions, and delimitation methods compatible and comparable across regions with different planning and survey practices.

To guide the empirical analysis, we pursue the following research aims:

- To delimit, harmonise and characterise brownfield sites across adjacent regions with divergent planning and institutional contexts.
- To evaluate how network-derived accessibility zones surrounding brownfield sites correspond to the socio-economic development potential of nearby municipalities, operationalised through a composite index capturing demographic vitality, migration patterns, population ageing, labour market conditions, and local economic activity.

By addressing these aims, the study contributes to the cross-border harmonisation of brownfield inventories and advances understanding of how spatial accessibility interacts with socio-economic structures in post-industrial regions.

2. Theoretical background

2.1 What are brownfields?

Despite its long history in academic literature, the term brownfield site still lacks a clear and universally accepted meaning. A variety of brownfield definitions are discussed both in scientific literature and in different cultural, urban, regional or policy contexts. Thus, it is difficult to provide consistent legal or operational definition of such a site, which could be applied at the scale of a city, metropolitan area, or region. Nevertheless, it is possible to define a couple of recurring elements that are used by various academics to explain what a brownfield site is (Alker et al., 2000). Using those lenses, brownfields encompass sites that were previously used and currently are vacant, it may contain vacant buildings, it might be partially occupied or utilised, and it might be derelict and contaminated. Brownfield sites emerge primarily as a result of structural economic shifts, particularly within the industrial sector. Nevertheless, some researchers use classifications of brownfields that go beyond traditional post-industrial heritage to include other former functions such as agri-food facilities, military sites, or railway infrastructure (Szabó & Bozsoki, 2022). Often such sites are delimitated in urban, peri-urban or metropolitan contexts, covering derelict urban land that have become problematic due to neglect or prior misuse (Alker et al., 2000; Oliver et al., 2005). From a planning and policy perspective, it is not possible to put a brownfield site to immediate use without specific interventions.

Some smaller brownfield sites may remain hidden due to lack of access, unclear land-use regulations, unclear ownership or ongoing dynamic processes of urbanisation and de-urbanisation. Such brownfields form a specific type of neglected spaces, often located in urban contexts and easily overlooked by planners and policymakers. Although small and less visible former industrial sites might be more prone to conversion due to their size, research in Central Europe shows that larger, well-known and clearly delimited brownfields are regenerated more frequently (Osman et al., 2015). Even in areas with an apparently low extent of brownfield land, a small share of the total area may still be classified as brownfield, often consisting of very small sites (Roberts et al., 2018). For example, the level of soil contamination could be too low for an area to be designated an 'official' brownfield site, yet the site would still not be ready for redevelopment due to such contamination. Furthermore, access to smaller potential brownfield sites could be restricted due to ownership issues and a lack of willingness for brownfield owners to provide reliable data concerning a site.

In the European Union (EU) context, up until now, there is no official and binding definition of a 'brownfield site'. This aspect was noted already in 2005 by Oliver et al. Since that time the most popular definition of a brownfield in EU become the one provided by the CABERNET (Concerted Action on Brownfield and Economic Regeneration Network) network focused on brownfield research and regeneration. Some local state agencies, such as CzechInvest, refer to this definition of brownfield sites in their documents. In Poland, for example, brownfield sites are often referred to as 'degraded areas' in planning documents. Some large EU projects, such as TIMBRE, use the CABERNET definition as a blueprint for researching these areas. The lack of a common definition of a brownfield site in the EU can be attributed to the fact that land-use planning is a matter for individual countries and environmental legislation is fragmented. Despite the lack of harmonised definition of a brownfield in the European Union, some projects suggest that the total area of brownfields can be estimated in EU alone on a level of 2–4 million of hectares. If we visualise that most brownfields are located in urban, peri-urban or metropolitan contexts, this number shows us a huge land reserve that should be used to fulfil development needs of European urban systems. This is specifically significant on a continent which in numerous municipalities or metropolitan regions are missing new land for investment.

The situation relating to brownfield sites is even more specific in post-socialist, mono-industrial cities located in the eastern parts of the EU. Deindustrialisation in the Eastern EU regions often occurred rapidly, leaving behind large areas of derelict land characterised with complex ownership issues, contamination, and infrastructure leftovers. The delimitation of brownfield sites poses distinct challenges in Central and Eastern EU, reflecting socio-economic and political contexts that differ from those in other parts of the EU. The issue of brownfield regeneration emerged later in these areas than in the western part of the EU. In the eastern EU, brownfield sites entered the policy debate after 2010 (Frantál et al., 2013). Here, the memory about past industry activity is still fresh and generates many emotions among people who were involved in development of those cities (Jigoria-Oprea & Popa, 2016). In the aftermath of the collapse of socialism, numerous cities were confronted with the challenge of extensive brownfield legacies, leading to the gradual emergence of policies aimed at their remediation and productive reuse. This historical perspective highlights the layers of social, economic, and political dimensions in this part of EU that often overshadow the environmental aspects of brownfield redevelopment.

2.2 Brownfields in cross-border contexts

Similar brownfield patterns may occur on both sides of a border in cross-border regions, reflecting shared processes of industrial decline, peripheral location and infrastructural legacies. Examples of such regions within the EU include the Upper Silesia area (Czech Republic–Poland), Lusatia/Lausitz (Germany–Poland), the Upper Rhine Industrial Belt (Germany–France–Switzerland), and the 'Raia Ibérica' mining zones in Spain and Portugal (REKULA INTERREG project). One specific example concerns peripheral cross-border regions characterised by parallel processes of decline related to the transformation of post-socialist countries. In the EU, such regions can be found between Romania and Bulgaria, where the decline of socialist-era industries in towns on both sides of the Danube began after 1990. The Trieste–Koper metropolitan area (Italy–Slovenia) is a more detailed example of a cross-border area due to its interconnected port economies, labour flows and transport networks (ESPON, 2007). Studying the patterns of similarities in brownfields located in such cross-border contexts suggest that regeneration strategy within these regions, or agglomerations, should consider not just the site in one country,

but its counterpart across the border. Cross-border aspects like functions, transport links, labour markets, contamination flows must be considered (Bondaruk et al., 2015).

The delimitation and assessment of brownfield sites is particularly challenging in cross-border regions or agglomerations. The main reasons behind this problem are the different planning and policy traditions, institutional settings related to brownfield revitalisation and dynamics of post-industrial transformation. Furthermore, inconsistent governance and planning alignment between neighbouring nations often leads to difficulties in implementing cohesive brownfield delimitation and management strategies. Thus, taking a comparable approach to the delimitation and assessment of brownfield sites can be challenging in such contexts. The challenges associated with cross-border governance are highlighted by the frequent absence of an integrated approach to brownfield sites. Governance actors situated on both sides of the border often have opposing interests, which not only complicate the delimitation of brownfield sites, but also the coordination of discussions relating to common policies concerning such sites (Spyra, 2014a). Cross-border governance actors face coordination challenges related to leading the policy or planning processes, sharing of data and information, and – most importantly – the alignment of development goals and their associated timelines (Singer, 2002).

2.3 Common challenges and importance of brownfield redevelopment

Redeveloping brownfield sites helps to reduce pressure on greenfield land, thereby limiting urban sprawl and preserving farmland (Frantál et al., 2013; Oliver et al., 2005). It mitigates ecological risks by addressing soil and water contamination, restoring degraded ecosystems and reducing urban health hazards (Havrlant & Krtička, 2014; Krzysztofik et al., 2022; Timbre Project, 2014). However, many sites remain contaminated or are suspected to be contaminated, requiring costly remediation before they can be reused (Timbre Project, 2014). In post-mining areas, long-term landscape degradation, subsidence, and water management issues pose additional challenges (Havrlant & Krtička, 2014). Uncertainty regarding the ecological condition of sites also discourages investors (Novosák et al., 2013). However, once redeveloped, brownfield sites can be transformed into urban green spaces that contribute to climate adaptation, resilience and the restoration of ecosystem services (Spyra et al., 2019; Starczewski et al., 2023).

Brownfield regeneration revitalises valuable inner-city land, supporting local economic growth, job creation and investment (Frantál et al., 2013; Osman et al., 2015). It often reuses existing infrastructure, making it a more sustainable option than outward expansion onto greenfield sites (de Sousa, 2000). However, due to high remediation, demolition, and infrastructure costs, as well as hidden contamination risks, redevelopment is often more costly and risky than greenfield projects (de Sousa, 2000). In practice, many successful European projects rely heavily on public subsidies and EU structural funds (Jarczewski & Koj, 2023). In the broader EU policy context, redevelopment is increasingly linked to just transition and territorial cohesion agendas, within which regeneration is framed as a tool for balancing uneven development trajectories and promoting more equitable economic opportunities across regions (Nadin et al., 2018).

The redevelopment of sites can enhance the quality of urban life by providing new housing, cultural venues and recreational amenities, while reducing the crime and stigma associated with derelict areas (Frantál & Martinát, 2013; Krzysztofik et al., 2020). However, brownfield sites are often concentrated in declining industrial districts, where they can exacerbate unemployment, depopulation and socio-spatial inequalities (Duží & Jakubínský, 2013). Local communities may also resist redevelopment if they fear gentrification, cultural loss or the neglect of local needs (Bosák et al., 2024). In post-socialist regions in particular, weak civic participation traditions reduce the inclusiveness and legitimacy of regeneration processes (Osman et al., 2015). Crucially, in cross-border landscapes, redevelopment can promote territorial equity by helping to ensure that residents on both sides of a boundary benefit more evenly from new green spaces or commercial transformations (Nadin et al., 2018).

Effective brownfield redevelopment requires integrated planning and cooperation between multiple stakeholders, often in the form of public-private partnerships (CABERNET, 2006; CzechInvest, 2023). It is regarded as a governance tool that can reduce land consumption and foster territorial cohesion. However, significant barriers exist in this area of governance. Complicated or fragmented ownership structures can delay regeneration and discourage potential investors (Novosák et al., 2013). Inconsistent legal definitions, fragmented policies and limited coordination between the state, regional and local levels can slow down strategic planning (Alker et al., 2000). In cross-border contexts, mismatches between ecological systems and administrative boundaries further complicate integrated reuse strategies (Spyra et al., 2019). Coordinated strategies are vital for managing transboundary ecological corridors, mitigating pollution across shared watersheds and airsheds, and enhancing green infrastructure networks across borders (Loures & Panagopoulos, 2007; Hansen & Pauleit, 2014).

3. Methodology

3.1 Case study area

The study focuses on the Katowice–Ostrava conurbation, a densely urbanised and industrialised cross-border region linking the Moravian-Silesian Region in the Czech Republic and the Silesian Voivodeship in Poland (Fig. 1). The study area comprises 467 municipalities – 300 on the Czech side and 167 on the Polish side. As of the end of 2024, Moravian-Silesian Region had 1,182,613 inhabitants, while the Silesian Voivodeship was home to 4,291,441 residents, resulting in a combined population of 5,474,054. Owing to its size, population density and industrial legacy, the region represents one of the largest post-industrial urban areas in Europe.

In spatial terms, Moravian-Silesian Region covers 5,427 km^2 and the Silesian Voivodeship 12,333 km^2, yielding a total area of approximately 17,760 km^2. The territory is characterised by a complex mosaic of metropolitan centres, industrial cities, suburban municipalities and rural hinterlands. Major urban nodes shaping the functional structure of the conurbation include Ostrava, Karviná, Havířov, Frýdek-Místek and Opava on the Czech side, and Katowice, Gliwice, Rybnik, Tychy, Bytom, Chorzów, Ruda Śląska, Sosnowiec and Zabrze on the Polish side. These cities form the core of a historically coal-metallurgical urban system shaped by underground hard coal mining, steel production, coking plants and other heavy industries.

An important characteristic of the study area is the pronounced difference in the size and spatial extent of municipalities across the Czech–Polish border. Polish gminas are generally larger than Czech municipalities, reflecting historical differences in administrative organisation and settlement structures. This spatial heterogeneity is particularly relevant in the context of analyses based on municipal-level data, as it represents a typical manifestation of the modifiable areal unit problem (MAUP) in cross-border comparative studies.

Brownfields are unevenly distributed across the conurbation. In the Moravian-Silesian Region, brownfields were identified in 41 municipalities, whose combined territorial area amounts

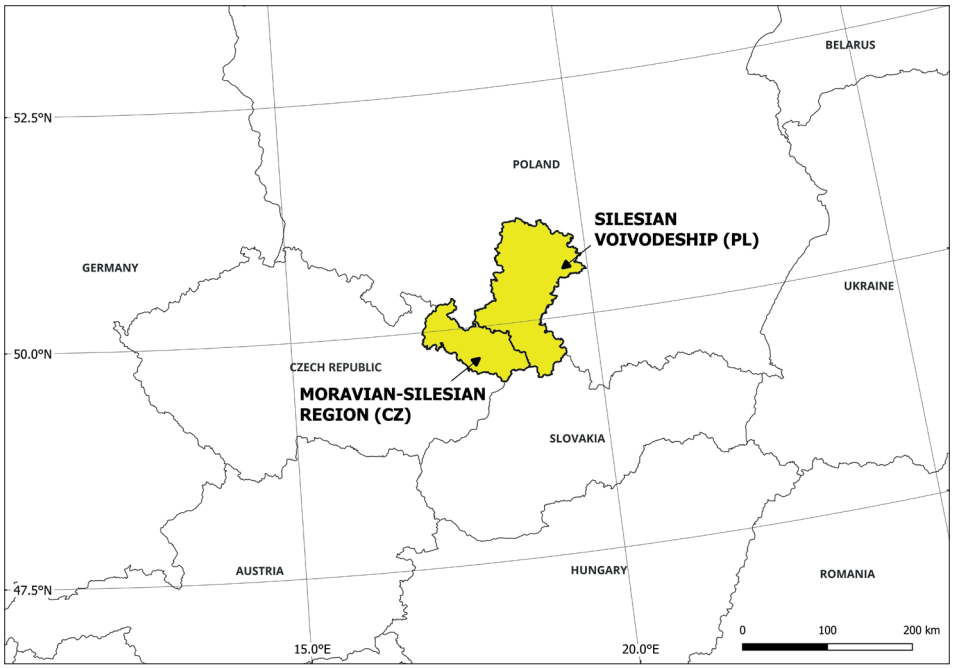


Fig. 1: Location of the case study area in Europe
Source: Authors' elaboration; projection: EPSG: 5514

to 1,369 km^2, while in the Silesian Voivodeship they were delineated in 90 gminas, encompassing 6,433 km^2. These municipalities represent the core territorial units affected by post-industrial land-use change and form the spatial focus of the subsequent analysis.

3.2 Data sources

The analytical framework implemented in this research integrates geospatial, demographic and socio-economic data from both national statistical systems and international open-data platforms. The key data sources include:

- OpenStreetMap (OSM) road network, consisting of all line features tagged under the highway key, was used to construct the road network graph for the service area analysis.
- Harmonised polygon layer of brownfields, compiled from national and regional inventories of the Czech Republic and Poland (OPI TPP, 2025), and further verified, complemented and harmonised using additional spatial sources, including, where relevant, orthophotos, cadastral maps, planning documents, contamination databases and other relevant materials (see Delimitation section).
- CORINE Land Cover 2018 (CLC, 2018), restricted to artificial surfaces to delineate built-up areas. The dataset was obtained from the Copernicus Land Monitoring Service (European Environment Agency) (https://land.copernicus.eu/).
- Municipal administrative boundaries and socio-economic indicators, obtained from: the Czech Statistical Office (ČSÚ) – municipal-level demographic and economic datasets for 2024 (Veřejná databáze ČSÚ: https://vdb.czso.cz), and Statistics Poland (GUS) – gmina-level demographic and labour-market datasets for 2024 (Bank Danych Lokalnych: https://bdl.stat.gov.pl).

It should be emphasised that CORINE Land Cover 2018 was not used to identify or delimit brownfield sites. Due to its spatial resolution and land-cover classification scheme, CLC is not suitable for detecting all brownfields, especially smaller, older or partially reused sites. In this study, CLC 2018 served only as an auxiliary layer for restricting the accessibility-based analysis to artificial/built-up surfaces, while brownfield polygons were derived from harmonised national and regional inventories.

Population figures for Moravian-Silesian Region and the Silesian Voivodeship used in the case study area section were sourced from the same national datasets and refer to the end of 2024.

Five variables were selected from the full set of available municipal indicators: natural increase, net migration, age structure, unemployment and business activity. These variables represent core demographic and economic dimensions relevant to post-industrial development and are consistently available and comparable across national statistical systems. All datasets were reprojected into a common coordinate system and clipped to the cross-border study area to ensure consistent spatial coverage.

3.3 Delimitation of brownfield sites

The delimitation and harmonisation of brownfield sites represent a central methodological contribution of this study. Regional brownfield inventories from the Czech Republic and Poland were standardised and merged into a single cross-border polygon layer. Each record was verified for geometric consistency, reclassified into comparable categories, and aligned with the local road network to enable integration with the accessibility model. Unlike continental datasets such as CORINE or Urban Atlas, which do not explicitly delineate brownfields, this harmonised dataset provides a unique and functionally comparable basis for assessing development potential across the border.

A crucial step in creating this dataset was the consolidation of national and regional delimitation approaches into a coherent definition of brownfields. For the purposes of this study and following the conceptualisation by Alker et al. (2000), brownfields were defined as post-mining and post-industrial sites, which may or may not be contaminated, and which can be partially occupied or utilised. Conversely, areas under active forest or agricultural management were excluded from the inventory, as they are considered to have an ongoing primary function incompatible with brownfield status. Furthermore, all sites had to meet a minimum size threshold of 0.5 ha, ensuring comparability across regions and relevance for analysis that can contribute to strategic planning on a regional level. These conditions were consistently applied to both national datasets to achieve conceptual harmonisation.

A key component of the cross-border data harmonisation process was the application of a unified delimitation approach that draws on principles originally developed in the Katowice region (OPI TPP, 2025). This approach defines brownfield sites as areas where industrial activities, including underground hard coal mining, were historically conducted. Their boundaries are delineated through the integration of three elements: the historical extent of industrial operations, the current configuration of cadastral parcels, and the present spatial structure. The resulting polygons therefore represent a synthesis of past industrial land use and current spatial reality. Only sites that have not been assigned new functions, or where new functions occupy only a minor share of the area, are included in the database. Importantly, such sites should not be conflated with the broader category of degraded areas, whose extent is significantly larger. Employing this generalised delimitation framework within the harmonisation process ensured that the final cross-border dataset is both methodologically consistent and capable of capturing the essential characteristics of brownfields across diverse regional contexts. The harmonisation process started with an initial pool of around 600 brownfield sites in the Moravian-Silesian Region and a much larger inventory in the Silesian Voivodeship. It resulted in a final selection of 95 and 500 sites, respectively.

3.4 Network accessibility model

To quantify spatial accessibility, brownfield polygons were converted to centroid vertices and snapped to the nearest road segment within 50 m, ensuring topological connectivity to the OSM transport graph. Using QGIS together with the QNEAT3 plugin, the Iso-Area (as Polygon) tool was applied to compute network-based service areas for each brownfield site. The generated accessibility polygons were intersected with CLC 2018 artificial surfaces to isolate built-up areas and subsequently with municipal boundaries containing socio-economic attributes. Each resulting sub-polygon inherited demographic and economic characteristics from its parent municipality, weighted proportionally by area share. This produced a harmonised spatial framework integrating accessibility, land cover, and socio-economic composition.

The model was calculated for a maximum network distance of 2,000 m and subdivided into four distance intervals (0–250 m, 251–500 m, 501–1,000 m, and 1,001–2,000 m). Although the tool is typically used to generate time-based isochrones, the outputs in this study represent distance-based service areas that correspond to functionally distinct intra-urban zones.

The selected distance intervals were intended to represent different levels of local accessibility around brownfield sites. The 0–250 m interval captures the immediate surroundings of brownfields and basic walkability conditions, which may influence site attractiveness where proximity to transport or amenities is relevant (Osman et al., 2015). The 251–500 m and 501–1,000 m intervals represent local and neighbourhood-scale accessibility, including access to community services, public transport and wider urban functions that may support redevelopment processes (Frantál et al., 2013; He et al., 2024). The 1,001–2,000 m interval captures broader intra-urban connectivity within continuous built-up areas, reflecting the role of accessibility and urban form in shaping functional linkages across the urban fabric (Guan & Peiser, 2018). Although the analysis is distance-based, the selected intervals can be approximately related to walking and short-distance urban mobility. The shortest interval (0–250 m) represents the immediate pedestrian surroundings of brownfield sites, while the maximum threshold of 2,000 m corresponds to approximately 30 minutes of walking at an average speed of 4–5 km/h. The upper distance thresholds also reflect the operational reach of cycling, micromobility and local vehicular connections. Together, the intervals provide a coherent framework for analysing multilayered accessibility conditions around brownfield sites within built-up areas.

3.5 Composite Index of External Development Potential

To evaluate the sociodemographic and economic conditions influencing the regeneration potential of brownfields in the Moravian-Silesian Region and the Silesian Voivodeship, we constructed a Composite Index of External Development Potential (CIEDP). The index synthesises five key variables capturing demographic vitality, migration dynamics, population ageing, labour market performance and local economic activity – dimensions widely recognised as shaping post-industrial regional development and influencing brownfield formation and reuse.

The CIEDP should be interpreted as a contextual and comparative indicator rather than as a direct predictor of brownfield redevelopment success. It captures the external demographic and socio-economic environment of brownfield sites within network-based accessibility zones, but it does not assess site-level redevelopment feasibility, profitability or functional suitability.

The variables were selected based on the availability of consistently measured and comparable municipal-level data across the study area. The five variables included in the index are:

- CRNI – Crude Rate of Natural Increase (births minus deaths per 1,000 inhabitants),
- CRNM – Crude Rate of Net Migration (inflows minus outflows per 1,000 inhabitants),
- Age Index – Ratio of elderly (65+) to youth (0–14),
- Unemployment Rate – Percentage of unemployed persons in the labour force,
- Business Entity Rate – Number of registered business entities per 100 inhabitants aged 15–64 (labour force).

All numeric variables were standardised by transforming each observation into a Z-score using the cross-border mean and standard deviation. A Z-score expresses how far a given value lies from the cross-border average in units of standard deviation, allowing all variables to be compared on a common scale.

For each variable, the Z-score was calculated as $Z = (x - \mu)/\sigma$, where μ and σ represent the mean and standard deviation computed across all municipalities in both countries.

Cost-type indicators (Age Index and Unemployment Rate) were inverted after standardisation so that higher Z-scores uniformly indicate better performance. The resulting standardised indicators were subsequently averaged to construct the CIEDP, which summarises the socio-economic context surrounding brownfield sites.

The calculation and interpretation of the CIEDP are restricted to built-up areas located within the 0–2,000 m network-based accessibility zones surrounding brownfield sites. Only those parts of municipal territories that fall inside these built-up service areas enter the socio-economic calculations; all other municipal land is excluded. The socio-economic attributes assigned to each built-up sub-polygon are inherited from the municipality in which it is located, as demographic and economic indicators are available only at the municipal level. This spatial constraint ensures that the index reflects the socio-economic context of brownfields within the functionally relevant urban fabric, rather than conditions across entire municipalities of varying size and heterogeneity.

3.6 Subregional clustering

To complement the accessibility analysis and to identify broader structural patterns shaping the socio-economic environment of brownfield sites, a data-driven subregional classification was

implemented using k-means clustering. The clustering was applied to municipality-level averages of the five standardised indicators used in the CIEDP (natural increase, net migration, age index, unemployment rate, and business activity). The same Z-standardised indicators were used to ensure that all variables entered the analysis on a common scale and with equal weight. The algorithm was then run with k = 3. Several values of *k* were tested, and k = 3 was selected as it provided the best balance between interpretability and the ability to distinguish the principal socio-economic contrasts within the cross-border region. Higher values of k resulted in increasingly fragmented cluster structures with limited additional explanatory value, while lower values failed to capture key structural differences among municipalities.

The resulting clusters represent functionally distinct municipal types, characterised by differing combinations of demographic vitality, migration dynamics, labour-market performance and age structure. Rather than imposing predefined administrative or historical boundaries, the clustering provides an empirically grounded delineation of subregional contexts, reflecting the underlying socio-economic structure of the Ostrava–Katowice conurbation.

This cluster typology is subsequently used in the results section to interpret subregional differentiation in CIEDP values and accessibility-based gradients, enabling a more nuanced understanding of how brownfield redevelopment potential varies across structurally distinct parts of the cross-border region.

4. Results

4.1 Delimitation, harmonisation and characterisation of brownfield sites across the cross-border region

4.1.1 Harmonised inventory and size structure

The harmonisation of national and regional brownfield inventories produced a unified cross-border dataset comprising 595 polygons embedded within 128 municipalities of the Ostrava–Katowice conurbation. Of these, 95 sites (1,156 ha) are located in Moravian-Silesian Region and 500 sites (9,383 ha) in Silesian Voivodeship. Because all polygons were delimited according to a unified conceptual and geometric approach, the resulting layer provides a consistent basis for subsequent accessibility modelling and socio-economic evaluation. In this way, the dataset demonstrates that brownfields can be coherently delimited and harmonised across cross-border regions with distinct planning and institutional contexts.

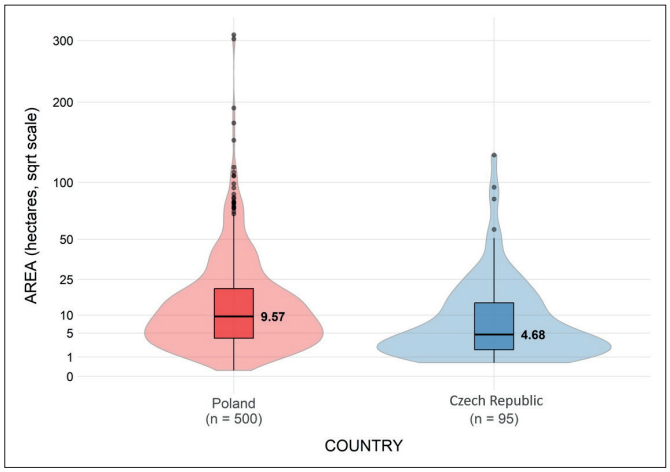


Fig. 2: Spatial characteristics of brownfield sites in the two regions of the cross-border case-study area
Source: Authors' elaboration

The size structure of brownfields differs markedly between the two national settings (Fig. 2). In Moravian-Silesian Region, the set of brownfields is dominated by small and medium-sized sites. More than half of all polygons are smaller than 5 ha, and the median area reaches only 4.7 ha. Large complexes exceeding 50 ha exist but are relatively rare and typically associated with specific historical mining and metallurgical operations. In Silesian Voivodeship, the distribution is more strongly shifted towards medium and large sites. A substantial proportion of polygons falls into the 10–50 ha category, and brownfields larger than 50 ha occur considerably more frequently than in the Czech Republic. The median Polish brownfield, at approximately 9.6 ha, is therefore roughly twice the size of the Czech median, reflecting a broader industrial land footprint and the historically extensive spatial reach of heavy industry in the Upper Silesia.

4.1.2 Spatial concentration and demographic context

The spatial concentration of brownfield areas further accentuates these cross-border contrasts (Fig. 3). In the Czech Republic, brownfields are heavily concentrated in a small cluster of core municipalities. Ostrava alone contains 31 brownfield sites with a combined area approaching 580 ha, representing nearly half of the region's total brownfield area. Together with Karviná, Havířov, Bohumín and several adjacent former mining municipalities, these urban centres account for more than three quarters of all brownfield land in Moravian-Silesian Region. This highly polarised concentration mirrors the historical monocentricity of the coal-metallurgical system in the Czech Republic.

In Silesian Voivodeship, brownfield land is distributed more broadly across the polycentric metropolitan network. Numerous municipalities – including Bytom, Katowice, Knurów, Ruda Śląska and Sosnowiec – host extensive clusters of brownfields, including some of the largest individual sites in the entire dataset. These include, for example, the Maczki Bór area in Sosnowiec (a post-extraction area exceeding 300 ha) and a similarly extensive spoil heap from hard coal mining located within Knurów. Yet even these municipalities collectively account for only about one third of the total Polish brownfield area, underscoring a more dispersed, multi-nodal spatial pattern.

A comparison that incorporates municipal population size highlights additional structural asymmetries. In Poland, several large brownfield complexes are situated within populous and demographically robust urban nodes such as Sosnowiec (≈ 190,000 inhabitants), Bytom (≈ 160,000) and Ruda Śląska (≈ 135,000), resulting in the coexistence of extensive post-industrial land and substantial settlement densities. Some medium-sized municipalities, including Bieruń and Bobrowniki, also contain significant brownfield areas despite their more moderate population totals. In the Czech Republic, by contrast, Ostrava (≈ 280,000 inhabitants) is the only municipality where both population size and total brownfield area are simultaneously extensive. Other municipalities with notable brownfield areas, such as Karviná or Havířov, have considerably smaller and often declining populations, while the majority o f small municipalities host only minimal brownfield surfaces.

Taken together, these findings show that the harmonised brownfield inventory not only resolves conceptual and geometric inconsistencies between national sources but also reveals systematic cross-border asymmetries related to the size, concentration and demographic embedding of brownfields. These structural characteristics form a necessary empirical foundation for the subsequent analysis of accessibility-based external development potential.

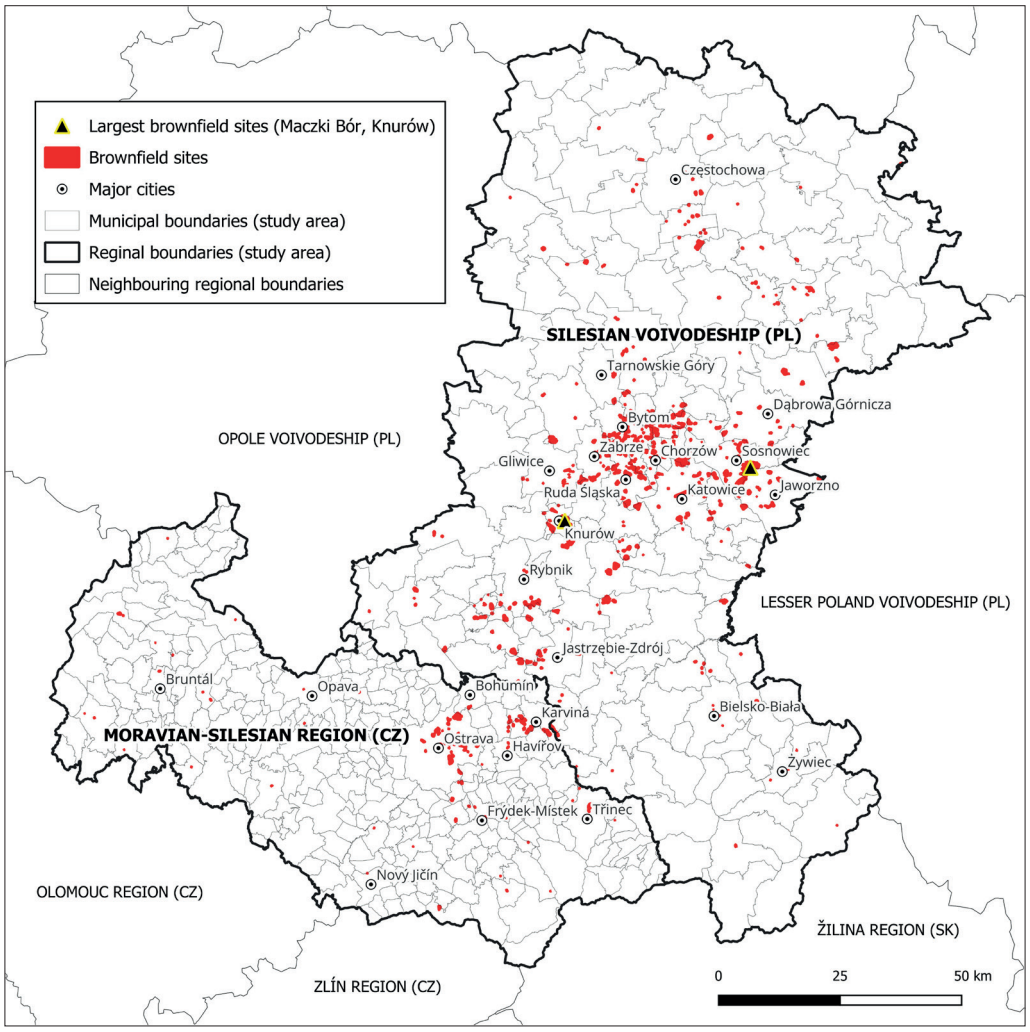


Fig. 3: Spatial distribution and concentration of delimited brownfield sites across the cross-border case-study region
Source: Authors' elaboration; projection: EPSG: 5514

4.2 Accessibility-based socio-economic potential around brownfield sites

4.2.1 Accessibility-based socio-economic gradients (CIEDP)

The CIEDP, derived from standardised indicators of natural increase, net migration, age structure, unemployment and business activity, was evaluated for all accessibility polygons across the four network-based distance intervals (0–250 m, 251–500 m, 501–1,000 m and 1,001–2,000 m). The results reveal systematic socio-economic gradients around brownfield sites in both national components of the cross-border region.

Across the entire study area, the innermost accessibility belt (0–250 m) exhibits the lowest average CIEDP values, indicating that brownfields tend to be embedded in comparatively weaker socio-economic environments. In both Moravian-Silesian Region and the Silesian Voivodeship, the mean composite Z-scores in this interval are clearly below the cross-border average, reflecting a combination of demographic decline, ageing populations and labour-market stress in the immediate surroundings of post-industrial sites.

With increasing network distance, CIEDP values rise monotonically in both countries. In the Moravian-Silesian Region, area-weighted mean CIEDP scores shift from strongly negative values in the 0–250 m interval toward less adverse values at distances of 1,001–2,000 m. Rather than indicating a direct proximity effect, this gradient reflects the spatial embedding of brownfields within historically industrial and structurally older parts of the urban fabric. Areas closest to brownfields tend to coincide with long-established residential environments characterised by demographic inertia, while more distant belts overlap with zones shaped by different housing, economic, and functional trajectories. Accordingly, Z-scores for the Crude Rate of Natural Increase (CRNI) increase only modestly with distance, signalling not demographic revitalisation but a relative attenuation of decline in outer zones. Similarly, outward-declining Z-scores of the Age Index indicate comparatively younger populations beyond the immediate surroundings of brownfields. Economic conditions follow a comparable pattern, as rising Z-scores of the Business Entity Rate suggest stronger business activity in more distant belts. By contrast, net migration remains negative across all Czech intervals and unemployment Z-scores change only moderately, underscoring that the observed spatial gradient in development potential is driven primarily by structural differences in age composition and economic activity rather than by short-term migration dynamics or labour-market reversals.

In Silesian Voivodeship, outward socio-economic improvements are visible as well but are more gradual. Area-weighted mean CIEDP values increase from low levels in the 0–250 m interval to less negative scores at 1,001–2,000 m, yet they remain below the cross-border average even in the outer belt. The component indicators show a distinct pattern. Natural increase (CRNI) remains below the cross-border mean across all intervals, though Z-scores improve slightly with distance. In contrast,

net migration (CRNM) is positive in all Polish intervals and increases monotonically outward, indicating that municipalities contributing to the more distant accessibility zones tend to experience stronger net in-migration. Unemployment is consistently lower than the cross-border average, with slightly more favourable Z-scores in the outer zones, while business activity also strengthens with distance. The Age Index remains above the cross-border mean in all intervals, reflecting structurally older populations throughout the Silesian part of the conurbation and only weak age-related gradients with distance from brownfields.

Comparing both national components, the gradient in CIEDP is steeper in Moravian-Silesian Region than in Silesian Voivodeship. This reflects the highly polarised Czech pattern, where large concentrations of brownfields are located in structurally weakened municipalities, and more favourable socio-economic conditions emerge only at greater distances. In Poland, the polycentric settlement structure and generally stronger labour market produce a smoother gradient: brownfields occur across municipalities of varying socio-economic strength, and outward improvements in CIEDP are driven mainly by incremental gains in migration balance and business activity.

Overall, the accessibility analysis shows that network distance from brownfield sites is systematically associated with socio-economic development potential. Immediate surroundings of brownfields are embedded in the weakest environments, while outer accessibility zones increasingly intersect with municipalities displaying more favourable demographic and economic characteristics. This pattern is present on both sides of the border, albeit with different intensity and internal structure.

4.2.2 Subregional differentiation

To further interpret these accessibility-based gradients, municipalities were grouped into three functional clusters using k-means clustering of their average Z-scores for natural increase, net migration, unemployment, business activity and age structure. This data-driven classification identifies three subregional types with distinct socio-economic profiles, which together frame the spatial embedding of brownfields within the Ostrava–Katowice conurbation (see Fig. 4).

Cluster A (with low development potential) comprises municipalities with strongly negative net migration, elevated unemployment, and often unfavourable age structures, producing the lowest CIEDP values in the study area. This cluster is concentrated exclusively in Moravian-Silesian Region and includes some of the most structurally affected post-industrial cities and towns, such as Karviná, Havířov, Nové Heřminovy or Vítkov. In these municipalities, large brownfield complexes coincide with persistent demographic decline and labour-market stress, making them the most challenging regeneration contexts in the cross-border region. Within the Czech accessibility zones, Cluster A accounts for a substantial share of the built-up area – particularly in the inner belts – and its influence decreases only slowly with distance.

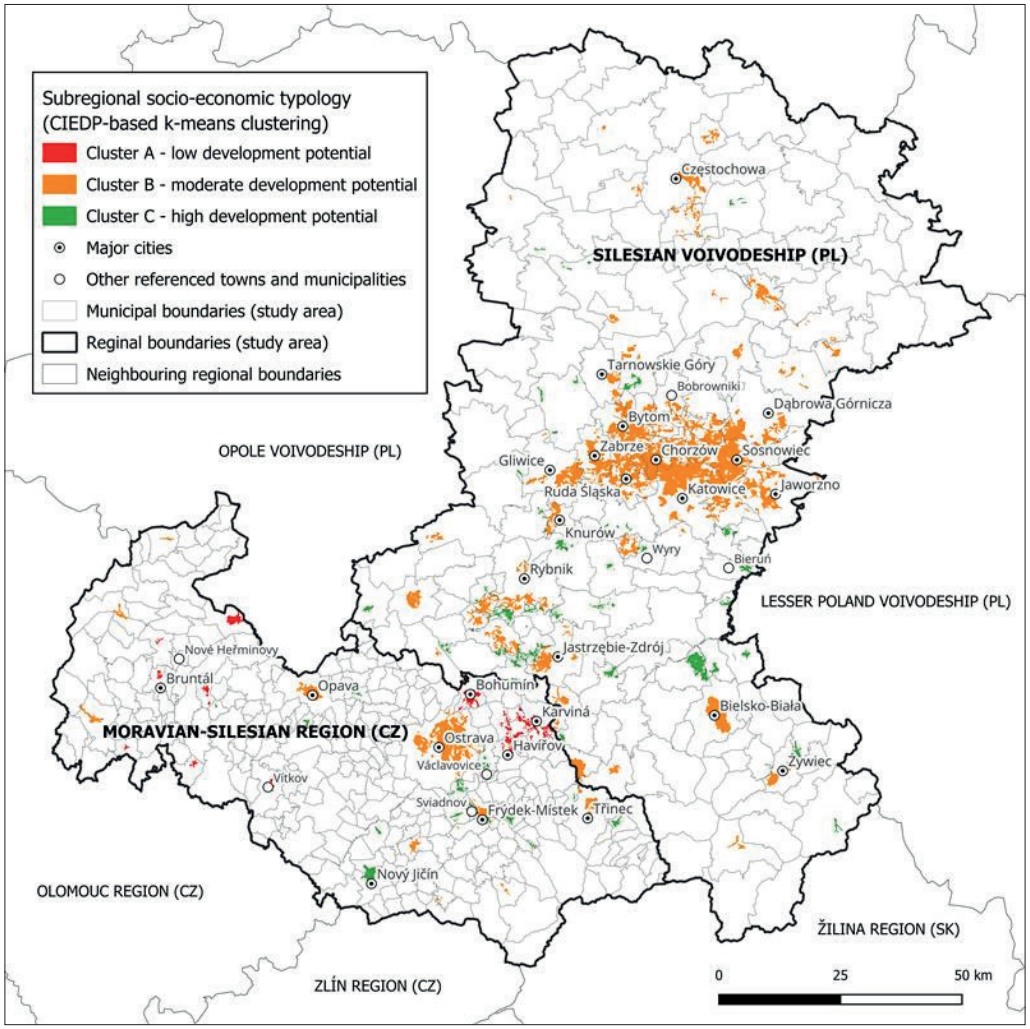


Fig. 4: Spatial typology of municipalities based on k-means clustering (k = 3) of external development potential indicators
Source: Authors' elaboration; projection: EPSG: 5514

Municipalities in Cluster B (with moderate development potential) display demographically older populations (high Age Index Z-scores) combined with relatively favourable labour-market and business-activity conditions. Their CIEDP values are negative on average but substantially higher than in Cluster A. This cluster type is especially common in Silesian Voivodeship, including major urban centres such as Katowice, Bielsko-Biała or Tarnowskie Góry, but is also represented in a number of Czech municipalities. In Poland, Cluster B dominates the built-up accessibility zones around brownfields across all distance intervals, accounting for the majority of brownfield-related area. Outward improvements in CIEDP within the Polish part of the region thus largely reflect incremental gains within this ageing yet economically robust cluster, supplemented by the gradually increasing presence of Cluster C in the outer belts.

Municipalities in Cluster C (with high development potential) combine above-average natural increase and net migration, low unemployment and younger age structures, resulting in strongly positive CIEDP scores. Many of these localities are situated in outer metropolitan belts and smaller, economically diversified towns, including Václavovice, Sviadnov or Wyry. Brownfields located in these municipalities are typically smaller and more dispersed, yet they are embedded in more favourable external socio-economic environments. This may support redevelopment processes, although actual feasibility depends on site-specific, institutional and market-related conditions. The area share of Cluster C within the built-up accessibility zones increases with distance from brownfields in both countries, particularly in the 1,001–2,000 m belt.

When these clusters are cross-tabulated with the accessibility intervals, a clear pattern emerges. In the Czech Republic, the inner zones around brownfields are heavily influenced by Cluster A, and to a lesser extent Cluster B, while the share of high-potential Cluster C increases towards the outer accessibility belts. This reinforces the interpretation that Czech brownfields are embedded in particularly fragile socio-economic environments, and that more favourable development conditions appear only at greater distances – often beyond the main post-industrial cores. In Poland, the built-up areas surrounding brownfields are dominated by Cluster B across all intervals, reflecting an ageing but comparatively strong urban-industrial base. The gradual outward increase in Cluster C, combined with consistently low unemployment, explains why socio-economic gradients in the Silesian part of the region are smoother yet still directionally positive.

Taken together, the accessibility-based gradients and subregional clustering show that brownfield-related development potential is shaped by the interaction of network distance and structural socio-economic context. Brownfields located in Cluster A municipalities and in the innermost accessibility zones face the weakest external conditions, while those situated in Clusters B and C – especially in the outer zones – benefit from more favourable demographic and economic environments. This nuanced differentiation demonstrates that multilayered accessibility zones provide a robust framework for assessing external development potential around brownfields in a complex cross-border, post-industrial conurbation.

5. Discussion

5.1 Methodological contribution and positioning within brownfield research

This study presents a novel methodological framework for assessing the external development potential of brownfields by linking socio-economic indicators to network-based accessibility zones surrounding brownfield clusters. Unlike site-oriented prioritisation tools such as the Timbre Brownfield Prioritization Tool (TBPT), which focus on evaluating individual sites or site portfolios using multi-criteria decision analysis (Pizzol et al., 2016), the proposed approach shifts attention to the wider socio-economic environments in which brownfields are embedded. Rather than modelling site-level feasibility or redevelopment probability, the framework evaluates regional and municipal contexts, identifies structural differences between the Czech and Polish parts of the study area, and classifies municipalities using a k-means socio-economic typology.

In this respect, the approach complements both applied prioritisation tools and econometric studies examining site-specific redevelopment determinants (Longo & Campbell, 2017). While many of the existing studies provide valuable insights into post-intervention effects or investment decisions at the site level, they offer limited leverage for understanding how broader socio-economic structures and accessibility conditions shape redevelopment potential across space. By contrast, the present framework enables a macro-regional perspective on brownfields, allowing for systematic cross-border comparison and for the detection of spatial patterns that are not apparent at the scale of individual sites.

Methodologically, the study builds on indicator-based assessment frameworks commonly used in planning practice (CABERNET, 2006; CzechInvest, 2023), extending them through a spatially explicit accessibility framework that enables systematic cross-border comparison – an aspect still rarely addressed in brownfield research. The integration of network-based distance measures with a socio-economic typology responds to long-standing calls for structured assessment approaches reflecting the heterogeneity of post-industrial landscapes (Alker et al., 2000).

5.2 Conceptualising external development potential

An important conceptual implication of the study concerns the understanding of development potential itself. Rather than treating development potential as an intrinsic property of brownfield sites, the findings support a relational interpretation in which redevelopment prospects emerge from the interaction between site-specific characteristics and external contextual conditions. Regions affected by structural transformation, weak market demand, or limited public-sector capacity may significantly constrain redevelopment, even where sites are technically suitable (Adams et al., 2010; Frantál et al., 2024).

The external socio-economic environment should therefore be understood as one component of brownfield redevelopment potential, not as its sole or necessarily dominant determinant. Brownfield redevelopment is shaped by both contextual factors, such as accessibility, neighbourhood conditions and local governance capacity, and site-specific constraints, including contamination, remediation costs, ownership structure, technical condition, public funding and investor strategies (de Sousa, 2000; Adams et al., 2010; Longo & Campbell, 2017; Osman et al., 2015). The CIEDP captures only the former dimension and should therefore be interpreted as a contextual screening tool rather than as a measure of technical, financial or legal redevelopment feasibility.

Brownfield sites and their surroundings are linked through mutually reinforcing relationships rather than one-directional impact mechanisms. Previous research demonstrates that the presence of brownfields is associated with declining property values, increased concentration of socio-economically disadvantaged populations, and reinforced patterns of residential segregation in adjacent neighbourhoods (Haninger et al., 2017; Lee & Mohai, 2012; Doussard et al., 2009). Socio-economic weakening of surrounding areas may, in turn, further reduce redevelopment potential by lowering demand and increasing perceived investment risk. Conversely, successful regeneration can transform brownfields

into poles of development, generating positive spillover effects and reshaping local development trajectories (de Sousa, 2008). From this perspective, brownfield regeneration should be conceptualised as a territorial intervention with impacts extending beyond the site boundary to the wider urban and regional system.

Importantly, the observed accessibility gradients should not be interpreted as short-term proximity effects driven by residential preferences. Given the slow-moving and structural nature of demographic processes, network distance functions here primarily as a spatial proxy that reveals historically embedded socio-economic patterns rather than as a direct causal mechanism.

5.3 Accessibility gradients and path-dependent development trajectories

The monotonic increase of CIEDP values with network distance is closely linked to the spatial embedding of brownfields within historically industrial and structurally older parts of the urban fabric. Areas closest to brownfields tend to coincide with long-established residential environments characterised by demographic inertia, ageing housing stock, and long-term exposure to industrial externalities. These conditions are not merely outcomes of post-closure decline but originate in development trajectories established during periods of active industrial use.

Such spatial configurations are consistent with the concept of path-dependent development, whereby past decisions, institutional arrangements, and spatial structures continue to shape present development options even after the original conditions have changed (Martin & Sunley, 2006; Martin & Sunley, 2010). In post-industrial regions, prolonged exposure to industrial activities historically influenced residential attractiveness, land values, and social composition in adjacent areas. These historically conditioned arrangements tend to persist after industrial closure, contributing to the reproduction of socio-economic disadvantage around brownfield clusters.

Against this background, socio-economic disadvantage becomes increasingly concentrated in former industrial cores, while growth is selectively redirected to more competitive locations (Doussard et al., 2009). Accordingly, outward increases in Z-scores for the Crude Rate of Natural Increase should be interpreted as modest attenuations of demographic decline rather than as evidence of demographic revitalisation. Similarly, outward-declining Z-scores of the Age Index indicate comparatively younger populations in zones that are spatially and historically distinct from the immediate surroundings of brownfields. Economic indicators follow a comparable logic: rising Z-scores for the Business Entity Rate with distance reflect broader structural differences in local economic environments rather than direct responses to brownfield proximity. By contrast, net migration remains negative across Czech accessibility intervals, and unemployment changes only moderately, underscoring the limited role of short-term migration or labour-market dynamics in shaping the observed gradients.

5.4 Cross-border physical and governance asymmetries

Beyond functional interdependencies, cross-border regions are fundamentally shaped by institutional frameworks and governance capacities, which influence both the intensity and the outcomes of cross-border cooperation (Perkmann, 2003). The cross-border comparison of the case study region reveals both shared post-industrial characteristics and pronounced structural asymmetries between the Czech and Polish parts of the study region. In both cases, areas immediately adjacent to brownfields exhibit older populations, weaker demographic dynamics, and less favourable economic conditions, while zones located approximately 500–2,000 m away display systematically stronger external development potential. However, the magnitude and internal structure of these gradients differ markedly.

In the Czech part of the region, the CIEDP gradient is steep and strongly polarised, reflecting the concentration of brownfields in structurally weakened post-industrial municipalities. More favourable conditions emerge only at greater network distances, consistent with the historically monocentric coal-metallurgical system and persistent post-socialist development trajectories observed in Czech regions (Duží & Jakubínský, 2013; Frantál et al., 2013). By contrast, the Polish part of the conurbation exhibits smoother gradients shaped by a more polycentric settlement structure and a comparatively stronger labour market. Outward improvements in development potential are driven primarily by migration balance and business activity, producing an 'outer-belt advantage' rather than a simple centre–periphery divide (Beames et al., 2018).

These differences are partly explained by institutional and governance asymmetries. While the Czech planning system remains highly decentralised, with limited coordination between municipalities in brownfield redevelopment, the Polish side benefits from stronger metropolitan governance through the Upper Silesian–Zagłębie Metropolis (GZM). This institutional framework facilitates regional coordination in land-use planning and economic promotion, mitigating socio-economic disparities associated with brownfield concentrations and supporting more balanced territorial development. More broadly, the findings align with research documenting how cross-border asymmetries in planning systems, land-use strategies, and governance capacities shape uneven development outcomes within shared functional regions (Spyra, 2014a; Spyra, 2014b; Spyra et al., 2019).

5.5 Methodological limitations and implications for further research

Despite its analytical advantages, the proposed methodology is subject to several limitations. Data availability and comparability constrain indicator selection in cross-border settings, often requiring harmonisation to the weaker statistical base and reducing thematic depth (Pediaditi et al., 2010). Additional limitations concern land-use and infrastructure data, including reliance on a harmonised land-cover dataset from 2018 and the uneven updating of OpenStreetMap-based road networks.

Another limitation concerns labour-market relations. The CIEDP is based on registered municipal-level demographic and socio-economic indicators and therefore does not capture commuting flows, temporary, seasonal or non-registered labour, wage levels, job quality, or the spatial mismatch between new employment sites and workers' places of residence. This is particularly relevant in post-industrial and suburbanising regions, where large redeveloped brownfield sites may generate labour demand that cannot be met by the resident population of the host municipality alone. Higher CIEDP values in suburban municipalities should therefore be interpreted as indicating more favourable external socio-economic conditions, not as evidence of local labour-market self-sufficiency or guaranteed demographic development.

Methodologically, the approach captures areal composition effects rather than continuous intra-municipal gradients, as accessibility zones aggregate indicators from intersecting administrative units. Moreover, reliance on quantitative data alone cannot capture governance, ownership, and site-specific constraints that often shape redevelopment outcomes (Rall & Haase, 2011). Nevertheless, the statistically robust and directionally consistent results suggest that network-based accessibility functions as a reliable spatial proxy for differentiating regional development potential. The methodology therefore provides a transparent screening tool for strategic spatial analysis and a foundation for more detailed site-level appraisal, complementing applied planning instruments and mixed-method approaches to brownfield redevelopment (Pizzol et al., 2016; CzechInvest, 2023).

6. Conclusion

Despite differences in historical background, planning systems, institutional frameworks and data sources, the study demonstrates that brownfield sites can be consistently delimited and harmonised across a cross-border region. The asymmetries described in this study are related to the size, structure, spatial concentration and demographic embedding of brownfield sites, reflecting distinct historical industrial trajectories. An accessibility-based analysis reveals systematic socio-economic gradients characterised by the weakest external development potential in the immediate vicinity of brownfield sites, with progressively more favourable conditions at greater network distances. These gradients are steeper in the Moravian-Silesian Region of the Czech Republic than in the Silesian Voivodeship of Poland, indicating stronger spatial polarisation in the Czech part of the case study region.

The study indicates that the external development context of brownfields cannot be understood solely through site-level characteristics. It also depends on how sites are embedded in wider socio-economic and accessibility structures. The CIEDP index proposed in this study provides a transferable screening framework for assessing the external socio-economic context of brownfield regeneration in post-industrial regions. The network-based accessibility zones implemented here offer a more nuanced alternative to administrative units for analysing brownfield–environment interactions and the external socio-economic conditions of nearby municipalities.

Brownfield sites located in structurally weak municipalities and inner accessibility zones present the most challenging regeneration contexts and require coordinated and effective transformation policies. These policies must go beyond site-specific interventions and address wider socio-economic and demographic conditions in the surrounding area. This is particularly challenging in cross-border regions, where effective brownfield policy requires institutional coordination and harmonised spatial concepts across borders to avoid fragmented and uneven outcomes.

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