



Territorial Sorting into Segmented Opportunity Structures: Commuting Networks and Formal Labour Market Access in a CEE Metropolitan Region

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Received: 30 March 2026 / Accepted: 21 September 2026
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Abstract

Metropolitan commuting flows reproduce the spatial organisation of registered employment. In FDI-led metropolitan regions, investment concentration generates a network with asymmetric branching: the core functions as a dense, multi-branching node connecting workers to diverse employment, while peripheral territories enter thin, single-path segments regardless of travel time. We reconstruct commuting network topology from mobile network signalling data covering approximately 150,000 daily flows in Cluj County (NUTS3), Romania, matched to the full registered employer dataset of the Cluj Territorial Labour Inspectorate. The analysis proceeds in four steps: destination field topology, time-threshold access dynamics, exposure to destinations outside the registered employment field, and PPML gravity models of flow formation. The results trace this branching asymmetry across each step. At the 90-minute threshold, 69% of peripheral origin territories retain zero direct network access to the core. Flows toward destinations with no detectable registered employment rise from under 1% in the core to nearly half of all peripheral flows, reversing the proximity gradient between registered and extra-registry opportunities. Gravity estimates show that peripheral origins operate under a distinct flow formation regime that travel-time reductions do not alter. The territorial implication is direct: transport-time investment reaches a structural plateau, and peripheral access depends on diversifying the registered employment base at origin rather than on shortening the corridor to the core. The paper reframes metropolitan inequality as differential territorial insertion into the registered employment opportunity structure, and identifies branching degree expansion in peripheral localities as the structural condition for effective labour market policy.

Keywords Commuting networks · Flow field topology · Metropolitan inequality · Labour market access · PPML · Mobile network data · CEE

JEL Classification R23 · R12 · J61 · C21

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Introduction

Metropolitan commuting research establishes that residential location shapes employment access and that access varies systematically across urban space (Ahrens & Lyons, 2021; Geurs & Van Wee, 2004; Pereira et al., 2017; Smith et al., 2020). Urban systems are constituted by multidimensional flow networks (commuting, migration, trade, information) that define functional interdependencies across territories and reshape metropolitan spatial structure (Meijers et al., 2016; Tong et al., 2024; Zhao et al., 2017). The commuting flow network constitutes the intra-metropolitan layer through which the spatial organisation of formal employment opportunity is reproduced daily.

A recurring pattern motivates this analysis. In metropolitan regions structured by concentrated FDI-led investment, average commuting times show limited variation across origin territories, while access to registered formal employment in the metropolitan core differs sharply across those same territories (Kain, 1968; Karner et al., 2025). This disconnect indicates that metropolitan inequality does not operate through the cost of travel but through the structure of the network connecting territories to the formal opportunity field (Galindo-Cabrera & Ospina, 2026). The commuting literature attributes labour market disadvantage to three mechanisms: residential distance from employment concentrations (Freiberg et al., 2024; Houston, 2005; Pereira et al., 2017), inadequate transport infrastructure (Geurs & Van Wee, 2004), and spatial mismatch between low-income residential zones and job growth locations (Pereira et al., 2017; Smith et al., 2020). Each mechanism locates disadvantage on a single axis of cost or distance and treats proximity to employment as the policy lever for reducing transport inequality. In the context of urban-rural integration, where commuting flows mediate the functional articulation between core cities and their peripheral hinterlands, this assumption systematically underspecifies the structural position from which peripheral territories enter the metropolitan labour market (Kolsut & Kudlak, 2024).

These accounts share a common assumption: all origin territories participate in a common metropolitan labour market and differ only in the cost at which they can enter it. What they leave unexamined is whether territories differ in the type of opportunity structure they can enter. The internal topology of the commuting flow network (the configuration of branching paths and flow concentration across origin territories) has not been treated as the unit through which metropolitan inequality operates.

This paper shows that commuting inequalities in Foreign Direct Investment (FDI)-led metropolitan regions (Ban & Mihály, 2023; Kovács et al., 2019; Petrovici et al., 2026; Smętkowski et al., 2021) arise from structural differences in flow field topology – the branching degree and flow concentration of the registered employment network reachable from each origin territory – and not from variation in travel cost along a common gradient. Territories with high branching and low concentration access a diversified employment field with multiple substitutable paths; territories with low branching and high concentration are structurally confined to a single-path segment of that field regardless of travel time budget. Branching degree and flow concentration are network properties (Tongjing et al., 2023) whose measurement makes topological assessment of metropolitan access structures tractable (Luo, 2025;

Xie et al., 2025). Flow field topology is measured through realised flow patterns and captures structural insertion into the observed commuting network; it is an empirical property of the destination field as accessed, not a measure of potential accessibility in the transport-planning sense.

We reconstruct commuting network topology from mobile network signalling data covering approximately 150,000 daily flows in Cluj County, Romania, cross-referenced against the full registered employer dataset of the Cluj Territorial Labour Inspectorate. The analysis proceeds in four steps: flow field topology, time-threshold access dynamics, employment across registered and extra-registry destinations, and PPML gravity models of flow formation. Distance decay functions estimated from signalling data in post-socialist cities show that impedance varies across origin zones in ways that standard gravity specifications do not capture (Šveda & Madajová, 2023), and that flow formation reflects the branching structure of the network as much as the cost of individual trips.

The case of Cluj County (NUTS3) is especially relevant as FDI has concentrated high-value registered employment in multinational companies (MNCs) in the metropolitan core (Ban & Mihály, 2023; Petrovici & Poenaru, 2025), while peripheral municipalities have absorbed residential and light industrial growth without generating autonomous poles of registered employment diversity (Petrovici et al., 2026). This investment geography, characteristic of post-socialist CEE metropolitan regions (Ban et al., 2025), produces a formal opportunity field that is spatially segmented before any commuting decision is made. Regional convergence analysis for CEE confirms that peripheral territories have experienced slow catch-up despite EU cohesion transfers, with growth concentrated in urban cores (Egri & Lengyel, 2024).

The paper proceeds as follows. Section 2 reviews the literature and develops the conceptual background. Section 3 describes data and methods. Section 4 presents results across four analytical steps. Section 5 discusses implications and Sect. 6 concludes.

Literature Review and Conceptual Background

From Accessibility to Flow Field Topology

The foundational concept in commuting research is accessibility: the employment opportunities reachable within a given travel-time or cost budget (Geurs & Van Wee, 2004; Guzman et al., 2024). Higher accessibility is associated with better employment outcomes, and residential location determines accessibility differentials (Kain, 1968; Pereira et al., 2017). Transport investment aimed at reducing commuting cost is the standard policy response to accessibility deficits.

Accessibility measures capture potential reach (Beza et al., 2025; Karner et al., 2025). They do not distinguish between network structures that offer multiple branching paths and those that channel all flows through a single corridor. Two territories with identical accessibility scores can face radically different field structures, one connecting to a wide range of registered employment types, the other funnelling workers toward a single dominant destination with no alternatives if that destination

becomes unavailable. This limitation has been documented empirically. Rosik et al. (2020) show that potential accessibility exhibits sharp discontinuity at the urban-rural boundary in European regional analysis, and that extending the trip distribution horizon does not dissolve the core-periphery asymmetry in employment reach. Smith et al. (2020), in a comparative analysis of occupational classes in the London Metropolitan Region, confirm that public transport accessibility advantages concentrate among professional classes, with low-income groups facing lower accessibility precisely for the most affordable modes. Accessibility scores aggregate opportunities across paths without accounting for whether those paths are redundant or singular: a territory served by a single dominant corridor is differently vulnerable from one with equivalent accessibility distributed across multiple routes.

What accessibility measures cannot produce is a characterisation of the structural position from which a territory enters the employment field: whether it connects through multiple branching paths or through a single dominant corridor, and whether its flows are distributed across a diverse set of destinations or concentrated on one. This distinction between field topology and field size is analytically prior to questions of cost. A territory can register high accessibility and still occupy a structurally marginal position in the employment network if its flows are captured by a single node.

Street-network circuitry offers a more precise way to read accessibility beyond simple proximity. (Poudyal et al., 2023) show that travel between urban amenity types can involve excess distance when routes follow the street network rather than a straight-line path. Pairwise circuitry captures this excess, making visible how the geometry of the network shapes the effective distance between destinations.

Complex network research provides the tools to formalise this distinction (González et al., 2008). Flow systems develop core-periphery structures in which central nodes concentrate connections and peripheral nodes are structurally dependent on them (Hidalgo et al., 2007). Applied to metropolitan commuting, this logic reframes peripheral disadvantage: peripheral territories occupy network positions with low branching degree and high flow concentration, and extending the travel-time budget does not alter the branching of the network they inhabit. Xie et al. (2025) apply PPML gravity models to commuting flows from mobile device data across three Chinese megacities and confirm that spatial heterogeneity in distance decay is systematic and origin-specific, with peripheral origins exhibiting structurally different flow formation from central ones. Dalberto and Amaral (2024) reconstruct functional regions from commuting flows in Brazil using network community detection and show that metropolitan reach structures internal labour markets independently of individual travel preferences.

This paper introduces flow field topology as the concept that captures this property. Flow field topology describes the internal structure of the set of registered employment locations reachable from a given origin territory, defined by two measurable dimensions: branching degree, the number of distinct registered destinations receiving flows from that territory, and flow concentration, the share of total flows absorbed by the dominant destination. High branching with low concentration defines an open field; low branching with high concentration defines a concentrated, single-path field. The concept is not specific to labour markets. Luo (2025), analysing China's higher education admission network, identifies an analogous bifurcation: elite universi-

ties at the core recruit nationally with no sensitivity to geographic distance, while regional clusters operate under strong spatial dependence and localised flow concentration. The structural logic is identical – a deterritorialised core regime and spatially bounded peripheral regimes – and it emerges from differential access to institutional resources, not from individual travel costs. Flow field topology is therefore a general property of access networks in which institutional resources are unequally distributed across territories.

Destination Field Segmentation in FDI-Led Export-Growth Regimes

Destination field segmentation is not a generic feature of metropolitan growth. Two alternative mechanisms produce suburban and peri-urban employment geographies that would not generate the topology documented here. In models based on scale economies, industrial and logistics decentralisation distributes registered employment toward peripheral zones as land costs fall and road accessibility improves, reducing core concentration over time (Glaeser & Kahn, 2004). In modernisation accounts, peri-urbanisation reflects transitional redistribution along the rural-urban gradient: peripheral residential growth precedes employment growth, with sectoral diversification following as population density rises (Tacoli, 2003). Both mechanisms generate convergence: peripheral territories acquire registered employment poles and their flow field branching increases as the metropolitan system matures. In FDI-led export-growth regimes (Ban & Adăscăliței, 2022), by contrast, high-value employment remains concentrated in the core, typically through the spatial concentration of foreign-owned firms, while peripheral expansion occurs without sectoral diversification. The prediction is persistent destination-field segmentation; the scale-economy and modernisation mechanisms predict convergence. This mechanism that sustains the Cluj configuration is typologically similar to other growing agglomerations in Romania (Jipa-Mușat et al., 2024; Petrovici & Poenaru, 2025) and CEE (Sandu, 2023; Smętkowski et al., 2021): it combines manufacturing firms drawing mobile rural labour through employer-subsidised commuting with business services spurring peri-urban residential growth (Petrovici & Ban, 2025).

Ban and Adăscăliței (2022) show that across CEE, the FDI-led growth model drives industrial expansion and export competitiveness while domestic investment, collective bargaining capacity, and endogenous innovation remain subordinate. The model operates through a dual circuit (Petrovici & Ban, 2025): foreign-owned firms, as the organisational carriers of FDI, concentrate engineering, digital, and coordination tasks in core urban zones with strong transport accessibility and skilled labour supply; and a domestic reproduction circuit absorbs wage income through housing, services, and consumption in the peri-urban fringe (Petrovici et al., 2026). Peripheral municipalities absorb residential relocation driven by wage growth in core services, and light industrial activity oriented toward manufacturing supply chains, without acquiring the sectoral diversity of registered employment that would constitute autonomous labour market poles (Ban & Mihály, 2023). Comparative analysis shows that peri-urbanisation is produced by economic restructuring and sectoral specialization (Tacoli, 2003). This pattern extends to metropolitan contexts structured by FDI-led growth, where peripheral residential growth proceeds independently of formal

employment decentralization (Petrovici & Poenaru, 2025). The result is a metropolitan employment field segmented at the structural level before any commuting decision is made: the core accumulates registered employment across diverse sectors with multiple branching paths; peripheral territories connect to a thin slice of this field, concentrated in a limited set of destinations, with reduced capacity to substitute across sectors.

The registered employment field also has an outside. In FDI-led metropolitan regions, a substantial share of working people operate through self-employment, family labour, agricultural activity, and unregistered arrangements not organised through wage contracts (Petrovici et al., 2026). This outside appears in the commuting network as extra-registry destinations, localities for which no registered employer appears in the Labour Inspectorate dataset. The category is defined by administrative absence from the registered employer dataset; work continues in these destinations. García et al. (2024), analysing Medellín, Colombia, document that labour informality clusters spatially in peripheral urban areas through mutually reinforcing mechanisms: precarious working conditions shape residential location, and marginalised residential location reinforces access to unregistered employment. The spatial clustering of extra-registry flows in peripheral territories parallels this structural property of peripherally inserted labour markets.

Torre (2025) identifies spatial exit – the departure of actors from a territory where they can no longer find the resources necessary to live on a daily basis, or in which the living conditions no longer allow them to live – as the mechanism through which peripheral territories enter spirals of non-development. The daily commuting flows documented in the present analysis are spatial exit measured at granular temporal resolution: peripheral workers move toward the metropolitan core each day while maintaining residential presence in their locality. Had peripheral localities generated the cooperative institutional arrangements and productive density sufficient to anchor formal employment locally, this directional asymmetry would not have consolidated into a structural property of the metropolitan network. If the central area offered sufficiently attractive rents and living conditions, these workers would be located in the centre. The flow field ramification asymmetry is therefore both a network measurement and a territorial development outcome: it records, in flow topology, the accumulated result of flawed-development issues, both in peripheral and central localities.

Access Regimes and the Limits of Travel-Time Policy

The destination field segmentation produced by FDI-led growth has a direct implication for transport policy evaluation. Standard metropolitan transport assessment treats disadvantaged territories as positioned further along a common accessibility gradient and evaluates interventions through travel-time savings. This evaluation framework assumes that the employment field is topologically uniform across origin territories, that peripheral residents face the same structure of opportunities as core residents and differ only in the cost of reaching them. The empirical record challenges this assumption across contexts.

Viguié et al. (2023) track job accessibility by income group in the Paris metropolitan area from 1968 to 2010 and find that major transport investments served all

groups roughly neutrally at construction, but systematic divergence emerged within years: accessibility gains accrued to richer households while poorer households experienced losses, driven by unequal changes in job location and residential composition. Pagliara et al. (2022) extend this to high-speed rail in four European countries, finding that HSR expansion increases the Gini coefficient of geographical accessibility: core areas gain connectivity while peripheral areas remain excluded. Freiberg et al. (2024) analyse São Paulo's mass transit expansion and show that lines designed through utilitarian criteria improve average accessibility while worsening its distribution. These results share a common mechanism: the employment geography that transport investment activates determines who benefits, and identical infrastructure produces divergent outcomes depending on where formal employment is located.

The critique can be specified at the level of mechanism. Travel-time policy presupposes a continuous accessibility gradient in which all territories are connected to a common employment field and differ only in the cost required to reach it, as formalised in standard accessibility-based evaluation frameworks (Geurs & Van Wee, 2004; Karner et al., 2025). This presupposition holds when the opportunity structure is topologically dense, with multiple alternative paths linking origins to destinations. Under such conditions, reductions in travel time expand the set of reachable opportunities by activating already existing connections. In FDI-led metropolitan configurations, the structure of the employment field is discontinuous. Peripheral territories are inserted into network segments characterised by low branching and high concentration, where the set of available connections is limited in number and weakly diversified across sectors. The constraint operates at the level of network topology. Increasing the travel-time budget expands movement along existing paths, yet does not generate new connections toward segments of the field to which the territory is not structurally linked. Access regimes therefore differ by the structure of the destination field that is reachable from each origin, not by the position of that origin along a shared gradient. Policy frameworks that evaluate interventions through travel-time savings address variation in movement cost within a given topology, while leaving the topology itself unchanged, a limitation already noted in accessibility-based transport evaluation (Karner et al., 2025). This diagnosis implies a corresponding evaluation criterion. An intervention is consequential for peripheral access when it changes the topology of the reachable field, by adding destinations or diversifying their sectoral composition. Lowering movement cost within the existing structure leaves that topology in place. The discussion develops this criterion as branching gain.

Case Study, Data and Methods

Case Study

The empirical analysis focuses on the Cluj metropolitan system, observed within the NUTS3 administrative boundary of Cluj County (see Fig. 1 left), which captures the full commuting field linking the metropolitan core and its surrounding territories (see Fig. 1 right). First, it constitutes a well-documented instance of the FDI-led metropolitan configuration (Ban & Mihály, 2023; Petrovici et al., 2026), observable through

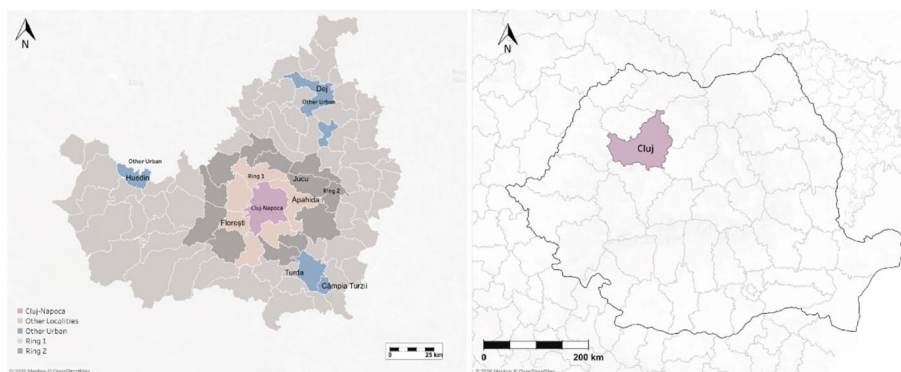


Fig. 1 Cluj county (left) and the typology of the municipalities (right). Note: The left panel shows inferred home anchors and the right panel inferred work anchors, aggregated to the 1 km² grid. Density values are capped at 25,000 per grid cell to reduce the dominance of Cluj-Napoca and improve the visibility of secondary centres and peripheral variation

the spatial concentration of foreign-owned firms, making it theoretically productive for testing whether destination field branching is a structural outcome of this growth model. Second, the availability of mobile network signalling data at county scale, combined with administrative employment and educational registers at building level, enables the four-step analytical framework to be applied at a spatial resolution unavailable in most commuting studies. Third, the post-socialist urban restructuring of Cluj County, combining socialist-era high-density residential stock with rapidly expanding peri-urban fringe development, exemplifies the configuration in which the scale-economy and modernisation mechanisms would predict convergence but the FDI-led mechanism predicts persistent branching asymmetry.

The study area comprises Cluj-Napoca and the surrounding municipalities of Cluj County, with a total population of approximately 700,000 according to the 2021 census and a functional urban area population of approximately 420,000. Cluj-Napoca concentrates the county's high-value formal employment: registered salaried employment totals 255,126 persons across all sectors in 2023, of which ICT (24,539 employees) and automotive manufacturing (8,494) alone represent over 12% of total employment and are located almost entirely within the city. The civilian employed population reaches 355,100 at county level, with the gap of approximately 100,000 persons distributed across agriculture, construction, and own-account activities outside the salaried employment field. This employment geography – high-value sectors anchored in the core, peripheral municipalities absorbing residential and light industrial growth – predates the commuting flows analysed here and constitutes their structural condition. It reflects the CEE FDI-led investment pattern, as observed through the spatial concentration of foreign-owned firms occupying the high-value segments of the economy, while domestic actors operate in fragmented niches centred on construction, services, and household reproduction (Ban & Adăscăliței, 2022; Petrovici et al., 2026).

Cluj County is organised into four territory types for comparative analysis: Cluj-Napoca (the metropolitan core), Ring 1 (first-tier adjacent municipalities including

Florești and Apahida), Ring 2 (second-tier municipalities), and other localities (more distant peripheral municipalities). This typology reflects both administrative structure and the pattern of employment concentration documented in the Labour Inspectorate Cluj data. The Romanian national context confirms that this configuration is not idiosyncratic: regional convergence analysis shows that peripheral and rural territories across Romania have experienced slow employment catch-up despite EU cohesion transfers, with growth concentrated in capital-region and major urban cores (Egri & Lengyel, 2024).

Data Sources and Disambiguation Procedure

Table 1 provides an overview of the six data sources. The primary source for the registered employment field is the Cluj Territorial Labour Inspectorate (Cluj TLI) dataset for 2023. The Labour Inspectorate covers all registered employers in the region, public and private, with sectoral employment breakdowns at the locality level. This is the administrative record from which the formal opportunity field is constructed. Destinations without any registered employer in this dataset are classified as extra-registry destinations.

The primary source for commuting flows is mobile network signalling data from Orange Romania for October 2023, comprising approximately one billion records from 339 base stations across Cluj County, aggregated at 15-minute intervals. This data source has been established as a valid basis for reconstructing large-scale commuting patterns at multiple geographical levels and has been validated against census-based OD matrices in European contexts (Calabrese et al., 2013; Hadachi et al., 2020).

Table 1 Data sources

Source	Content	Analytical role
Cluj Territorial Labour Inspectorate	All registered employers, public and private, with sectoral employment by locality, 2023	Registered employment field; destination mass; sectoral composition; extra-registry classification
NSD Orange Romania, October 2023	~1 billion mobile signalling records; 339 base stations; 15-minute aggregation	Home and work anchor detection; daily OD flow construction; ~150,000 flows
GEOSTAT 1 km ² grid	EU standard spatial reference grid	Spatial unit for all analyses; residential location validation
Cluj County School Inspectorate (ISJ Cluj)	Pupil enrolment by school building, 2023	Spatial identification of education locations; control for pupils-related mobility
Ministry of Education, university registers	Student enrolment by faculty building, all Cluj universities, 2023	Spatial identification of university locations; control for student-related mobility
Road network and POI data	Travel-time matrices; land-use controls	Threshold analysis; gravity model covariates

Raw signalling events are clustered into stay episodes using a 100 m radius and a minimum five-minute dwell threshold (Andor et al., 2024). Stay episodes are then aggregated to the 1 km² grid and classified by time of day. Home and work locations are inferred from temporal regularities in stay episodes, following established approaches in mobile phone data analysis that identify home as the dominant overnight location and work as the dominant daytime location (Csáji et al., 2013; Isaacman et al., 2011). Operationally, home corresponds to the grid cell with maximum cumulative overnight dwell (00:00–05:00), subject to a minimum of 1.5 h total presence, while work corresponds to the cell with maximum daytime dwell (05:00–18:00), subject to the same threshold (Fig. 2).

Daily commuting flows are constructed as the first confirmed movement from the home anchor to the work anchor, aggregated to origin-destination locality pairs to produce an OD matrix of approximately 150,000 daily flows (LeSage & Pace, 2008). Home detection accuracy was validated against the 2021 census population grid: direct cell-level correlation $r=0.73$; neighbourhood-level agreement using Queen-1 focal sums $r=0.82$. Bivariate Local Moran's I (KNN, $k=8$) confirms statistically significant spatial co-location between detected home locations and census population ($p<0.001$). The distance decay properties of the resulting flow matrix are consistent with those documented for mobile signalling data in post-socialist urban contexts (Šveda & Madajová, 2023): flows decay with distance but exhibit substantial heterogeneity across origin zones, with central zones showing weaker distance sensitivity than peripheral ones.

Mobile network signalling data contain no age or demographic variables, creating a disambiguation challenge: individuals spending extended daytime hours at educational institutions generate staypoint signatures indistinguishable from workers. To address this, two administrative educational registers are incorporated. Pupil enrolment records from the Cluj County School Inspectorate (ISJ Cluj), disaggregated to school building level, identify the spatial footprint of secondary and primary education. Student enrolment records from the Ministry of Education, disaggregated to faculty building level for all Cluj universities, identify university presences. Daytime staypoint episodes in grid cells containing educational facilities are screened against

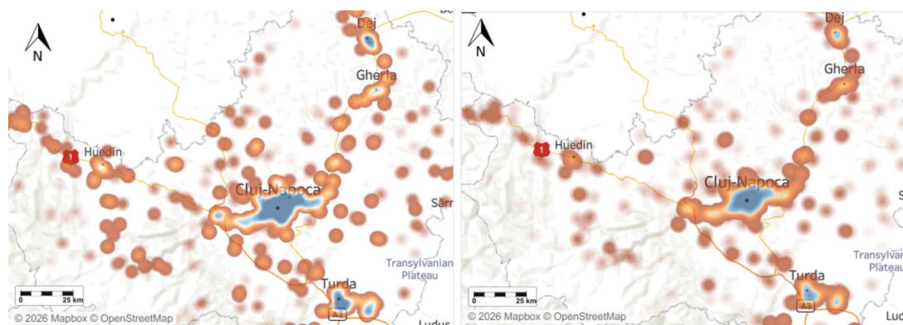


Fig. 2 Probable home location (left) and probable work location (right). Note: The left panel shows inferred home anchors and the right panel inferred work anchors, aggregated to the 1 km² grid. Density values are capped at 25,000 per grid cell to reduce the dominance of Cluj-Napoca and improve the visibility of secondary centres and peripheral variation

these registers before OD matrix construction, removing student-attributed presences prior to work anchor detection and flow aggregation. This disambiguation step is applied to the signalling data before the OD matrix is constructed; the educational variables that appear as destination controls in the gravity models (Students_{*j*}) are a separate use of the same administrative data, capturing education-related destination attractiveness in the flow formation analysis rather than performing individual-level filtering. This procedure, possible because of the spatial resolution of the educational registers, resolves a limitation that affects most mobile-data commuting studies (Hadachi et al., 2020; Šveda & Madajová, 2023).

Network Flow Structure

The formal commuting network visualized in Fig. 3 is constructed from the disambiguated OD matrix through a five-stage computational pipeline applied independently to each of the five destination territory categories. Each OD pair is weighted by an opportunity mass $m_{ij} = flow_{ij} \times \log(1 + E_j)$, where E_j denotes total registered employment in the Queen-1 neighbourhood of destination grid cell j , scaling corridor prominence by the local employment stock at the destination. Each weighted OD pair is rendered as a Bézier-curved corridor with a lateral offset to separate co-directional flows and rasterized onto a high-resolution grid. The rasterized surface is convolved with a Gaussian kernel to produce a continuous density field; the field is normalized to its per-category maximum before applying a fixed percentile threshold, so that

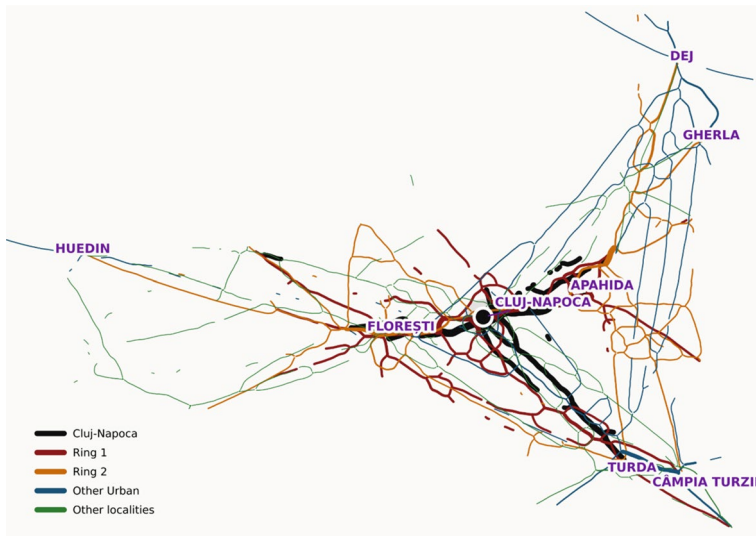


Fig. 3 Formal commuting flow network of Cluj County. Note: Corridors are thresholded density masks skeletonised to a one-pixel medial axis. Line thickness is the log-scaled flow volume along each corridor. Junction nodes of degree three or more mark points where corridor density fields fuse into a continuous region after Gaussian smoothing; terminal nodes of degree one mark peripheral flow origins with no downstream convergence. Colour denotes destination territory type (core, Ring 1, Ring 2, other localities). Source: Mobile Network Signalling data aggregated to OD locality pairs, October 2023

low-volume peripheral corridors survive at the same relative intensity as dominant central axes. The thresholded density mask is morphologically skeletonized to a one-pixel-wide medial axis and interpreted as a pixel graph: terminal nodes of degree one correspond to peripheral flow origins, junction nodes of degree three or more to points of corridor convergence. Non-junction chains between junctions are traced into continuous polylines, smoothed via a running-mean filter, and log-scaled for line weight. Corridor connectivity is emergent: two corridors are topologically joined if and only if their underlying density fields fuse into a continuous region after Gaussian smoothing, producing a shared skeleton branch at their point of convergence. The visualization serves an illustrative function: the topological metrics reported in Table 2 are computed directly from the OD matrix and are independent of kernel bandwidth, normalization, and skeletonization parameters.

Cluj County (NUTS3) is organised into four territory types for comparative analysis: Cluj-Napoca (the metropolitan core), Ring 1 (first-tier adjacent municipalities including Florești and Apahida), Ring 2 (second-tier municipalities), and other localities (more distant peripheral municipalities). The classification is defined at the LAU2 level and combines administrative proximity to the core with observed patterns of registered employment concentration in the Labour Inspectorate dataset. Ring 1 includes municipalities directly adjacent to Cluj-Napoca, Ring 2 includes municipalities connected through secondary adjacency, and the remaining localities form the peripheral tier.

Analytical Steps and PPML Gravity Models

The analysis proceeds through four sequential steps. First, flow field topology is reconstructed for each territory type by computing branching degree and flow concentration across the disambiguated OD matrix. Second, time-threshold access dynamics are measured by computing, at each five-minute increment from 5 to 90 min, the

Table 2 Model specifications: added terms Θ_j^i by model

Model	Sample	Added terms Θ_j^i	Research question
M1 Boundary	Full field $N = 13,013$	$\delta_1 \text{FormalBoundary}_j$ + $\delta_2 \text{FieldType}_j$	Do flows distinguish the formal boundary?
M2 Sectoral allocation	Formal field $N = 10,457$	$\gamma_1 \text{Ind}_{ij} + \gamma_2 \text{Bus}_{ij}$ + $\gamma_3 \text{Soc}_{ij}$	Do sectoral structures sort flows into distinct circuits?
M3 Local lock-in	Formal field $N = 9,208$	$\eta_1 \text{sim}_{ij} + \eta_2 \text{Ind}_{ij}$ + $\eta_3 (\text{sim}_{ij} \times \text{Ind}_{ij})$	Is compositional alignment local or metropolitan?
M4 Territorial substitution	Full field $N = 13,013$	$\sum_k \lambda_k \cdot 1(\text{home_type}_{ei} = k)$ $\times \text{DestType}_j$	Do peripheral origins enter a different destination regime?

All models estimated using PPML with origin fixed effects (home grid) and standard errors clustered at origin. Ind, Bus, Soc denote within-sector origin-destination matches for industry, business services, and social services. sim_{ij} is the cosine similarity of sectoral employment vectors. d_{ij} is travel distance. DestType_j denotes destination territory-type categories

share of origin territories with zero access to any registered employment destination and the share with zero access specifically to Cluj-Napoca. Third, extra-registry exposure is computed as the share of observed flows directed toward extra-registry destinations, and the average distances to registered versus extra-registry destinations are compared across territory types. Fourth, PPML gravity models estimate how flows form within the differentiated field structure.

Four models are estimated using Poisson Pseudo-Maximum Likelihood (PPML), which accommodates zero-valued origin-destination flows and yields consistent estimates under heteroskedasticity (Silva & Tenreiro, 2006). PPML is standard in gravity models applied to commuting flows derived from mobile device data, where OD matrices are sparse and overdispersed (Ahrens, 2018; Xie et al., 2025). Estimation is implemented in R using the *fixest* package (Bergé, 2018), which supports high-dimensional fixed effects and clustered standard errors. All models include origin fixed effects α_i , absorbing time-invariant characteristics of origin locations, including population size and baseline mobility intensity. Standard errors are clustered at the origin level.

The baseline specification is:

$$E[\text{flow}_{ij}] = \exp(\alpha_i + f(\text{time}_{ij}) + \beta_1 \ln M_j + \beta_2 \ln \text{Jobs}_j + \beta_3 \ln \text{Students}_j + \beta_4 \text{Density}_j + \Theta_{ij}) \quad (1)$$

Travel-time deterrence is specified as a piecewise linear function:

$$f(\text{time}_{ij}) = \gamma_1 \cdot \text{time}_{ij}^{(0,40)} + \gamma_2 \cdot \text{time}_{ij}^{(40,70)} + \gamma_3 \cdot \text{time}_{ij}^{(70,+)} \quad (2)$$

where $\text{time}_{ij}^{(a,b)}$ denotes travel time truncated to the interval $[a, b)$. This specification follows He et al. (2023) and captures non-linear distance deterrence across commuting regimes. We tested for robustness alternative models (see Appendix) using conventional 30/60-minute knots, closer to the commuting-budget interpretations associated with the Marchetti constant and the golden-hour literature (Marchetti, 1994).

Destination characteristics include: M_j : destination employment mass, measured as leave-one-out employment totals from the Labour Inspectorate dataset, excluding employment originating from *it* to avoid simultaneity. Jobs_j : registered salaried employment at destination. Students_j : enrolled student population at destination, capturing education-related mobility. Density_j : population density at destination. The term Θ_{ij} captures model-specific extensions that vary across the four specifications, including interactions and regime indicators. Table 2 details the construction of Θ_{ij} , the estimation samples, and the corresponding research questions.

Results

Flow Field Topology

Figure 3 reveals the asymmetric corridor structure of the formal commuting flow field, that is, the realised configuration of movements generated from an underly-

ing distribution of employment opportunities. Trunk corridors from all quadrants of the region converge on Cluj-Napoca through shared skeleton segments at points of high junction degree, while peripheral localities generate terminal corridor segments with no downstream convergence node within the regional network. Floreşti and Apahida produce corridor segments that terminate in the Cluj-Napoca skeleton and do not form independent junction nodes, a configuration that indicates structural dependence and limited autonomous polarity. The per-category normalization of the density fields ensures that this contrast does not reflect volume differences: peripheral corridor segments remain visible at the same relative threshold as dominant central axes, so their terminal topology reflects network structure.

Table 3 formalises these findings using network metrics computed across 10,475 formal employment OD pairs. The branching asymmetry is expressed in the topology of realised flows, which constitute a selective projection of the underlying opportunity field. The asymmetry is sharp and monotonic. Core residents navigate dense open fields: Cluj-Napoca origins average 71.2 reachable destinations, with the top three nodes absorbing 10% of total reachable opportunity and a flow HHI of 0.09. Peripheral localities face a different configuration: other localities average 8.4 reachable destinations, approximately 8.5 times fewer than the core, with 72% of opportunity concentrated in the top three nodes and a flow HHI of 0.37.

Figure 4 maps this projection explicitly by locating territory types in the joint space of branching degree and flow concentration, linking realised flows to the structure of the opportunity field from which they are drawn. This difference reflects variation in relational embedding within the metropolitan network. A branching degree of 71.2 indicates access to a diversified destination field, while a value of 8.4 corresponds to a highly concentrated structure with limited substitution possibilities. Flow field topology captures how origin territories convert the opportunity field into realised mobility patterns under differentiated structural constraints. Structural position in the network defines the configuration of accessible destinations, while metric distance from the core operates as a secondary property. The two representations are consistent: the network metrics in Table 3 quantify the selective contraction of the opportunity field observed in Fig. 4. The analysis captures realised flows rather than potential reallocations under extended travel-time budgets. Within this observed

Table 3 Flow field topology by territory type

Territory type	Branching degree	Reachable opportunity	Top-3 share	Flow HHI	Field profile
Cluj-Napoca (core)	71.2	574,100	0.1	0.09	Dense, open
Ring 1 and other urban	33.3	267,300	0.34	0.19	Diversified, moderately dependent
Ring 2	24.1	187,600	0.4	0.22	Constrained, transitional
Peripheral localities	8.4	51,100	0.72	0.37	Concentrated, single-path

Network analysis on formal employment OD pairs ($N=10,475$). Branching degree=number of distinct registered employment destinations receiving flows from each origin tier. Reachable opportunity=total registered employment at reachable destinations. Top-3 share=share of total reachable opportunity absorbed by the three largest destinations. Flow HHI=Herfindahl-Hirschman index of realised flows across destinations

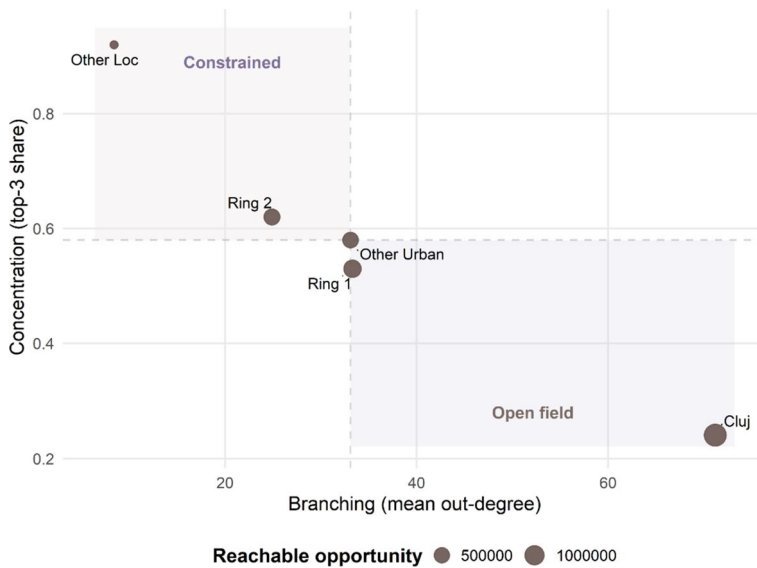


Fig. 4 Destination field topology by territory type. Note: Branching degree and flow concentration are plotted for each territory tier. Cluj-Napoca shows maximum branching and minimum concentration; peripheral localities show minimum branching and maximum concentration. Source: authors' calculations

structure, peripheral territories show limited expansion of destination sets beyond their immediate field, such that increases in travel-time budget add marginal destinations without increasing branching toward the metropolitan core.

Table 4 disaggregates the destination field by ownership regime, cross-referencing commuting flows with Romanian Trade Registry data on firm ownership. Foreign-owned firms enter the metropolitan commuting field as a territorially and sectorally differentiated set of destination regimes. A binary distinction between foreign-owned and domestic firms captures only a limited share of the observed structure ($\chi^2_{(4)}=277$, $p < 0.001$, Cramér's $V = 0.044$), while decomposing the destination field into ownership-based regimes reveals strong territorial differentiation ($\chi^2_{(16)}=88,004$, $p < 0.001$, $V=0.371$). The sectoral composition of flows directed toward foreign-owned firms is likewise differentiated by origin territory ($\chi^2_{(8)}=2,136$, $p < 0.001$, $V=0.362$). Core origins direct flows toward destinations with a significant presence of foreign-owned firms across both industry and business services (6.0%), while peripheral localities direct only 2.7% of flows toward such destinations, concentrated in industrial and logistics channels. A large share of peripheral flows, 63.7%, target destinations outside the formal employment field.

Time-Threshold Access Dynamics

Figure 5 tracks the share of origin territories with zero access to any registered employment destination and to the metropolitan core specifically, across the full 5-to-90-minute travel-time range. Yet access to the metropolitan core follows a different trajectory. The gap between peripheral and core origin territories does not narrow as the time

Table 4 Foreign-owned firm regimes of commuting flows by origin territory

Origin	MNC share (%)	Main regime	MNC sector	Field position
Cluj-Napoca	6.0	Formal (92%)	Industrial 50%; Business 33%	Diversified core
Ring 1	5.4	Formal (89%)	Industrial 75%	Industrial inner-ring
Ring 2	8.5	Formal (71%); Extra-registry (22%)	Industrial 90%	Industrial lock-in + extra-field
Other Urban	4.5	Formal (54%); Extra-registry (43%)	Logistic 88%	Logistics + extra-field
Other localities	2.7	Extra-registry (64%)	Industrial 54%; Logistic 39%	Peripheral extra-field

Reported shares are based on weighted OD flows. MNC-dominant destinations are grids in which foreign-owned firms account for more than 50% of total employees. χ^2 =chi-square association test; V=Cramér's V effect size. Source: ONRC ownership data matched to Cluj TLI employment records and NSD Orange commuting flows. *** $p < 0.001$

Top: exclusion from Cluj-Napoca; bottom: exclusion from any detectable formal opportunity

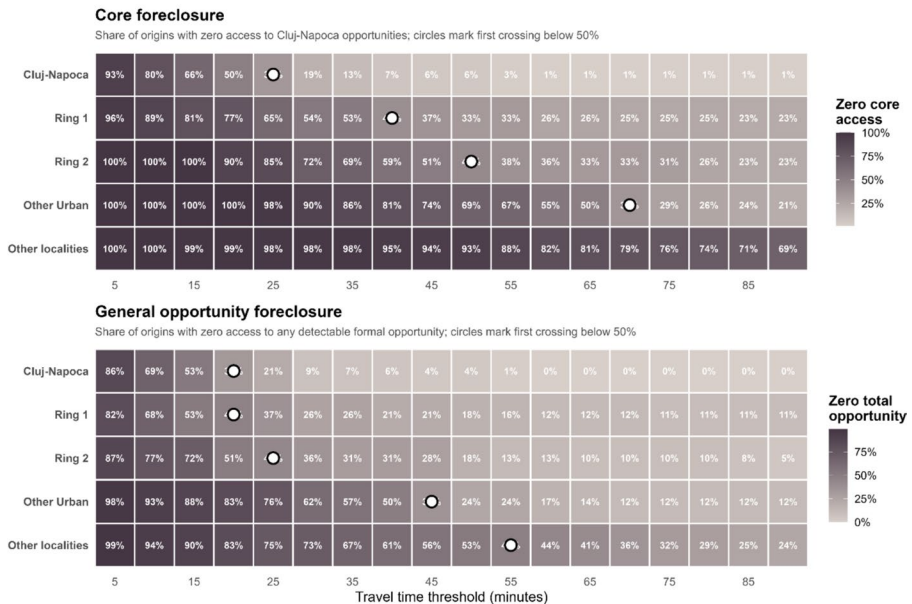


Fig. 5 Share of origin territories with zero access to any registered employment destination and to Cluj-Napoca specifically, by travel-time threshold (5–90 min). Note: At the 90-minute threshold, 69% of peripheral origin territories retain zero direct access to the metropolitan core. Source: authors' calculations

budget grows; it persists at the 90-minute mark, where 69% of peripheral origins retain zero direct access to Cluj-Napoca. The finding parallels the spatial polarisation effect documented for European regions by Rosik et al. (2020): extending the trip distribution horizon does not dissolve the core-periphery asymmetry in employment reach, because network connectivity does not change with individual willingness to travel. This ceiling reflects a topological constraint: many peripheral territories are not connected to the metropolitan core through direct or low-cost paths in the commuting flow network. The set of reachable destinations expands with additional travel time, but the network does not contain new links toward the core that could be activated by longer travel budgets. Extending the time threshold increases the complexity of the accessible field by incorporating additional peripheral destinations, while leaving the underlying network topology unchanged and without creating new connections to the metropolitan core.

The threshold diagnostics inform the travel-time segmentation used in the PPML models. General access to any registered employment opportunity opens earlier than access to the metropolitan core: most origin tiers cross below 50% zero access to any formal opportunity between 20 and 55 min. Core access opens later and more unevenly. Ring 1 crosses below 50% zero core access at 40 min, Ring 2 at 50 min, and Other Urban at 70 min; Other localities stay above 50% zero core access even at 90 min. This pattern motivates the 40- and 70-minute knots used in the main PPML specification. The model intervals summarise the observed access-regime transitions and stand on the empirical diagnostics rather than on externally defined commuting thresholds.

Extra-Registry Exposure

Figures 6 and 7 document the extra-registry exposure gradient of peripheral commuting regimes. The share of flows directed toward extra-registry destinations rises from 0.8% in Cluj-Napoca, through 2.4% in Ring 1 and 9.3% in Ring 2, to 14.0% in other urban localities and 47.6% in peripheral localities. For the most peripheral tier,

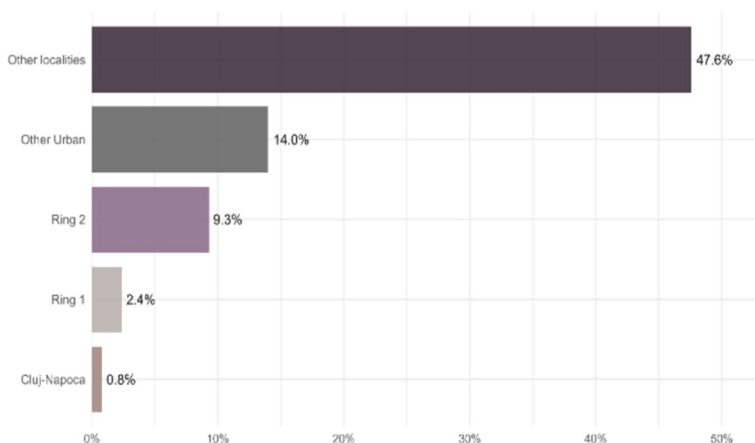


Fig. 6 Share of flows to extra-registry destinations by territory type. Note: The proximity gradient reverses in peripheral localities: extra-registry destinations are on average closer than registered ones. Source: authors' calculations

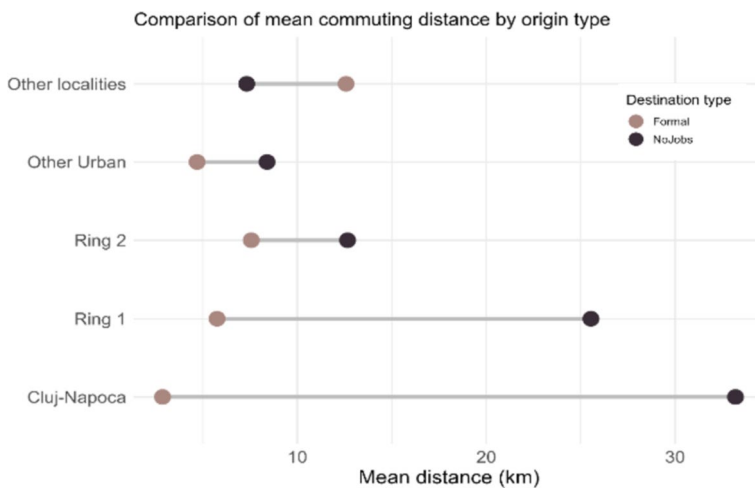


Fig. 7 Average distance to registered versus extra-registry destinations by territory type

approximately half of all observed commuting flows are directed toward destinations where no registered employer appears in the Labour Inspectorate dataset, indicating absence from the formal salaried employment field. The territorial gradient is statistically decisive: across 159,578 total daily commuting flows, 8,874 (5.56%) are directed toward extra-registry destinations, and the distribution across origin types departs from proportional allocation ($\chi^2 = 35,646.9$, $df = 4$, $p < 0.001$).

The extra-registry category is defined by administrative absence: a destination locality for which the ITM Cluj dataset records no registered employer. This absence may reflect informal or unregistered work, but it may also reflect geocoding mismatch between firm registration address and actual work location, multi-site firms registered at the headquarters address, mobile or construction-site work, or agricultural employment. The gradient documented here is robust to these alternative interpretations: regardless of their cause, extra-registry flows are concentrated in peripheral territories and their proximity advantage over registered destinations is a structural property of the observed commuting network, not an artefact of any single source of administrative noise.

Figure 7 adds a spatial dimension. In Cluj-Napoca and Ring 1, registered employment destinations are on average closer to origin territories than extra-registry destinations, and the proximity gradient follows the structure of the formal employment field. In Ring 2, the distance gap narrows. In peripheral localities, the gradient reverses: extra-registry destinations are on average geographically closer than registered ones. The distance contrast is substantial: flows from Cluj-Napoca toward extra-registry destinations average 33.2 km ($SD = 14.1$), while flows from peripheral localities toward extra-registry destinations average 7.3 km ($SD = 7.5$; $t = 51.78$, $p < 0.001$).

This reversal reflects the spatial configuration of the employment field. Registered employment remains concentrated in the metropolitan core, while extra-registry activities are distributed within or near peripheral territories. As a result, peripheral commuting flows are organised around proximate extra-registry destinations, while access to registered employment requires longer-distance connections to the core. This pat-

tern follows from the territorial concentration of formal employment under FDI-led investment and does not arise from individual-level preferences for informal work.

To assess the internal composition of the extra-registry category, we added a spatial plausibility check at destination-grid level. No-jobs destination grids were cross-tabulated with CORINE land-cover classes (European Environment Agency, 2020) and 2021 population. The check shows that extra-registry destinations are heterogeneous. Agricultural contexts account for 46.9% of workers entering no-jobs grids, populated urban and residential contexts for 28.5%, forest and semi-natural contexts for 22.1%, and mine, dump, and construction contexts for 2.5%. A focused contrast indicates that workers from other localities are more likely to enter agricultural no-jobs contexts than workers from Cluj-Napoca and the metropolitan rings, 48.4% versus 30.8% (one-sided Fisher test, $p < 0.001$; OR = 2.11). The results support a cautious reading of extra-registry exposure as administrative absence from the registered employer-location dataset, compatible with agricultural, mobile, own-account, or unregistered work, and also with registration-address mismatch and spatial imprecision.

Flow Formation: PPML Gravity Models

Table 5 reports the PPML estimates of commuting flow formation across four model specifications. Travel time exhibits a non-linear relationship with flows in all models. The positive coefficient on log travel time and the negative quadratic term indicate an inverted-U pattern, with flows increasing at moderate travel times and declining beyond that range. This pattern is stable across specifications, with the quadratic term ranging from -0.883 to -2.477 and remaining highly significant.

Destination employment mass is positive and statistically significant throughout. The coefficient on destination pulls ranges from 0.373 in M1 to 0.574 in M3, confirming that larger concentrations of registered employment attract higher flows. Additional destination characteristics, including registered employment (0.118^{**}) and student presence (0.046^{**}), further increase flow intensity, indicating that both labour demand and institutional concentration structure destination attractiveness.

Model 1 evaluates the role of the formal boundary. Flows toward extra-registry destinations are substantially higher than predicted by standard gravity factors (coefficient 2.940^{***}). This result indicates that extra-registry destinations constitute a structurally relevant component of the commuting system. The positive and significant coefficients for peripheral destination types, particularly other urban (1.049^{***}) and other localities (0.866^{**}), further indicate that flows extend beyond the metropolitan core into differentiated territorial segments of the opportunity field.

Model 2 examines sectoral allocation within the formal field. Compositional similarity has a large and highly significant effect (3.728^{***}), indicating that commuting flows are strongly organised along sectoral lines. The magnitude of this coefficient confirms that sectoral alignment between origin and destination is a primary structuring mechanism of the registered employment field.

Model 3 introduces spatial interaction into this mechanism. Compositional similarity remains positive and significant (1.666^{***}), while its interaction with distance is negative (-1.106^{***}), indicating that sectoral alignment weakens as spatial separation increases. The direct effect of distance is also negative (-1.025^{***}), confirming that

Table 5 Flow formation in a differentiated opportunity field, PPML gravity models

Variable	M1 Boundary	M2 Sectoral	M3 Lock-in	M4 Territorial
Dependent: Trip count	Full field	Formal field	Formal field	Formal field
Travel impedance				
log(Travel time)	18.79*** (1.151)	20.56*** (1.442)	7.403*** (0.573)	20.99*** (1.596)
log(Travel time) ²	-2.200*** (0.129)	-2.401*** (0.161)	-0.883*** (0.064)	-2.477*** (0.182)
Destination structure				
log(Destination pull, LOO)	0.373*** (0.062)	0.506*** (0.051)	0.574*** (0.029)	0.455*** (0.053)
log(Registered jobs, Q1)	0.118** (0.037)			
Destination population density	1.59e-5* (8.06e-6)			
log(Students, Q1)	0.046** (0.016)			
Destination territory (ref.: Cluj-Napoca)				
Ring 1	0.355 (0.220)			
Ring 2	0.519* (0.242)			
Other Urban	1.049*** (0.241)			
Other localities	0.866** (0.272)			
Extra-registry destination	2.940*** (0.375)			
Sectoral composition				
Compositional similarity (cosine)		3.728*** (0.393)	1.666*** (0.324)	5.674*** (0.409)
log(Distance)			-1.025*** (0.145)	
Compositional similarity × log(Distance)			-1.106*** (0.175)	
Territorial heterogeneity:				
log(Travel time) × Origin (ref.: Cluj-Napoca)				
× Ring 1				-3.843 (3.859)
× Ring 2				-7.129* (2.935)
× Other Urban				23.63** (7.836)
× Other localities				-5.264 (6.918)
log(Travel time) ² × Origin (ref.: Cluj-Napoca)				
× Ring 1				0.465 (0.448)
× Ring 2				0.802* (0.340)
× Other Urban				-2.473** (0.841)
× Other localities				0.748 (0.746)
Compositional similarity × Origin (ref.: Cluj-Napoca)				
× Ring 1				-1.088 (1.008)
× Ring 2				-5.014** (1.591)
× Other Urban				-3.937*** (0.719)
× Other localities				-3.267*** (0.859)

Table 5 (continued)

Variable	M1 Boundary	M2 Sectoral	M3 Lock-in	M4 Territorial
Fixed effects				
Origin grid cell	Yes	Yes	Yes	Yes
Fit statistics				
Observations	10,475	9,208	9,208	9,208
Pseudo R ²	0.451	0.512	0.798	0.534
BIC	328,133	252,293	105,687	241,510

PPML estimation with origin fixed effects at the 1 km² grid cell level; standard errors clustered at origin grid. M1 uses the full destination field (dt_all), including extra-registry destinations. M2 - M4 restrict to formal destinations, where sectoral composition is defined. Destination pull measured as leave-one-out employment totals from the Cluj TLI dataset to avoid simultaneity. Compositional similarity=cosine similarity of origin and destination sectoral employment vectors (Queen-1 neighbourhood). $\log(\text{Travel time})^2$ tests the concavity of the time, flow relationship; the quadratic specification implies an inverted-U with a peak at moderate travel times. Reference territory for all interactions: Cluj-Napoca. Significance: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

spatial frictions constrain sectoral matching. The results indicate that sectoral lock-in operates primarily at shorter distances and diminishes with increasing separation.

Model 4 tests territorial heterogeneity in flow formation. Interaction terms between travel time and origin types indicate systematic variation in distance sensitivity across territories. The negative coefficient for Ring 2 origins (-7.129^*) indicates stronger distance deterrence relative to the core, while the large positive coefficient for other urban origins (23.63^{**}) indicates a different travel-time response pattern. Quadratic interaction terms further differentiate these effects, with significant curvature adjustments for Ring 2 (0.802^*) and other urban origins (-2.473^{**}).

Interaction terms between compositional similarity and origin type show that sectoral alignment is significantly weaker outside the core. The coefficients are negative and significant for Ring 2 (-5.014^{**}), other urban (-3.937^{***}), and other localities (-3.267^{***}), indicating that peripheral territories operate under structurally different matching regimes. The results indicate that commuting flows are generated within differentiated access regimes. The estimated relationships do not follow a single accessibility gradient. The compositional lock-in effect is stable to the inclusion of destination territory controls, with negligible coefficient change (Appendix Table 6), indicating that the mechanism is not driven by territorial composition alone.

Robustness Checks

A first check addresses whether the peripheral disadvantage reflects physical route inefficiency rather than destination-field structure (Appendix Table 7). A compact pairwise-circuitry contrast by origin territory and destination field shows that, for Other localities, extra-registry destinations are closer than registered employment destinations by road (12.00 km against 17.13 km) while their excess road distance is almost identical (4.54 km against 4.40 km). The peripheral proximity of extra-registry destinations follows from the spatial distribution of destination types and not from more efficient road access.

A second check targets the pairwise-circuitry robustness models (Appendix Table 8). In the full-field specification, pairwise circuitry is strongly negative (-1.742 , $p < 0.001$), indicating that circuitous road access reduces flow intensity. The extra-reg-

istry coefficient remains positive and statistically significant after this control (2.320, $p < 0.001$), so the formal and extra-registry boundary holds independently of road-network inefficiency. In the formal-field specification, adding circuitry leaves the sectoral lock-in terms stable: compositional similarity remains positive and the compositional similarity by distance interaction remains negative. Circuitry is a relevant spatial friction, and it operates inside the destination-field topology rather than replacing it.

As a further robustness check, the main boundary and lock-in models were re-estimated using conventional 30/60-minute knots (Appendix Table 9), Marchetti's (1994)'s golden hour. The results remain substantively unchanged. In the boundary model, the outside-formal-field coefficient is 1.991 under the empirical 40/70 specification and 2.034 under the 30/60 specification, both statistically significant at $p < 0.001$. In the lock-in model, the compositional similarity coefficient remains positive and highly significant, while the interaction between compositional similarity and distance remains negative and highly significant. The core conclusions hold independently of the empirically selected 40/70-minute knots.

Across specifications, the results support the existence of a segmented opportunity structure. Peripheral territories are embedded in network configurations characterised by lower branching and higher concentration, which limits access to diversified employment destinations. Travel-time reductions do not modify this structure, as the constraint is defined by the topology of available destination fields and the configuration of connections within them.

Discussion

The results converge on a finding that the commuting literature has not systematically addressed. Metropolitan territories differ in the branching degree and sectoral diversity of the registered employment field that is structurally reachable from their network position. They differ in this property beyond the travel-time cost of reaching formal employment locations. This difference is consistent with the investment geography associated with FDI-led growth – observable in the spatial concentration of foreign-owned firms across origin territories – and remains irreducible to travel time. FDI-led investment concentration operates here as the macro-structural context that differentiates the Cluj case from convergent metropolitan trajectories. It functions as that macro-structural context, distinct from a causally identified mechanism in the sense of experimental or quasi-experimental designs.

Core territories participate in an open, diversified destination field: high sectoral variety, strong compositional matching capacity, and extra-registry exposure below 1%. Peripheral territories participate in a concentrated, single-path field: limited sectoral variety, within-tier lock-in that does not extend to the core, and extra-registry exposure above 40%. The gravity model estimates confirm that this is a structural regime difference, not a positional degree difference.

The large negative coefficients on the interaction terms between Cluj-Napoca as destination and peripheral origin types (ranging from -3.7 to -5.1 log points) indicate that peripheral origins generate core-directed flows at a fundamentally lower rate than proximity and employment mass would predict. This gap reflects a disconnect

tion from the core's opportunity field that is topological in the observed flow field: peripheral localities generate markedly fewer core-directed flows than their travel-time position would predict in a topologically uniform field.

The circuitry analysis separates route efficiency from flow-field topology. Circuitry measures physical efficiency along the road network (Poudyal et al., 2023); topology measures the destination field an origin enters. Circuitous access reduces flows while the formal and extra-registry boundary and the sectoral lock-in hold. Physical friction operates inside a differentiated destination field, and the field defines the constraint.

The policy implication follows directly. Evaluation frameworks that incorporate flow field topology alongside travel-time savings make the structural limits of infrastructure-based interventions visible at the assessment stage. A commuting time reduction of 15 min for a peripheral locality shifts its position on an access curve that has already reached a structural plateau: at 90 min, 69% of peripheral localities retain zero direct access to the metropolitan core, and that plateau reflects flow field structure, not individual willingness to travel. The planning object moves from the individual corridor to the origin-destination structure of the opportunity field. The operative metric is branching gain. Two distinct properties are at stake. Branching is topological: the number of registered destinations reachable from an origin. Sectoral diversity is economic: the range of branches of activity present in that reachable set. An intervention raises branching gain when it adds reachable destinations, creates junctions between existing corridors, or connects an established workforce pool to matching employment sectors, and it raises sectoral diversity when those added destinations widen the composition of activity. Transport investment is one route to branching gain. The location of new employment, the consolidation of intermediate employment nodes between periphery and core, and education and workforce-development capacity are others. The topology reconstructed here is a diagnostic instrument: it locates where labour pools, destination sectors, and flow corridors meet, and identifies where an intervention rewires peripheral access. Transport-time reduction enters this assessment as one option among several, measured by its branching gain.

The extra-registry exposure finding – defined as work destinations not recorded through registered employer addresses – extends this argument in a specific direction. Approximately half of all peripheral commuting flows in Cluj County are directed toward destinations with no identifiable registered employer. García et al. (2024) document the same structural co-persistence of labour and residential informality in peripheral Medellín: marginalised residential location and precarious working conditions reinforce each other spatially, generating clusters of informality that persist independently of improvements in transport access. Ouassou and Idrissi (2025) generalise this mechanism for Morocco: investments in peripheral territories generate weak spillovers because spatial lock-in channels resources toward established cores, leaving peripheral development structures unchanged. Policies designed to improve access to registered employment address only a subset of commuting behaviour in peripheral territories, where extra-registry destinations constitute the proximate opportunity structure. A complete account of peripheral mobility, including its extra-registry component, is necessary for designing interventions that correspond to the actual commuting regime of the territory.

These findings extend the territorial development literature in a specific direction. Torre (2025) identifies spatial exit – the departure of actors from a territory when local

solidarities and productive exchanges prove insufficient to sustain development – as the mechanism through which peripheral territories enter spirals of non-development. The commuting flows analysed here, reconstructed as average daily movements, capture spatial exit at granular temporal resolution: repeated departures from peripheral localities toward Cluj-Napoca constitute the routine expression of this dynamic. Torre's framework also captures a complementary movement: spatial exit from the core operates in reverse for workers who are employed in the metropolitan centre but cannot relocate near their workplace because of the housing cost premium generated by FDI-led investment concentration. These workers are residentially displaced outward by housing markets, and their daily commuting represents a forced long-distance movement rather than voluntary attachment to place. Both populations are products of the same investment geography that concentrates formal employment in the core while pricing out residential proximity to it. The flow field ramification asymmetry records accumulated spatial exit in network topology: low branching and high concentration are the structural signature of territories that have not generated sufficient local productive density to retain economic activity within their own registered employment field. Commuting policy that targets travel-time savings addresses the friction of exit while its cause remains in the employment geography.

Cluj-Napoca, alongside Bucharest, is a frontrunner of Romanian metropolitan development, and destination field ramification is a property of the FDI-led configuration rather than of the city (Petrovici & Ban, 2025). The Romanian urban typology locates several formations that share it (Petrovici & Poenaru, 2025), and the Timișoara enclave evidence documents the same concentration alongside peripheral residential growth (Petrovici et al., 2026). The structural continuity between the Cluj finding and patterns documented across post-socialist and peripheral contexts – from Bratislava's distance decay heterogeneity (Šveda & Madajová, 2023) to CEE regional convergence stagnation (Egri & Lengyel, 2024; Smętkowski et al., 2021) to post-Soviet land use restructuring (Li et al., 2020) – suggests that destination field segmentation is a durable property of metropolitan systems in which FDI-led investment geography concentrates formal employment in core zones while peripheral territories absorb residential and light industrial growth. Other metropolitan areas can monitor the same property with the same instruments. The warning signal is a widening gap between core and peripheral flow concentration, the peripheral Herfindahl index rising while peripheral branching stays flat as residential growth proceeds. This divergence marks declining peripheral branching, observable before commuting times deteriorate, and the spatial concentration of foreign-owned firms is the macro-structural indicator that anticipates it. This macro-structural condition predates individual commuting decisions and constrains them.

Conclusions

This paper has proposed and operationalised flow field topology as a network property that determines the type of registered labour market access available from each origin territory in a metropolitan commuting system. Applied to Cluj County (NUTS3), Romania, using mobile network signalling data covering approximately 150,000 daily commuting flows, cross-referenced against the full registered employer dataset

of the Cluj Territorial Labour Inspectorate, the analysis has identified a structural segmentation between the metropolitan core and peripheral origin territories.

Four findings constitute the empirical contribution. Flow field ramifies asymmetrically: the core exhibits high branching and low concentration while peripheral localities exhibit low branching and high concentration, a difference that increases monotonically across the four territory tiers. Time-threshold analysis shows that access to the metropolitan core does not equalise with additional travel time: 69% of peripheral origin territories retain zero core access at the 90-minute threshold. Extra-registry exposure rises from 0.8% in the core to 47.6% in peripheral localities, and the proximity gradient reverses, extra-registry destinations are geographically closer to peripheral residents than registered employment destinations. PPML gravity models confirm regime discontinuity: peripheral origins participate in a structurally distinct flow formation logic in which within-tier substitution partially compensates for core inaccessibility, and in which extra-registry destinations constitute a structural commuting target.

The methodological contribution is threefold. The paper proposes flow field topology as a replicable analytical approach for characterising commuting network structure from large-scale mobility data. It introduces extra-registry exposure as a measurable structural property of peripheral commuting regimes, providing a more precise alternative to generic informality classifications. And it demonstrates how educational administrative registers, disaggregated to building level, can resolve the student-worker disambiguation problem that limits most mobile-data commuting studies (Hadachi et al., 2020; Šveda & Madajová, 2023).

The present study has limitations that future research should address. The analysis draws on a single month of signalling data (October 2023). October falls at the end of the agricultural cycle, and peak-harvest months plausibly generate larger flow volumes toward agricultural extra-registry destinations than the observation window records. In the PPML specification this enters through the destination flow mass, so the single-month cross-section underestimates the annualised extra-registry flow mass for peripheral and rural origins. The estimated 47.6% peripheral exposure is therefore a lower bound, and a full-year panel would widen rather than narrow the core-periphery contrast. Applying the gravity specification to multi-season signalling data is the necessary validation step for confirming that destination field ramification is stable across the agricultural calendar. The validity of the administrative data sets a second boundary. The registered employer dataset records the registration address of each firm, which can differ from the operating site for multi-site firms and produces geocoding mismatch at the destination grid. The signalling data reflect the market share of a single operator. Extra-registry exposure is, in consequence, a proxy for administrative absence from the registered employer dataset. It records destinations for which no registered employer appears, a condition consistent with informal, agricultural, mobile, or own-account work, and with geocoding mismatch and multi-site registration. Disambiguating these components is a task for future research with firm-level operating-address data. The territory typology is administratively derived and does not capture within-tier heterogeneity. Cross-national replication of the destination field topology framework would establish whether the branching asymmetry documented here is specific to the Cluj institutional context or a structural property of FDI-led metropolitan regions across the CEE region.

For transport and urban planners, the findings indicate that mobility policies should be evaluated by their capacity to expand flow field branching in peripheral territories, alongside any travel-time savings. Investments that reduce commuting time without altering the topology of the network connecting peripheral localities to the registered employment field do not address the structural property of peripheral disadvantage. Effective policy for peripheral labour market access requires diversifying the registered employment base in peripheral localities, generating the multiple branching paths that currently characterise only the metropolitan core.

Appendix

Table 6 Stability of sectoral lock-in under destination territory controls (PPML estimates)

Variable	M3 Base	M3 + Territory controls
Dependent variable: trip count	Formal field	Formal field
Travel impedance		
log(Travel time)	7.403*** (0.573)	7.303*** (0.577)
log(Travel time) ²	−0.883*** (0.064)	−0.867*** (0.064)
Destination structure		
log(Destination pull, LOO)	0.574*** (0.029)	0.630*** (0.030)
Sectoral composition		
Compositional similarity (cosine)	1.666*** (0.324)	1.762*** (0.312)
log(Distance)	−1.025*** (0.145)	−0.980*** (0.130)
Compositional similarity × log(Distance)	−1.106*** (0.175)	−1.121*** (0.165)
Destination territory (ref.: Cluj-Napoca)		
Ring 1		0.308*** (0.073)
Ring 2		0.861*** (0.134)
Other Urban		0.591*** (0.114)
Other localities		0.785*** (0.213)
Fixed effects		
Origin grid cell	Yes	Yes
Fit statistics		
Observations	9,208	9,208
Pseudo R ²	0.798	0.803
BIC	105,687	103,199
Stability of lock-in coefficient		
Δ Compositional similarity × log(Distance)		−0.015 (1.3%)

Both models estimated on the formal destination sample (dt_formal, $N=9,208$) with PPML, origin fixed effects at the 1 km² grid cell level, and standard errors clustered at origin grid. M3 Base reproduces column M3 from Table 4. M3 + Territory controls adds destination territory dummies (work_Loc_Type, ref.: Cluj-Napoca). Δ reports the absolute change in the compositional lock-in coefficient between the two specifications. Significance: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Table 7 Pairwise-circuitry contrast by origin territory and destination field

Origin territory	Registered road km	Extra-registry road km	Registered PC km	Extra-registry PC km	Δ road km	Δ PC km
Cluj-Napoca	3.87	42.82	1.01	9.62	38.95	8.62
Ring 1	7.20	35.93	1.44	10.38	28.73	8.94
Ring 2	10.22	20.29	2.64	7.63	10.08	4.99
Other Urban	6.11	10.91	1.41	2.52	4.81	1.11
Other localities	17.13	12.00	4.40	4.54	-5.13	0.14

Pairwise circuitry is defined as $PC_{ij} = d_{ij}^{road} - d_{ij}^{euclidean}$, where d_{ij}^{road} and $d_{ij}^{euclidean}$ denote shortest-road and Euclidean distances between origin and destination grid centroids. Distances are weighted by commuting flows $\left(d = \frac{\sum_{ij} w_{ij} d_{ij}}{\sum_{ij} w_{ij}} \right)$. Differences are calculated as $\Delta = X^{extra-registry} - X^{registered}$.

Positive Δ values indicate longer distances to extra-registry destinations; negative values indicate shorter distances. PPML models include origin-grid fixed effects and standard errors clustered by origin grid. Full-field models include all destinations; formal-field models are restricted to registered employment destinations. Standard errors in parentheses

Table 8 Pairwise-circuitry robustness models

Variable	Full field: no PC	Full field: + PC	Formal field: no PC	Formal field: + PC
Extra-registry destination	0.641 (0.419)	2.320*** (0.303)		
Extra-registry $\times$ Ring 1	0.834** (0.287)	0.341 (0.247)		
Extra-registry $\times$ Ring 2	2.071*** (0.215)	0.619* (0.311)		
Extra-registry $\times$ Other Urban	1.711*** (0.177)	-0.637** (0.196)		
Extra-registry $\times$ Other localities	2.924*** (0.164)	0.213 (0.183)		
log(1+PC excess)		-1.742*** (0.064)		-0.100 (0.086)
Compositional similarity			1.876*** (0.309)	1.929*** (0.312)
log(Distance)			-0.940*** (0.127)	-0.871*** (0.140)
Compositional similarity $\times$ log(Distance)			-1.140*** (0.164)	-1.183*** (0.167)
Origin grid fixed effects	Yes	Yes	Yes	Yes
Observations	12,932	12,932	9,142	9,142
Pseudo R ²	0.485	0.623	0.809	0.809
BIC	306,856	225,826	99,831	99,747

PPML estimates with origin-grid fixed effects and standard errors clustered by origin grid. Pairwise circuitry is defined as $PC_{ij} = d_{ij}^{road} - d_{ij}^{euclidean}$, where d_{ij}^{road} and $d_{ij}^{euclidean}$ denote shortest-road and Euclidean distances between origin and destination grid centroids. Distances are weighted by commuting flows $\left(d = \frac{\sum_{ij} w_{ij} d_{ij}}{\sum_{ij} w_{ij}} \right)$. Full-field models include both registered and extra-registry

destinations; formal-field models are restricted to registered employment destinations. Standard errors are reported in parentheses. Significance: *** ($p < 0.001$), ** ($p < 0.01$), * ($p < 0.05$)

Table 9 Robustness to alternative travel-time knots

Variable	M1 40/70	M1 30/60	M3 40/70	M3 30/60
Outside formal field/extra-registry	1.991*** (0.349)	2.034*** (0.327)		
Compositional similarity			1.885*** (0.309)	1.852*** (0.306)
log(Distance)			−0.927*** (0.126)	−0.946*** (0.127)
Compositional similarity × log(Distance)			−1.152*** (0.162)	−1.138*** (0.163)
Origin grid fixed effects	Yes	Yes	Yes	Yes
Observations	13,013	13,013	9,208	9,208
Pseudo R ²	0.473	0.466	0.808	0.808
BIC	314,971	318,957	100,491	100,794

PPML estimates with origin-grid fixed effects and standard errors clustered by origin grid. The 40/70 specification uses empirical knots informed by the threshold-access diagnostics. The 30/60 specification uses conventional commuting-budget knots as a robustness check. Standard errors in parentheses. Significance: *** $p < 0.001$, ** $p < 0.01$, * $p < 0.05$

Author Contributions Vlad Alexe made the calculations Norbert Petrovici wrote the first version of the text Andre Torre revised the text and the calculations.

Data Availability The data are available at the fig share: <https://figshare.com/s/f07bad828125fe7e9164> We cannot share them publicly now, but we could do if the paper is accepted.

Declarations

Competing interests The authors declare no competing interests.

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