Multiplex networks in regional knowledge production

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Regional knowledge production is shaped by the joint influence of internal capabilities, spatial spillovers, and interregional collaboration structures, yet empirical research usually captures only one collaboration channel at a time. This creates a measurement problem: co-patenting, co-publication, and collaborative research and development (R&D) networks each reflect different institutional settings, partner compositions, and stages of knowledge creation, so findings based on a single layer can overfit to the properties of that specific network rather than represent interregional knowledge dynamics more generally. A multiplex network framework addresses this limitation by modelling the same regions across multiple collaboration layers simultaneously, making it possible to compare layer-specific effects and identify patterns that remain invisible in single-layer analyses. Building on this logic, the paper integrates multiplex network analysis into a regional knowledge production framework and examines how regional network position relates to innovation performance when collaboration is treated as a multi-layered phenomenon rather than a single observed tie structure.

Regional knowledge production is grounded in the knowledge production function tradition, where innovation output is generated from inputs such as R&D effort and human capital, and is further reinforced by the cumulative effect of previously accumulated knowledge. In this perspective, innovation is path dependent: regions with larger stocks of past knowledge are better positioned to generate new knowledge in subsequent periods. Later regional science work expands this framework beyond purely intra-regional inputs by showing that regions also benefit from external knowledge sources. Two external channels are central: geographical proximity, which supports spillovers through interpersonal and interorganizational interactions, and relational proximity, which operates through interregional collaboration networks. The empirical literature consistently shows that both channels matter for regional innovation, but their relative importance varies across contexts and knowledge types. In some settings, network position can partly compensate for geographic disadvantage; in others, spatial and relational proximity operate as complements. This makes it necessary to model spatial and network effects jointly rather than treat one as a residual control for the other.

The single-layer treatment of collaboration networks is a major source of bias in this literature because different network types encode different mechanisms of knowledge circulation. Framework Programme R&D networks reflect policy-driven project collaboration and are often structurally dominated by universities and large public research organizations; co-patenting networks capture formal technological cooperation but are more representative of patent-intensive sectors and stronger innovation systems; co-publication networks capture scientific collaboration and international academic exchange but primarily represent research-based knowledge relations. These layers differ in topology, spatial reach, and temporal dynamics, so centrality in one layer does not imply the same role or effect in another. A multiplex framework is therefore methodologically preferable because it preserves this heterogeneity while allowing a unified assessment of regional embeddedness across channels. In regional innovation analysis, this provides a stronger basis for identifying which dimensions of network position are consistently associated with innovation outcomes and for reducing inference errors caused by relying on any single collaboration proxy.

The empirical analysis is conducted on a panel of EU-28 NUTS3 regions over a 15-year period, using NUTS3 as the unit of observation to capture territorially embedded innovation dynamics more precisely than higher-level administrative aggregation. Interregional collaboration is reconstructed from three harmonized RISIS2 sources[1]: Framework Programme project participation for policy-driven R&D ties, PATSTAT-based co-patent applications for technological collaboration, and Web of Science based CWTS co-publications for scientific collaboration. All datasets are aggregated to the regional level and restricted to interregional ties (excluding within-region collaborations) in order to measure external knowledge inflows consistently across layers. Regional innovativeness is operationalized as patent applications per million inhabitants, complemented by the standard RKPF controls: lagged/depreciated patent stock (from the RISIS patent database), human capital (share of tertiary-educated population aged 25-64), R&D intensity (R&D expenditure relative to GDP), and GDP per capita.

Interregional knowledge flows are modelled as weighted networks in which nodes are regions and edge weights represent the intensity of collaboration (number of joint activities). The three collaboration channels are analyzed both separately and as an overlapping multiplex network, where each channel forms a distinct layer over the same regional node set. Regional network position is measured with weighted, normalized degree, betweenness, closeness, and alpha-coreness centralities, capturing complementary dimensions of access, brokerage, reach, and core embeddedness. Multiplex indicators are constructed by first computing centralities layer by layer and then aggregating them across layers using the arithmetic mean, which provides a balanced measure of regional embeddedness while limiting dominance by any single collaboration type. These network indicators are then embedded in a panel RKPF specification with one-year-lagged regressors to reflect diffusion delays and reduce endogenity concerns. Estimation proceeds from pooled OLS benchmarks to region and time fixed-effects models, and then to spatial econometric specifications. Spatial dependence is diagnosed using Moran's I under multiple row-standardized weight matrices and Lagrange Multiplier tests for different spatial dependences. Tests show, that the preferred specification is a spatial error model estimated by maximum likelihood, using the four-nearest-neighbors matrix selected from the diagnostics. This modelling strategy isolates network-position effects from spatially correlated unobserved influences and allows a direct comparison of layer-specific versus multiplex estimates.

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The results confirm that the network-innovation relationship is strongly layer-dependent. Across the three collaboration channels, the same centrality metric can change in both magnitude and sign, confirming that network embeddedness is not a uniform mechanism but depends on the institutional nature of the collaboration layer. Degree centrality is positively associated with regional patenting in all layers, but its effect is substantially stronger in the Framework Programme network than in co-patenting or co-publication. Closeness centrality is positive and significant in the Framework Programme and co-publication layers, with the strongest association in co-publication, while betweenness centrality is negatively associated with patenting in the co-patenting network and remains insignificant elsewhere. This pattern suggests that broad access and shorter network distance are generally beneficial, whereas brokerage roles in technological collaboration may generate coordination costs that weaken innovation performance. The control variables also behave in line with the regional knowledge production literature: past patent stock is the most robust predictor of current patenting, confirming cumulative knowledge dynamics, while human capital and GDP per capita remain positively associated with innovation output.

A second key result is that spatial dependence and multiplex aggregation materially change inference. Spatial diagnostics identify the strongest autocorrelation in patenting activity under a four-nearest-neighbors matrix, and the preferred spatial error specifications show that part of the variation in regional patenting reflects spatially correlated unobserved factors rather than network position alone. Once this spatial structure is accounted for, degree and closeness retain positive associations, indicating that these measures capture genuine access to external knowledge beyond simple geographic clustering. At the same time, multiplex estimates reveal effects that are weaker or invisible in single-layer models: while many multiplex coefficients lie between the corresponding layer-specific values (as expected from aggregation), multiplex closeness remains as strong as the best-performing single layer, and multiplex alpha-coreness becomes significantly positive even when alpha-coreness is not significant in any individual layer in the extended specifications. This indicates that core embeddedness matters primarily when it is sustained across multiple collaboration channels, and it provides the central empirical justification for the multiplex approach: aggregating collaboration layers is not a smoothing exercise, but a way to recover structurally meaningful dimensions of regional embeddedness that single-network proxies miss.

The central finding of the conducted research is that interregional network effects on regional innovation are non-uniform, and they become interpretable only when collaboration is treated as both multi-layered and spatially embedded. Across Framework Programme R&D, co-publication, and co-patenting networks, the same centrality measure can have different signs and magnitudes, which shows that network position is not a generic advantage but depends on the collaboration channel and the specific role a region occupies within it. Positions associated with connectivity and short reach to knowledge sources (especially degree and closeness) are generally more favorable for patenting, while brokerage in the regional network (betweenness) is not consistently beneficial and can be negatively associated with innovation output, particularly in technological collaboration where coordination burdens may outweigh informational gains. The multiplex specification adds an important substantive result beyond averaging: some effects that are weak or invisible in single-layer models become statistically meaningful when regional embeddedness is sustained across multiple channels, most notably for alpha-coreness, which indicates that durable core membership across collaboration types is more relevant than layer-specific core status alone.

The implications are both policy-relevant and methodological. For regional innovation policy, the results argue against one-size-fits-all networking strategies: strengthening innovation performance requires channel-specific collaboration policies, because what improves outcomes in Framework Programme participation (expanding connectivity) is not necessarily what works in co-patenting (where intermediary brokerage may be counterproductive), and scientific collaboration appears to reward stronger connection and shorter path to other regions. At the same time, the persistence of spatial dependence implies that collaboration policy cannot substitute for place-based development; network interventions and territorial capabilities must be designed jointly, since part of observed innovation advantage reflects spatially clustered conditions that interact with network position. Methodologically, the study implies that single-layer network proxies are likely to produce biased or incomplete inference, and that combining multiplex network representations with spatial econometric modelling provides a more reliable basis for identifying which dimensions of regional embeddedness actually matter for innovation outcomes.