Exploring International Collaboration Dynamics through Multilayer Network Analysis

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International collaboration is hailed as one of the main pillars of modern science and the driving force behind the fourth age of research [1, 5]. Rich literature has addressed concerns ranging from perceived patterns and shaping factors of international collaboration [10, 11, 13] to integration and inequalities in global science [8, 9, 12] using bibliometric or network approaches. However, two notable gaps exist: Cognitively, the internal heterogeneity of international collaboration remains understudied, except for a few studies on the rise of multiple institutional affiliations [6, 7]. Methodologically, while network perspectives have provided important insights into the structure and dynamics of collaboration networks, most studies overlook the heterogeneity of ties and interdependency between them [cf. 2]. These gaps may hinder our ability to fully grasp the intricate mechanisms driving international collaboration, which could have significant policy implications in an era where international collaboration has increasingly become an integral part of science diplomacy.

To address the gaps mentioned above, this project aims to uncover the dynamics of international collaboration through multilayer networks, leveraging its capability of organizing nodes (e.g., collaborating countries) into distinct layers that represent the multiplicity of links (e.g., different categories of co-authorship types). By considering multiple layers simultaneously, our analysis extends beyond mere connections between nodes to include interactions between layers. Hence, the multilayer network approach has the potential to offer insights on the internal heterogeneity of collaborations by co-authorship patterns. Specifically, we pose the following question: What are the similarities and differences across multilayer, aggregate, and layered co-authorship networks in terms of network properties and structures? As a proof of concept, we focus on international collaboration between Taiwan and its eight New Southbound Policy (NSP) priority countries, including Australia, India, Indonesia, Malaysia, the Philippines, Singapore, Thailand, and Viet Nam.

Data and Method

The sample consists of 18,139 papers (journal articles, conference papers, and review articles) published between 2017 and 2021, indexed in Clarivate's Web of Science, with at least one author from Taiwan and one from NSP priority countries, as determined by institutional affiliations. To better understand collaboration dynamics, we have identified five co-authorship patterns based on first and last authors' affiliation: *TWN-led*, *NSP-led*, *Equal*, *Minimal*, and *Co-affiliation* (see Table 1 for their definitions). The multilayer network analysis is conducted using the `muxViz` package in R [3, 4], and the layers are the five co-authorship types.

Preliminary Results

Among the 18,139 papers in the sample, nearly one-fourth are led by NSP priority countries (24.8%), closely followed by Equal co-authorship (21.9%) and TWN-led papers (21.5%), with Minimal and Co-affiliation patterns accounting for 16.8% and 15.1%, respectively. Applying common network measures to each layer representing specific co-authorship patterns, as well as to the aggregate network, reveals that these patterns have distinct sizes and characteristics such as density (i.e., the proportion of all possible edges that are present in the network) and transitivity (i.e., the probability for the two neighbors to be both connected to the third one), as indicated by Table 2. Notably, the aggregate network's high density and high transitivity seem largely attributed to collaboration with minimal involvement from both Taiwan and NSP priority countries.

Different measures for inter-layer connectivity in the multilayer co-authorship network are presented in Figure 1, including: mean node overlapping (the number of nodes existing simultaneously in a pair of layers), mean edge overlapping (the number of edges replicated across a pair of layers), inter-layer assortativity (the average degree–degree correlations across layers), and inter-layer similarity (by shortest-path distance between nodes) [3]. The correlation between pairs of layers reveals qualitative similarities between edge overlapping and inter-layer assortativity (Pearson correlation), with Equal and Co-affiliation patterns forming a close cluster, followed by TWN-led and NSP-led patterns. In contrast, Minimal and NSP-led collaborations are clustered first in node overlapping. A two-cluster structure is visible in both inter-layer assortativity (Spearman correlation) and similarity, segregating NSP-led and Minimal from Co-affiliation, Equal, and

TWN-led collaborations. Together, the results indicate that Equal and Co-affiliation collaborations exhibit the most similar network structures. Moreover, countries involved in NSP-led collaboration also actively participate in collaborations not led by Taiwan or NSP priority countries.

Lastly, Figure 2 shows the correlations of strength versatility and PageRank versatility with their respective classical counterpart across each individual layer and the aggregate network, where versatilty refers to centrality within the multilayer context. Strength versatility (a weighted version of degree versatility) and PageRank versatility (an extension of the classic PageRank algorithm based on multilayer random walks) are detailed in [3]. It is evident that strength versatility correlates strongly with strength centrality derived from both the aggregate network and the Minimal layer, albeit to a much lesser extent with other layers. Conversely, PageRank versatility demonstrates a robust correlation with PageRank centrality across separate layers, except for the Minimal layer, which instead closely aligns with the aggregate network's PageRank centrality. These observations underscore the nuanced interplay between versatility and classic centrality measures, highlighting how the relative importance of countries varies across different co-authorship patterns.

Tentative Conclusion and Future Direction

Our preliminary results suggest that analyzing international scientific collaboration networks without distinguishing between different co-authorship patterns may overlook the nuanced collaboration dynamics reflected in authorship order. Rather than capturing the full spectrum of international collaboration, the conventional approach tends to highlight collaboration with minimal involvement among the countries of interest. Although limited by its scope and sample characteristics, this study provides preliminary evidence challenging long-held assumptions that equate specific characteristics and properties of aggregate networks with participation or inclusion levels in global science. Future research should aim to broaden the scope and refine co-authorship patterns, facilitating scalable analyses with more generalizable implications.

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Table 1: Co-authorship patterns.

Pattern	Definition
TWN-led	Either first or last authors are affiliated with Taiwan but not NSP priority countries
NSP-led	Either first or last authors are affiliated with NSP but not TWN
Equal	Either first author is affiliated with TWN and last author with NSP or vice versa
Minimal	Neither first nor last authors are affiliated with TWN or NSP
Co-affiliation	Either first or last authors are co-affiliated with TWN and NSP

Table 2: Descriptive measures for the aggregate co-authorship network bewteen Taiwan and NSP priority countries and for its five layers: number of nodes, number of edges, density, and transitivity.

Network	# Nodes	# Edges	Density	Transitivity
Aggregate	178	10885	0.691	0.890
Minimal	169	10747	0.757	0.896
NSP-led	138	3724	0.394	0.690
TWN-led	111	1638	0.268	0.574
Equal	98	1051	0.221	0.482
Co-affiliation	86	731	0.200	0.484

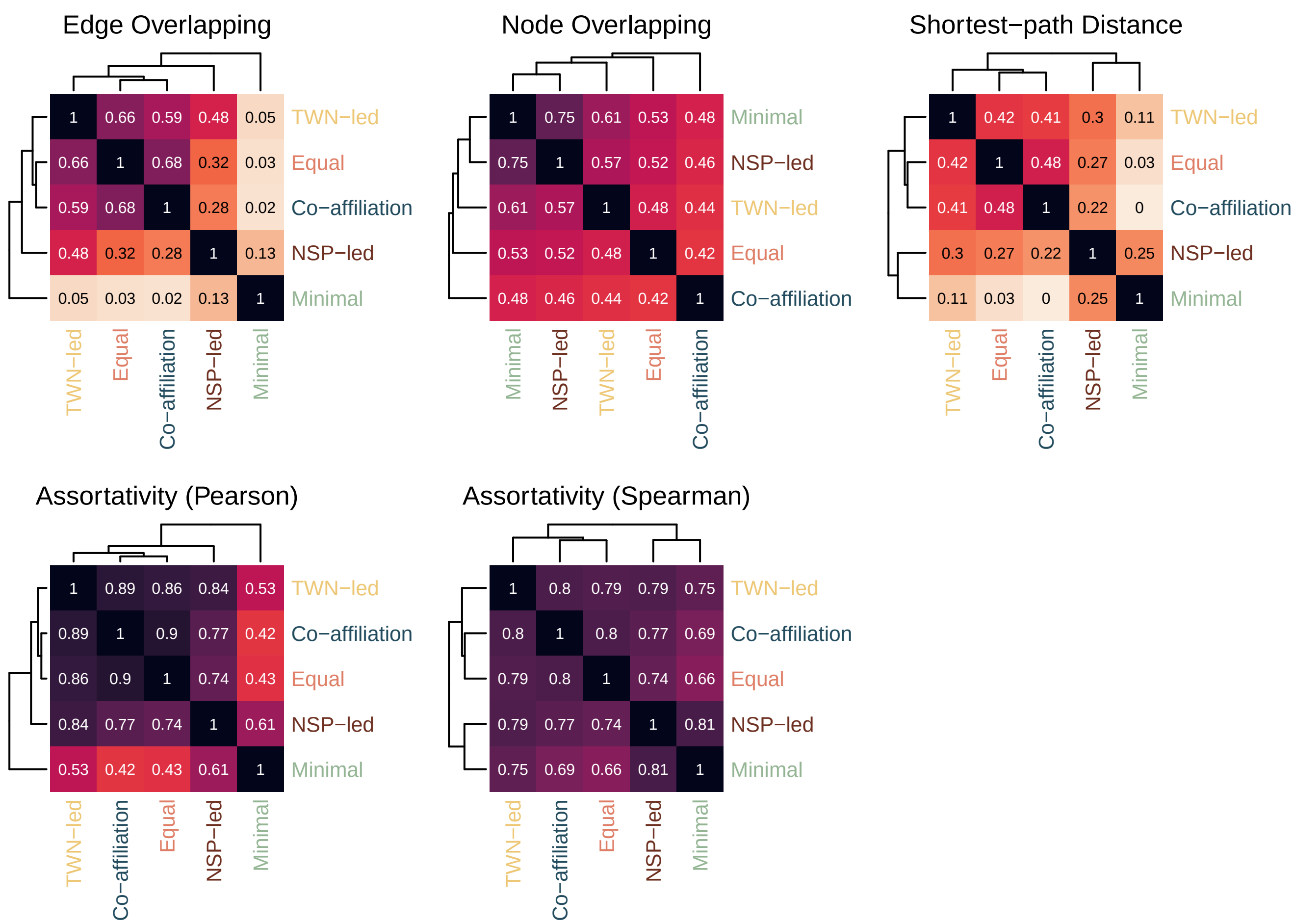

Figure 1: Different measures of layer–layer correlations for the multilayer co-authorship network. The strength of the correlation is color-coded. Dendrograms on the x-axis and y-axis show hierarchical clustering based on the correlation values.

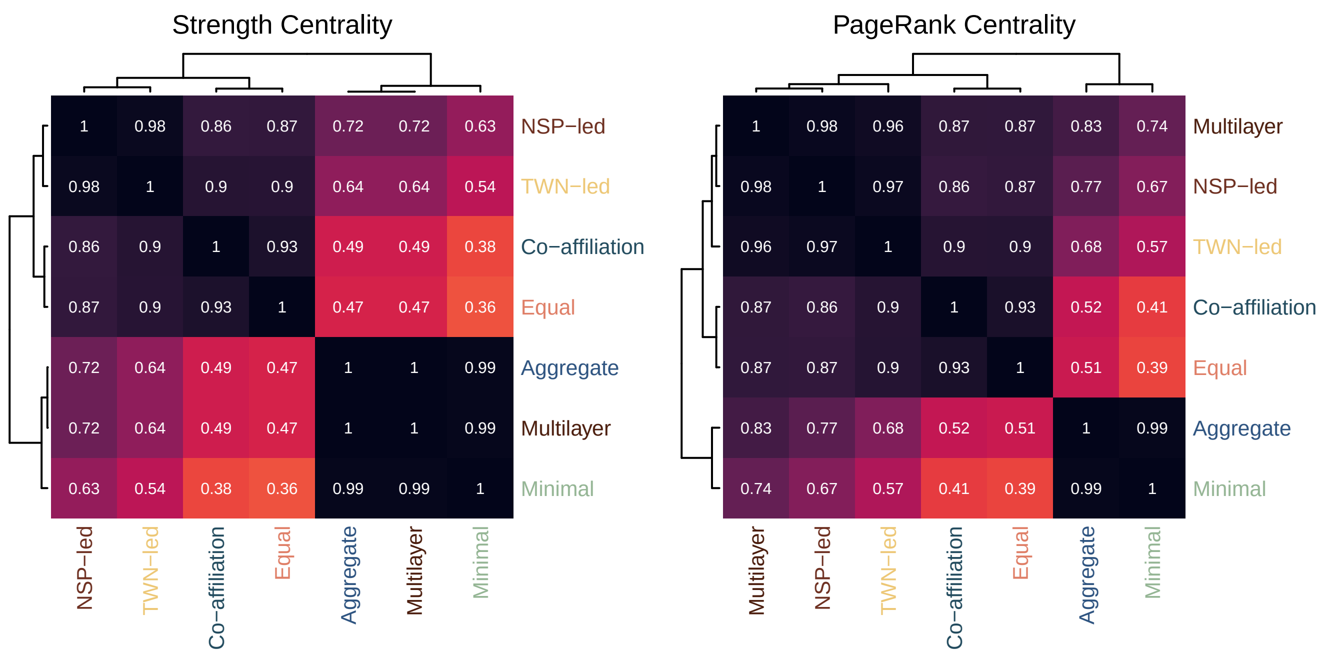

Figure 2: Correlation plots for PageRank as well as strength versatilities and centralities in the multilayer co-authorship network. The strength of the correlation is color-coded. Dendrograms on the x-axis and y-axis show hierarchical clustering based on the correlation values. Note that Taiwan, the ego of the network, has been excluded from the correlation calculations.