Using Bipartite Network Analysis to Examine Global Collaboration between Engineering and STEM Education (2014–2024)

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Abstract

Background: Over the past decade, both engineering education and STEM education have expanded rapidly worldwide. However, most prior studies have examined each field independently, and the connections between these two domains remain underexplored. Understanding cross-domain collaboration structures is essential for advancing interdisciplinary integration and sustaining innovation in education research.

Purpose: This study examines global collaboration patterns between engineering education and STEM education through a network perspective. The specific goals are to: (1) characterize the collaboration networks, (2) identify boundary-spanning authors and evaluate their structural importance for network connectivity, (3) assess the influence of research field and country homophily on collaboration formation.

Methods: Bibliographic data were collected from Scopus covering publications from 2014 to 2025 across ten representative journals, five in engineering education and five in STEM education. An author-paper bipartite network was constructed and projected into co-authorship networks. Network properties including density and giant component size were computed. Boundary-spanning authors were identified based on cross-domain publication histories, and their structural contributions were assessed through node-removal simulations. Exponential random graph models (ERGMs) were estimated to examine the effects of country and field homophily on collaboration formation.

Results: The combined collaboration network is sparse but connected, with a low overall density and a giant component comprising 9,100 of 19,619 nodes (46.38%) in the bipartite network. STEM education exhibits higher connectivity than engineering education. Cross-domain authors constitute only 3.4% of the author population, yet their average degree substantially exceeds that of single-domain authors. Removing these authors reduces the giant component by more than half, indicating their critical bridging role. ERGM results show that country homophily strongly shapes collaboration patterns, while field homophily also exerts a significant but weaker effect. Cross-domain collaboration increased steadily from 2017 to 2021 before declining after 2022.

Conclusion: Global collaboration between engineering education and STEM education exhibits a “dense-within, sparse-between” structure, with strong internal clustering but fragile cross-domain connectivity. A small group of boundary-spanning authors plays a disproportionate role in maintaining network integration, making cross-field collaboration vulnerable to disruption. Strengthening durable cross-domain and cross-national collaboration mechanisms is essential for fostering a more resilient and integrated global education research ecosystem.

Introduction

STEM education has increasingly emphasized interdisciplinary integration, with engineering often positioned as a central integrative driver [1]. As the field has developed, engineering education has been recognized as a distinct discipline rather than merely an application of science [2]. Understanding the mechanisms of collaboration between engineering education and STEM education becomes crucial for strengthening the knowledge base that informs educational innovation.

Co-authorship is a well-documented record of collaboration that can be used to infer social structures and patterns of knowledge production [3]. Previous bibliometric research in engineering education suggests that collaboration networks have historically been uneven; a small fraction of scholars contribute disproportionately to research capacity, while interdisciplinary scholars serve as bridges between isolated teams [4]. Collaboration patterns also appear to be geographically constrained. Scholarship remains strongly U.S.-centered in authorship, institutional influence, and network position [5], [6], with low rates of international co-authorship and substantial frictions in cross-regional collaboration [7]. The networks in STEM education show similarly uneven structures [8].

Despite extensive bibliometric research, empirical evidence on global cross-domain collaboration between engineering education and STEM education remains limited. Prior work often treats the fields separately and rarely tests structural collaboration barriers within inferential network models [4], [8]. Drawing on publications and authors from leading engineering education and STEM education journals between 2014 and 2025, this study examines global collaboration between the two fields. We use a bipartite network approach to explore network characteristics, key author nodes, and the factors shaping these networks. Our research questions include:

1. What are the structural characteristics of the combined collaboration network across engineering education and STEM education, and how do these structures differ between the two fields?
2. How important are cross-domain authors for network connectivity?
3. To what extent do geographic location and research field affiliation influence link formation in the overall collaboration network?

Literature Review

Engineering education and STEM education have expanded rapidly, driven by policy agendas aimed at strengthening national innovation capacity and the future STEM workforce [9]. In engineering education, publications in major venues such as the American Society for Engineering Education (ASEE) Annual Conference more than tripled from the mid-1990s to the early 2010s [10]. The field also shifted from instructional case reports toward theoretically grounded empirical research on learning, assessment, diversity, and faculty development [6]. STEM education research has undergone a similar development. STEM education has become a well-established domain within educational research [11]–[13], with publications having increased exponentially since the early 2000s, particularly after 2015 [5], [8], [14]. Together, engineering education and STEM education are positioned as key contributors to international STEM agendas [2].

Previous bibliometric and network-analytic studies show that the engineering education collaboration network is structurally concentrated. Research activity, authorship, and citation are dominated by a limited group of highly central scholars and a small number of countries, particularly the United States, with Europe and the Asia-Pacific region playing secondary roles [4], [7], [15] . Collaboration is primarily organized through in-state and within-subdiscipline ties, which far outnumber national and international collaborations, resulting in loosely connected clusters of practice and limited cross-cluster knowledge exchange [10], [16]. Bibliometric studies of STEM education similarly depict a rapidly expanding global literature characterized by clustered collaboration patterns, increasing interdisciplinarity, and evolving thematic concentrations across learning contexts and educational levels [1], [8], [13], [17], [18] .

In education research, network-based approaches have been advocated as a means of quantifying knowledge structures and the development of expertise [19]. Recent methodological work further calls for moving beyond single-mode coauthorship networks toward affiliation-based representations, particularly through bipartite networks, which can reveal boundary-spanning and cross-community participation [20]–[22].

Methods

Data Collection

Bibliographic records were retrieved from the Scopus database covering the period from 2014 to 2025. Peer-reviewed journal articles were collected from ten representative outlets spanning engineering education and STEM education. The engineering education corpus comprised articles published in the *Journal of Engineering Education, European Journal of Engineering Education, International Journal of Engineering Education, Journal of Pre-College Engineering Education Research,* and *Journal of Women and Minorities in Science and Engineering*. The STEM education corpus included articles from *Science Education, Journal of Research in Science Teaching, Journal of Science Teacher Education, Cultural Studies of Science Education, and International Journal of STEM Education.*

For each publication, metadata were extracted including author names, Scopus Author IDs, publication year, source title, institutional affiliations, and the Scopus EID. The Scopus EID was used to uniquely identify publications, while Scopus Author IDs were employed to disambiguate authors. The final dataset comprised 6,407 articles, including 3,032 engineering education articles and 3,385 STEM education articles, authored by 13,212 unique authors.

Data Analysis

A bipartite author-paper network was constructed, consisting of author nodes and paper nodes connected by authorship ties. Based on publication histories, authors were categorized as engineering education-only authors, STEM education-only authors, or boundary-spanning authors with publications in both fields. An author was classified as boundary-spanning if they had at least one publication in each of the two domains during 2014–2025. The bipartite network was subsequently projected into an author-author collaboration network to capture direct co-authorship relationships. Network-level properties were computed at two levels: density and giant component statistics on the bipartite author–paper network, and average clustering and average path length on its one-mode author co-authorship projection restricted to the giant component.

Author-level influence was evaluated using degree centrality as the mean number of co-authorship ties per author, and the power multiplier of boundary-spanning authors was compared with that of single-field authors. Network resilience was examined through node-removal experiments simulating targeted attacks, in which boundary-spanning authors were sequentially removed to assess changes in giant component size and to quantify their contribution to overall network connectivity.

To identify the direction of knowledge flows between the two fields, we examined which field each cross-domain author published first and which field they subsequently entered by comparing their first publication year in each field. We then calculated, for each year, the proportion of publications involving cross-domain authors to capture changes in the level of cross-field knowledge integration over time.

To investigate the mechanisms underlying collaboration formation, an exponential random graph model (ERGM) was estimated on the bipartite author–paper network using the *ergm* package in R. The model included an edges term and two bipartite homophily terms (b1nodematch) for country and field. Because initial MCMC maximum likelihood estimation produced model degeneracy due to network size and structure, parameters were estimated using maximum pseudolikelihood estimation (MPLE).

Results

Network Structure

The 6,407 publications collectively form a collaboration network that is sparse yet connected. The overall network density is extremely low (1.09×10^{-4}), indicating that most authors do not collaborate directly with the majority of other authors. Nevertheless, the network is not fragmented. The giant component (GC) of the bipartite author–paper network includes 9,100 nodes (46.38% of all 19,619 nodes), encompassing 5,726 authors (43.34% of the 13,212 authors) linked through chains of co-authorship.

Comparisons across subdomains reveal differences in the level of collaborative integration. The STEM education subnetwork demonstrates higher connectivity, with its GC comprising 54.23% of authors, compared to 29.28% in the engineering education subnetwork. This pattern suggests that STEM education supports more integrated collaboration structures. Both subdomains exhibit high clustering coefficients (0.78), indicating that scholarly collaboration is concentrated within tightly knit groups. Table 1 summarizes the key structural characteristics of the author collaboration networks for the full dataset and each subdomain.

Table 1. Descriptive Statistics of Collaboration Network Structure

Domain	Density	Giant Component (%)	Average Clustering
Whole Network	1.09×10^{-4}	46.38	0.78
Engineering Education	1.95×10^{-4}	29.28	0.78
STEM Education	2.22×10^{-4}	54.23	0.78

Note. Density and giant component percentages are computed on the bipartite author–paper network. Average clustering is computed on the one-mode author co-authorship projection of the giant component.

Cross-domain Authors

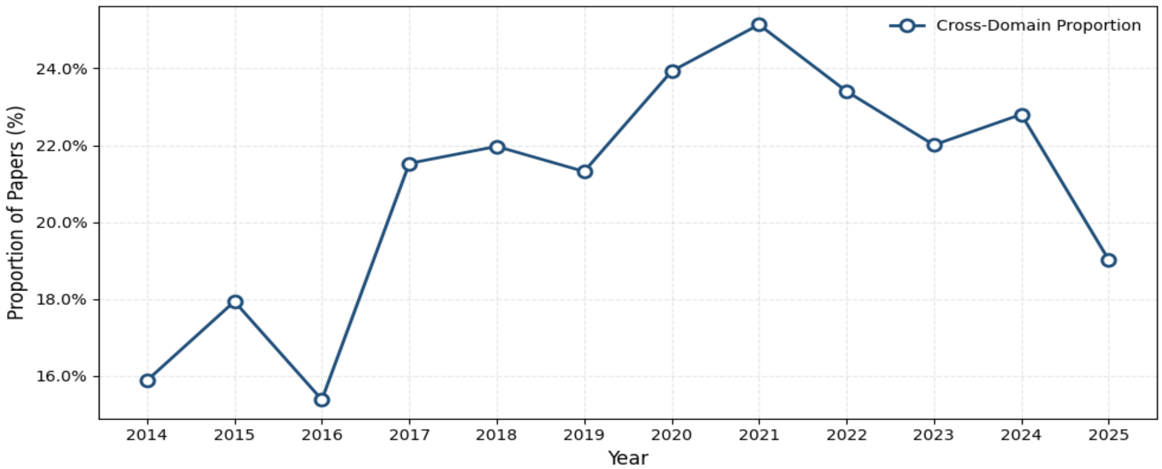
Cross-domain authors represent only 3.4% of the author population, corresponding to 451 individuals. Their distribution shows pronounced geographic inequality and a clear head effect. The United States dominates this group with 374 cross-domain authors, while all other countries contribute fewer than 11 each (Sweden = 10, Australia = 6, with Uganda, the United Kingdom, Denmark, and China each at 5).

Despite their small proportion, cross-domain authors exhibit a pronounced amplification effect within the collaboration network. Their average degree is substantially higher than that of single-domain researchers. Specifically, cross-domain authors have an average degree 1.93 times higher than engineering education-only authors and 1.45 times higher than STEM education-only authors. Removing this 3.4% of core authors reduces the size of the bipartite giant component by 53.97%, from 9,100 nodes to 4,189 nodes. This finding indicates that knowledge exchange between engineering education and STEM education relies heavily on this group.

Cross-domain migration patterns exhibit a clear asymmetry between engineering education and STEM education. Nearly half of cross-domain authors (49.89%) initially published in engineering education before transitioning into STEM education, whereas 38.14% followed the reverse trajectory, indicating a trend for engineering education scholars to move into the broader STEM education field. A smaller subset of authors (11.97%) entered both domains simultaneously.

Cross-domain publications display a rise-and-decline pattern: the proportion remained relatively stable between 2014 and 2016 (15-18%), increased sharply from 2017 to 2021 to a peak of 25.14%, and became volatile before declining in 2025 (19%). Figure 1 illustrates the annual proportion of publications involving cross-domain authors across engineering education and STEM education from 2014 to 2025.

Figure 1. Annual trend of cross-domain collaboration between engineering education and STEM education, 2014–2025.



ERGM

The country homophily term exhibits a statistically significant positive coefficient, indicating that country affiliation is a strong driver of collaboration. Field homophily also shows a significant positive effect. Although weaker than country homophily, this effect suggests the continued presence of disciplinary silos in academic collaboration. Table 2 reports the maximum pseudolikelihood estimation results.

Table 2. ERGM Estimates of Bipartite Author–Paper Network (MPLE)

Effect	Estimate	Std. Error	P-value
Edges (baseline)	−8.5498	0.0075	< 0.001
Country Homophily	0.1175	0.0014	< 0.001
Field Homophily	0.0381	0.0016	< 0.001

Discussion and Limitations

While previous scholarship suggests that engineering education and STEM education have developed along convergent paths [23], our findings indicate that the two fields remain only weakly integrated. Engineering education scholars are moving toward broader STEM education contexts, while most scholars still conceptualize the two disciplines as distinct career pathways. Prior research argued that engineering design can serve as a central integrative framework for connecting other STEM disciplines [24]. Further studies should examine how the two disciplines can be meaningfully integrated.

The finding is also consistent with prior research showing that high clustering in co-authorship networks often reflects localized knowledge production [3]. Geographic constraints pose a greater barrier to collaboration than disciplinary differences, consistent with prior work describing these research communities as regionally concentrated [25]. This poses a critical challenge for the internationalization of research. The network relies on a small number of bridging scholars, consistent with prior studies showing that interdisciplinary connectivity often depends on a limited set of boundary-spanning actors whose absence can lead to network fragmentation [4]. As a result, collaboration between engineering education and STEM education is highly sensitive to external shifts in the research landscape.

Several limitations should be acknowledged when interpreting these findings. First, our analysis is restricted to ten Scopus-indexed journals and excludes conference proceedings (e.g., the ASEE Annual Conference), which constitutes a substantial venue for engineering education scholarship. Second, the ERGM was estimated using maximum pseudolikelihood (MPLE) as MCMC-MLE produced model degeneracy on a network of this size. MPLE standard errors rely on a naive likelihood approximation and should be read as suggestive rather than definitive. Boundary-spanning authors were also identified using a permissive threshold ($\geq$1 publication in each domain), which may classify incidental cross-domain authors alongside genuinely integrative scholars.

Future work could address these limitations in several directions. Expanding the corpus to conference proceedings and additional STEM education venues would broaden the empirical base and reduce the science-education skew of the current sample. Sensitivity analyses using stricter boundary-spanning thresholds would help distinguish incidental from genuinely integrative cross-domain authors. Finally, complementing co-authorship structures with citation, topic-modeling, or interview data would capture forms of knowledge transfer that lie beyond formal authorship.

Conclusion

In conclusion, cross-domain integration between engineering education and STEM education currently rests on a small set of boundary-spanning authors, leaving the network vulnerable to disruption. Future efforts should prioritize sustained interdisciplinary and cross-national exchange. International funding agencies should explicitly support Global North–South and East–West partnerships to mitigate geographic homophily. By expanding and diversifying the pool of bridging authors and incentivizing cross-border collaboration, the field can evolve from loosely connected clusters into a more resilient and genuinely integrated global research network.

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