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Aníbal Ignacio Román Cortés

anibal.roman@usach.cl

Universidad de Santiago de Chile

María Teresa Santander Gana

Universidad de Santiago de Chile

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Original Paper

Asymmetric consolidation in a research field: A longitudinal scientometric analysis of Chile-associated engineering education research, 2015-2025

Aníbal Ignacio Román Cortés1,* María Teresa Santander Gana2

1 Centro de Integración Ingeniería y Sociedad, Facultad de Ingeniería, Universidad de Santiago de Chile, Santiago, Chile

2 Departamento de Ingeniería Industrial, Facultad de Ingeniería, Universidad de Santiago de Chile, Santiago, Chile

* Corresponding author: anibal.roman@usach.cl; ORCID: 0000-0001-7223-4197

María Teresa Santander Gana: mariateresa.santander@usach.cl; ORCID 0000-0002-8228-1613

Abstract

Publication growth is often interpreted as evidence that a research field is maturing, yet cumulative bibliometric indicators can obscure whether social, organizational, and cognitive structures reproduce over time. This study introduces asymmetric consolidation as a multilayer scientometric diagnostic and applies it to 451 publications associated through author affiliation with engineering education research in Chile. Primary longitudinal analyses covered 2015-2024; 2025 was retained as a descriptive extension. The design combined periodized author and institutional networks, incidence-preserving global-mixing null models, publication and collaboration models, author-keyword mapping, reference co-citation, bibliographic coupling, and a purposive content-validation sample of 55 publications. Annual output rose from 24 publications in 2015 to 51 in 2024, but the author-network giant component remained near 9%-12% across comparable periods and author and tie retention were low. Institutional projections were substantially more connected than author networks, although recurrent institutional ties were not unusually persistent relative to the cumulative null benchmark. The keyword-supported subset showed limited temporal overlap, and contemporary coupling fronts differed markedly in their connection to shared co-citation bases. These results show that growth, social integration, organizational aggregation, and cognitive continuity can develop at different rates. Asymmetric consolidation therefore provides a cross-layer, temporally explicit alternative to inferring field maturity from publication volume, cumulative connectivity, or thematic diversification alone.

Keywords: scientometrics; research-field consolidation; science mapping; collaboration networks; bibliographic coupling; engineering education research

MSC: 91D30; 62P25 JEL: I23; O30

1 Introduction

Scientometric assessments of research-field development often begin with publication growth, collaboration, citation visibility, and thematic diversification. These indicators are informative, but cumulative summaries can obscure whether a field reproduces the social and cognitive structures that generated its visible expansion. Output may rise because new teams enter, conference coverage changes, or established groups publish more intensively, while author relations, institutional partnerships, and shared knowledge bases turn over rapidly. A field can therefore become larger without becoming more integrated or temporally reproducible. Distinguishing growth from consolidation is a central measurement problem for the quantitative study of science.

Scientific fields are simultaneously social and cognitive organizations. Collaboration networks describe one layer of the social structure of science, while co-citation, bibliographic coupling, and thematic networks describe different forms of intellectual organization (Crane, 1969; Small & Griffith, 1974; Whitley, 2000). Studies of field emergence and maturity show that publication growth can coincide with topological transitions, stable communication channels, or persistent cores, but no single indicator defines a mature field across contexts (Bettencourt et al., 2009; Ding et al., 2000; Keathley-Herring et al., 2016). This motivates a multilayer approach in

which productive, social, organizational, and cognitive structures are measured separately rather than collapsed into one maturity score.

Measurement choices further shape apparent field structure. Database coverage, publication language, document type, entity resolution, counting rules, and citation indexing determine which publications and relations can be reconstructed (Harzing & Alakangas, 2016; Mongeon & Paul-Hus, 2016; Zupic & Čater, 2015). Coauthorship is a useful but partial proxy for collaboration because mentoring, shared grants, informal exchange, and infrastructure use may never produce a joint publication (Katz & Martin, 1997). Institutional projections aggregate multiple teams and can therefore appear highly connected even when author networks remain fragmented. Cross-layer comparison is consequently necessary if field development is to be interpreted rather than merely mapped.

Temporal reproduction adds a further requirement. A cumulative network can connect actors or ideas that were prominent in different years and never coexisted as a stable configuration. Periodized networks, entity and tie retention, community agreement, and overlap in thematic or intellectual resources make it possible to distinguish accumulated connectivity from structures that recur over time. Incidence-preserving null models can then ask whether observed connectivity differs from what would arise under the same publication-team sizes and entity productivity, while remaining explicit about which temporal opportunities the null does and does not preserve.

Engineering education research provides an informative empirical field for this problem. Prior studies document sustained publication growth, internationalization, thematic diversification, distinctive national trajectories, and uneven collaboration and citation systems (Borrego, 2007; Borrego & Bernhard, 2011; Xian & Madhavan, 2014; Williams et al., 2018; Valentine & Williams, 2021; Qiu & Natarajarathinam, 2024; Kondrashev et al., 2024). These studies establish engineering education research as an internationally recognizable domain, but they largely examine productive, collaboration, citation, or thematic structures separately and often through cumulative maps.

That limitation matters because evidence of consolidation in one layer does not imply consolidation in another. Established research domains may possess durable journals and recognizable intellectual structures while retaining fragmented collaboration systems, geographical concentration, or thematic islands (Daenekindt & Huisman, 2020; Fu et al., 2022; Hallinger & Kovačević, 2019; Hernández-Torrano & Kuzhabekova, 2020; Vlegels & Huisman, 2021). A scientometric account of field consolidation therefore requires both cross-layer alignment and temporal reproduction.

Chile-associated engineering education research offers a bounded affiliation-based case in which these dimensions can be examined within one multisource corpus. The portfolio spans multiple universities, engineering disciplines, document types, publication languages, and international relationships without assuming that they form a single national community. Association with Chile is defined through normalized author affiliation and does not imply that every empirical setting, participant group, or intervention was located in Chile.

This article makes four scientometric contributions. First, it operationalizes research-field consolidation as a multilayer configuration rather than inferring maturity from publication volume or one cumulative network. Second, it separates author-level community reproduction from organizational aggregation, allowing highly connected institutional projections to be interpreted independently from author integration. Third, it introduces temporal reproduction as an explicit criterion through periodized retention, overlap, and community-continuity measures. Fourth, it combines these indicators with incidence-preserving null models and linked co-citation/bibliographic-coupling structures to define asymmetric consolidation: a configuration in which productive, social, organizational, and cognitive development advance at different rates. The Chile-associated portfolio is used as an empirical test case for this diagnostic rather than as a national ranking.

2 Scientometric framework for research-field consolidation

2.1 From field growth to consolidation

Research-field maturity and consolidation have been operationalized with heterogeneous indicators, including publication growth, collaboration structure, journal stability, intellectual organization, and institutional development. Reviews of maturity assessment find no universal definition or threshold (Keathley-Herring et al., 2016). From a scientometric perspective, each indicator observes a different layer of the scientific system, so apparent maturity in one layer cannot be assumed to represent field-wide integration.

Productive expansion is the most visible layer. Annual output, document type, source distribution, language, and citation visibility describe the scale and communication profile of an indexed domain (Donthu et al., 2021; Zupic & Čater, 2015). Yet output can increase through new entrants, temporary projects, conference indexing, international partnerships, or intensified publication by existing teams. Citation visibility is additionally database- and exposure-dependent (Harzing & Alakangas, 2016; Mongeon & Paul-Hus, 2016). Growth is therefore necessary evidence of field activity but insufficient evidence of integration or temporal stability.

Social, organizational, and cognitive indicators capture different forms of structure. Author networks represent publication-based relations among researchers; institutional and country projections aggregate those relations at higher levels; keyword networks capture explicit thematic positioning; co-citation identifies references used together; and bibliographic coupling links contemporary publications through shared reference lists (Kessler, 1963; Small, 1973). These projections are analytically complementary rather than interchangeable.

For this study, consolidation refers to the development and temporal reproduction of connected productive, social, organizational, and cognitive structures that support sustained scientific communication and cumulative inquiry. The term does not imply centralization, uniformity, or a linear stage model. Asymmetric consolidation occurs when some layers are clearly developed while others remain weakly connected, weakly reproduced, or dependent on localized communities. A focused content characterization is used as a validation layer for interpreting what bibliometric structures represent; it is not treated as a field-wide quality score.

2.2 Empirical signatures of consolidation and uneven maturity

Studies outside education show that consolidation can be observed through more than publication growth. In longitudinal analyses of eight scientific fields, Bettencourt et al. (2009) identified a topological transition from small disconnected collaboration networks to structures containing a giant connected component as fields developed from emergence toward maturity. Bettencourt and Kaur (2011) subsequently documented rapid growth, broad geographic participation, disciplinary diversity, and increasing collaboration in sustainability science. These studies do not establish a universal component-size threshold, but they demonstrate that productive expansion can be accompanied by a qualitative change in the social organization of a field.

Consolidation can also be organizational and communicative. Leydesdorff and Wagner (2008) found that international scientific collaboration reinforced a persistent core of highly connected national systems, while also producing a pronounced core–periphery structure. Ding et al. (2000) interpreted the relative stability of central journals and communication channels in information retrieval as evidence of a mature intellectual space. Together, these cases show that consolidation may involve reproducible organizational cores and recognizable communication channels without eliminating hierarchy, specialization, or links to neighboring fields.

Educational domains provide comparable evidence of institutional and cognitive development. Hallinger and Kovačević (2019) mapped nearly six decades of educational-administration research, documenting sustained growth and an identifiable intellectual structure. Hernández-Torrano and Kuzhabekova (2020) described gifted education as a relatively mature field supported by long-lived specialized journals and a recognizable publication infrastructure. These studies are stronger evidence of editorial and cognitive institutionalization than of complete

author-level or interorganizational integration, illustrating why no single layer is sufficient to establish consolidation.

Maturity, moreover, does not imply uniform integration. Higher education research has established journals, a large international literature, and recognizable intellectual communities, yet topic modeling shows relatively stable thematic islands that became more separated through specialization (Daenekindt & Huisman, 2020). Longitudinal collaboration analysis likewise found a dense core alongside persistent fragmentation and a large periphery (Vlegels & Huisman, 2021). An analysis of 9,067 coauthored articles further showed that rising publication and collaboration volume did not produce a more geographically diverse network; established Anglophone patterns remained dominant (Fu et al., 2022). These cases support a configurational interpretation: a field may be institutionally or cognitively consolidated while remaining weakly integrated in its social, geographical, or temporal structures.

2.3 Engineering education research as a scientometric test case

Engineering education research (EER) provides a particularly informative setting for examining this distinction. Early field-building work studied coalition publication patterns and debated whether EER should be understood as a discipline, community, or field (Borrego, 2007; Jesiek et al., 2009). Subsequent scholarship documented international connections, shifts toward student-centered learning and design, and growing methodological self-consciousness (Borrego & Bernhard, 2011; Froyd et al., 2012; Streveler & Smith, 2010). These developments establish EER as a recognizable and increasingly institutionalized international domain, but they do not show that its social, organizational, cognitive, and temporal structures are consolidated in the same form across settings.

National accounts suggest that durable EER capacity depends on more than a critical mass of publications. Professional societies can create recurring venues; doctoral pathways can reproduce researchers; dedicated centers can provide infrastructure; and cross-institutional networks can circulate methods and mentoring (Godfrey & Hadgraft, 2009; Wint & Nyamapfene, 2023; Wolff et al., 2019). These mechanisms need not produce the same network structure. A system organized around a few centers may show strong institutional aggregation, whereas a distributed professional community may show wider author-level circulation. International partnerships may increase visibility and methodological access while leaving domestic relations intermittent.

Existing bibliometric research reinforces this mixed picture. Large-scale coauthorship analysis identified interdisciplinary brokers but also substantial barriers between EER teams (Xian & Madhavan, 2014). Citation flows across major US and European publication systems were internationally uneven (Williams et al., 2018), and national scientometric work found distinct developmental trajectories in Portugal and Spain (Valentine & Williams, 2021). Recent overviews document sustained growth, thematic diversification, influential journals, and concentration in particular countries, sources, and collaboration systems (Kondrashev et al., 2024; Qiu & Natarajarathinam, 2024). Taken together, these studies support EER's productive and institutional development, but they do not establish uniform consolidation across productive, social, organizational, cognitive, evidentiary, and temporal dimensions. Most examine these layers separately or through cumulative maps, leaving unresolved whether communities and knowledge structures reproduce together over time.

Prior scientometric studies of engineering education research do not operationalize consolidation consistently. Some infer development from publication growth, journal stability, citation structure, or thematic diversity; others analyze coauthorship, international citation flows, or national trajectories. Because these indicators refer to different layers, evidence from one layer cannot establish field-wide integration. Moreover, cumulative maps can connect actors, institutions, terms, and references that were prominent at different times, obscuring turnover and the persistence of relations. The unresolved methodological question is therefore whether a growing research field exhibits aligned and temporally reproducible structures across multiple scientometric layers.

2.4 Multilayer indicators: social, organizational, cognitive, and content structure

Scientific and educational research fields are simultaneously social and intellectual organizations (Crane, 1969; Small & Griffith, 1974; Whitley, 2000). At the author level, consolidation concerns whether publication relations connect researchers beyond isolated papers and local teams, whether participants recur, and whether ties persist. Components, largest-component coverage, recurrent ties, entity retention, tie retention, and community continuity provide complementary evidence about publication-based integration (Newman, 2001, 2004). Coauthorship remains partial because it omits mentoring, grants, professional associations, informal exchange, and other relations that do not produce a joint publication (Katz & Martin, 1997). It is therefore evidence of one form of scholarly connection, not a complete measure of collaboration.

Institutional and country networks answer a different question. Universities aggregate departments, projects, and authors, so an institutional projection can appear connected even when the underlying researchers remain in separate communities. Such connectivity can provide opportunities for doctoral training, shared data, multi-site research, and coordinated capacity building, but it does not prove that those opportunities are realized (Godfrey & Hadgraft, 2009; Hall et al., 2018; Oancea et al., 2021). Brokerage is consequently interpreted as a potential convening position rather than a measure of leadership, quality, or educational effectiveness (Borgatti, 2005; Opsahl et al., 2010).

Cognitive organization is expressed through terminology, problems, methods, theories, and references. Author keywords selectively represent how researchers position their work, while co-citation identifies references used together and bibliographic coupling identifies contemporary publications connected through shared references (Boyack & Klavans, 2010; Kessler, 1963; Small, 1973). Cognitive consolidation does not require a single cluster: a plural but connected structure may represent differentiated capacity rather than conceptual disorder (Jacobs & Frickel, 2009; Rafols & Meyer, 2010; Stirling, 2007). Evidentiary organization adds a further distinction. Bibliometric prominence cannot establish whether claims are supported by direct outcomes, whether theory is used mechanistically, or whether findings accumulate across contexts. In this framework, evidentiary development is an analytic extension that asks whether visible research designs, measures, and theoretical resources are appropriate to the educational claims being made; the focused characterization does not treat these features as prevalence estimates or a corpus-wide quality appraisal.

2.5 Temporal reproduction and comparative propositions

Temporal reproduction distinguishes a connected snapshot from a structure that persists. A cumulative network may join researchers who were never active in the same period, while stable local groups may recur without becoming connected to a wider field. For this reason, entity retention, tie retention, community agreement, and overlap in thematic or intellectual resources are interpreted as layer-specific evidence of reproduction. They are not treated as directly comparable rates of development because author, institution, keyword, and reference networks represent different relations.

Observed connectivity also requires a conditional reference. Component structure depends partly on team size and on how frequently particular entities participate. Fixed-margin bipartite randomization can ask whether an observed projection is more or less connected than networks preserving those incidence totals (Miklós & Podani, 2004). Such benchmarks remain specification-dependent. Bibliometric networks are constructed representations whose form depends on corpus coverage, entity resolution, counting rules, and analytical thresholds (Lim & Kumar, 2024; Lim et al., 2024; Zupic & Čater, 2015). Centrality and cluster membership must therefore be interpreted as relational indicators, not as measures of quality or effectiveness (Borgatti, 2005; Good et al., 2010; Opsahl et al., 2010).

The framework distinguishes broad consolidation, generalized fragmentation, and asymmetric consolidation. Broad consolidation refers to mutually reinforcing development across several layers; generalized fragmentation refers to weak connectivity and continuity across most layers; asymmetric consolidation occurs when some structures are clearly developed while others remain weakly connected or poorly reproduced. The concept is

not a stage model and does not assume that greater centralization is desirable. Interdisciplinary fields may benefit from multiple theoretical traditions, local communities, and external links (Jacobs & Frickel, 2009; Klassen & Case, 2022). Asymmetry becomes consequential when one layer cannot support the functions implied by another—for example, when institutional reach is not converted into recurrent cross-community collaboration, when thematic expansion lacks shared intellectual resources, or when publication visibility is not accompanied by evidence appropriate to educational claims.

Four propositions follow. First, organizational aggregation can exceed author-level publication integration because institutions connect outputs produced by otherwise separate teams. Second, recurrence within local communities can coexist with persistent portfolio-wide fragmentation; local stability becomes field-level integration only when cross-community relations also reproduce. Third, cognitive plurality contributes to consolidation when distinct fronts remain sufficiently linked and temporally reproducible to support comparison and cumulative debate. Fourth, productive growth becomes durable research-field capacity only when at least some of the people, relations, infrastructures, intellectual resources, and evidentiary practices that produced it can be reproduced over time.

Table 1 summarizes the conceptual-to-analytical alignment used in the study.

Table 1 Conceptual-to-Analytical Alignment for Asymmetric Research-Field Consolidation

Dimension	Analytical question	**Primary analytical evidence**	**Interpretive boundary**
Productive expansion	Is indexed research activity expanding and becoming more visible?	Annual output and trend; sources; document types; languages; source-specific citation visibility	Growth and visibility do not establish social, cognitive, or temporal consolidation.
Author-level community reproduction	Do researcher relations connect groups and recur beyond isolated projects?	Periodized author networks; components; entity and tie retention; recurrent ties; community continuity	Coauthorship omits informal relations; local recurrence does not imply portfolio-wide integration.
Organizational aggregation	Do institutions connect distributed production and sustain interorganizational relations?	Institutional and Chilean-institution networks; retention; brokerage; global-mixing benchmarks	Institutional nodes aggregate different teams; centrality is not quality, leadership, or realized capacity.
Cognitive organization	Are themes and intellectual resources differentiated yet sufficiently linked?	Author keywords; co-citation; bibliographic coupling; bridge matrix; temporal overlap	Coverage and clusters depend on metadata and specifications; plurality is not disorganization.
Content validation	What substantive evidence and theoretical framing are visible in selected publications?	Focused characterization of design, evidence, outcomes, and explicit theory	Purposive counts are not prevalence estimates or a corpus-wide quality appraisal.
Temporal reproduction	Do entities, relations, communities, and knowledge resources recur?	Cross-period retention; Jaccard similarity; adjusted Rand index; reference overlap	Windows differ in duration; 2025 is descriptive; unlike network layers are not compared as rates.

3 Research objective and questions

The objective of this longitudinal scientometric study is to test whether productive expansion in a bounded research field was accompanied by comparable social, organizational, cognitive, and temporal consolidation. Chile-associated engineering education research provides the empirical case. Association with Chile is defined through normalized author affiliation; the study does not rank scholars or institutions and does not assume that the educational setting or participants were located in Chile. Primary longitudinal claims concern 2015-2024, while 2025 is retained as a clearly separated descriptive extension.

- RQ1. How did the scale and publication composition of Chile-associated engineering education research change during 2015-2024, and what does the descriptive 2025 extension show?
- RQ2. To what extent did author and institutional publication networks connect and reproduce entities and ties across periods, and how did their cumulative structures compare with incidence-preserving global-mixing benchmarks?
- RQ3. How were thematic and intellectual structures organized in keyword- and reference-supported subsets, how stable were they across periods and specifications, and what did focused content validation add to interpretation?

Together, the questions test whether field growth was accompanied by aligned consolidation across scientometric layers or instead produced an asymmetric configuration.

4 Data and methods

4.1 Study design, corpus definition, and search strategy

This study used a systematic, longitudinal scientometric design combining performance analysis, social-network analysis, science mapping, and focused content validation (Donthu et al., 2021; Zupic & Čater, 2015). The unit of inclusion was a publication. A record was considered Chile-associated when at least one normalized author affiliation resolved to an institution in Chile; this did not imply that the empirical setting, participants, intervention, or data collection were located in Chile.

Corpus construction followed a version-controlled and auditable workflow. PRISMA 2020 was used only as a reporting scaffold for multisource search, reconciliation, and eligibility decisions (Page et al., 2021), not as an intervention-review framework. The study was not prospectively preregistered and no published protocol preceded the searches. Search configurations, eligibility rules, adjudication logic, normalization dictionaries, network specifications, thresholds, statistical models, and coding rules were frozen before the final analyses to which they applied. Reproducibility materials are publicly archived at https://doi.org/10.60547/USACH/KELBSX.

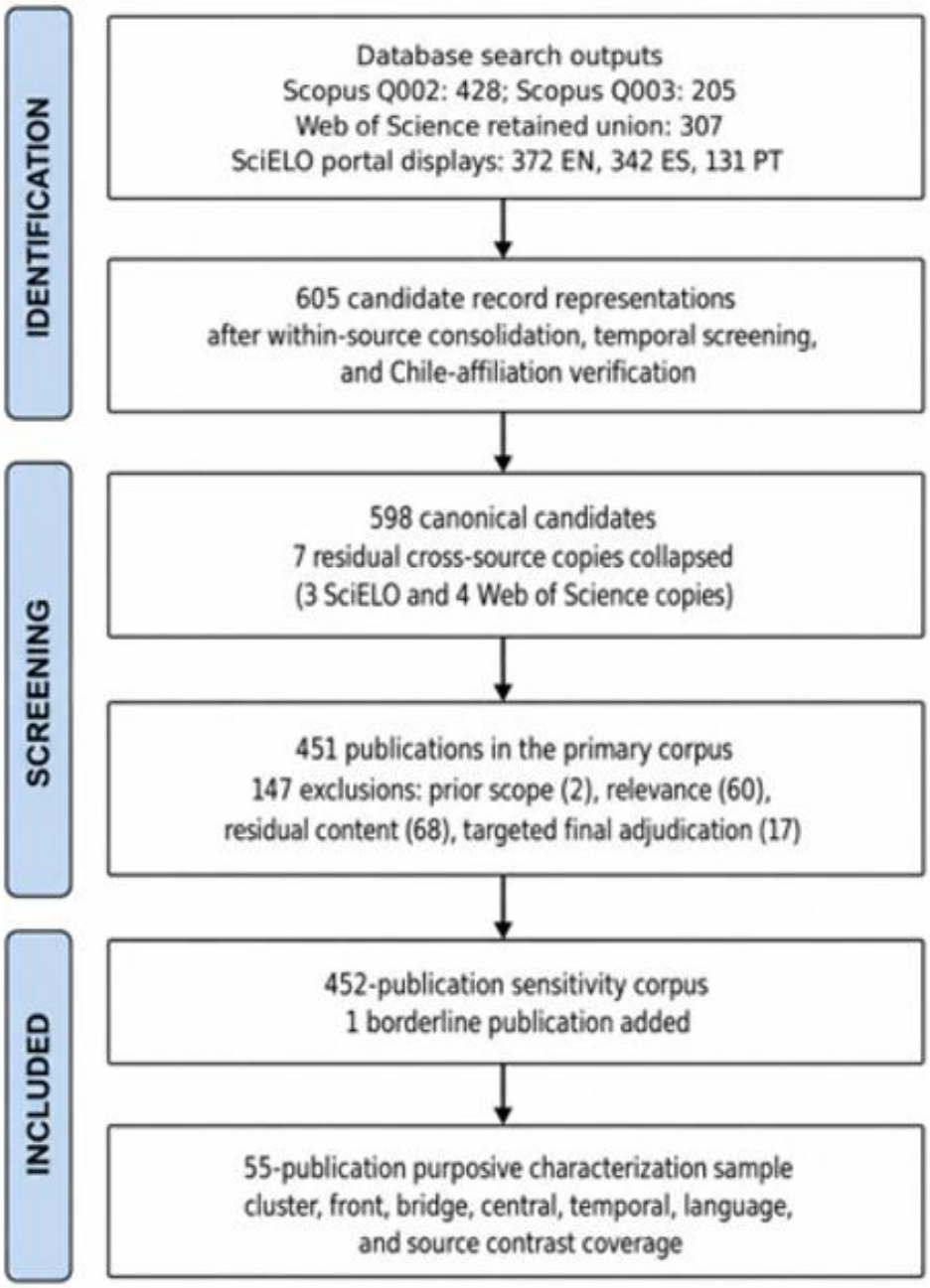
Scopus, Web of Science Core Collection, and SciELO were searched between June 29 and July 6, 2026 without language restrictions. Multilingual strategies combined engineering terms with education, teaching, learning, curriculum, pedagogy, assessment, professional formation, students, and selected EER topics. Database-specific fields, restrictions, exact strings, execution dates, yields, and export formats are reported in Online Resource 1.

Eligible publications centrally addressed teaching, learning, curriculum, assessment, competencies, student participation or trajectories, educator development, educational technology, professional formation, or another educational process situated in engineering education. Exclusions covered technical engineering research with incidental educational language; general STEM or higher-education research without a distinct engineering-education focus; occupational training disconnected from engineer formation; incidental or unreported engineering subgroups; corrections or records without analyzable content; and publications outside the period.

4.2 Corpus Construction and Entity Resolution

Database exports were harmonized to a common schema while retaining source provenance and original values (Lim et al., 2024). Within-source consolidation, cross-source harmonization, temporal screening, and Chile-affiliation verification produced 605 candidate representations. Seven residual duplicates were collapsed, yielding 598 canonical candidates. Successive scope, relevance, residual-content, and final audits excluded 147 publications, producing the 451-publication primary corpus; a sensitivity corpus added one borderline record. Search identification, reconciliation, screening, and inclusion were reported using a PRISMA-informed multisource corpus flow. Fig. 1 summarizes the resulting source-representation-to-publication sequence. Detailed search yields, adjudication stages, and exclusion codes appear in Online Resource 1, and the record-level registers are included in the deposited reproducibility materials.

Fig. 1 Multisource search, reconciliation, and corpus-selection flow



Note. The flow adapts PRISMA 2020 to a multisource scientometric study in which initial query outputs are source representations rather than additive unique studies. SciELO portal display counts are language-specific displays and are not additive unique records. Exact search strings, source yields, adjudication stages, and exclusion codes are reported in Online Resource 1; the complete 147-record exclusion register is available in the public repository.

Screening applied versioned eligibility rules to identify clear decisions and cases requiring adjudication; indexed keywords alone were not sufficient evidence. Each exclusion retained a reason code, rationale, evidence fields, adjudication stage, and source-record link. Generative AI supported workflow structuring, code drafting, and rationale organization, but was not treated as independent bibliographic evidence; final decisions remained the authors' responsibility.

Canonicalization prioritized DOI and stable identifiers, followed by conservative title-, author-, and year-based signatures; approximate matches were audited rather than merged automatically. Authors were resolved using source identifiers, ORCID when available, exact aliases, co-affiliation evidence, and manual adjudication. Institutions were normalized through curated aliases, language variants, country checks, and documented merge or split decisions, with subunits aggregated to parent organizations when metadata did not support stable resolution. Versioned logs preserve raw strings and adjudication decisions for authors, institutions, keywords, and references. Because no independent author-identity ground truth was available, author-network results remain subject to residual splitting or merging error.

4.3 Performance Indicators and Network Construction

Performance indicators included annual output, source, language, document type, outlet, source-recorded citation visibility, and collaboration form. Publications were classified as multi-authored, multi-institutional, international, or Chile–Chile interinstitutional using normalized authors, institutions, and countries. Citation indicators were summarized separately by canonical database because the three sources represent different citation universes.

Undirected one-mode networks for authors, all institutions, Chilean institutions, and countries were projected from document–entity incidence matrices. Each entity was counted once per publication, and an edge indicated co-occurrence in at least one publication. Complete networks supported structural statistics; filtered networks were used only for display.

Full counting assigned one unit to each co-occurring pair, while fractional counting reduced the influence of large teams using $1/(n - 1)$ per incident pair (Perianes-Rodriguez et al., 2016). Indicators included nodes, edges, components, largest-component coverage, recurrent ties, transitivity, maximum k-core, communities, and brokerage. Ties observed in at least two publications were recurrent but were interpreted as durable only when they also reappeared across periods. Weighted betweenness used inverse full-count weight as distance and was interpreted as brokerage, not quality or leadership (Opsahl et al., 2010). Weighted Louvain communities used seed 1601; VOSviewer 1.6.21 supported layout and rendering (van Eck & Waltman, 2010). Because modularity solutions may be nonunique, communities were treated as descriptive partitions (Good et al., 2010). Display settings are reported in Online Resource 2, and the full generating configurations are included in the deposited reproducibility materials.

4.4 Longitudinal Analysis and Incidence-Preserving Null Models

Networks were reconstructed for 2015–2018, 2019–2021, and 2022–2024, which preserved chronology while yielding periods with broadly comparable publication volume. The 2025 network was retained as a noncomparable one-year descriptive extension.

For authors, all institutions, and Chilean institutions, entity and tie retention measured the proportion of earlier-period nodes or edges that reappeared in the next period. Node and edge Jaccard coefficients summarized symmetric overlap, adjusted Rand index measured community agreement among entities present in both periods, and recurrent-tie shares distinguished one-off from repeated publication relations.

Secondary cumulative benchmarks used separate bipartite null models for authors, all institutions, and Chilean institutions. The 2015–2025 document–entity matrices were randomized through double-edge swaps that preserved publication size and entity productivity (Miklós & Podani, 2004). For each entity type, 500 matrices were generated with seed 1601 using burn-in and thinning procedures documented in Online Resource 1. Projected networks were compared on components, largest-component share, recurrent ties, k-core, and transitivity; reported statistics included observed values, null means and standard deviations, standardized contrasts, and plus-one-corrected empirical p values.

Because these randomizations do not preserve year- or period-specific activity, they are interpreted only as cumulative global-mixing sensitivity benchmarks. Primary claims about temporal continuity rely on the periodized

2015–2024 networks; a temporally constrained randomization would be required for a primary null-adjusted test of consolidation over time.

4.5 Thematic and Intellectual Network Analyses

The primary thematic analysis used author keywords, with indexed keywords and Keywords Plus retained for sensitivity checks. Processing applied case, Unicode, accent, spelling, and singular–plural normalization through a version-controlled thesaurus; ambiguous abbreviations were adjudicated at document level. General stemming, fuzzy matching, and automatic similarity merging were not used. Generic context terms were retained for audit but excluded from the principal map.

The cumulative 2015–2025 keyword map required at least four publications per term and contained 61 terms and 122 links. Document-to-cluster assignment used normalized terms and the keyword-community solution, with minimum support of .20, confidence of .55, margin of .05, and propagation limited to three steps. This assigned 288 of 451 publications; unassigned records were not forced into clusters. Period-specific networks used a two-publication threshold, and primary 2015–2024 comparisons used node and edge Jaccard coefficients and adjusted Rand index. Results therefore describe the author-keyword-supported subset rather than records without usable keywords.

Cited references were normalized by DOI or stable identifier and then by conservative author–year–title or author–year–source signatures, yielding 12,911 canonical references. Reference co-citation represented shared intellectual bases (Small, 1973), while document bibliographic coupling represented contemporary fronts (Kessler, 1963). The displayed co-citation solution contained 95 references and 662 links; the coupling display retained 150 eligible publications and 603 links. Complete networks supported coverage and robustness checks, displayed networks supported interpretation, and community detection used resolution .50.

A bridge matrix linked 12 coupling fronts to five co-citation bases. Base share was the proportion of a front's observed bridge links directed to each base; coverage was the proportion of front publications with at least one such link. Continuous values were primary. For concise description, prespecified heuristics classified fronts as dominant (coverage $\geq$ 50% and one base $\geq$ 60%), mixed (coverage $\geq$ 50% without a 60% base), low coverage (0% < coverage < 50%), or no observed bridge. These labels are interpretive aids, not statistical tests; full values appear in Online Resource 3.

4.6 Focused content validation and claim boundaries

A purposive sample of 55 publications extended interpretation beyond network topology. The deterministic frame selected up to two publications from each of nine thematic clusters and 12 coupling fronts, up to eight bridging documents, and up to six recent central documents. After deduplication, contrast cases improved representation of SciELO, Web of Science, Spanish-language publications, and 2015–2018. Selection paths and verification status are reported in Online Resource 3.

Titles, abstracts, and author keywords were coded for educational problem, population, discipline, design, evidence, outcome, named theory or framework, contribution, limitations, and cumulative role. Nonexclusive categories were permitted. Inspectable rules generated a first-pass registry and flagged 17 records; 12 were checked against full texts, while five unavailable publications remained conservatively coded from indexed material.

Because inclusion probabilities were unknown, these counts are not prevalence estimates for the 451-publication corpus. They describe patterns among structurally and substantively selected documents and do not support field-wide effectiveness or causal claims.

No formal study-level risk-of-bias assessment was applied because the primary questions concern publication structures, collaboration networks, metadata-supported themes, and intellectual relations rather than intervention effectiveness. The focused characterization was descriptive and purposive; interpretation distinguishes

self-report, direct learning or performance evidence, theory identification, and verification status, and remains limited to the available coded material.

4.7 Statistical models, robustness, reproducibility, and AI support

Annual publication counts for 2015–2024 were modeled with a log-link Poisson model and Pearson-scaled standard errors because dispersion was 1.95; exponentiated coefficients were reported as incidence-rate ratios. The 2025 total was excluded from the primary model. Logistic models estimated annual change in international and Chile–Chile interinstitutional collaboration, adjusting for canonical source, language, and conference-paper status. Results are document-level associations, not causal effects.

The coverage audit compared publications with and without primary thematic assignments across source, language, document type, year, collaboration, and keyword metadata. Because SciELO status and absence of usable author keywords perfectly predicted nonassignment, no adjusted assignment model was fitted. Categorical comparisons used proportions, chi-square tests, and Cramér's V; continuous comparisons used Mann–Whitney tests and standardized mean differences. Effect sizes, denominators, and coverage boundaries guided interpretation (Lim & Kumar, 2024).

Robustness checks examined corpus scope, counting method, temporal specification, thresholds, metadata coverage, and document strata. Analyses compared the 451- and 452-publication corpora, full and fractional counting, alternative keyword thresholds, and primary versus sensitivity co-citation and coupling solutions. Models were repeated with the descriptive 2025 extension, and selected network conclusions were checked after excluding conference papers, among articles only, and across English- and Spanish-language strata. Full specifications and results are reported in the Supporting Information and deposited reproducibility materials.

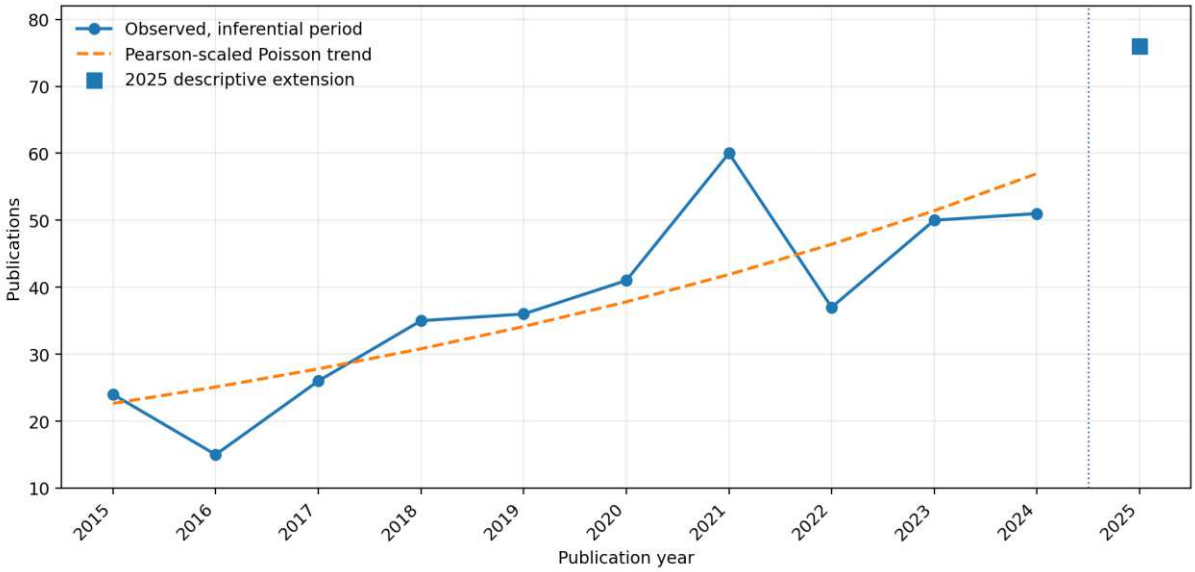
The pipeline used Python 3.11 or later with pandas, NumPy, NetworkX, SciPy, scikit-learn, and supporting libraries; VOSviewer 1.6.21 rendered maps. Randomized analyses used seed 1601. Versioned search documentation, adjudication records, controlled vocabularies, normalized entities, derived matrices, code, configurations, checksums, and validation outputs are available at https://doi.org/10.60547/USACH/KELBSX. Full licensed database exports and article full texts are not redistributed. OpenAI ChatGPT was used to support workflow structuring, code drafting and debugging, literature-search support, language editing, manuscript organization, and figure-layout development. AI outputs were not treated as independent bibliographic evidence and did not determine eligibility, entity resolution, statistical results, network construction, or final coding decisions; all analytical and textual outputs were reviewed by the authors.

5 Results

5.1 Productive Expansion and Changing Publication Composition

Annual output increased from 24 publications in 2015 to 51 in 2024. The Pearson-scaled Poisson model estimated an annual incidence-rate ratio of 1.108 (95% CI [1.053, 1.165], $p < .001$), corresponding to an estimated 10.8% annual increase during 2015–2024. The 76 publications observed in 2025 are reported as a descriptive one-year extension; their composition included 43 Scopus conference papers, 25 Scopus articles, three Scopus reviews, three Web of Science articles, and two Scopus book chapters. Fig. 2 displays the observed series, the estimated 2015–2024 trend, and the separately marked 2025 descriptive extension.

Fig. 2 Annual Publication Output and Pearson-Scaled Poisson Trend, 2015–2024, With 2025 Shown as a Descriptive One-Year Extension



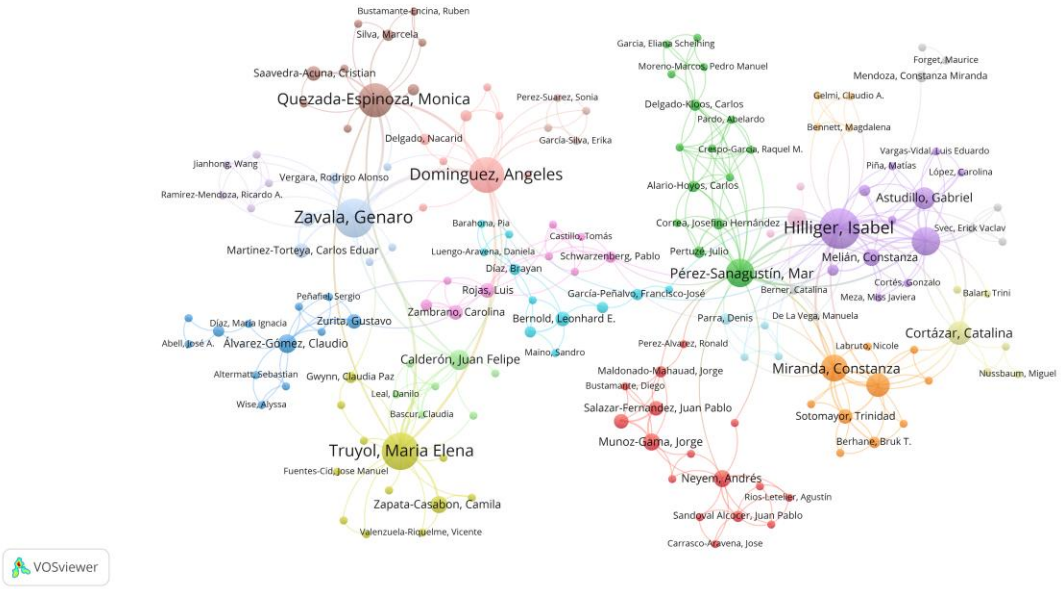
Note. The inferential trend excludes 2025.

5.2 Weak Reproduction of Author Relations Despite Local Recurrence

Author-level integration remained low across the three comparable inferential periods. Giant-component coverage was 11.5% in 2015–2018, 9.1% in 2019–2021, and 10.0% in 2022–2024. Author retention from one inferential period to the next was 20.9% and 16.9%, while coauthorship-tie retention was 16.6% and 4.9%. Among authors present in both periods, community agreement was high (ARI = .837 for 60 shared authors and .946 for 61 shared authors), indicating stability within recurring local configurations rather than convergence toward one portfolio-wide author core. The 2022–2024 to 2025 transition is shown separately as a descriptive, noncomparable one-year extension. Fig. 4 visualizes these temporal patterns, and Table 2 reports the corresponding retention and Jaccard statistics.

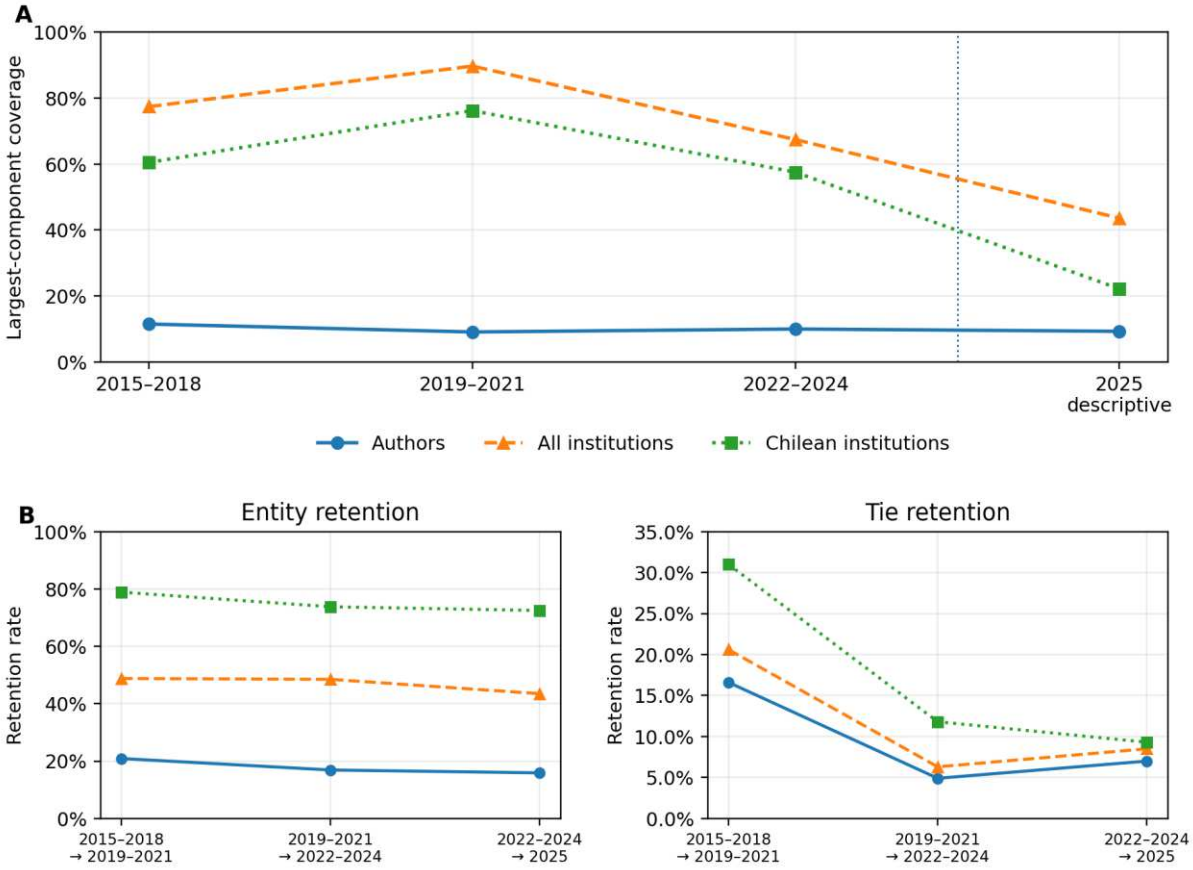
The filtered cumulative display in Fig. 3 makes the distinction between local density and portfolio-wide integration visible: several cohesive author groups are present, but only a small portion of the full author set is connected through the largest component.

Fig. 3 Filtered Descriptive Cumulative Author-Coauthorship Network, 2015–2025



Note. The display is filtered for legibility and does not redefine the complete analytical network. Node size represents publication count, color indicates community membership, and edge width represents collaboration weight. Structural statistics are reported for the complete network.

Fig. 4 Temporal Continuity of Author and Institutional Structures



Note. Panel A shows largest-component coverage across comparable inferential periods. Panel B shows entity and publication-tie retention between adjacent periods. Dashed segments beyond the vertical separator identify the noncomparable 2025 descriptive extension.

Table 2 Longitudinal Indicators of Author and Institutional Integration

Network	Transition	Entity retention	Tie retention	Node Jaccard	Edge Jaccard
Authors	2015–2018 → 2019–2021	20.9%	16.6%	0.102	0.058
Authors	2019–2021 → 2022–2024	16.9%	4.9%	0.095	0.034
Authors	2022–2024 → 2025	15.9%	7.0%	0.099	0.036
Institutions	2015–2018 → 2019–2021	48.8%	20.6%	0.293	0.063
Institutions	2019–2021 → 2022–2024	48.5%	6.3%	0.331	0.048
Institutions	2022–2024 → 2025	43.5%	8.5%	0.308	0.048
Chilean institutions	2015–2018 → 2019–2021	78.9%	31.0%	0.600	0.134
Chilean institutions	2019–2021 → 2022–2024	73.8%	11.8%	0.608	0.078
Chilean institutions	2022–2024 → 2025	72.5%	9.3%	0.617	0.060

Note. Rows involving 2025 are descriptive and are not directly comparable with the preceding multi-year transitions.

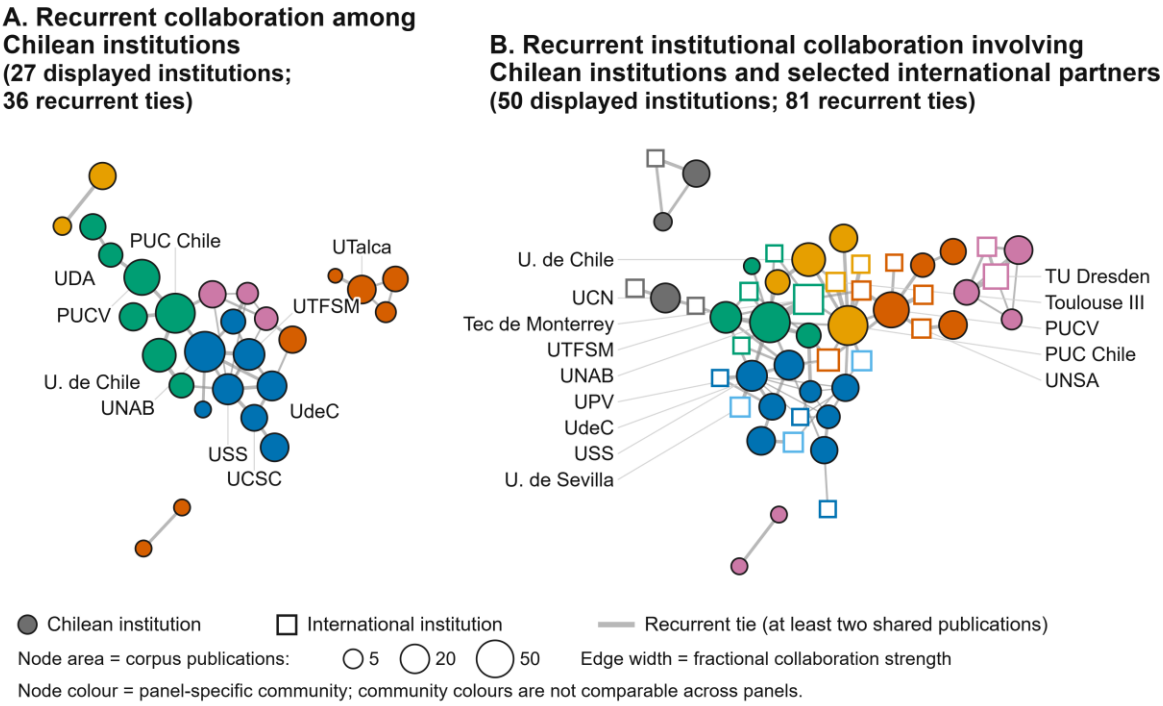
As a secondary global-mixing benchmark, the cumulative 2015–2025 author network contained 164 components compared with a null mean of 72.9, and its largest component contained 15.7% of authors compared with 82.7% under the null model. Its recurrent-tie share was 9.5% versus a null mean of 0.7%, indicating stronger recurrence within groups than under unrestricted cumulative mixing. Because the null model does not preserve period-specific activity, these contrasts do not by themselves demonstrate temporal fragmentation; they complement, but do not replace, the periodized retention results. Fig. 6 and Table 3 report these cumulative sensitivity comparisons.

5.3 Organizational Reach Without Equivalent Temporal Continuity

Institutional projection was more connected than author coauthorship, but it did not follow a linear consolidation trajectory. Giant-component coverage rose from 77.4% in 2015–2018 to 89.7% in 2019–2021 and then declined to 67.4% in 2022–2024. Institutional entity retention was 48.8% and 48.5% across the comparable inferential transitions, whereas edge retention fell from 20.6% to 6.3%. After adjustment for database source, language, and conference status, publication year was not associated with a detectable trend in international collaboration (OR = 0.983, 95% CI [0.910, 1.061], p = .660) or collaboration among multiple Chilean institutions (OR = 1.014, 95% CI [0.930, 1.104], p = .758). The transition to 2025 remains descriptive. The institutional trajectories can be compared directly with the author patterns in Fig. 4 and Table 2.

Fig. 5 visualizes recurrent institutional collaboration at two organizational scales. Panel A displays 27 Chilean institutions connected by 36 recurrent ties, whereas Panel B displays 50 Chilean and international institutions connected by 81 recurrent ties after the prespecified selection and filtering procedure. Panel-specific community colors reveal multiple organizational groupings, while the international display shows that recurrent institutional reach extends beyond a single domestic core. Because the panels use filtered node sets and independently optimized layouts, their apparent densities should not be compared directly. Read alongside the fragmented author display in Fig. 3, the figure illustrates why organizational aggregation and author-level community reproduction must be interpreted separately.

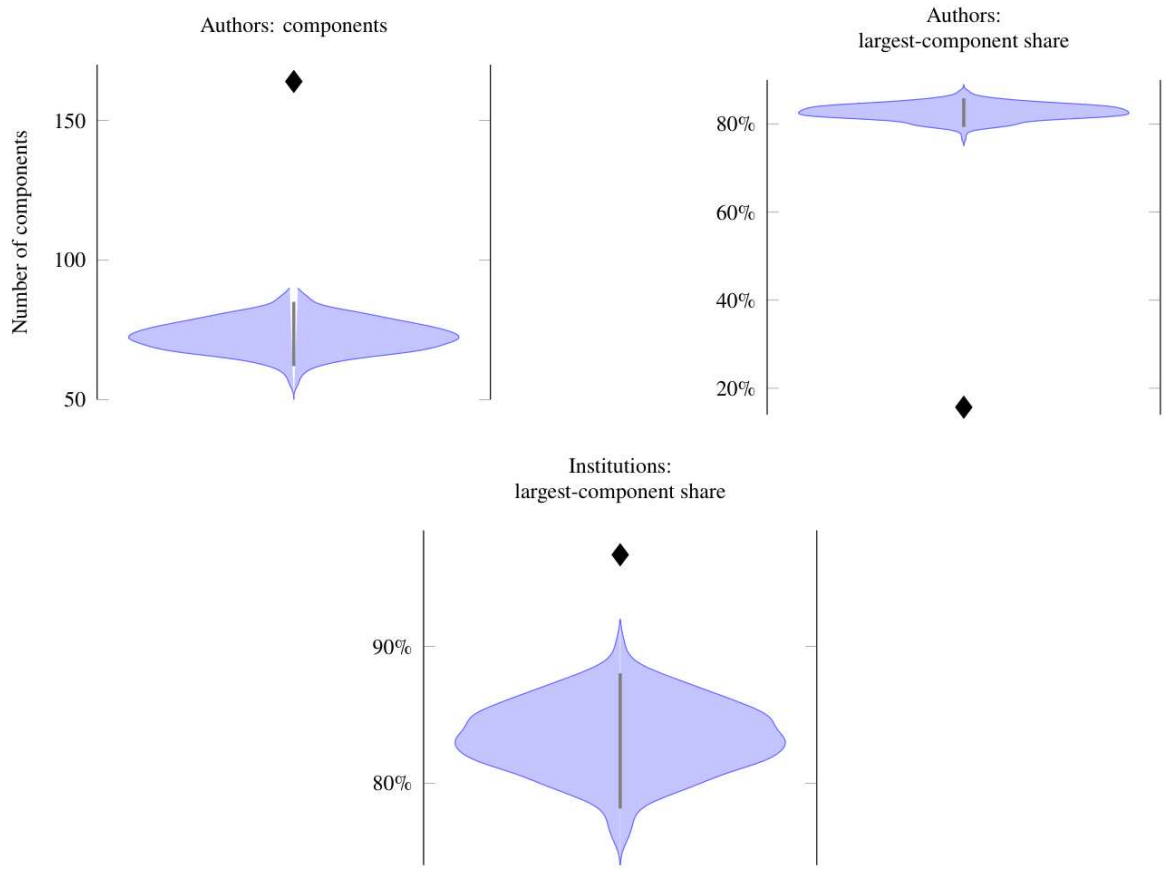
Fig. 5 Organizational Aggregation and Recurrent Institutional Collaboration in the Chile-Associated Engineering Education Research Portfolio, 2015–2025



Note. Panel A displays recurrent publication ties among 27 selected Chilean institutions. Panel B displays recurrent publication ties among 50 Chilean and international institutions meeting the prespecified display criteria. Filled circles represent Chilean institutions, and open squares represent international institutions. Node area represents the number of corpus publications associated with each institution using a common scale across panels; node color represents panel-specific community membership; and edge width represents fractional collaboration strength. A recurrent tie was observed in at least two publications. For Panel B, institutions were initially eligible when they had at least three corpus publications, at least two shared publications with a Chilean institution, or ranked among the 15 institutions with the highest fractional total link strength. Because 95 institutions met at least one criterion, all qualifying Chilean institutions were retained and the remaining positions were filled to a maximum of 60 by prioritizing top-link-strength institutions, partners with at least three shared publications with a Chilean institution, shared-publication count, publication volume, and fractional total link strength; removing institutions without a displayed recurrent tie yielded the 50 institutions shown. Labels are restricted to institutions with high publication volume, collaboration strength, or brokerage. Display thresholds and layouts were applied for legibility; structural statistics reported in the text were calculated from the complete analytical networks. Community colors and panel layouts are panel-specific, and apparent visual density should not be compared directly across panels. Institutional abbreviations: U. de Chile = Universidad de Chile; UNAB = Universidad Andrés Bello; PUC Chile = Pontificia Universidad Católica de Chile; PUCV = Pontificia Universidad Católica de Valparaíso; UDA = Universidad de Atacama; UCN = Universidad Católica del Norte; USS = Universidad San Sebastián; UCSC = Universidad Católica de la Santísima Concepción; UdeC = Universidad de Concepción; UTFSM = Universidad Técnica Federico Santa María; UTalca = Universidad de Talca; U. de Sevilla = Universidad de Sevilla; Tec de Monterrey = Tecnológico de Monterrey; TU Dresden = Technische Universität Dresden; UNSA = Universidad Nacional de San Agustín de Arequipa; UPV = Universitat Politècnica de València; Toulouse III = Université Toulouse III – Paul Sabatier.

As a secondary cumulative benchmark, the institutional network was more globally connected than unrestricted null mixing: its largest-component share was 96.7% compared with a null mean of 83.4% ($p = .004$). Its recurrent-tie share was not distinguishable from the null expectation (15.1% observed versus 13.7% null mean, $p = .347$). This contrast describes accumulated organizational reach under a non-temporal benchmark; it does not establish unusually durable organizational relationships or coordinated national infrastructure. Fig. 6 and Table 3 report the cumulative sensitivity comparisons.

Fig. 6 Cumulative 2015–2025 Author and Institutional Structures Relative to 500 Incidence-Preserving Global-Mixing Null Models



Note. Mirrored density curves show null distributions, vertical intervals show empirical 95% ranges, and diamonds show observed values. The randomizations preserve team size and total entity productivity but not year- or period-specific activity; the contrasts are secondary, non-temporal sensitivity benchmarks.

Table 3 Selected Cumulative Global-Mixing Null-Model Comparisons, 2015–2025

Network	Metric	Observed	Null mean	Empirical p	Interpretation
Authors	Components	164	72.9	.004	More fragmented than unrestricted cumulative mixing
Authors	Largest-component share	15.7%	82.7%	.004	Lower connectivity than unrestricted cumulative mixing
Authors	Recurrent-tie share	9.5%	0.7%	.004	Greater within-group recurrence than unrestricted cumulative mixing
Institutions	Components	6	32.1	.004	Fewer components than unrestricted cumulative mixing
Institutions	Largest-component share	96.7%	83.4%	.004	Greater connectivity than unrestricted cumulative mixing
Institutions	Recurrent-tie share	15.1%	13.7%	.347	Not distinguishable from unrestricted mixing

Network	Metric	Observed	Null mean	Empirical p	Interpretation
Chilean institutions	Largest-component share	85.7%	75.3%	.036	Greater connectivity than unrestricted cumulative mixing

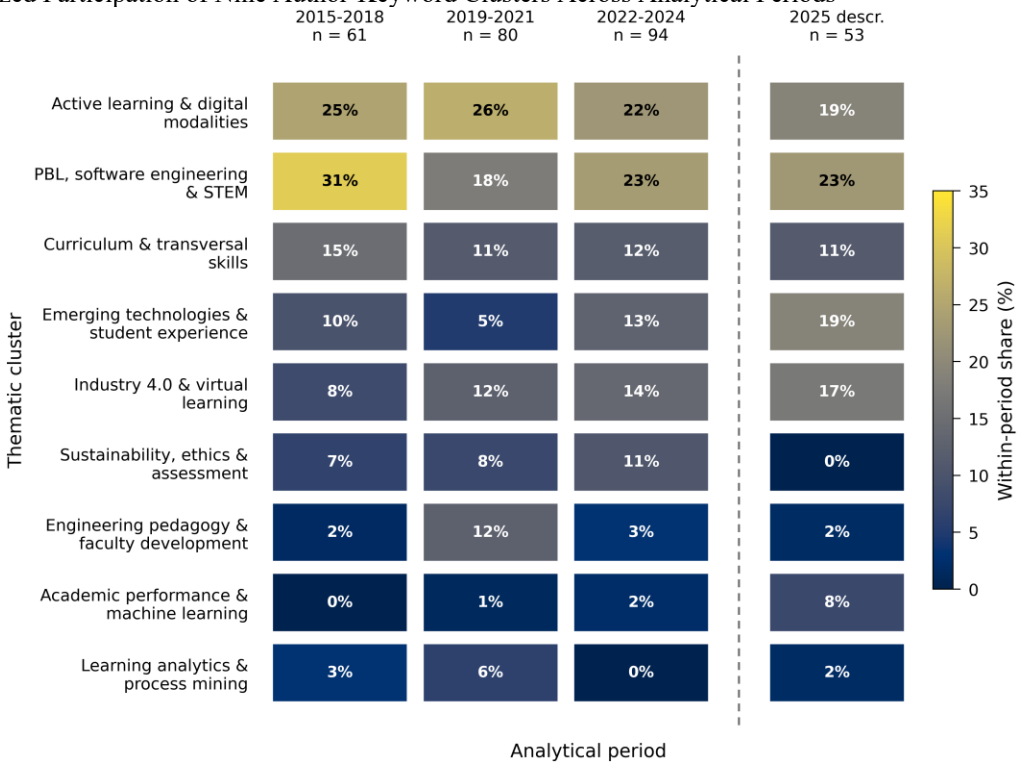
5.4 Thematic and Intellectual Differentiation

The author-keyword assignment procedure covered 288 of 451 publications (63.9%). Usable author-keyword availability was necessarily associated with assignment, and observed coverage differed by canonical source and language: Scopus 275/416, Web of Science 13/23, and SciELO 0/12. No record canonically assigned to SciELO carried usable author keywords for the primary procedure. The thematic and intellectual results below therefore describe the keyword-supported subset rather than the full Chile-associated portfolio.

Within that subset, the descriptive cumulative 2015–2025 author-keyword map yielded nine clusters, and the intellectual analyses identified five reference co-citation bases and 12 contemporary bibliographic-coupling fronts. The clusters spanned active and project-based learning, educational innovation, software and digital technologies, competencies, sustainability, professional formation, and emerging concerns with belonging, equity, and artificial intelligence. A thresholded version of the map appears in Online Resource 2, Figure S2.

Participation was uneven across clusters but never concentrated in one. PBL, software engineering, and STEM held the single largest share, 31% in 2015–2018, and active learning and digital modalities remained prominent throughout at 19% to 26%. Only two clusters rose monotonically: Industry 4.0 and virtual learning, from 8% to 17%, and academic performance and machine learning, from no assigned publications to 8%. No cluster exceeded one third of any period. Fig. 7 reports normalized cluster participation; the 2025 column remains a descriptive extension.

Fig. 7 Normalized Participation of Nine Author-Keyword Clusters Across Analytical Periods

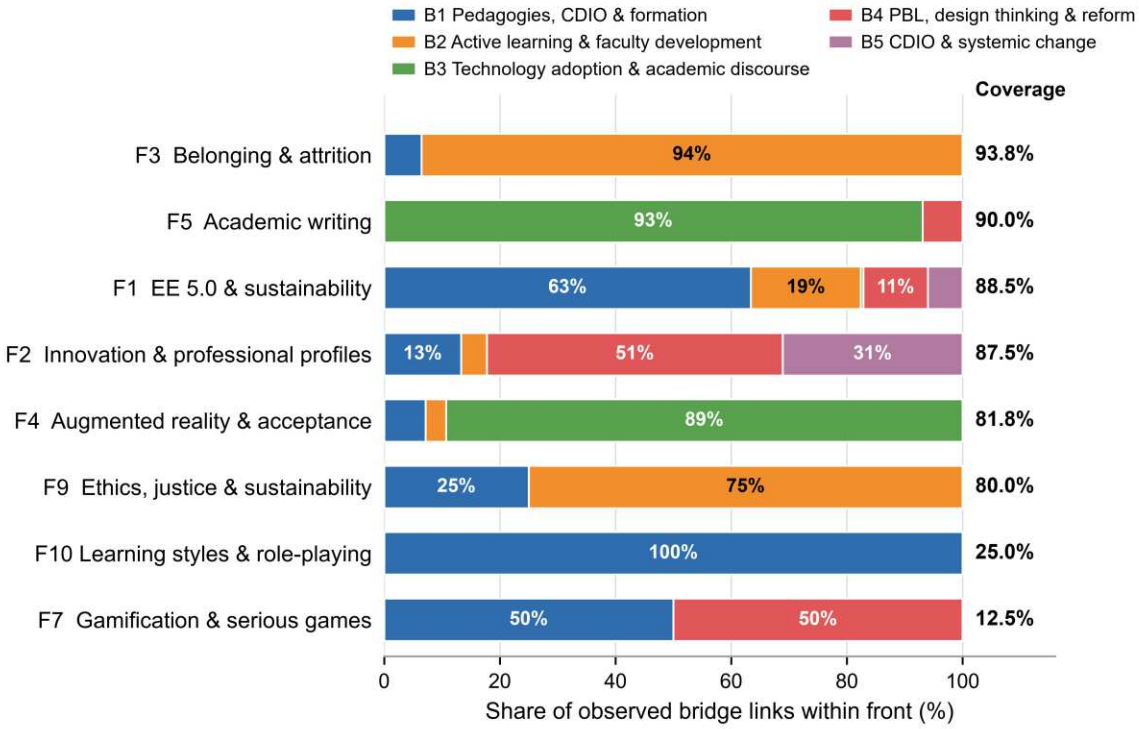


Note. Percentages are compositional within each period and may not sum to exactly 100% because of rounding. Changes in percentage should not be interpreted as absolute publication growth, because they may also reflect changes in the number of assigned publications, the relative participation of other clusters, and author-keyword availability. The 2025 column is a one-year descriptive extension and is not directly comparable in duration with the preceding multi-year periods.

Temporal overlap was limited under the stated thresholds. Across the two comparable 2015–2024 transitions, adjacent-period node Jaccard coefficients were .123 and .136, edge Jaccard coefficients were 0 and .027, and community agreement among shared terms fell from an ARI of .243 to approximately zero. Only four of the 50 leading cited references recurred in each adjacent-period contrast. These values may reflect substantive change as much as variation in metadata, source composition, document type, period size, and threshold eligibility; they should not be read as field-wide vocabulary instability.

Bridging between contemporary fronts and established bases was similarly uneven. Six of the 12 fronts reached bridge coverage of at least 80%, two fell at or below 25%, and four had no observed bridge link under the stated specification. Observed links were also concentrated: one front accounted for 216 of the 356 bridge links. The prespecified descriptive heuristics summarized the 12 fronts as 5 dominant, 1 mixed, 2 low-coverage, and 4 with no observed bridge, but these labels do not replace the continuous values and are not tests of front quality or maturity. Fig. 8 compares the composition of observed bridge links and the corresponding front-level coverage for the eight fronts with at least one observed bridge. The four fronts without an observed bridge are identified in the figure note; complete profiles are reported in Online Resource 2, Table S21, and Online Resource 3.

Fig. 8 Composition and Coverage of Observed Intellectual Links Between Contemporary Bibliographic-Coupling Fronts and Reference Co-Citation Bases



Note. Base share and bridge coverage represent different quantities. Segment width indicates the distribution of observed bridge links across the five bases, whereas coverage is the percentage of publications in the front with at least one link to any selected base. F6, F8, F11, and F12 had no observed bridge and are omitted from the plotted rows. Complete front profiles, base shares, coverage values, publication counts, and bridge-link counts are reported in Online Resource 2, Table S21, and Online Resource 3. CDIO = Conceive-Design-Implement-Operate; EE 5.0 = Engineering Education 5.0; PBL = project-based learning.

5.5 Content patterns in the purposive validation sample

The 55-document purposive sample was methodologically heterogeneous but not intended to represent the corpus statistically. Quantitative observational designs were identified in 18 selected documents, design-and-development studies in 8, and reviews or evidence syntheses in 6. Six selected documents were coded as experimental, quasi-experimental, or mixed-method evaluations.

Among these purposively selected publications, self-report evidence was identified in 29 documents, direct learning or performance evidence in 10, and technology adoption or usability without direct learning evidence in 4. These counts suggest that acceptance, perception, and implementation evidence is prominent among structurally visible technology-oriented work, but they are not prevalence estimates for the 451-publication corpus.

Undergraduate students appeared in 30 selected documents and faculty or instructors in 22. Graduate education, workplace learning, longitudinal trajectories, and cross-institutional comparative populations were less visible in the selected set. An explicit named theory or conceptual framework was identifiable in 14 documents. Project-based learning, active learning, CDIO, technology acceptance, self-efficacy, and sustainability frequently served as organizing labels, although the available abstracts did not always articulate a mechanism connecting an intervention to a validated outcome.

Across the selected traditions, active and project-based learning were commonly connected to course implementation and competency development, whereas technology-acceptance and immersive-technology studies often emphasized intention, perception, usability, or prototype feasibility. Learning-styles language remained visible

in part of the intellectual base; bibliometric presence documents continued use but does not validate instructional matching claims. Equity, belonging, and participation appeared as newer concerns but were less prominent among the selected central documents than technology and pedagogical implementation.

Twelve of the 17 records flagged by the deterministic first-pass rules were checked against full texts; five unavailable publications remained conservatively coded from titles, abstracts, and keywords. Accordingly, Table 4 reports only patterns identifiable in the available coded material. The analysis is not a formal risk-of-bias assessment and does not support field-wide prevalence claims.

Table 4 Patterns Identified in the Purposively Selected 55-Publication Set

Indicator	Selected, n	Interpretive boundary
Self-report evidence	29	Count within a nonprobability sample; perception or attitude should not be equated with learning.
Direct learning/performance evidence	10	Direct outcomes were heterogeneous and often course-specific.
Technology adoption/usability without direct learning evidence	4	Adoption does not demonstrate educational effectiveness.
Explicit named theory or conceptual framework	14	Framework mention does not guarantee explanatory or mechanistic use.

Note. Counts describe a purposive, nonprobability sample and are not prevalence estimates for the 451-publication corpus.

6 Discussion

6.1 Publication growth is not equivalent to field consolidation

The central result is not simply that Chile-associated EER grew. It is that productive expansion was not matched by comparable reproduction of author relations. Output increased during 2015–2024, yet author giant-component coverage remained near 9%–12% across the three comparable periods, author retention declined, and tie retention fell sharply in the second transition. Among the authors who recurred, high community agreement indicated continuity within local configurations rather than convergence toward one portfolio-wide core. Growth was therefore generated through a combination of recurring groups, new entrants, and changing teams rather than through progressively integrated author relations.

This finding contrasts with the topological transition described in some developing scientific fields, where growth was accompanied by the emergence of a giant connected collaboration component (Bettencourt et al., 2009). It extends educational research-capacity scholarship in two ways. First, it gives a relational and temporal specification to the claim that capacity is more than individual productivity. Oancea et al. (2021) distinguish individual, organizational, and system-level capacity, while Rees et al. (2007) emphasize the social practices through which research communities reproduce participation and learning. The present analysis shows how those ideas can be operationalized at field level: a portfolio may expand at the productive layer while reproducing only a small part of its author base and even fewer of its publication ties. Second, it demonstrates why cumulative collaboration rates can overstate consolidation. A large proportion of multi-authored publications does not show whether relationships persist across projects or periods.

The author null-model contrast adds a bounded qualification. The observed cumulative network was far less connected than randomized networks preserving team size and total author productivity, while recurrent ties were more common than under unrestricted mixing. This pattern is consistent with strong local recurrence and weak

global mixing, but the randomization did not preserve period-specific activity. It could therefore connect cohorts that were never simultaneously active. The periodized retention results carry the stronger temporal inference. Methodologically, this distinction matters for other educational research maps: cumulative networks should not be interpreted as evidence of a current community unless cohort turnover and temporal opportunity have been examined.

The implication is not that local teams are undesirable. Stable groups can support trust, mentoring, methodological specialization, and sustained programs of inquiry. The problem arises when growth depends on many local successes that do not create routes for ideas, methods, data, or researchers to circulate across groups. Asymmetric consolidation identifies that condition without treating centralization as the goal. The relevant question is whether local capacity is connected sufficiently to support cumulative debate and collective learning at the field level.

6.2 Organizational connectivity can exceed author-level integration

Institutional projection produced a much more connected surface than author coauthorship. Period-specific institutional giant-component coverage was comparatively high, and the cumulative institutional network was more connected than the global-mixing benchmark. Yet institutional edge retention declined, the recurrent-tie share was not distinguishable from the benchmark, and neither international nor Chile–Chile interinstitutional collaboration showed a detectable annual trend after adjustment. These results indicate accumulated organizational reach, not steadily reproduced partnerships.

This distinction is important for scientometric interpretation because research systems are frequently monitored through organizations. The persistent international core observed by Leydesdorff and Wagner (2008) shows that organizational consolidation can be real while remaining hierarchical; the present case instead combines broad accumulated reach with limited evidence of recurrent institutional ties. Universities can aggregate different departments, teams, and projects into one node, so organizational connectivity should not be treated as evidence that the underlying author community is equally integrated.

The contrast between Figs. 3 and 5 makes this aggregation effect visible. A university node can connect publications produced by different departments and teams, thereby creating an institutional bridge without an equivalent author-level bridge. This is not a measurement error; it is a substantive difference between levels of organization. It also cautions against evaluating national research capacity through counts of collaborating institutions alone. One-off multi-institutional outputs may broaden reach, but durable capacity requires repeated opportunities for researchers to work, learn, and circulate across organizational boundaries.

Brokerage should be interpreted as structural opportunity rather than performance. Institutions located between groups may be positioned to connect otherwise separated communities, but centrality does not show that they exercise leadership, produce higher-quality research, or sustain collaboration over time. Evaluative interpretation should therefore combine brokerage with recurrence, retention, and the substantive function of ties.

6.3 Cognitive differentiation and temporal continuity

The cognitive analyses revealed recognizable pedagogical, technological, professional, and student-experience concerns rather than an undifferentiated collection of topics. In mature intellectual domains, relatively stable journals or knowledge structures can provide continuity without eliminating multidisciplinarity (Ding et al., 2000; Hallinger & Kovačević, 2019). Active and project-based learning, software and digital technologies, competencies, sustainability, belonging, equity, and artificial intelligence formed linked regions. Co-citation and bibliographic coupling likewise identified established intellectual bases and contemporary fronts. This plurality is compatible with an interdisciplinary educational field and should not be read as a failure to converge on one paradigm (Jacobs & Frickel, 2009; Klassen & Case, 2022).

What is less secure is temporal reproduction. Within the author-keyword-supported subset, overlap in terms, links, communities, and leading references was low across comparable transitions. The bridge analysis also showed that some fronts drew strongly on shared bases, one combined several bases, and others had low or no observed coverage. These patterns suggest that cognitive expansion can occur through rotating agendas and selective intellectual connections rather than through a uniformly shared core. As with the social networks, the relevant issue is not diversity itself but whether sufficient connections remain for studies to compare findings, refine concepts, and contest interpretations cumulatively.

The analysis also demonstrates why cognitive maps require coverage auditing. Only 288 of 451 publications received a primary thematic assignment, no canonically assigned SciELO record had usable author keywords for that procedure, and eligibility depended on metadata and thresholds. Bedenlier et al. (2025) show more broadly that language decisions shape what educational evidence syntheses can see. In this corpus, database and language structures affected which publications could contribute to the keyword map. The warranted claim is therefore about the author-keyword-supported subset, not the total intellectual life of Chile-associated EER. For multilingual educational fields, coverage is not a technical footnote; it is part of the substantive interpretation of whose terminology and knowledge structures become visible.

The content-validation sample adds information that is not available from network topology alone. Explicit named theory or conceptual framing was identifiable in 14 of the 55 selected publications, and available abstracts did not always specify mechanisms linking interventions to outcomes. Because the sample was purposive, these counts are not prevalence estimates. Their role is to illustrate how substantive interpretation can qualify conclusions drawn from thematic and intellectual maps.

6.4 Science maps and substantive content answer different questions

The focused content characterization was included because network position cannot establish substantive warrant. Among the 55 purposively selected publications, self-report evidence was identified more often than direct learning or performance evidence, and technology adoption or usability sometimes appeared without direct evidence of learning. These patterns are not field-wide quality estimates; they show why bibliometric prominence and the evidentiary basis of individual studies should be treated as separate properties.

A visible thematic front may be socially and intellectually connected while containing studies that support different kinds of claims, and a small or weakly connected area may contain rigorous work. Content validation is therefore kept analytically separate from the consolidation dimensions rather than converted into a bibliometric quality score. The practical implication for science mapping is that cluster size, centrality, and bridge position should not be interpreted as evidence of methodological strength.

The analysis also shows the limits of abstract-based content characterization. Twelve flagged records were verified against full texts, five remained unavailable, and the purposive selection emphasized clusters, fronts, bridges, and central documents. A stronger field-wide conclusion would require a probability-based or explicitly stratified full-text sample and a formal study-quality protocol. The present contribution is narrower: focused coding is used to validate and qualify the interpretation of science maps.

6.5 Asymmetric consolidation as a scientometric framework

The Chile-associated case supports a broader scientometric claim: research fields can consolidate asymmetrically. Productive, social, organizational, cognitive, and temporal structures are related, but none can substitute for the others. Publication growth does not guarantee community reproduction; institutional connectivity does not guarantee recurring author relations; thematic diversity does not guarantee shared intellectual resources; and cumulative connectivity does not establish temporal persistence.

The framework extends existing science-mapping approaches by making cross-layer alignment and temporal reproduction explicit measurement targets. It treats field consolidation as a profile rather than a scalar

maturity score: productive expansion, author integration, organizational aggregation, thematic organization, and intellectual continuity can each be strong or weak under different mechanisms. This avoids interpreting network centrality, cluster size, citation visibility, or output growth as interchangeable evidence of field development.

Analytical generalization from this case does not require claiming that Chile represents other national systems. The value of the case is methodological: it combines rapid indexed growth, multiple organizations, international ties, multilingual publication, and disciplinary dispersion, allowing the proposed indicators to be observed within one bounded portfolio. Comparative replication across fields and national or regional systems can test whether the same asymmetries appear under different collaboration cultures, database coverage, funding structures, and institutional arrangements.

The resulting comparative agenda is to test when organizational aggregation is converted into author-level reproduction, whether recurrent local groups develop cross-community bridges, when cognitive plurality is supported by temporally persistent shared references, and which null models best distinguish structural consolidation from mechanical effects of productivity and team size. This moves scientometric assessment beyond cumulative maps toward explicit analysis of persistence and cross-layer alignment.

7 Implications for scientometric analysis and research policy

7.1 Measuring field development

Scientometric assessment should distinguish output, connectivity, and reproduction. Publication counts, coauthorship rates, and institutional participation remain useful, but they should be accompanied by indicators of entity retention, tie retention, component coverage, recurrent ties, community continuity, thematic overlap, and intellectual overlap. Reporting these dimensions separately can distinguish expansion by new entrants from the reproduction of existing structures and can identify when cumulative connectivity is driven mainly by aggregation.

For comparative research, aligned temporal windows and layer-specific definitions are essential. Author, institution, keyword, and reference networks represent different relations and should not be collapsed into one consolidation score. Null models can help separate observed structure from the mechanical consequences of team size and productivity, but temporal claims require randomizations that preserve activity opportunities across time. Asymmetric consolidation is therefore best treated as a multivariate diagnostic profile.

7.2 Interpreting collaboration and organizational aggregation

For research policy, the distinction between organizational reach and author-level reproduction matters. Policies that increase the number of interinstitutional publications may produce visible organizational connectivity without generating durable cross-community ties. Longitudinal indicators can therefore complement output-based monitoring when the policy objective is sustained research capacity rather than episodic collaboration.

Brokerage should also be interpreted cautiously. Institutional or author betweenness identifies a relational position, not research quality, leadership, or educational effectiveness. Evaluative uses should therefore combine network position with evidence on persistence, participation, and the substantive function of ties rather than treating centrality as an ordinal performance measure.

Database and language coverage should be reported as part of the measurement model. A field can appear more or less consolidated depending on which publication systems are visible, which metadata fields are available, and how multilingual records are normalized. Coverage auditing is therefore not a peripheral data-cleaning step but part of responsible interpretation.

7.3 Connecting science maps with substantive content

Science maps and content coding answer different questions. Network structure identifies relations among publications, authors, organizations, terms, and references; it does not establish the substantive strength of the claims

made in those publications. Focused content validation can therefore be used to check whether the semantics assigned to clusters or fronts are supported by the underlying documents and to prevent bibliometric prominence from being interpreted as evidentiary quality.

The purposive content sample in this study is deliberately limited and should not be generalized to the full corpus. Its methodological role is illustrative: adding a transparent content-validation layer can improve interpretation of thematic and intellectual structures without converting a scientometric study into an intervention-effect review. Future work could extend this step with probability-based or stratified full-text samples.

8 Limitations

8.1 Corpus, language, and metadata boundaries

The corpus is bounded by Scopus, Web of Science, and SciELO, which differ in journal, conference, regional, linguistic, and citation coverage. It does not represent all Chile-associated engineering education research, particularly locally circulated, practice-based, or non-indexed knowledge production. Association with Chile was defined through normalized author affiliation and does not establish that the empirical setting, participants, leadership, intervention, or data collection were located in Chile. The analysis therefore concerns an indexed affiliation-based publication portfolio rather than a complete national research system.

Language and metadata differences also affected analytical participation. The primary keyword procedure assigned 288 of 451 publications, including 275 of 416 Scopus records, 13 of 23 Web of Science records, and none of the 12 records canonically assigned to SciELO. Keyword and reference maps consequently represent supported subsets. Database and metadata structures can therefore make some linguistic and regional knowledge less visible; nonassignment should not be interpreted as absence of thematic content.

8.2 Network, entity-resolution, and temporal boundaries

Coauthorship and institutional projection do not capture mentoring, grants, professional associations, informal exchange, research use, or educational impact. Author and institutional resolution used identifiers, curated aliases, affiliation evidence, and adjudication logs, but no independent blinded precision–recall audit against an external identity ground truth was available. Residual splitting would inflate components and depress retention, while erroneous merging would have the opposite effect. Centrality, brokerage, citation visibility, and cluster membership remain relational indicators rather than measures of excellence or causal effectiveness.

The primary temporal analyses cover 2015–2024. Records from 2025 were retained for clearly labeled descriptive extensions, cumulative cognitive maps, global-mixing benchmarks, and focused content characterization. The three inferential windows differ in duration, although they contain broadly comparable publication volumes. Louvain communities were estimated under a fixed seed and stated resolution; adjusted Rand indices describe agreement between selected solutions rather than algorithmic stability across every seed and parameter.

The cumulative incidence-preserving null models control publication team size and total entity productivity but not year-specific activity, discipline, geography, funding, institutional hierarchy, or topic. Randomization can therefore create cross-cohort bridges unavailable in the observed chronology. The contrasts are secondary global-mixing benchmarks, not primary tests of temporal consolidation. A temporally constrained randomization is required before null-adjusted claims about longitudinal field integration can be made.

8.3 Cognitive and content-validation boundaries

Keyword and reference comparisons are sensitive to metadata availability, document type, reference-list completeness, normalization, frequency thresholds, and period size. Low temporal overlap may reflect substantive change, source composition, or threshold eligibility. Title-and-abstract analyses covering all records would provide

an important sensitivity test. The selected co-citation and coupling displays also represent interpreted solutions rather than unique partitions of the intellectual structure.

The focused characterization used a purposive sample selected for cluster, front, bridge, and centrality coverage. Coding began largely from titles, abstracts, and author keywords; 12 flagged records were verified against full texts and five remained unavailable. Counts from the 55 publications are not prevalence estimates, do not constitute a corpus-wide risk-of-bias assessment, and should not be used to rank topics or institutions. Their purpose is to identify evidentiary patterns that network topology alone cannot reveal.

Finally, asymmetric consolidation is a framework developed and examined through one case. Its propositions require comparative testing across educational fields and systems with different sizes, languages, funding arrangements, professional infrastructures, and histories. The framework may need modification where collaboration is expressed through forms not captured in publications or where national boundaries are less meaningful than regional, linguistic, or transnational communities.

9 Conclusions

This study examined a general scientometric problem through Chile-associated engineering education research: whether increasing publication activity develops into aligned and temporally reproducible field structure. The indexed portfolio expanded substantially during 2015-2024, but author-level relations reproduced only weakly across periods. Institutions connected the portfolio more broadly than authors were connected, yet recurrent institutional ties did not become unusually persistent. The keyword-supported subset was thematically plural but showed limited temporal overlap, and contemporary coupling fronts differed in their connection to shared intellectual bases.

The strongest conclusion is not that the field lacked collaboration or intellectual organization, but that its layers did not develop uniformly. Productive expansion, local community recurrence, organizational reach, cognitive differentiation, and temporal reproduction formed an asymmetric configuration. This motivates asymmetric consolidation as a diagnostic for field evolution: the concept asks which structures are present, which persist, and whether evidence from one scientometric layer is being incorrectly used as a proxy for another.

For scientometric research, the implication is methodological. Field maturity should not be inferred from publication growth, cumulative giant components, thematic diversification, or institutional centrality alone. Periodized networks, retention measures, coverage audits, cross-layer comparison, and appropriately constrained null models provide a more explicit basis for distinguishing accumulated visibility from reproduced structure. Comparative applications across fields and research systems can test the external validity of this framework.

10 Statements and Declarations

Ethics approval: This study analyzed bibliographic metadata and published scholarly documents and did not involve human participants, identifiable private data, or animals. Ethics approval and informed consent were therefore not applicable.

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