Factors Associated with Collaboration Networks in ASEE Conference Papers

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Abstract

Research collaborations are essential to advance rigorous scholarship, perform transformative science, and accelerate engineering education innovation. With this in mind, the engineering education community should continue investigating and evaluating the key factors that hinder or promote collaborative research within and across institutions, especially amidst efforts to continue to grow the field. Over the last few decades, research collaborations across institutions have grown significantly—however, few studies have examined the relationship between such collaborations and the institutional characteristics such as ranking, geographic location, or classifications (e.g., the Carnegie Classification of Higher Education Institutions) when studying collaboration networks. Our paper uses social network analysis (SNA) to help fill this gap by examining how some of these institutional characteristics are related to the institutions' collaborations and network positions.

Social network analysis has emerged as a useful approach to measure research collaboration by evaluating several types of collaboration networks, including co-authorship networks. In this paper, we consider the institution network. Nodes in this type of network represent institutions, while links represent the pairwise collaboration between two institutions. Each link also has a weight that represents the collaboration frequency. Thus, the links form a social space that we can map and analyze to reveal systematic patterns in the broader engineering education community that might otherwise pass unobserved.

We collected information about all papers published between 1996 and 2020 in the American Society for Engineering Education (ASEE) annual conference proceedings for this study. We built the inter-institutional collaboration network and identified structural network properties, connected components, and modularity classes from this dataset. The network data were then linked to data regarding each institution's (i) Carnegie classification, (ii) rankings based on the 2020 QS World University Rankings, and (iii) geographic location. With this augmented dataset, we answered research questions about factors associated with inter-institutional collaborations through statistical analysis. In doing so, we identify the key patterns, trends, and associations from our networked data.

Among the results, we found that a research institution's classification is significantly related to its network positions in the collaboration network, specifically its modularity class. Additionally, we found correlations between the institutions' centrality measures in the network, including the degree centrality, betweenness centrality, and structural holes. Finally, our findings indicate an association between the institutions' geographical proximity and their research collaborations.

Overall, this study provides a lens through which engineering education researchers, faculty members, and administrators can understand the current state of research collaborations within and across institutions. The results can help researchers answer (and raise more) important research questions, support administrators in making decisions on funding and institutional partnerships, and help faculty members design and develop more effective programs that facilitate research collaborations.

1. Introduction

1.1 Background and Motivation

Research collaboration has become a norm and common practice within and across higher education institutions [1,2]. Bibliometric analysis of publications over time presents an illustration of growth in faculty collaboration. Jones et al. [2] examined 4.2 million research papers from 1975 to 2005, including different fields, science and engineering, social science, and arts and humanity, that involved 662 universities in the U.S. and concluded that there had been a universal rise in publications resulting from collaborations. The authors illustrated that between-school collaboration had been the fastest and the most steady growing type (single author, within-school, and between-school). The general growth in the number of collaborative research has also been reported within the domain of engineering education research (EER) [3,4]. It has been speculated that increasing funding opportunities, expansion of engineering education, and increasing numbers of engineering education research centers have contributed to the growth of collaborative research in engineering education [3]. Intuitively, the collaboration trend in EER has also been influenced by the shift towards pedagogic research within the last few decades. In addition to publications and knowledge production [1,5], research collaborators may benefit from professional development and faculty growth [5,6], developing links and social capital [1], and learning and innovations [7]. Nevertheless, broader institutional factors in terms of mission, structures, and resources may influence collaborative patterns. Jones et al. [2] argued that multi-university partnership influenced by institution's status level; "elite universities are more intensely interdependent, playing a higher-impact and increasingly visible role in SE [science and engineering] and SS [social sciences]" (p. 1261).

This paper aims to explore some factors that may influence inter-institutional collaboration, such as ranking, geographic location, or classifications. The analysis of publications over time provides an invaluable illustration of the patterns of collaborations and how the contributing factors and micro-mechanisms can be identified, explained, and relate to the overall structure. At the same time, missing opportunities and pathways for improvements can be speculated. Considering co-authorship as a (partial) indicator of collaboration, we incorporate social network analysis (SNA) to examine some institutional characteristics in relation to inter-institutional collaboration and network positions. SNA has emerged as a useful approach to measure research collaboration by evaluating several types of collaboration networks focusing on different factors such as authors, institutions, and countries [8-10].

1.2 Contributions

Our major contributions include: 1) a data collection pipeline to gather and analyze publications between 1996 and 2020 in the American Society for Engineering Education (ASEE) annual conference proceedings, 2) descriptive and social network analysis of the harvested data and the institution collaboration network, and 3) linking the network data to external data sources regarding each institution's (i) Carnegie classification, (ii) rankings based on the 2020 QS World University Rankings, and (iii) geographic location.

2. Data Collection Pipeline

The bibliographic data collection pipeline consists of five main phases: harvesting, archiving, storing, linking, and analysis. The main steps of the data collection pipeline are presented in figure 1. The harvesting step is performed through a python script that connects to the ASEE Peer online document repository (https://peer.asee.org/) and searches for all the publications that belong to the ASEE Annual Conference between 1996 and 2020. For each publication, we extracted metadata including title, authors, year published, authors' affiliation, and abstract.

From this data, we built the inter-institutional collaboration network, and the network data were then linked to IPEDS data regarding each institution's (i) Carnegie classification, (ii) rankings based on the 2020 QS World University Rankings, and (iii) geographic location. The final stage consists of quantitative and social network analyses that help identify factors associated with inter-institutional collaborations through statistical analysis and the relationship between the institutions' position in the collaboration network and their academic standing and geographic location.

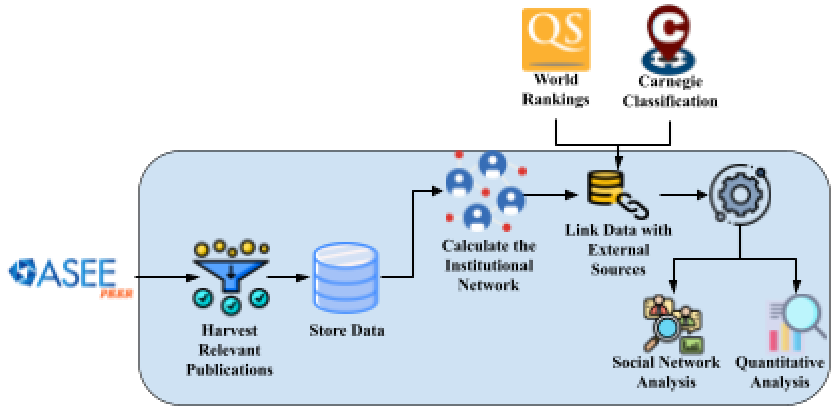


Figure 1: The data collection pipeline steps.

3. Descriptive Data Analysis

Descriptive analysis is used as an exploratory analysis to understand the study's data better and provides the measures and numbers that can help reveal interesting patterns and themes. The collected publications span around twenty-four years from 1996 until 2020, with a total of 35,460 publications, as shown in figure 2. The authorship analysis has revealed that the number of multi-author publications has increased compared to single-author papers during the last 14 years, as shown in figure 3.a. Additionally, the analysis revealed an overall increase in multi-institution publications.

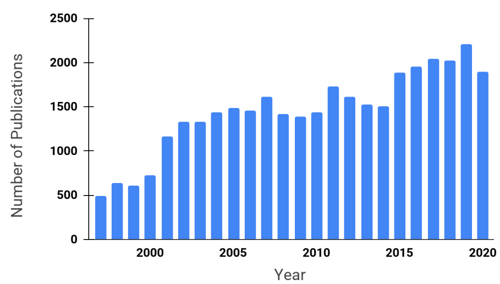
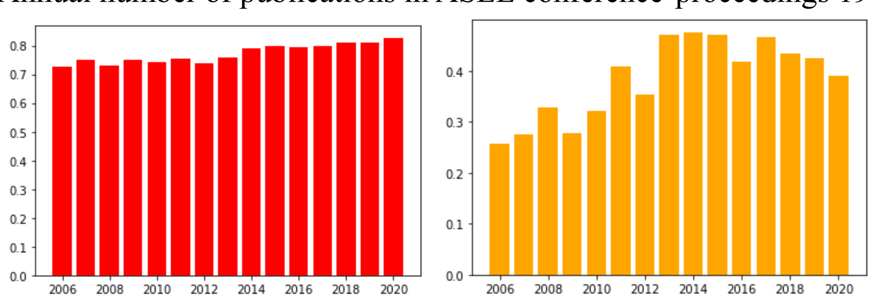


Figure 2: Annual number of publications in ASEE conference proceedings 1996 - 2020.

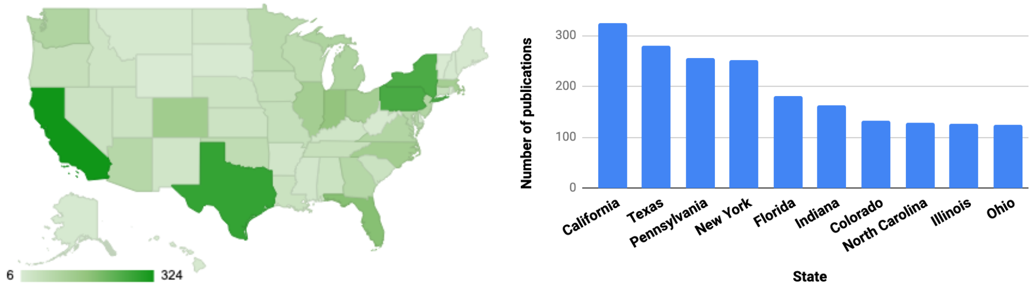


(a) (b)

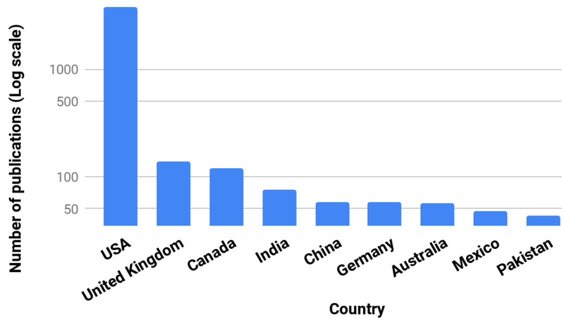
Figure 3: Proportion of (a) multi-author and (b) multi-institution publications compared to total publications in the ASEE conference proceedings from 2006 to 2020.

A mapping of the ASEE publications to geographic locations was carried out. The school information was extracted from the author's affiliation. A geocoding process was conducted to transform the text-based description or the name of the school to geographic coordinates, frequently latitude/longitude pairs. The total number of publications by state and by country were evaluated. The results show that the largest number of publications came from schools within

California at the state level. The United States of America was the most productive country based on the number of publications, unsurprisingly, as shown in figure 4.



(a)



(b)

Figure 4: Geographic mapping of the publications based on the authors' institution location at state (a) and country (b) levels.

4. Network Analysis

We were interested in studying networks as they reveal the structure of the collaboration network of the authors, institutions, and the interactions between them. In network analysis, institutions are represented as nodes and connections as links or edges. We are interested in identifying key network properties, including hubs (important nodes), brokers (nodes connecting two or more groups together), isolated nodes, communities, and connected structures. In this part of the analysis, we constructed a network from the harvested publications where each node represents an institution. Each edge represents the relationship through the co-authorships of affiliated authors. The number of nodes and edges is 5,321 and 13,818, respectively. The average number of connections of each node (co-authorship interactions) in our network is 5.194. Purdue University has the highest number of connections (degree = 442), reflecting the high number of co-authorship collaborations of Purdue-affiliated authors with other institutions. Following Purdue University, Virginia Tech had a degree equal to 255. The nodes with the highest degree in our collaboration network are mostly the institutions that are classified as research-oriented institutions according to the Carnegie classification. These nodes are often referred to as hubs, and calculating degree is the quickest way of identifying hubs.

Betweenness centrality is another network measure useful to capture broker nodes that stand between groups and give the network connectivity and cohesion [18]. Purdue University also had the highest betweenness centrality. Arizona State University and Virginia Tech followed Purdue in this ranking. After linking our network with the Carnegie classification data, we found that the top universities based on degree and betweenness centrality are most likely to be doctoral or masters universities with high research activity. The collaboration network density (the number of existing collaborations relative to all possible numbers) is low and equals 0.001. Dense networks are more important for control than for information.

Table 1: Top institutions with Carnegie classification based on degree and betweenness centrality. (15: Doctoral/Research Universities—Extensive, 16: Doctoral/Research Universities—Intensive, 18:Master's L: Master's Colleges and Universities (larger programs), 27: Spec/Eng: Special Focus Institutions--Schools of engineering)

Top 10 based on Degree	Degree	Carnegie classification	Top 10 based on Betweenness Centrality	Betweenness Centrality	Carnegie classification
Purdue University	447	15	Purdue University	1937616.167	15
Virginia Tech	255	15	Arizona State University	928181.9163	18
Arizona State University	249	15	Virginia Tech	894583.4466	15
Texas A&M University	221	15	Penn State University	786256.2697	15
Penn State University	217	15	Texas A&M University	720395.2214	15
Georgia Institute of Technology	187	15	Georgia Institute of Technology	597683.6262	15
California State Polytechnic University	178	15	California State Polytechnic University	511554.6863	15
Rose-Hulman Institute of Technology	165	27	Rose-Hulman Institute of Technology	395380.4728	15
Michigan Technological university	151	16	Michigan Technological university	378998.4078	16
University of Washington	148	15	Stevens Institute of Technology (school of engineering and science)	376243.1118	16

Low dense networks such as this observed collaboration network tend to generate less redundant information and higher diversity in knowledge compared to high-density networks [20]. The low density indicates the presence of weak ties in our network. Weak ties exist between institutions that know each other's work and research but do not necessarily collaborate directly [21]. A detailed structural analysis of the collaboration network is shown in table 2.

Table 2: Collaboration network structural characteristics.

Network Property	Description	Value
Number of Nodes	Total number of institutions	5321
Number of Edges	Total number of co-authorships	13818
Density	The ratio of the number of edges to the number of possible edges	0.001
Average Degree	The average number of edges connected to a node	5.194
Network Diameter	Longest of all the calculated shortest paths in the network	13
Modularity	The fraction of edges that fall within a group, minus the expected number of edges within a group	0.584
Number of Communities	Number of node groups in the network	214
Average Clustering Coefficient	The measure of the degree to which the nodes tend to cluster together	0.752
Average Path Length	Sum of shortest paths between all pairs of nodes divided by the total number of pairs	3.84

4.1 Institution Network Visualization

Network or graph visualization is the process of visually presenting connections or edges between entities or nodes and properties. Network visualization helps intuitively identify trends, outliers, and interesting patterns of behavior. Exploring connected data allows us to gain more in-depth knowledge, understand the context and ask more questions than just looking at raw data. A visualization of the institutions’ collaboration network was generated using the Gephi software. To provide a better insight into the network structure and key nodes (institutions), we focus on nodes within the largest connected component with a degree of at least 5. The largest component is the maximal set of nodes such that a path connects each pair of nodes. In the visualization, node size reflects the node degree, which means nodes with a higher degree will be more visible. We found within the collaboration network multiple community structures where the nodes of the network are grouped into sets of nodes such that each set of nodes is densely connected internally. Thus, communities reflect internal collaboration within the same group more than with other institutions. The Louvain method [11] for community detection was used to identify communities from the collaboration network. Nodes from the same community are assigned the same color. Figure 5 shows a visualization of the institutions' collaboration network.

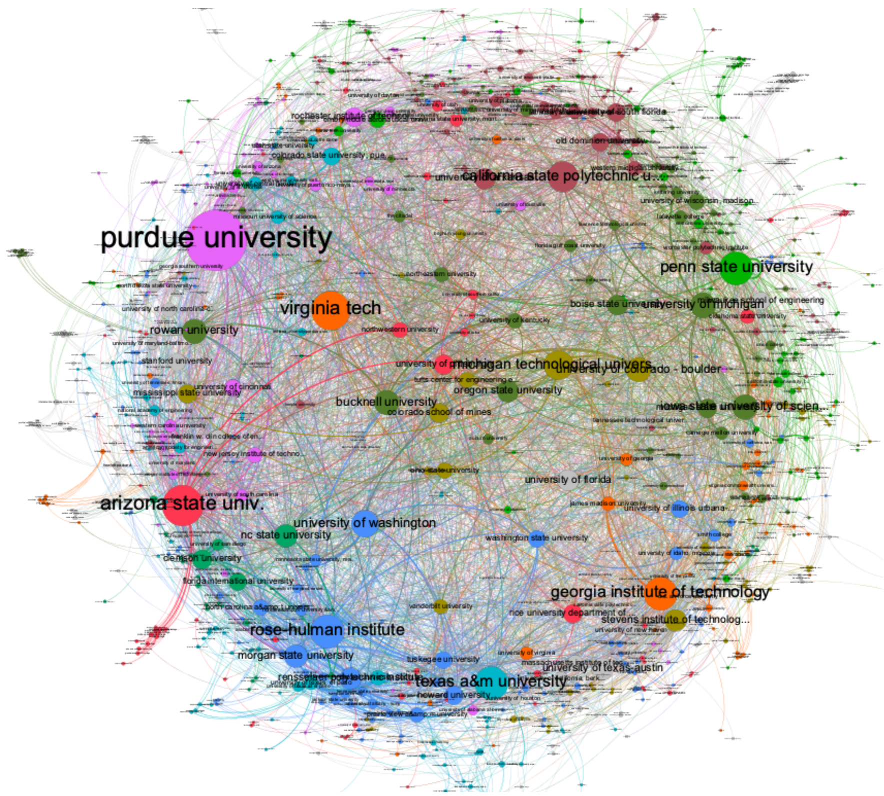


Figure 5: A visualization of the giant component within the institutions' collaboration network. Nodes (institutions) within the same communities are assigned the same color. Node size is relative to the degree (number of collaborations).

The visualization shows key nodes (institutions) and their collaborators within each community. The largest connected component is dominated by six communities that represent around 40% of the total number of nodes. Most of the nodes (institutions) within these six communities are classified according to Carnegie classification as doctoral or masters universities with high research activity.

4.2 Term Network Visualization

This part of the analysis aims to identify key topics of research collaborations and how these topics change over time. We used "Cortext," which is an online data analysis platform. This process consists of extracting the title and abstract from each publication, creating a corpus for each time period (4 years), recognizing and extracting terms in various forms (e.g., engineering education research, research in engineering education), calculating terms co-occurrences within the same publication title or abstract, and finally constructing term networks. The process employed various linguistic, text mining, and term automatic extraction techniques [12]. In this type of network, nodes represent terms, and edges represent co-occurrence relationships. Figure

6 shows the term networks for each period (5 years) from 2006 to 2020. Communities or clusters of terms that appear more frequently together are assigned different colors. Node size represents the node (term) degree which is the number of times a term co-appeared with other terms. Figure 6 shows how ASEE clusters of key terms have changed over time. The list of associated institutions, based on publication affiliation data, is shown in table 3.

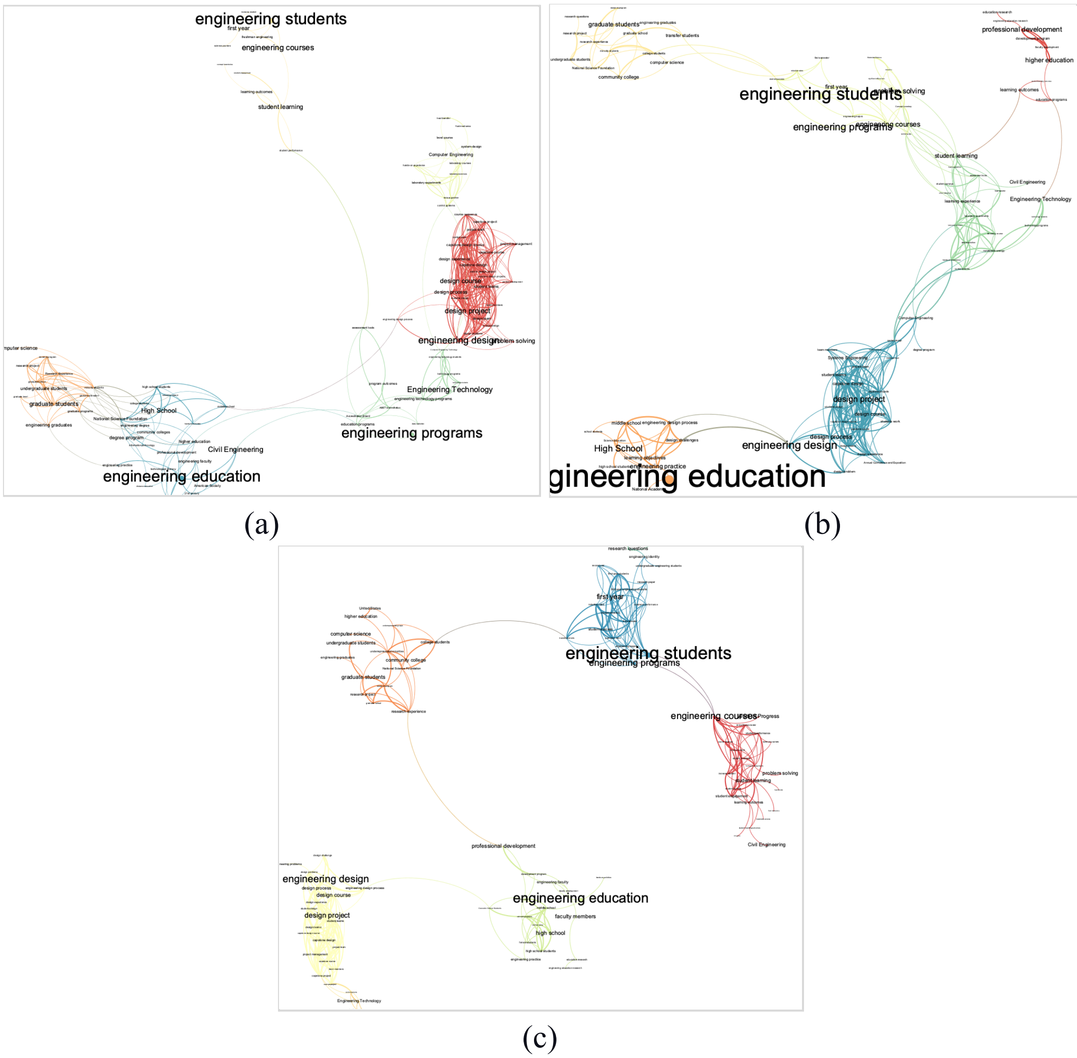


Figure 6: Clusters of key terms discussed in ASEE conference papers during three periods (a) 2006 - 2010, (b) 2011- 2015, and (c) 2016 - 2020.

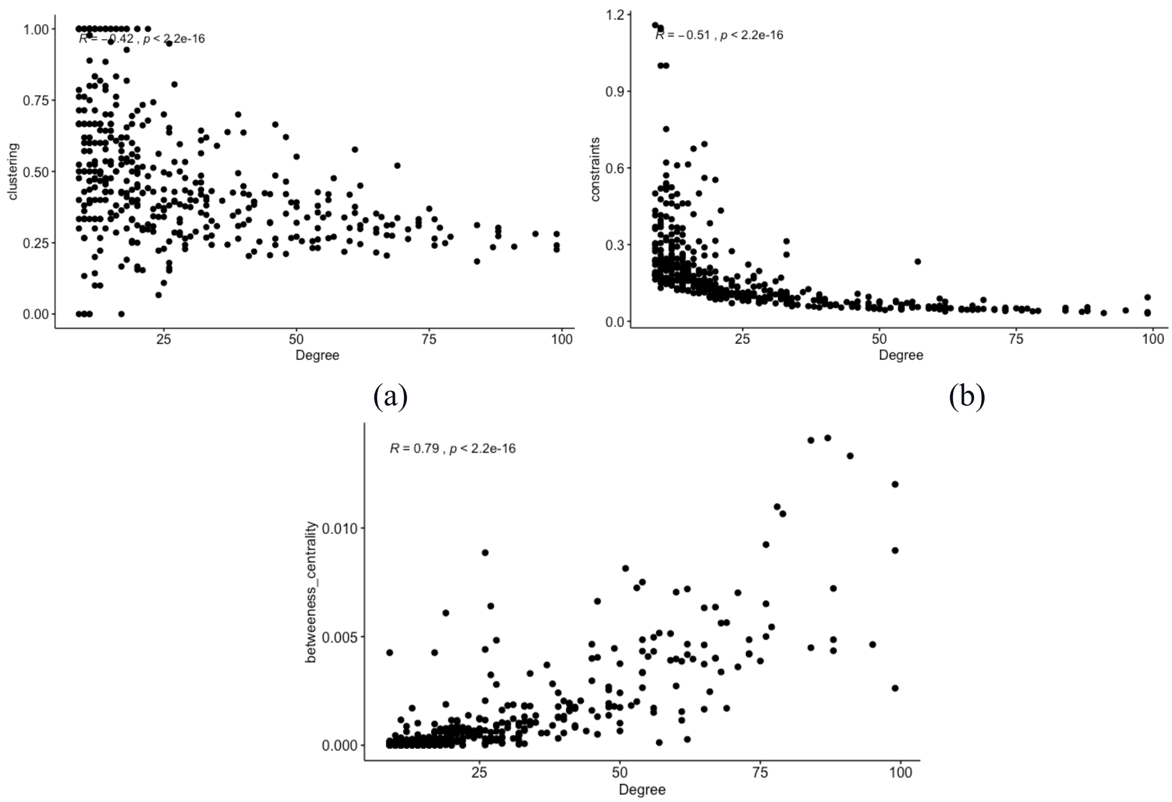
5. Quantitative Data Analysis

The purpose of this part of the analysis is to examine relationships (if any) among various factors associated with collaboration networks. Among the results, we found correlations between the institutions' centrality measures in the collaboration network, including the degree centrality, betweenness centrality, and structural holes, shown in figure 7. The results in figure 7.a indicate that the institution network is showing an important characteristic of scale-free networks where the clustering coefficient distribution decreases as the node degree increases. This distribution also follows a power law that implies that the low-degree nodes (institutions with few research collaborations) belong to very dense subgraphs. Those subgraphs are connected through hubs (mostly). The results show that institutions tend to form communities, i.e., small groups in which everyone knows everyone.

Table 3: key terms discussed in ASEE conference papers over three periods from 2006 to 2020.

2006 - 2010	Topic	2011- 2015	Topic	2016 - 2020	Topic
University of Michigan, Rose-Hulman Institute of Technology, University of Colorado, Boulder	Learning outcomes and student learning process	Arizona State University, Purdue University West Lafayette, Western Washington University	Minority students and research experience	University of Illinois, Urbana-Champaign, University of Florida, Purdue University, West Lafayette, Clemson University, Texas A&M University	First-year students and retention
Kettering University, Pennsylvania State University, University of Hartford	Student teams and design projects	Arizona State University, Clemson University, Rowan University	Engineering courses and first-year students	Virginia Tech, Arizona State University, North Carolina State University	Research programs and underrepresented minorities
Eastern Washington University, University of Dayton	Engineering technology programs	Purdue University, West Lafayette, Georgia Institute of Technology, Texas A&M University	Professional development	Iowa State University, Utah State University, Washington State University	High school, middle school students, professional development
North Carolina State University, Iowa State University	High School students	University of Virginia, North Carolina State University, Purdue University, West Lafayette	Engineering design process and middle school students	Northeastern University, Rose-Hulman Institute of Technology, Colorado School of Mines	Engineering design teams and project
		Texas AM University, Minnesota State University, Northeastern University	Design courses and design-related projects		

In addition, the members of a community also have a few acquaintance relationships with other institutions outside that community. Some institutions, however, are connected to a large number of communities. Those institutions may be considered the hubs responsible for the small-world phenomenon [13]. Figure 7.b shows that as the node degree (number of collaborations) increases, the network constraint decreases. The constraint is a measure of the extent to which a node (institution) is collaborating with those nodes that are themselves collaborating with the neighbors of the node. This finding indicates that in the ASEE collaboration network, institutions with higher degrees (number of collaborations) have access to more institutions with more diverse information and ideas. These high-degree institutions tend to act as mediators between two or more closely connected groups of institutions and gain important comparative research advantages. These results are related to the concept of structural holes [14]. The theory states that the heterogeneity of information, new ideas, and behavior is generally higher between two groups of people than within any group of people. In particular, the position of a bridge in the ASEE network allows highly collaborative institutions to transfer or impede valuable information from one group to another [15]. The position of high-degree institutions allows them to combine all the ideas they receive from different sources and come up with innovative research ideas. At the same time, as brokers, they have an important position, as ties with diverse groups can be fragile, and without brokers, the network will become disconnected. With low-density networks like the ASEE network, the role of high-degree institutions becomes more important as they act much more like the network backbone and have more responsibility to mediate knowledge and findings across groups. These findings are confirmed with the result in figure 7.c, which shows the positive correlation between the node degree and betweenness centrality.



(a) (b)

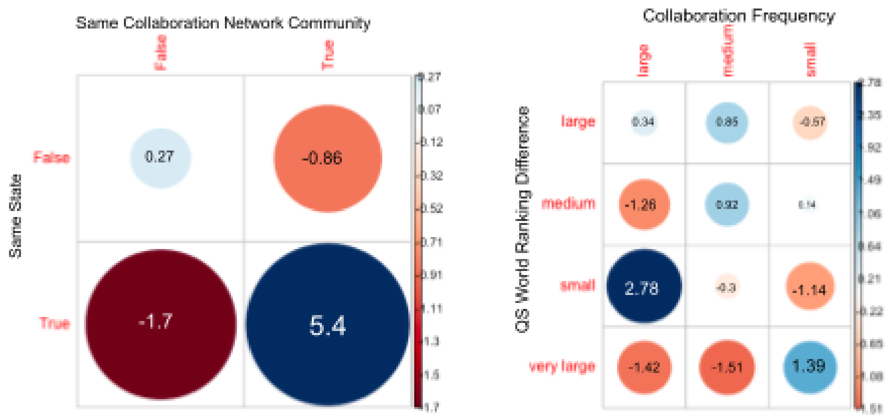
(c)

Figure 7: Correlations between the institutions' various network properties. (a) negative correlation between degree and clustering coefficient, (b) negative correlation between network constraint and degree, and (c) positive correlation between degree and betweenness centrality.

This finding confirms that nodes (institutions) with high-degree centrality tend to have high betweenness centrality. Betweenness centrality measures the number of times a node acts as a bridge along the shortest path between two other nodes. According to [16], it can quantitatively show how high-degree institutions have control over the communication between other institutions in the ASEE collaboration network.

Our findings also indicate an association between the institutions' geographical proximity and their research collaborations. In this part of the analysis, we focused only on US institutions. We examined whether highly collaborating institutions (within the same network community) are also from the same state or not. The data aggregation resulted in a four-column table containing the two institutions' names, whether they are located in the same state (yes/no), and whether they are members of the same network community (yes/no). From this table, we created a "fourfold table" or "2 x 2 contingency table". Finally, a chi-squared test of independence was conducted on the contingency to examine the relation between the two categorical variables, "same state" and "same network community." The relation between these variables was significant, X^2 (1, N = 69378) = 32.42, p = 1.24×10^{-8}. Since the p-value is less than or equal to the significance level, we reject the null hypothesis and conclude that there is a statistically significant association between the two variables. A visualization of the test residuals is shown in figure 8.a. Positive values in cells specify a strong positive association between being from the same state and also from the same collaboration network community.

Additionally, we studied the relationship between the institutions' QS world ranking and their tendency to collaborate. A chi-squared of independence was conducted to identify the relation between the two categorical variables, "QS World Ranking Difference" and "Collaboration Frequency." We found that X^2 (6, N = 4849) = 18.929, p = 0.0042. Since the p-value is less than or equal to the significance level, we reject the null hypothesis and conclude that there is a statistically significant association between the two variables. A visualization of the test residuals is shown in figure 8.b. There is a strong positive association between small differences in ranking and an increased number of collaborations.



(a) (b)

Figure 8: Sign of the standardized residuals is important to interpret the association between rows and columns. Positive values in blue cells specify an attraction (positive association) between the corresponding row and column variables. Negative values in red cells imply a repulsion (negative association) between the corresponding row and column variables. (a) a strong association between being a member of the same collaboration community and location in the same state, (b) strong association between collaboration frequency and closeness in QS World Ranking.

6. Discussion and conclusion

The present study evaluated the association of several factors, including geographical locations, Carnegie classification, and QS world university rankings with a network of inter-institutional engineering education research collaboration based on the analysis of ASEE conference publications between 1996-2020. We found a high degree of association between geographical proximity and the number of collaborative relationships. Previous studies showed the role of geographical locations [10]. Collaborations involving several institutions have higher coordination costs that impact communications between collaborators [17]. In addition, the results showed that top-rank universities appear to be involved in a significant number of collaborations in particular with one another, which was partly expected considering the emphasis of ranking systems on research productivity. One of the major criteria in the QS rankings is the number of citations per faculty [18]. The research institutions have access to different resources and funding opportunities and are expected to have a higher number of publications and citations, which is also evident from our results analyzing the association of the collaboration network and Carnegie classifications. A major limitation with the QS rankings is significant reliance on reputational surveys (academic and employer), and its reliability is under question. However, the results of the collaboration network analysis in connection with the QS rankings and Carnegie classifications reveal that engineering education collaborations across institutions are more about status and resources than geographical proximity. Reflecting on their findings of an analysis of multi-university collaborations across the different academic field (science and engineering, social sciences, and arts and humanities) from 1975 to 2005, Jones et al. [2] argued: "...geographic distance is of decreasing importance, social distance is of increasing importance in research collaborations." (p. 1261). They elaborated that elite universities in science and engineering and social sciences are now dependent on one another to an extreme degree and have a substantial advantage in terms of the number of citations.

In our institution's network, the contribution of high-rank research universities in producing collaborative publications is evident; in addition, they play a critical role in providing access and making connections between different communities and across different research topics. This should not be simply taken for granted; future research may critically analyze the number of collaborations and their impacts by focusing closely on the types of institutions. This line of research should raise critical questions about the collaborations across different institutions, including those that serve different demographic groups or have different missions and identities, and further the understanding of key factors involved in collaborations both at the institutional level and individual level [19]. The analysis presented in this paper can also be expanded to explore the role of engineering education research centers and graduate programs as well as relevant funding opportunities. Importantly, there is an interconnection between research areas of collaborative projects and the number and connections made between universities. The results of our analysis of key terms between 2006 and 2020 are the starting point of further discussion about the role of different internal factors within the engineering education community, such as the increasing number of advanced degree programs in engineering education, recognition of engineering education research within a broader network of researchers, and the increasing number of funding opportunities in particular through National Science Foundation, and external factors such as changes in the ABET criteria. For example, considering the impact of the adopted ABET Engineering Criteria 2000 (EC2000) within the United States, there is no surprise to see students' learning outcomes and learning process as one of the major research areas between 2006 and 2010. Another major shift was the emphasis on the engineering design process that started along with the changes in ABET criteria and continues through the early 20th century. Its impact is evident in the results presented in this paper. Our goal here is not to make a conclusive argument about the connection between research topics and collaborations across universities but rather highlight that the changes in major research areas, for example, in response to funding opportunities, may play a role in connecting researchers with different degrees of expertise across institutions; future research may examine such multi-variable relationships.

References

1. Bozeman, B., Fay, D., and Slade, C.P. (2013). Research collaboration in universities and academic entrepreneurship: the-state-of-the-art, Journal of Technology Transfer, 38, 1, 1-67.
2. Jones, B.F., Wuchty, S., Uzzi, B. (2008). Multi-university research teams: Shifting impact, geography, and stratification in science, Science, 322, 5905, 1259-1262.
3. Jesiek, B.K., Borrego, M., Beddoes, K., Hurtado, M., Rajendran, P., and Sangam, D. (2011). Mapping Global Trends in Engineering Education Research, 2005–2008, International Journal of Engineering Education, 27, 1, 77-90.
4. Nowaz, S., Strobel, J. (2016). Authorship and content analysis of engineering education research: A case study, International Journal of Engineering Pedagogy, 6, 2, 39-51.

5. Austin, A.E., Baldwin, R.G. (1991). Faculty Collaboration: Enhancing the Quality of Scholarship and Teaching, ASHE-ERIC Higher Education Report, No. 7, Washington, D.C.: The George Washington University, School of Education and Human Development.
6. Clark, C., Moss, P.A., Goering, S., Herter, R.J., Lamar, B., Leonard, D., Robbins, S., Russel, M., Templin, M., Wascha, K. (1996). Collaboration as dialogue: Teachers and researchers engaged in conversation and professional development, American Educational Research Journal, 33, 1, 193-231.
7. Creamer, E.G. (2004). Assessing outcomes of long-term research collaboration, The Canadian Journal of Higher Education, 34, 1, 27-46.
8. Han, P., Shi, J., Li, X., Wang, D., Shen, S., Su, X. (2014). International collaboration in LIS: global trends and networks at the country and institution level, Scientometrics, 98, 53–72.
9. Li, Y., Li, H., Liu, N., Liu, X. (2018). Important institutions of interinstitutional scientific collaboration networks in materials science, Scientometrics, 117, 85–103.
10. Xian, H., Madhavan, K. (2014). Anatomy of Scholarly Collaboration in Engineering Education: A Big-Data Bibliometric Analysis, Journal of Engineering Education, 103, 3, 486-514.
11. Blondel, V. D., Guillaume, J. L., Lambiotte, R., & Lefebvre, E. (2008). Fast unfolding of communities in large networks. Journal of statistical mechanics: theory and experiment, 2008(10), P10008.
12. Kageura, K., & Umino, B. (1996). Methods of automatic term recognition: A review. Terminology. International Journal of Theoretical and Applied Issues in Specialized Communication, 3(2), 259-289.
13. Milgram, S. (1967). The small world problem. Psychology today, 2(1), 60-67.
14. Burt, R. S. (2004). Structural holes and good ideas. American journal of sociology, 110(2), 349-399.
15. Burt, R. S. (2009). Structural holes: The social structure of competition. Harvard university press.
16. Freeman, L. C. (1977). A set of measures of centrality based on betweenness. Sociometry, 35-41.
17. Cummings, J.N., Kiesler, S. (2007). Coordination costs and project outcomes in multi-university collaborations, Research Policy, 36, 1620-1634.
18. QS. (2021). The QS World University Rankings Methodology. https://www.topuniversities.com/qs-world-university-rankings/methodology
19. Jalali, Y., Matheis, C., Tysor, C., Lohani, V. (2021). Sustaining Faculty Collaboration: An Exploratory Process-Based Study of Research Collaboration Across Universities, Collaborative Network for Engineering and Computing Diversity (CoNECD), January 25-28.
20. Tan, J., Zhang, H., & Wang, L. (2015). Network Closure or Structural Hole? The Conditioning Effects of Network–Level Social Capital on Innovation Performance. Entrepreneurship Theory and Practice, 39(5), 1189-1212.
21. Ebers, M. (2004). Interorganizational relationships and networks. International Encyclopedia of the Social & Behavioral Sciences, 7855-7860.