Tool Usage Patterns of Mechanical Engineering Students in Academic Makerspaces

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***Abstract*– Academic makerspaces have continued to rise in popularity as research shows the diverse benefits they provide to students. More and more engineering curriculums are incorporating makerspaces and as such there is a need to better understand how their student users can best be served. Surveys administered to makerspace users at a public research university in the Southwest United States during Fall 2020, Spring 2021, Spring 2022, and Fall 2022 tracked student tool usage trends with academic career stages. The survey asked questions about prior experience, motivation, tool usage, and demographics. Analyzed results for mechanical engineering student users provide insight into how curriculum and class year affect the specific tools used and the percentage of student who used a particular tool. The survey results also create a bipartite network model of students and tools, mimicking plant-pollinator type mutualistic networks in ecology. The bipartite network models the student interactions with the tools and visualizes how students interact with the tools. This network modeling enables ecological network analysis techniques to identify key makerspace actors quantitatively. Ecological modularity, for example, identifies divisions in the student-tool makerspace network that highlight how students from different majors (here we investigate mechanical) utilize the makerspace's tools. Modularity is also able to identify "hub" tools in the space, defined as tools central to a student's interaction within the space, based on student-tool connectivity data. The analysis finds that tools commonly used for class by mechanical engineering students, such as the 3D printer or laser cutter, act as gateway tools that bring users into the space and help spark interest in the space's other tools. Using the combined insights from the survey results and the network analysis, ecological network metrics are shown here to be a promising route for informing makerspace policy, tool purchases, and curriculum development. The results can help ensure that the space is set up to give students the best learning opportunities.**

Keywords— makerspace, design, interaction networks, bio-inspired design

I. Introduction

Continued research into university makerspaces shows that college students are positively impacted by their participation in such spaces [1-8]. University makerspaces allow students to apply the material they learn in their coursework to iterative hands-on projects with real consequences [1, 2] and provide students with a safe space to ask questions and experiment with ideas. This increases students' ownership of their work, engagement in the design process, and motivation to participate in engineering activities [2, 5, 8]. Studies conducted at a variety of schools have shown that makerspace involvement improves communication and teamwork [1, 5], creativity and innovation [5, 6, 9], design self-efficacy [3, 4, 6], and sense of belonging in engineering [2, 6]. Participation may even improve students grades in engineering coursework [7, 8]. At many universities, makerspaces have become social hubs for likeminded students to gather together and learn from others with similar interests [5].

Given these benefits and strong correlation between makerspace course involvement and future voluntary participation in makerspaces [10], university makerspaces continue to spread at rapid speed and many programs now incorporate their use into curriculum such as cornerstone and capstone design classes. Not only are they beneficial to students, but also makerspaces help propel the development of engineering design courses and maintain program accreditation [11]. As more and more schools begin to build similar spaces and offer them to students, it is important that makerspace staff and design course instructors understand student usage habits. This paper describes the use of surveys to better understand how and why students are using makerspaces.

Ecology inspired network analysis and modularity metrics are further used to understand student tool interactions and provide additional information not otherwise gained from survey results. Modularity analysis is often used to identify and analyze complex networks, such as plant-pollinator networks [12, 13]. One such way modularity can aid in evaluating complex networks is by sectioning actors into their individual modules, and from the modules, key actors can be identified [14, 15]. In the case of a makerspace, this can aid in determining the structure and interactions of the makerspace as well as finding key tools in the space. Analysis utilizing modularity in makerspaces was previously conducted, with the findings indicating key tools for a space can be identified [16]. The metrics thus provide a quantifiable value as to *how much* a network is changing and allow for comparisons to be made amongst groups.

II. Methods

A. Location of Research

The makerspace studied is housed in an engineering building at a large public research university in the Southwest United States. The space contains a variety of equipment including 3D printers, wood tools, metal tools, hand tools, project workspaces, and CAD computers. The makerspace is free for all undergraduate engineering students to use for class projects and club projects. A small number of graduate students may also pay to have access for research purposes. No personal projects are permitted in the space, but frequent workshops are offered where students can come in and be trained on the machinery regardless of whether they have a class project that requires them to use the space or not. Students are permitted to use tools such as electronics benches, 3D printers, hand tools, project workspaces, CAD computers, and basic wood tools after completing an online orientation and passing a safety quiz. They may also complete additional training to use tools like mills, lathes, and waterjets or submit service requests to have a part fabricated on these machines by trained machinists. The makerspace is primarily staff run, but some student workers are paid to help carry out the fabrication requests.

B. Survey Methods

Data was collected over four semesters (Fall 2020, Spring 2021, Spring 2022, and Fall 2022) using online Qualtrics surveys. More detail on these surveys can be found in prior work [17]. The surveys were sent out to students who signed into the makerspace each semester as well as to students taking classes that require use of the space. The survey contained questions asking about prior makerspace experience, tool usage, and student demographics. Emails were also sent to professors who incorporated or required use of the makerspace into their curriculum to learn what tools the students were expected to use for class.

Students who reported not using any tools were removed from the analysis. Additionally, the sample was narrowed down to only include mechanical engineering students, though any major could have been similarly examined. This left sample sizes of 29 students for Fall 2020, 90 students for Spring 2021, 56 students for Spring 2022, and 39 students for Fall 2022. These populations were then combined, and tool usage patterns were examined based on students' year in school: 2nd Year, 3rd Year or 4th / 5th Year. Few 1st year students use the makerspace, so they were excluded. Additionally, any students who transferred into the school were removed as their year at the school may not be indicative of their progress through the mechanical engineering curriculum. The 4th and 5th year students were combined because most senior level classes could be taken either year depending on the student's anticipated graduation date.

C. Network Analysis

The steps for converting the survey information to a final matrix representation can be found on Fig. 1. From the survey usage information (step 1), a directional bipartite form can be generated. A bipartite matrix visualizes the space in two separate groups, or in the case of the makerspace, a student-tool interaction. For more details on the process, please see [18] for further details. This representation of the network allows for the space to be modeled as a network (step 3) with 1's indicating an interaction between a student and tool and 0's indicating no interaction. The network representation allows the different ecological metrics to be conducted and ultimately, for the different key tools to be identified.

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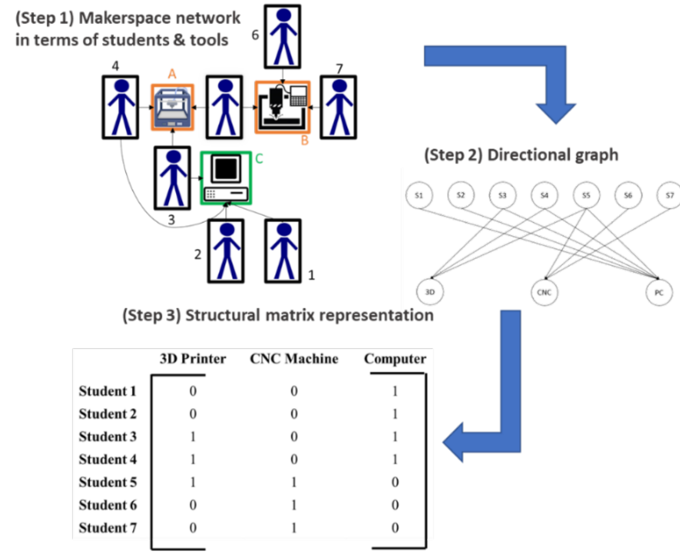

Fig. 1. Process for converting a makerspace into a Structural matrix representation. Step 1 highlights the interactions between students and tools. Step 2 converts these interactions between students and tools into a directional graph (bipartite) form, and Step 3 constructs the structural matrix

From the bipartite network representation, modularity analysis is conducted by first splitting the network interactions into modules and afterwards calculating the participation and z-values [13]. The MATLAB software BiMat was utilized to calculate both the modules as well as the final participation and z values [19]. Equation (1), based on the Newman/Leading Eigenvector method, highlights how modularity is calculated, with E representing the total number of interactions between students and tools, Bij the bipartite adjacency matrix (as shown in Step 3), and ki and dj the number of interactions for each individual tool and student, respectively [15, 19, 20]. The final modularity value ranges from 0 to 1, with a 0 indicating no modularity and 1 indicating perfect modularity [19]. For a makerspace, a high modularity would indicate students used subsets of tools in combination, with a high modularity indicating students are not using a variety of tools but rather a small subset.

$$Q_b = \frac{1}{E}\sum_{ij}(B_{ij} - \frac{k_i d_j}{E})\delta(g_i, h_j) \tag{1}$$

As for the *connectivity* (z) and *participation* (p), Equations (2) and (3) describe the process for obtaining these values. The k_i in (2) is the number of links of node i to other students/tools within its own module, ksi is the average number of links of each node in the module, and σ_{ksi} is the standard deviation of k_{si}. The k_{is} in (3) is the number of links of node i (a specific tool) to other nodes in module s, and k_i is the total number of interactions that node i has with other nodes [14, 16]. Connectivity indicates how well connected a member is connected *within* its module while participation indicates how well connected it is with *other* modules [14]. A high score in both these values indicates a very well connected, critical component in the space.

$$z_i = \frac{k_i - k_{si}}{\sigma_{ksi}} \tag{2}$$

$$p_i = 1 - \sum_{s=1}^{N_M} (\frac{k_{is}}{k_i})^2 \tag{3}$$

With the participation and z-values, different *roles* for each of the tools can be calculated. Fig. 2 highlights the different regions a tool can be categorized in based on both its participation and z value.

Each of the regions aid in providing an understanding of how critical a tool is to the space. The analysis will be used in later sections to identify key tools for each of the student groups. The cutoffs for each region are as follows [14].

- **R1** (p≈0, Z<2.5): *Ultra Peripheral Nodes*, niche or rarely used tools
- **R2** (p<0.625, Z<2.5): *Peripheral Nodes*, tools that are not used as often
- **R3** (p<0.8, Z<2.5): *Non-Hub Connectors*, tools that interact heavily within their own module
- **R4** (p>0.8, Z<2.5): *Non-Hub Kinless Nodes*, tools critical to their own module
- **R5** (p<0.3, Z<2.5): *Provincial Hubs*, tools that interact with a variety of tools of different modules
- **R6** (p<0.75, Z<2.5): *Connector Hubs*, tools that interact heavily within their module and with other modules
- **R7** (p>0.75, Z<2.5): *Kinless Hubs*, tools that interact heavily with everything in the space and cannot be assigned a module

Lastly, connectance is a metric that indicates how many interactions from all possible interactions actually occurred [21, 22]. Utilizing connectance will aid in understanding if students used a wider array of tools in the space.

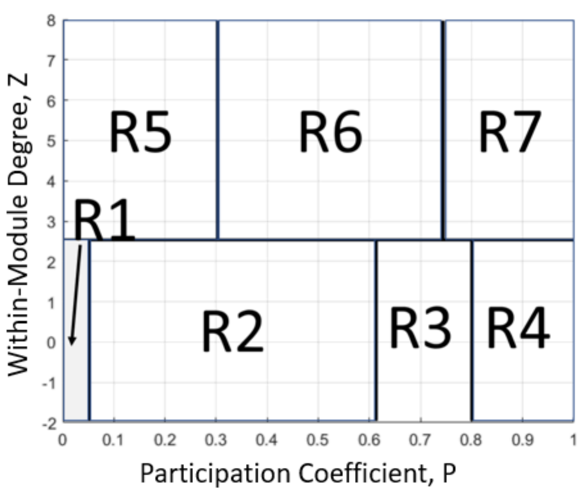

Fig. 2. Tool hub analysis region breakdown. Tools are placed in the region based on their connectivity (z) and participation (p) values. Each region indicates a different "role" the tool falls under [14].

III. RESULTS AND DISCUSSION

Table 1 lists the primary courses in the mechanical engineering undergraduate curriculum that require students to use the makerspace. While most courses are required components of the curriculum, computer aided engineering is taken voluntarily by some students as an elective.

A. Survey Results

Fig. 3 shows the percentage of mechanical engineering students who used each general tool category. Most tool groups, including 3D printers, wood tools, handheld tools, workstations, and social activities had increased percentage usage as students completed more years of school. Interestingly, metal tool usage peaked for 3rd year students and then declined slightly for 4th/5th year students. This is likely due to the materials and manufacturing course (listed in Table 1) that introduces students to several metal tools. Some tool categories, such as electronics and laser cutter, do not show large changes between years in school. This could be due to no mechanical engineering courses explicitly requiring students to use these tools. The percentage of students giving and receiving help increases drastically in year 3, when students are most likely to be using more complex machinery. It then plateaus for 4th and 5th year students which could indicate they have become more comfortable and competent in the space. The overall increase in tool usage as student progress through the curriculum indicates that once students are introduced to a tool, they are likely to use it in the future, regardless of whether it is required. For example, 2nd year mechanical engineering students use the 3D printers for their geometric modeling class and sometimes for their materials and manufacturing class. However, 3D print usage is highest in student's 4th/5th years when they may voluntarily be using it for Capstone or other elective coursework.

Fig. 4 depicts the tool usage of mechanical engineering students who use the space for class vs those who did not use the space for class. It should be noted that students who used the space for class may also have used the space for non-class purposes, but this scenario is not represented in the survey.

TABLE I. MECHANICAL ENGINEERING COURSES THAT USE MAKERSPACE

Course	Year Generally Taken	Required?	Tools Used
Geometric Modeling	2nd	Yes	3D Printers / Scanners
Materials and Manufacturing	3rd	Yes	Lathe, Mill, Bandsaw, Hand Tools, 3D Printer
Computer Aided Engineering	4th / 5th	No (Elective)	Metal Tools (vary based on project)
ME Senior Design	4th / 5th	Yes	Varies based on project

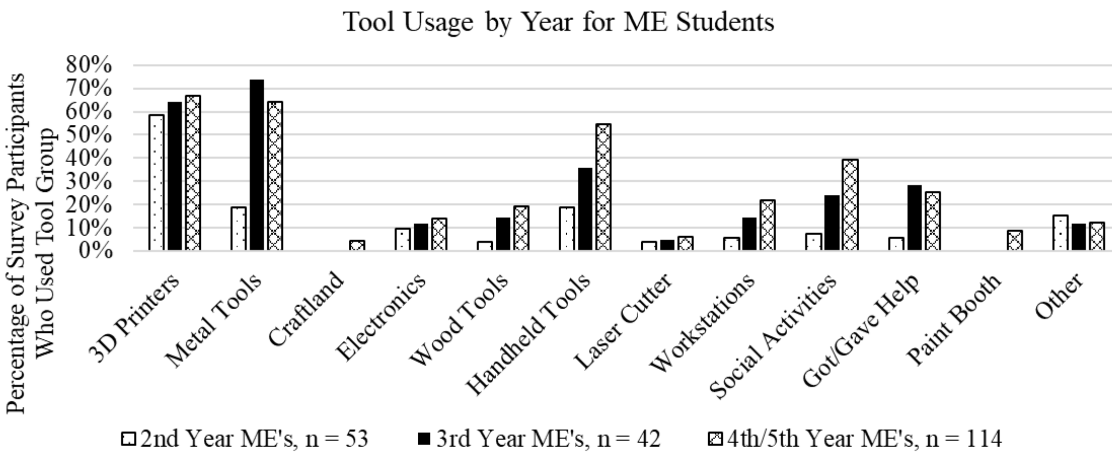

Fig. 3. Percentage of Mechanical Engineering Students Who Used Each Tool Group

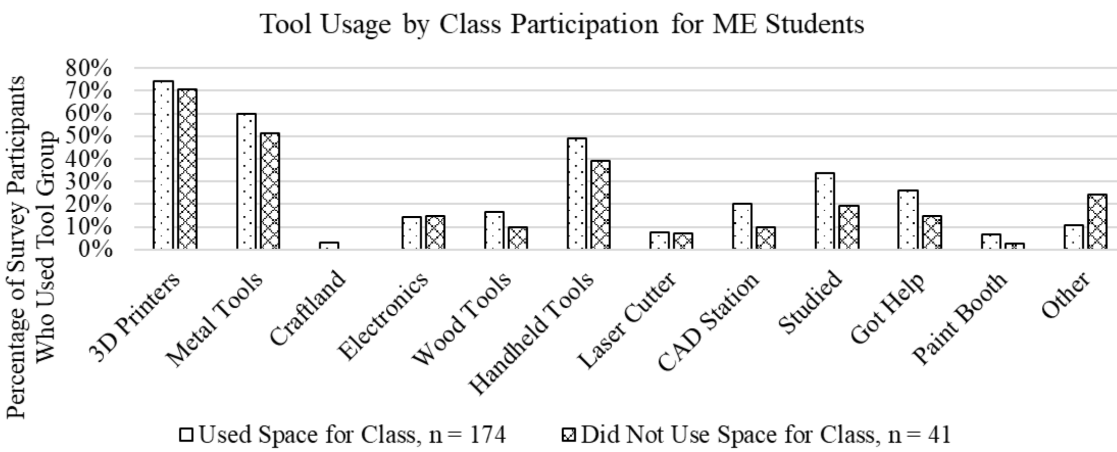

Fig. 4. Mechanical Engineering Student Tool Usage Compared Based on Whether or Not They Use the Space for Class

In most cases, students who used the space for class have slightly higher percentage tool usage, but the differences are very small. The largest differences are 9% for metal, 7% for wood, 10% for handheld tools, 10% for CAD station, 14% for studying, and 11% for giving / receiving help. Electronics and laser cutter usage are nearly identical with differences of 1% and 0% respectively. This supports the idea that required class usage increases student use of certain tools.

B. *Network Analysis Results*

Table 2 highlights the general network metrics calculated from the space. Modularity and connectance for each of the student/year categories across four semesters was calculated. Overall, modularity decreases significantly from the second year onwards. On the other hand, connectance increases from the 2nd year onwards. The trends indicate that students in later years utilize a wider array of tools, with lower modularity highlighting the fact that students are not solely interacting with tools in specific groupings. This is supported by the rise in connectance, with higher connectance highlighting students are utilizing a wider number of tools in the space.

Fig. 5 highlights the key tools identified in the space for each of the semesters. For second year students, 3D printing was a major hub tool to aid students in familiarizing themselves with the space. For third year students, along with the 3D printer, metal tools and handheld tools were a key tool utilized in the space with all three falling within the "hub" tool region. Lastly, for 4th year onward students, all tools from previous semesters as well as wood tools and the CAD station are highlighted as key tools. This further supports Table 2's findings of students branching out to learn a wider variety of tools and these being critical to their usage of the space. The key tools highlighted also match with those that the students learned from classes from Table 1.

TABLE II. NETWORK METRIC FINAL VALUE FOR EACH OF THE DIFFERENT STUDENT SEMESTERS

Year	Modularity	Nestedness	Connectance
2nd Year	0.44	0.23	0.14
3rd Year	0.25	0.56	0.23
4th/ 5th Year	0.24	0.56	0.29

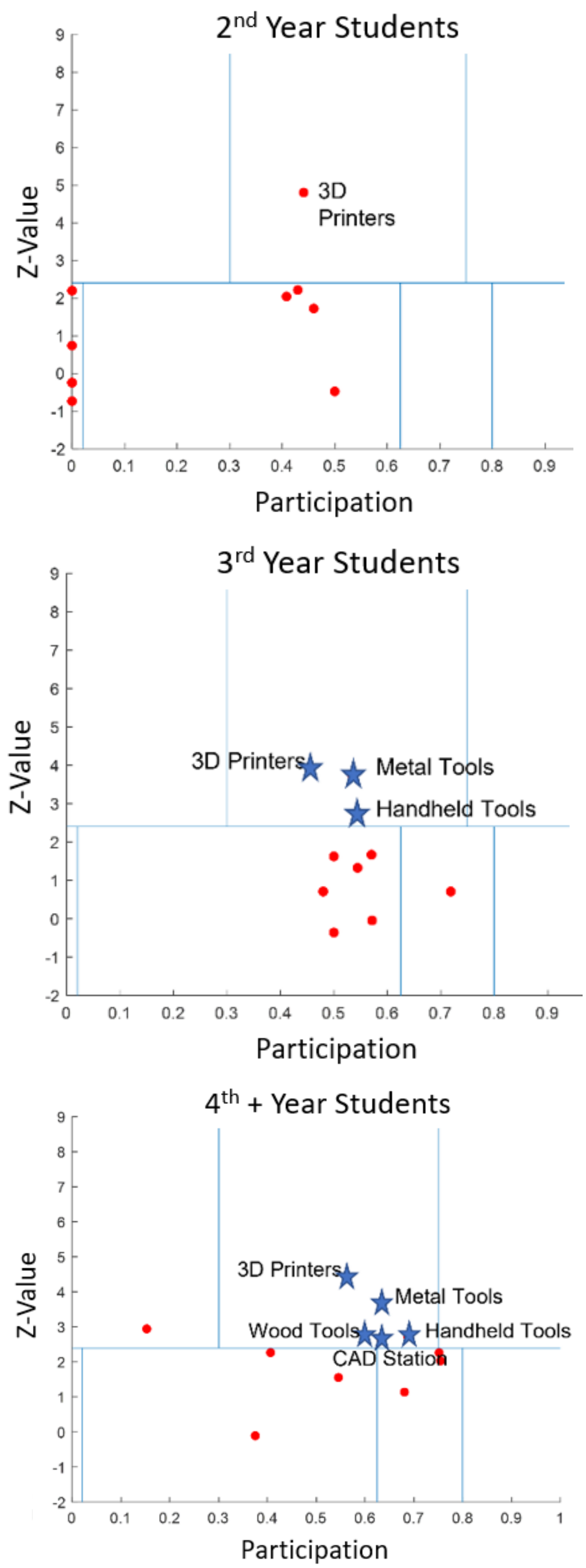

Fig. 5. Mechanical Engineering Student hub tool analysis by year. From top to bottom: 2nd year students, 3rd year students, 4th year students across four separate semesters

Results from both the general network metrics as well as the key-hub tool analysis match results found within the survey, with usage increasing across most tools the longer the student was at the university. Both these findings show a strong support for classes introducing a student to a tool, and once learned, the student searching out that tool in future semesters even if it is not directly required.

IV. CONCLUSIONS AND NEXT STEPS

Survey information along with ecological network analysis techniques were utilized to further understand and highlight the drivers for mechanical engineering students in a makerspace. Surveys captured the usage of students in the space, and when split by year, indicate a strong correlation with learning with students utilizing a wider array of tools in later years. Class information on what tools students are required to use is highlighted, with tools closely lining up to when a spike in usage for that particular tool was first seen. Survey results provide a general understanding of the trends occurring within the space. On the other hand, the network analysis results provide valuable data that not only *supports* survey results but also provides a deeper understanding of the underlying structure of the space. The metrics provide a measurable value that can be used to compare across semesters, as well as the tool-hub analysis quickly visualizing all the key tools within the space. Overall, both the survey and the network analysis results provide strong evidence that introducing a student to a tool, whether it be through classes as was the case in this makerspace, often leads to the student seeking out that tool in future semesters even if they are not required to use it again. These metrics will be further applied to additional university spaces to validate the process and further understand how different spaces operate.

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REFERENCES

[1] M. Galaleldin, Bouchard, F., Anis, H., & Lague, C., "The Impact of Makerspaces on Engineering Education," presented at the Proceedings of the 2016 Canadian Engineering Education Association (CEEA) Conference, Halifax, Canada, January 28th, 2017.

[2] L. Nadelson, Villanueva, I., Bouwma-Gearhart, J., Lanci, S., Youmans, K., Lenhart, C. A., & Van Winkle, A. K., "Knowledge in the Making: What Engineering Students are Learning in Makerspaces," presented at the 2019 ASEE Annual Conference & Exposition, Tampa, FL, June 15th, 2019. [Online]. Available: https://peer.asee.org/33039.

[3] E. C. Hilton, Talley, K. G., Smith, S. F., Nagel, R. L., & Linsey, J. S., "Report on Engineering Design Self-Efficacy and Demographics of Makerspace Participants Across Three Universities.," *Journal of Mechanical Design,* vol. 142, no. 10, May 8th 2020. [Online]. Available: https://doi.org/10.1115/1.4046649.

[4] E. Hilton, Tomko, M., Murphy, A., Nagal, R., & Linsey, J., "Impacts on Design Self-Efficacy for Students Choosing to Participate in a University Makerspace.," in *The Fifth International Conference on Design Creativity*, Bath, UK, 2018, pp. 369-378.

[5] J. Bouwma-Gearhart, Ha Choi, Y., Lenhart, C. A., Villanueva, I., Nadelson, L. S., & Soto, E., "Undergraduate Students Becoming

Engineers: The Affordances of University-Based Makerspaces," *Sustainability,* vol. 13, no. 4, February 4th 2021.

[6] R. M. Carbonell, Andrews, M. E., Boklage, A., & Borrego, M. J., "Innovation, Design, and Self-Efficacy: The Impact of Makerspaces," presented at the 2019 ASEE Annual Conference & Exposition, , Tampa, FL, June 15th, 2019. [Online]. Available: https://peer.asee.org/32965.

[7] E. C. Hilton, Nagel, R., Linsey, J., "Makerspace Involvement and Academic Success in Mechanical Engineering.," in *2018 IEEE Frontiers in Education Conference (FIE)*, San Jose, CA, October 3rd - 6th 2018.

[8] A. Longo, Yoder, B. & Geurra, R. C. C., "University Makerspaces: Characteristics and Impact on Student Success in Engineering and Engineering Technology Education.," presented at the 2017 ASEE Annual Conference & Exposition, Columbus, OH, June 24th - 28th, 2017.

[9] S. Farritor, "University-Based Makerspaces: A Source of Innovation," *Technology and Innovation,* vol. 19, pp. 389-395, 2017.

[10] T. Sawchuk, Hilton, E., Nagel, R., Linsey, J., "Understanding Academic Makerspaces through a Longitudinal Study at Three Universities," presented at the ASEE Annual Conference & Exposition, Tampa, FL, 2019.

[11] V. A. Wilczynski, R., "Higher Education Makerspaces and Engineering Education," presented at the ASME 2016 International Mechanical Engineering Congress and Exposition (IMECE2016), Phoenix, AZ, November 11th - 17th, 2016.

[12] J. Bascompte and P. Jordano, "Plant-Animal Mutualistic Networks: The Architecture of Biodiversity," *Annual Review of Ecology, Evolution, and Systematics,* vol. 38, no. 1, pp. 567-593, 2007, doi: 10.1146/annurev.ecolsys.38.091206.095818.

[13] J. B. Jens M. Olesen, Yoko L. Dupont, Pedro Jordano, "The modularity of pollination networks," *Proceedings of the National Acedemy of Sciences,* 2007.

[14] R. Guimerà and L. A. N. Amaral, "Cartography of complex networks: modules and universal roles," *Journal of Statistical Mechanics: Theory and Experiment,* vol. 2005, no. 02, p. P02001, 2005/02/02 2005, doi: 10.1088/1742-5468/2005/02/p02001.

[15] M. J. Barber, "Modularity and community detection in bipartite networks," *Physical Review E,* vol. 76, no. 6, p. 066102, 2007.

[16] S. Blair, H. Banks, G. Hairtson, J. Linsey, and A. Layton, "Modularity Analysis of Makerspaces to Determine Potential Hubs and Critical Tools in the Makerspace," *2022 ASEE Annual Conference & Exposition,* 2022.

[17] H. Banks, "A Comparison of Tool Use Rates in Two Makerspaces During COVID," MS Thesis, GT, 2023.

[18] L. Z. F. B. K Song Yang, "Social Network Analysis," *Sage Publications,* 2017.

[19] C. O. Flores, T. Poisot, S. Valverde, and J. S. Weitz, "BiMat: a MATLAB(R) package to facilitate the analysis of bipartite networks," *Methods Ecol Evol,* vol. 7, doi: 10.1111/2041-210X.12458.

[20] T. P. Cesar O. Flores, Sergi Valverde, and Joshua S. Weitz, "BiMat: a MATLAB(R) package to facilitate the analysis of bipartite networks."

[21] T. Poisot and D. Gravel, "When is an ecological network complex? Connectance drives degree distribution and emergin network properties," *PeerJ,* vol. 2, no. e251, 2014, doi: 10.7717/peerj.251.

[22] R. Heleno, M. Devoto, and M. Pocock, "Connectance of species interaction networks and conservation value: Is it any good to be well connected?," *Ecological Indicators,* vol. 14, no. 1, pp. 7-10, 2012, doi: 10.1016/j.ecolind.2011.06.032.