

A BIO-INSPIRED NETWORK ANALYSIS APPROACH TO IMPROVE UNDERSTANDING
OF ENGINEERING MAKERSPACES

A Thesis

by

SAMUEL ENRIQUE BLAIR

Submitted to the Graduate and Professional School of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Astrid Layton
Committee Members,	William Grant
	Cynthia Hipwell
Special Appointment	Julie Linsey
Head of Department,	Guillermo Aguilar

May 2023

Major Subject: Mechanical Engineering

Copyright 2023 Samuel Blair

ABSTRACT

Globally, universities have heavily invested in makerspaces. This investment requires an understanding of how students use tools and how tools to aid in engineering education, as well as how the spaces can be improved. Network analysis of human systems can often yield valuable information about how the networks work and function. Applying network techniques to makerspaces can yield helpful information that is otherwise not visible.

This thesis's primary focus is the application of a variety of bio-inspired network techniques to improve the understanding of the makerspace. Several parallels can be drawn between makerspace networks and other mutualistic networks, such as plant-and-pollinator networks where the system's success depends on the interaction between the two species. The ecological metrics would establish measurable values that the health and conditions of a network can be evaluated using. These three metrics are nestedness, modularity, and connectance, which can provide structural information about the network and act as diagnostics tools that can change depending on different system conditions. The makerspace at the universities went through several regulatory changes due to COVID-19, providing a unique opportunity to utilize the metrics to analyze the health of the space under higher regulatory restrictions and return to normal operations. The makerspace is converted into a bipartite network to allow for ecological analysis techniques where the spaces are modeled with students interacting with tools. Null models evaluate the significance of the nestedness and modularity results.

Findings indicate that makerspaces tend to be structurally nested, but when compared to normal operating conditions, they can be seen to exhibit modularity during the higher restriction environment. The makerspace network and subsequent analysis provide insight into the use of ecological metrics in human systems and provide potential ideas for results to be used in various

networks. The following network analysis also yields valuable information identifying essential hub tools and student interactions within the space, showcasing the capabilities the ecological study of human networks can have on human systems.

ACKNOWLEDGEMENTS

I want to acknowledge my committee Chair, Dr. Astrid Layton, as well as my committee members, Dr. William Grant, Dr. Cynthia Hipwell, and Dr. Julie Linsey, for their guidance and support throughout the research.

I would also like to thank my collaborators for this research, Garret Hairston, Claire Crose, Henry Banks, and Carson Kennedy, for their continuous support and conversation, and the Bio-Inspired Sustainable Systems lab members for their continued support and advice throughout my time in the lab.

A special thank you to my advisor, Dr. Astrid Layton, for her continued guidance and support in my pursuit of research and for providing all the necessary resources for my success.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by my thesis committee consisting of Dr. Astrid Layton of the Department of Mechanical Engineering as the advisor, Dr. Cynthia Hipwell of Mechanical Engineering, Dr. William Grant of the Department of Ecology & Conservation Biology, and special committee member Dr. Julie Linsey of the Department of Mechanical Engineering at Georgia Tech. Data for the study was gathered in collaboration with Dr. Julie Linsey and graduate students Henry Banks and Claire Cross from Georgia Tech. The software used to run the analysis was developed in cooperation with Carson Kennedy. Portions of the study of chapter 5 were collected by Claire Crose. All other work conducted for the thesis was completed by the student independently.

Funding Sources.

Graduate study was supported by the J. Mike Walker '66 Department of Mechanical Engineering Fellowship

This work is supported through the National Science Foundation under grants 2013505 and 2013547. Any opinions, findings, or conclusions herein do not necessarily reflect the views of the NSF and its employees.

NOMENCLATURE

ENA	Ecological Network Analysis
NODF	Nestedness (metric based on) Overlap and Decreasing Fill
B	A network's Bipartite interaction matrix
Q	Network Modularity
N	Total number of actors in the network
L	Total number of interactions or links in the network
N_{column}	Number of column actors
N_{row}	Number of row actors
C	Connectance
P	Inter-module degree
Z	Within module degree
p	Probability value
z	Standard score

TABLE OF CONTENTS

	Page
ABSTRACT.....	ii
ACKNOWLEDGEMENTS	iv
CONTRIBUTORS AND FUNDING SOURCES	v
NOMENCLATURE	vi
LIST OF FIGURES	ix
LIST OF TABLES.....	xi
1. INTRODUCTION	1
1.1. Motivation.....	1
1.2. Research Questions and Objectives	2
1.2.1. Research Questions	2
1.3. Contributions	3
1.3.1. Ecological analysis.....	3
1.3.2. Systems Analysis	4
1.3.3. Engineering education analysis.....	4
1.4. Methodology	4
1.5. Assumptions and Limitations	5
1.6. Thesis Layout.....	6
2. LITERATURE REVIEW	7
2.1. Prior research on Makerspaces and Potential for Study	7
2.2. Network Analysis and Ecological Metrics	8
2.3 Nestedness and Modularity: dual metrics to analyze the makerspace.....	10
2.3. Chapter 2 Conclusions	12
3. CONDUCTING ECOLOGICAL ANALYSIS OF THE NETWORK	14
3.1. Data Gathering Methods.....	14
3.2. Network Creation.....	18
3.3. Chapter Summary	20
4. CONDUCTING NESTEDNESS AND MODULARITY ANALYSIS OF THE SPACE	21
4.1. Modularity Analysis	21
4.1.1. Participation and Z – Value	24
4.2. Nestedness	27

4.3. Connectance	31
4.4. Null Models	32
4.5. Relationship between the metrics	34
4.6. Developing a tool to conduct analysis	35
4.7. General Results from the Ecological Network Analysis	36
4.8. Impact from Initial Nestedness and Modularity Analysis of Space	41
4.9. Chapter 4 Summary	46
5. NETWORK ANALYSIS TO IDENTIFY HUB TOOLS AND POTENTIAL BARRIERS ...	47
5.1. Key hub-tool analysis	47
5.2. Student Demographic Analysis	56
5.3. Summary of Chapter 5	60
6. CONCLUSIONS AND FUTURE WORK	61
6.1. Summary	61
6.2. Future Work	62
6.2.1. Enhancing the User Experience	62
6.2.2. Expanding Research to Other Makerspaces.....	64
6.3. Conclusions.....	65
REFERENCES	67
APPENDIX A: NETWORK MATRIXES	76
APPENDIX B: TOOL USE SURVEY	92
APPENDIX C: HUB TOOL ANALYSIS SUPPLEMENTARY PLOTS AND TABLES	93
APPENDIX D: DEMOGRAPHIC ANALYSIS BREAKDOWN TABLES AND PLOTS.....	114
APPENDIX E: MODULARITY AND NESTEDNESS PLOTS	130
APPENDIX F: NETWORK ANALYZER SOFTWARE DOCUMENTATION	134

LIST OF FIGURES

	Page
Figure 1: Hypothetical representation of the makerspace outlining the matrix quantification of interactions: a) A small-scale hypothetical makerspace with interactions b) the resultant makerspace. Image modified from published work [58].....	19
Figure 2: Left - Bipartite representation of the network with students (S1-S10) interacting with tools (T1-T10) and color organized by module. Right - BiMat software output highlighting the network from Figure 1 with interactions (colored in squares) organized.	22
Figure 3: Modularity analysis sectioning determined by connectivity (z) and participation (p) values. The regions R1-7 specify the role that a tool and/or student has in a network, as described in the main text. Image from published work [58].	25
Figure 4: A hypothetical makerspace of 5 students and 5 tools with a nested structure. a) Diagram of the sample makerspace. b) Bipartite graph of the makerspace. c) BiMat nested network output visualizing the network matrix, where the curve indicates the nested interactions boundary.	28
Figure 5: Process for calculating NODF of a hypothetical 4x4 network (top-left, actors R1-4 interacting with actors C1-4). The top-right process shows the column nestedness calculations and the bottom-left process shows the row nestedness calculations. The culmination of which is shown in the bottom right with the overall NODF value.	30
Figure 6: The same curve is shown for a variety of network sizes, describing the impact of network size on the relationship between modularity (x-axis), nestedness (y-axis), and connectance (color scale on the right).	34
Figure 7: Difference between each semester's null model's nestedness (right) and modularity (left) to the modularity and nestedness of each school, each semester for both the general and specific network models.	40
Figure 8: Difference between the normal (SP22) null models' nestedness (right) and modularity (left) to the modularity and nestedness of each school, each semester for both the general and specific network models.	40
Figure 9: Participation and Z-value analysis for School A across the different semesters. Each point is one of the general tools listed in the survey for School A. Tool numbering matches the names in Table 2.	48
Figure 10: Participation and Z-value analysis for School B across the different semesters. Each point is one of the general tools listed in the survey for School B. Tool numbering matches the names in Table 2.	50

Figure 11: Participation and Z-value analysis for School A for the specific tool categories across the different semesters. Each point is one of the specific tools listed in the survey for School A. For detailed tool labels on each plot, please refer to Appendix C.	52
Figure 12: Participation and Z-value analysis for School B for the specific tool category across the different semesters. For detailed tool labels, refer to Appendix C.	53
Figure 13: Proportion of students (as a % of the total survey population) at School A that indicated using a tool out of all survey participants for each Semester.	54
Figure 14: Proportion of students (as a % of the total survey population) at School B that indicated using one of the general tools out of all survey participants for each Semester.	54
Figure 15: School A bipartite makerspace network and module assignments for various student demographic groupings: A) Gender B) Race C) Major. A connection between a student demographic group and a tool grouping indicates that at least 10% of that demographic interacted.....	58
Figure 16: School A specific tool breakdown with labels found in Table 24.....	112
Figure 17: School B Specific Tool breakdown with labels found in Table 25.....	113
Figure 18: Demographic analysis School A Fall 2020	122
Figure 19: Demographic analysis School A Spring 2021	123
Figure 20: Demographic analysis School A Spring 2022.....	124
Figure 21: Demographic analysis School A Fall 2022	125
Figure 22: Demographic analysis School B Fall 2020	126
Figure 23: Demographic analysis School B Spring 2021	127
Figure 24: Demographic analysis School B Spring 2022.....	128
Figure 25: Demographic analysis School B Fall 2022	129
Figure 26: School A modularity and nestedness plots for general tool network.....	130
Figure 27: School A modularity and nestedness plots for specific tool network	131
Figure 28: School B modularity and nestedness plot for general tool network.....	132
Figure 29: School B modularity and nestedness plot for specific tool network	133

LIST OF TABLES

	Page
Table 1: The tool list included in the surveys. Relevant differences between the two schools (A and B) are highlighted in terms of the barriers to their use (training required, course-directed use, and no supervision required). Tools not part of the Fall 2020 dataset are marked by asterisks (*). Table from published paper [58]	17
Table 2: Tool category breakdown with specific tools available in the space. Tools with one “*” were not included in the Fall 2020 Survey for School A. Tools with two “**” were not in the survey for School A at all. Table modified from published paper [58] 17	17
Table 3: Network size (rows = students x columns = tools), nestedness (NODF), modularity (Q), and connectance (C) for Schools A and B in Fall (FA) and Spring (SP) 2020, 2021, and 2022. Null models are listed for both the corresponding semester AND for SP22 only.....	37
Table 4: Network size (rows = students x columns = tools), nestedness (NODF), modularity (Q), and connectance (C) for Schools A and B in Fall (FA) and Spring (SP) 2020, 2021, and 2022. Null models are listed for both the corresponding semester AND for SP22 only.....	38
Table 5: Subset of the full demographic results for School A, Spring 2021. See Appendix D for the full results.	57
Table 6: School A Fall 2020 General Tool interaction matrix	76
Table 7: School A Fall 2020 Specific Tool interaction matrix.....	77
Table 8: School B Fall 2020 General Tool interaction matrix.....	78
Table 9: School B Fall 2020 Specific Tool interaction Matrix.....	79
Table 10: School A Spring 2021 General Tool interaction matrix	80
Table 11: School A Spring 2021 Specific Tool interaction matrix	81
Table 12: School B Spring 2021 General Tool interaction matrix	82
Table 13: School B Spring 2021 Specific Tool interaction matrix.....	83
Table 14: School A Spring 2022 General Tool interaction matrix	84
Table 15: School A Spring 2022 Specific Tool interaction matrix	85
Table 16: School B Spring 2022 General Tool interaction matrix	86

Table 17: School B Spring 2022 Specific Tool interaction matrix.....	87
Table 18: School A Fall 2022 General Tool interaction matrix	88
Table 19: School A Fall 2020 Specific Tool interaction matrix.....	89
Table 20: School B Fall 2022 General Tool interaction matrix.....	90
Table 21: School B Fall 2022 Specific Tool interaction matrix	91
Table 22: School A P&Z Values	93
Table 23: School B General Tool P&Z Values	94
Table 24: Specific Tool Analysis Participation and Z-Value	95
Table 25: School B Specific Tool P&Z table with tool number.....	101
Table 26: School B Fall 2020 demographic data.....	114
Table 27: School A Fall 2020 demographic Data.....	115
Table 28: School B Spring 2021 demographic data	116
Table 29: School A Spring 2021 demographic data	117
Table 30: School B Spring 2022 demographic data	118
Table 31: School A Spring 2022 demographic data	119
Table 32: School B Fall 2022 demographic data.....	120
Table 33: School A 2022 Fall demographic data.....	121

1. INTRODUCTION

1.1. Motivation

Makerspaces have recently become integrated into a wide variety of engineering programs at universities worldwide [1]. This has drawn increasing attention as to how best to create an area where students gain hands-on experience [2, 3]. Several studies in the past few years have focused on barriers to entry and how tools vary in different makerspaces [4-6], identifying impediments to student use that are often linked to a student's self-confidence and fear of failure as their training and mentoring [7]. In addition, research has identified the need for rapid prototyping tools in makerspaces and a community infrastructure where students are comfortable with the space[8]. Still, work has yet to delve deeper into the intricacies of student-tool interactions. While the focus has been heavily on what makes a space *successful*, a metric for evaluating the current maker space health has yet to be developed. More information on the barriers to entry and studies of makerspaces can be found in the literature review section 2.1. The goal of this research is to utilize inspiration from nature and mutualistic networks where species work closely with one another to thrive to evaluate better *how* student-tool interactions in the makerspace can lead to a healthy space where students learn a variety of tools.

Comparing a makerspace network to nature closely mimics mutualistic networks where both species benefit from interacting with one another [9]. The primary example of mutualistic networks closely matching the makerspace is the plant-pollinator network [9], where in a makerspace, the students would act as the pollinators and the tools of the

plants. By linking the comparison, various ecological network metrics can be used to understand the makerspace network more closely and provide quantifiable information that can be used to compare makerspaces.

Thus, the goal of the thesis is to make use of the metrics found in ecology to provide measurable metrics for evaluating a makerspace and, by using these metrics, identify critical actors for both students and tools obtaining a deeper understanding of the space.

1.2. Research Questions and Objectives

The following research questions serve to highlight the goal of the thesis as well as the tasks necessary to be completed to address the research questions posed

1.2.1. Research Questions

The overall objective of the thesis is summarized below

Overall objective: Understand the impact of tools generically, the potential presence of gateway and/or specialized tools, and the potential presence of barriers on how students use a university makerspace

The overall objective can be further broken down into four separate research questions. The numbers in parentheses at the end of the research question indicate the task they correlate to in further sections.

- 1)** Can university makerspaces be modeled as interaction networks? (1)
 - a.** Is the network bipartite or unipartite, and how can it be set up?
 - b.** What data is needed to create the network model, and is it available?

- 2) How can mutualistic ecological networks be used as inspiration for a healthy makerspace? (2)
- 3) Can a network model and its analysis identify the health characteristics of a specific makerspace? (2,3)
 - a. Issues students have with accessing tools
 - b. Tools that students are initially drawn to
 - c. Tools that are less often used
 - d. Specific Students demographic groups encountering barriers to the space
- 4) Can understanding a makerspaces network guide the creation of opportunities for improving the students' experience (4)

1.3. Contributions

Analysis of the makerspace network utilizing ecological techniques will expand understanding of systems analysis, engineering education, and ecology, as integrating the environmental methods into a human system will require knowledge from each field. The advancements for each area are summarized below.

1.3.1. Ecological analysis

Applying ecological metrics to human networks will aid in further validating the techniques used in nature and open the avenue for future research to be used in a wide array of human systems. The makerspace network also provides a unique opportunity for applying ecological metrics. It will allow for the study of a dynamic system that can change drastically from year to year. Understanding the analysis of ecological metrics

can then be used to understand better ecological networks that can be tracked through the years.

1.3.2. Systems Analysis

To apply the ecological metrics, a network that can be analyzed must first be generated. Different approaches to generating the network will be explored with usage data not readily available for each of the individual tools at good accuracy. Successful validation and network creation will allow a wide variety of systems to be explored utilizing survey-gathering techniques.

1.3.3. Engineering education analysis

Engineering education will significantly be improved with an understanding of network analysis. By identifying essential tools and barriers of entry, curriculums and workshops can be modified and created that aid in expanding the learning experience of students in a makerspace. These enhanced experiences will aid in making tool usage more accessible and allow students to acquire meaningful learning they will use in their future careers.

1.4. Methodology

The following task highlights the order in which each of the research questions will be answered

- 1) Generate bi-partite network models of university makerspaces highlighting tool interactions.
 - a. Utilizing Entry/exit surveys vs. end-of-semester surveys and how to translate information into a network format (ex., mutualistic network)

- 2) Conduct nestedness and modularity analysis of the bipartite makerspace network model
 - a. Understand how connectance/modularity/nestedness are all related and can be used to evaluate the health of a makerspace
 - b. What parallels are there between ecological networks and makerspace networks
 - c. Evaluation of general tool categories matrix and specific tool category matrix
 - d. COVID-19 effects on network models (general roadblocks to space)
- 3) Breakdown nestedness/ modularity results of makerspace using insight with demographic information (class, year, major)
 - a. More detail into student groups and do they show different network patterns.
 - b. COVID-19 effects (specific student group effect)
- 4) Workshop/outreach with tools and demographic breakdown to see if network patterns (hub/specialized tools) can be changed to move the students toward the space.

1.5. Assumptions and Limitations

The assumptions and limitations listed below will aid in modeling the network

1. Survey data is used to investigate students' tool usage in the space. Because students are asked to remember which tools they used during a semester, there is

the possibility of human error in remembering the tools used. The differences associated with this error are assumed to be negligible.

2. Tool usage is simplified to a *used* or *not used* binary form, thus students using a single tool several times does not affect the weight of an interaction.

1.6. Thesis Layout

The thesis layout follows the methods outlined in Section 1.4. Chapter 2 provides a literature review with background for the research and the metrics used for the makerspaces. Chapter 3 presents the surveys used to capture data and differences between the two schools' makerspaces. The second part of the thesis then focuses on the ecological network results with Chapter 4 introducing the ecological techniques in more detail and providing results with each of the metrics. Chapter 5 dives deeper into the analysis for a hub tool analysis and a demographic analysis of the space. The thesis then concludes with a summary and future work section in Chapter 6

2. LITERATURE REVIEW*

The literature review expands upon the different aspects that are here integrated for the bio-inspired network analysis of engineering makerspaces, including an understanding of the barriers affecting makerspaces and how ecological network analysis is used in nature. The review identifies the selection of ecosystem metrics that can potentially provide greater insight into the makerspace network.

2.1. Prior research on Makerspaces and Potential for Study

The benefits of makerspaces for educating modern engineers require careful analysis as the prevalence of these hands-on spaces increases. Research on makerspaces has focused on student impact, with three elements suggested as essential for success by Martin [8]: 1) rapid prototyping, digital tools, and low-cost microcontroller; 2) events and interactions within the community; and 3) a failure-positive mindset that encourages collaboration. Research on the barriers to makerspaces is limited, focusing primarily on inclusive environments and training/mentoring [7]. Other barriers that impede student interaction include student lack of self-confidence, fear of failure, and a lack of visibly alike peers [10-12]. A deeper understanding of makerspaces, which provide a uniquely creative and accessible hands-on experience to students, is vital to enhance engineering curriculums further [2, 13].

Results of a survey on student makerspace participation suggest that students who were self-motivated and participated in the space outside of the required class times

*Reprinted with permission from “Analyzing Makerspaces using a Modularity Analysis to Determine Key Tool and Student Interaction” by Samuel Blair, Henry David Banks, Julie S. Linsey, Astrid Layton, 2021, *ASEE Virtual Annual Conference*, Copyright [2021] by ASEE

showed higher confidence in their work for design tasks [2, 14-16]. The work highlights the importance of involving students in the space early, allowing for growth and experimentation with different tools. Interactions with friends, classes, projects, and other staff and instructors have also been shown to aid student involvement within the space [2]. Reoccurring tools such as the 3D printer and computer stations were also often identified as "gateway" tools that could aid in the early introduction of the students into the space [17]. Knowing the importance of tools and their interactions can help create a pathway for students to enter the space and become more comfortable with tools in the future [17, 18]. Thus, identification and verification of these “gateway” tools in various makerspaces can further aid in enhancing these spaces.

2.2. Network Analysis and Ecological Metrics

Many of the world’s complex networks can be simplified to directed graphs where variables and interactions are mapped between actors. Simplifying complex systems down to a graph network of interactions enables analyses that can improve our understanding of their functioning. Ecologists, for example, use graph and information theory-based approach to study complex biological ecosystems. Plant-pollinator networks become bipartite models, and interspecies predatory networks become unipartite food web models [19]. Network graphs and their matrix depictions are used in ecological and social network analyses to map and study complex networks and their interactions [20, 21]. Social science utilizes bipartite matrices where rows are actors and columns are events to understand how actors are related to each other through shared events [20]. A bipartite model can be used any time two unique groups can be identified

within a chosen system boundary where interactions are only between the two groups and not within. NASA, for example, uses graphs to study innovation in their space challenge app, finding that mapping the innovation space of participants and ideas as a bipartite network can aid in understanding the transfer of information [22]. Other examples of bipartite networks include neuron-to-synapse interactions in neural networks, airports-flights transportation networks, and plant-pollinators models of ecosystems [19, 23, 24].

Ecological network analysis (ENA) provides insight to ecologists about ecosystem structure and functioning that couldn't obtain otherwise [25]. For example, this approach can identify critical actors who deserve extra conservation efforts [26], patterns in redundant feeding that support both growth and resilience [27], and the importance of the "brown food web" in maintaining cyclic interactions that maximize value extraction [28, 29]. The graph-based approaches investigated are nestedness and modularity [30]. Ecologists primarily use these analyses to study plant-pollinator and other bipartite networks, where two groups of actors interact across – not within – groups [20, 21, 31, 32]. Prior work investigated Eco-Industrial Parks as unipartite networks, finding that they can improve their sustainability and resilience with more ecologically-similar nested structures [33, 34]. Nestedness has also been used to predict the stability of bipartite networks to perturbations, looking at the failure rate of global trading companies based on their role in more extensive industrial networks [35, 36]. That work found that when companies deviated from the highly nested structure of their

global training network, a few years later, they had disappeared/were replaced by one that more closely followed the more extensive network's nested structure [35].

The makerspace analysis draws inspiration from nature's mutualistic networks (modeled as bipartite networks, for example, plant-pollinator and soil networks) - their resistance to disturbances has been found to relate to the levels of modularity and nestedness in their architectures [37, 38]. Enhanced resilience is highly desirable in human networks and identifying ecological network structures associated with resilience can offer valuable bio-inspired design guidance. The ENA metrics that describe these network characteristics [39] offer a route for applying this biological system inspiration. Power grids, industrial manufacturing networks, water distribution, and supply chains have all been shown to improve their performance when they mimic topological and functional characteristics of biological food webs [40-45]. Food webs, for example, have been found to have a unique balance of redundancy and efficiency in their networks [46, 47], a characteristic that is translatable to human-engineered systems and systems of systems in such a way that their resilience is improved [48, 49]. Ecological network analysis thus offers a strong avenue for analyzing the makerspace network to obtain valuable insight into the stability as well as resistance to change of the network, particularly when the network is modeled in a bipartite form.

2.3 Nestedness and Modularity: dual metrics to analyze the makerspace

Nestedness quantifies the structural hierarchy amongst actors in a network [30, 50, 51]. Multiple methods exist to calculate nestedness, but *Nestedness based on Overlap and Decreasing Fill* (NODF) is used. For example, NODF has supported the understanding

of the impact of invasive species in soil networks and resilience to external and unexpected disturbances in plant-pollinator networks [37]. Furthermore, nested ecological networks have been found to avoid mass extinction events because their structure promotes interactions between specialists and generalists, creating a more stable environment [52]. Nestedness alone can thus provide a strong indication of the stability of the network, with higher nestedness assuring that actors with few interactions are connected to actors with several interactions, preventing the former from failing [50].

Ecologists have used *modularity* to identify critical species in plant-pollinator networks [19]. The analysis of over 29 different plant-pollinator networks identified modular structures with the plants often linking the modules together [19]. Modularity also aids in understanding how a network is partitioned. Modularity identifies groupings of actors based on their interactions, hub actors that highly connect the network, and specialized actors that may be at risk of losing connection [53, 54]. For example, a modularity analysis of global flights identified airport hubs [24]. The complex global aerial transportation network was broken up into modules that easily identified the airports that connected these modules and dangerously disconnected airports [24].

Connectance quantifies how connected a network is to its total number of possible interactions [30]. Connectance is used in ecology to measure ecosystem complexity, with a higher connectance indicating a more diverse network [55]. While connectance alone cannot describe network stability, it provides critical information for understanding a network's nestedness and modularity as it controls its bounds [30, 55, 56]. Thus, a better understanding of a network's structure and functioning is achieved by

pairing the metrics together. Therefore, connectance must be included whenever modularity and nestedness are analyzed, as will be the results following.

Nestedness, modularity, and connectance of bipartite networks as a group describe a network beyond just a density of connections, highlighting *where* connections are found and where they are sporadic [51]. The insight they can provide for bipartite human networks is investigated here using *university engineering makerspaces*. These spaces aim to provide engineering students with a unique and hands-on educational experience where students use a wide variety of tools that serve as stepping stones through the space. The spaces, however, are still relatively new, with only a minimal amount of research into hidden roadblocks that can limit use by certain demographics and indirect effects that can have a huge influence on usage patterns. These characteristics are almost impossible to see with the naked eye but may be visible using network models. These spaces also provide a unique case study in contrast with traditional unipartite networks that hopefully broaden readers' scope of when system perspectives and biological inspiration may be of value.

2.3. Chapter 2 Conclusions

The literature review offers a look into the different aspects of the makerspace that need to be explored in more detail. Barriers to entry in the space can have a massive impact on how the students interact with the space. A student's feelings about the space are also critical to evaluate, as their sense of belonging and expertise plays a role into their use of the space.

The literature review also highlights the different ecological techniques that will be used to analyze the makerspace to obtain deeper insight. Modularity, nestedness, and connectance have been used previously in human network as well as ecological networks to identify key players in the space. In the next section, the metrics will be introduced in more detail as well as initial analysis of the space utilizing the techniques.

3. CONDUCTING ECOLOGICAL ANALYSIS OF THE NETWORK *

The first item addressed is *how* to convert makerspace usage data into a network model to be analyzed. The process first gathers data, outlines the universities that will be studied and their differences, and creates bipartite network models from the survey data.

3.1. Data Gathering Methods

Students tool usage data was collected across four semesters at two large university engineering makerspaces [57]. School A is primarily a staff-run space where a variety of tools can be used by the students with proper training, while some tools are restricted to staff only, and students will need to submit a fabrication request to use. The goal of the space in School A is to support the engineering classroom curriculum, with some club use allowed. School B is primarily a student-run space where students are welcome to use tools with proper training. The space is open to all engineering students and students are allowed to use the space to work on personal projects.

The first two semesters (Fall 2020 and Spring 2021) were under increased COVID-19 restrictions limiting student use of the space. These restrictions were removed by the third semester and fourth semester (Fall 2022, Spring 2022), allowing for a look at “normal” operating conditions for the space. For School A, the space was restricted to only class use in the Fall 2020 semester, with some clubs allowed to return to the space in Spring 2021. On the other hand, School B restricted the number of people who could be in the space at a time in both their Fall 2020 and Spring 2021 rather than

*Reprinted with permission from “Modularity Analysis of Makerspaces to Determine Potential Hubs and Critical Tools in the Makerspace” by Samuel Blair, Garret Hairston, Henry Banks, Julie S. Linsey, Astrid Layton, 2022, *ASEE Virtual Annual Conference*, Copyright [2022] by ASEE

restricting to class use only. These COVID-19 restrictions for both schools were lifted by Spring 2022.

The primary method for gathering results will be through self-reported student surveys. The surveys consist of end-of-semester surveys focusing primarily on the student's usage of the space throughout the semester and entry/exit surveys where students can indicate what tools they used. The use of entry/exit surveys will be evaluated with time to see if it is necessary or if the end-of-semester survey is sufficient. In addition, the order in that students learned the tools and the classes students used the tools for will also be found in self-reported surveys. Students were compensated \$20 for their completed end-of-semester survey and \$1 per entry/exit survey combination completed. The survey was designed to take about 15 minutes to complete and consisted of approximately 50 questions about tool usage, prior makerspace involvement, and student demographics. The Fall 2020 survey asks students to indicate which tools they used, while the Spring 2021, Spring 2022, and Fall 2022 surveys also inquire into the frequency with which they used them. Minor edits to the questions and tools listed were made between semesters. The full survey is included in the Appendix B of the report.

For distributing the survey, the method of distribution varied slightly between semesters. The first Fall 2020 semester students who signed up for the space in both universities for that semester. In the Spring 2021 semester onwards, the survey was sent to students that signed up for the space as well as courses that utilized the space at both universities. For School B in the Fall 2022 semester, surveys were additionally

advertised in the space itself, leading to the higher number of responses for that semester.

After the first semester of data gathering, it was found that the entry/exit survey to the space was insufficient at capturing the regular use information of students in the space. Number of student's filling out the entry/exit survey was below ten students, compared to the over 50 students that filled out the end of semester survey for the first Fall 2020 semester. Due to the low number of responses for entry/exit survey, no analysis could be completed with the data, and the process of capturing entry/exit surveys was discontinued with the end of semester surveys providing the bulk of the data for the analysis.

For the tool usage questions of the end of semester survey, students were first asked to select the *general* tool categories they used. Based on the tool categories selected, they were then asked subsequent questions about the *specific* tools they used in each general tool group. Some general tools, such as the laser cutter or paint booth, are standalone tools and do not have corresponding specific tools. In these cases, the general tool was used in the hub tool analysis. Table 1 details the differences between the two universities of each tool category and their restrictions. The tool nomenclature will be kept consistent in later parts of the analysis in chapter 5. Tool names are normalized between the two schools surveyed for consistency in comparisons. Table 2 shows the 14 general tool categories used for analysis and compares the tools at each school within that category. School A has more training before each tool can be used and does not teach laser cutting, while School B has fewer restrictions for tool usage and does teach

the laser cutter. The difference in restrictions between the two schools is important to note when delving deeper into the analysis.

Slight modifications were made to the survey between the two semesters, such as increasing the variety of tools students could pick to reflect the selection within the makerspaces better. The main difference is that three categories (crafts, paint booth, and CAD station) were not included for School A in the Fall 2020 survey but showed up in the Spring 2021 survey. Therefore, these tools are separate from the modularity analysis for School A for the Fall 2020 semester.

Table 1: The tool list included in the surveys. Relevant differences between the two schools (A and B) are highlighted in terms of the barriers to their use (training required, course-directed use, and no supervision required). Tools not part of the Fall 2020 dataset are marked by asterisks (*). Table from published paper [58]

TOOL CATEGORIES		Requires Training		Used by a Class		Student Use Without Supervision	
		A	B	A	B	A	B
Tool 1	3D Printing	X	X	X	X		X
Tool 2	Metal Tools	X		X	X	X	X
Tool 3	Laser Cutter	X			X		X
Tool 4	Wood Tools	X				X	X
Tool 5	Handheld Tools			X	X	X	X
Tool 6	Electronic Tools			X	X	X	X
Tool 7	Social Activities					X	X
Tool 8	Got/Gave Help			X	X		
Tool 9	Soft Materials	X				X	X
Tool 11	Paint Booth*					X	X
Tool 12	Cad Station*	X		X	X	X	X

Table 2: Tool category breakdown with specific tools available in the space. Tools with one “*” were not included in the Fall 2020 Survey for School A. Tools with two

“*” were not in the survey for School A at all. Table modified from published paper [58]

Tool Category	Specific Tools Included
(1) 3D Printing	Ultimaker 3D Printer, Formlabs Form 2 Printer, Stratasys 3D Printer, 3D Scanner Arm
(2) Metal Tools	Angle Grinder, Band Saw, CNC Metal Mill, Manual Mill, Manual Lathe, Drill Press, Belt Sander, Polishing Wheel, Table Vice
(3) Laser Cutter	Laser cutter
(4) Wood Tools	Band Saw, Belt Sander, Circular Saw, Miter, Jigsaw, Drill Press, CNC Wood Router, Router, Planer, Table Saw, Hammers, Measuring Tape, Hand Saw, Dremel
(5) Handheld Tools	Pliers, Vice Grips, Clamps, Screw Drivers, Hand Drills, Chisels, Tin Snips
(6) Electronic Tools	Circuit Board Plotter, Multimeter, Power, Supply, Soldering Station, Oscilloscope, Logic Analyzer
(7) Social Activities	Studied, Hung out, Met with a Group
(8) Got/Gave Help	Got Help From Makerspace Volunteer, Got Help From Someone Who Wasn't a makerspace volunteer, and Gave Help
(9) Soft Materials*	Embroidery Machine, Sewing Machine, Vinyl/Paper Cutter, X-Acto Knife, Scissors, Glue Gun, Wire Cutters
(10) Other	
(11) Paint Booth*	Paint Booth
(12) CAD Station*	Cad Station, Workbench, Whiteboards
(13) Volunteer on Duty**	
(14) Prototyping**	

3.2. Network Creation

The data is represented as a bipartite network: a network with two different groups of actors whose interactions can only go between the two groups (no interactions within a group are modeled) [59]. The survey data was used to create the bipartite network matrix: when student j interacts with the tool i a value of one is assigned in the a_{ij} entry of the adjacency matrix. A zero is entered if there is no interaction [59, 60]. Specifically, the student self-reported tool usage was utilized to create the network. If a student

indicated using a tool in the survey, a value of one was provided. If no tool were used, a value of 0 would be used. A hypothetical small-scale scenario is shown in Figure 1, where ten students interact with ten different tools.

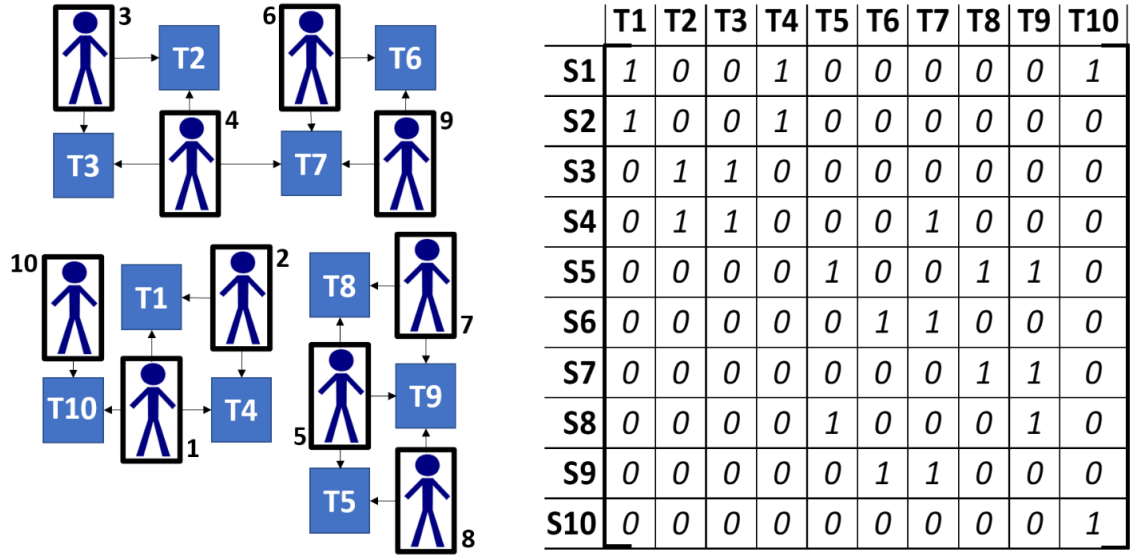


Figure 1: Hypothetical representation of the makerspace outlining the matrix quantification of interactions: a) A small-scale hypothetical makerspace with interactions b) the resultant makerspace. Image modified from published work [58]

The adjacency matrix in Figure 1 provides a big-picture view of the many complex interactions in a makerspace. Representing the space in matrix form allows for network analysis techniques to be applied, providing valuable information about the student and tool interactions making up the space. The adjacency matrix has students as the rows and tools as the columns.

A major limitation of the bipartite network representation is that the model is binary, which causes the frequency of interaction information to be lost [61]. As a result,

the results only describe the frequency a student has used *at least once*. This limitation can result in both inflated or under-represented tool usage results – for example, some tools may be used by a student once and get a value of one, while a student may use a tool hundreds of times and still only receive a one. However, despite the limitation, the analysis will aid in understanding how students interact with the space.

3.3. Chapter Summary

The surveys were able to gather relevant demographic information from the students and students self-reported tool usage is converted to a bipartite network model. The end of semester survey was utilized over the entry/exit survey due to the larger number of responses as well as thorough documentation of tool usage.

With the network models created, a variety of different ecological analysis techniques can now be applied. Chapter 3 uses these network models to conduct modularity, nestedness, and connectance analysis to develop a connection between makerspace student-tool topology and space functioni

4. CONDUCTING NESTEDNESS AND MODULARITY ANALYSIS OF THE SPACE*

The three metrics frequently or primarily used in ecology (modularity, nestedness, and connectance) are explored to develop a quantitative understanding of the makerspace's health and functioning from their network models. Results from each analysis are presented and discussed in Section 4.7.

4.1. Modularity Analysis

Once the network of interest is created and an interaction matrix constructed, its modularity can be analyzed. A modularity analysis identifies modules present in the network by reorganizing the structure and links until its maximum modularity value is reached [62]. This optimization can be done using several methods [63]. The Newman/Leading Eigenvector method ([63], Eq. 1) is used here for its added benefit that modules are reproducible given the same inputs, allowing for a consistent modularity value to be obtained as well as providing the maximized modularity for the network [64]. The MATLAB package BiMat [64] runs the Newman method to find the modules (Q).

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

Equation 1 calculates the overall network modularity (Q), where E is the total number of interactions or links in the network, B_{ij} is the matrix entries representing (1) for

*Reprinted with permission from “Modularity Analysis of Makerspaces to Determine Potential Hubs and Critical Tools in the Makerspace” by Samuel Blair, Garret Hairston, Henry Banks, Julie S. Linsey, Astrid Layton, 2022, *ASEE Virtual Annual Conference*, Copyright [2022] by ASEE

a link or (0) for no link, g_i and h_j are the module indices of the nodes i and j , and k_i and d_j represent the degree of the node i and j respectively. The δ term parses the module indexes for pairings between actor groups (in this case, students and tools) and assigns a value of one if they are in the same module and a value of zero if they are in different modules. The process is carried out by splitting the network into two modules using the algorithm and calculating the Q_b . Then, the network is further split up into more modules until the splitting no longer increases the overall network's modularity [62]. Modularity can be any value between zero and one, with a value of one indicating a perfectly modular network.

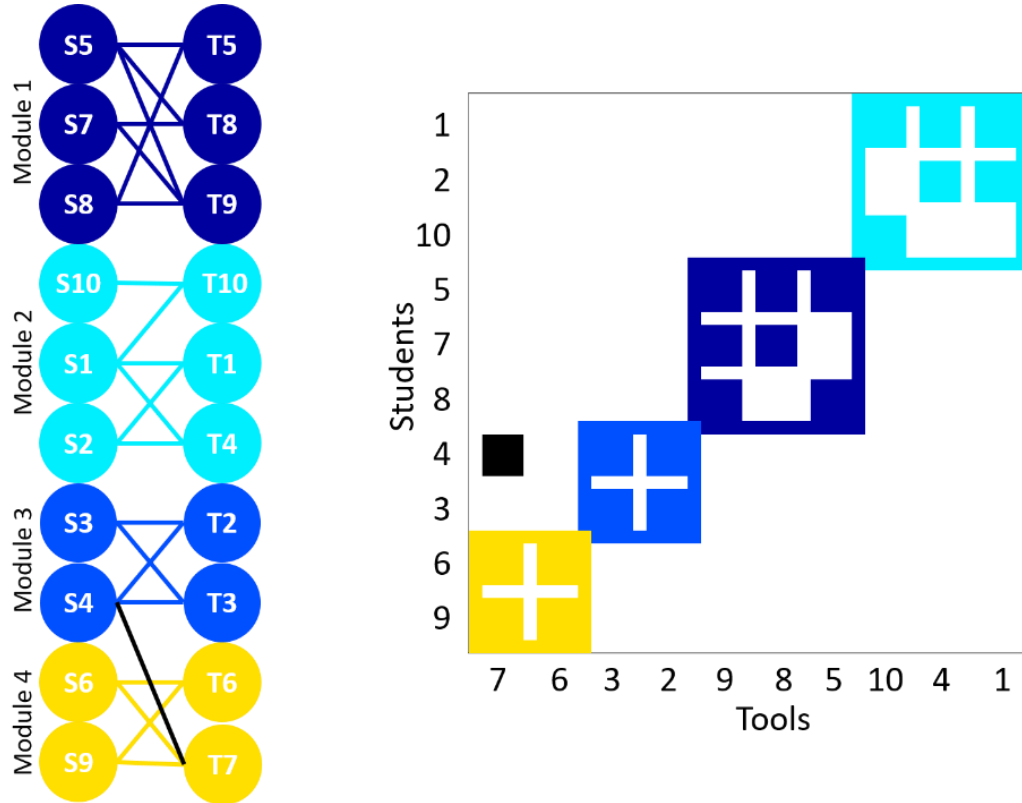


Figure 2: Left - Bipartite representation of the network with students (S1-S10) interacting with tools (T1-T10) and color organized by module. Right - BiMat

software output highlighting the network from Figure 1 with interactions (colored in squares) organized.

Figure 2-Right shows the **B** matrix for the hypothetical makerspace network of Figure 2-Left with ten tools (T1-10), tracking ten students' (S1-10) use of the space. The matrix denotes all the network interactions in the space with a one, and zeros indicate no interaction. As seen in Figure 2-Left, the students fall into modules based on common tool usage. For example, students 1 and 2 both use tools 1 and 2, which are not used by any other students in the network. Together with student 10, who, along with student 1, uses tool 10, this group of students and tools form a module (teal color). These patterns can be identified relatively easily visually in a small network that is highly modular. As a network grows, the number of interactions increases, becoming exponentially harder, if not impossible. MATLAB's BiMat package was used here to find modules and calculate the overall modularity following Eq. 1. BiMat produces a visual depiction of a network's interactions, rearranging them to show modules best (as shown in Figure 2-Right) [64]. The modularity value for the hypothetical network of Figures 1 and 2 is 0.69. The main drivers of this modularity can be seen in Figure 2-Right, where the colored boxes indicate within-module interactions, and the black box indicates outside-of-module interactions. The one out-of-module interaction, student four using tool 7, reduces the network's modularity from a perfect value of one. A null model analysis (described in the following section) is needed to understand whether the value of 0.69 indicates that the network is *statistically significantly modular* based on a network of the same size and connectance (in this case, connectance is 0.22) [30, 65].

4.1.1. Participation and Z – Value

The *connectivity* (z) and *participation* (p) values of Eq. 2 and 3 quantify how connected a particular tool is to the rest of the network. For these bipartite makerspace networks, tools and students act as nodes (N), while links between nodes represent the interaction of a specific student using a specific tool [54]. Since tools and students are both placed in modules within the space, all links between nodes can be classified as links within a module or between two modules. The k_i in Eq. 2 is the number of links of node i to other students/tools within its module, k_{si} is the average number of links of each node (other tools/students) in the module, and $\sigma_{k_{si}}$ is the standard deviation of k_{si} . The k_{is} in Eq. 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 [53].

$$z_i = \frac{k_i - k_{si}}{\sigma_{k_{si}}} \quad (2)$$

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

While one tool may be in a module due to its dominant interactions, tools can still interact with tools outside of their module. For example, while the mill and lathe may be used primarily by students who only use mechanical tools, there may still be students who primarily use craft tools and the mill and lathe, thus creating a connection with tools outside of the mill/lathe's module. The z or *connectivity* value quantifies the *within-module degree* of a tool or student. If many students using the same set of tools are also using the laser cutter, the laser cutter would have a high *connectivity* value. If,

within that same group of students, only one of them had used the laser cutter, it would have a low *connectivity* value. These metrics are calculated from the modular network matrix and quantify the patterns and characteristics of connections between students and tools in the space.

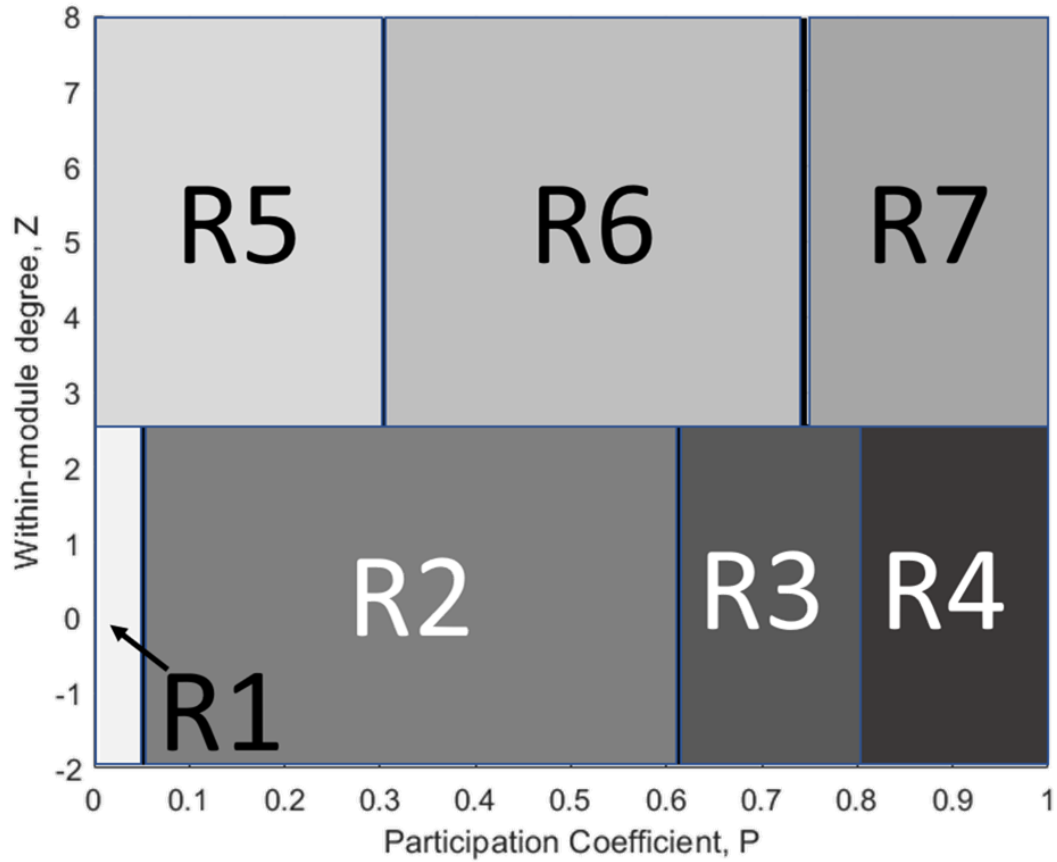


Figure 3: Modularity analysis sectioning determined by connectivity (z) and participation (p) values. The regions R1-7 specify the role that a tool and/or student has in a network, as described in the main text. Image from published work [58].

Equations 2 and 3 are plotted in Figure 3 illustrating the different regions as defined by the p and z values. These regions describe seven different roles that students and tools can have within the space and are used in network analysis as a cartographical

representation of the roles in a complex network and better understand the functions of actors in the network [53]. The work here tests an analogy between makerspaces and mutualistic ecosystems, where the interactions between species groups (here, students and tools) are mutually beneficial. Ecologists have classified each region as serving a different role for the network (or, in this case, the students and tools). The cutoff lines shown in Figure 3 are non-trivial and come from the work of Guimerà and Amaral [53].

- **R1** ($p \approx 0$, $Z < 2.5$): *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 module
- **R4** ($p > 0.8$, $Z < 2.5$): *Non-Hub Kinless Nodes*, tools critical to their 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

The seven roles in the space guide conclusions depend on where the tools/students fall when plotted. A tool in the R6 region is considered a *Connector Hub*, meaning it is critical to the space and interacts with a wide variety of students in its own and other modules. A tool in the R1 region is considered an *Ultra-Peripheral Node* and is less important to the network's functioning, likely being a niche or rarely used tool. The

analysis can aid in the identification of hub tools in the space, and will be a major discussion point of Section 5.1.

4.2. Nestedness

Nestedness can be calculated for either a bipartite or unipartite network from the interaction matrix. Nested networks, when rearranged from most connected actor to least connected actors top to bottom rows and left to right columns, will wind up with the most general actor in the upper left of the matrix and the least general actor in the bottom-left and top-right, as seen in the sample perfect nested matrix in Figure 4c [50]. Nestedness can be calculated in a few different ways, with some techniques normalizing the resultant metric on a scale of zero to one and others, like the one used here, from zero to one hundred [36, 50, 66]. NODF (Nestedness based on Overlap and Decreasing Fill) is based on “overlap and decreasing fill” to evaluate a network’s architecture and is considered a more appropriate metric for interaction networks [50, 66]. NODF calculates nestedness values for each row and column individually before combining those values into an overall nestedness result. These column and row nestedness values can also aid in understanding a network’s architecture in more detail.

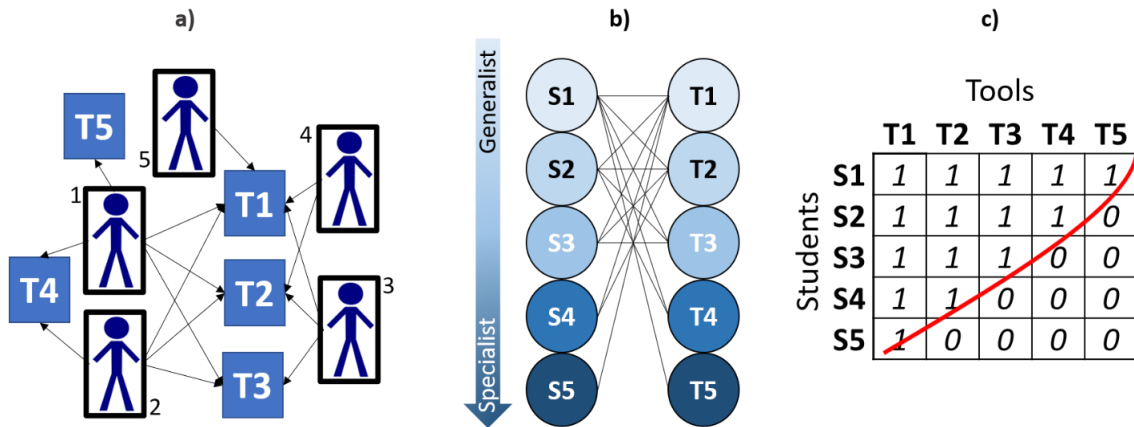


Figure 4: A hypothetical makerspace of 5 students and 5 tools with a nested structure. a) Diagram of the sample makerspace. b) Bipartite graph of the makerspace. c) BiMat nested network output visualizing the network matrix, where the curve indicates the nested interactions boundary.

NODF first organizes the bipartite network in order of the total number of interactions, with the rows organized from most to the least interactions from top to bottom and the columns organized from most to least interactions from left to right. For example, the organized matrix for the hypothetical student-tool network in Figure 4a can be seen in Figure 4c. Once organized, NODF is calculated to find the overall nestedness, ranging from 0 to 100 (or 0 to 1 if normalized), with the higher value indicating a more nested network [30, 66]. In nature, like plant-pollinator and soil networks, mutualistic networks tend to have NODF values ranging from 0.35 to 0.7 (on a scale of 0-1) [66, 67].

Equations 2 and 3 are used to calculate NODF, and **Figure 5** walks through this process of calculating NODF for a very small 3x3 network. The two main aspects of the NODF analysis are the “decreasing fill” and “overlap.” NODF pairs and compares each row with every other row and each column with every other column (as seen in **Figure**

5). The “decreasing fill condition” is checked first for each pair to ensure that the number of interactions in the first is more than in the second by at least one (from left to right for columns and top to bottom for rows). If this condition is not met, NODF defaults to zero. When met (for example, in the C1-C2 comparison at the top of Figure 5, where C1 has more interactions than C2), the number of interactions that match from the second to the first is checked. For a column comparison, C1-C3 in **Figure 5**-top clarifies that only one of the two C3 interactions is also found in C1, giving this subset a N_{paired} value of 50 (i.e., 50% of interactions match between the two columns). In the case of C1-C2, both C2 interactions are found in C1, so the value is 100. Once all comparisons have been made, the N_{paired} values are averaged, producing N_{column} and N_{rows} . The final NODF value is the average of N_{column} and N_{rows} . NODF can be calculated manually for smaller networks but becomes increasingly difficult for larger networks. Matrix ordering and NODF calculations can be done within the BiMat MATLAB package [64].

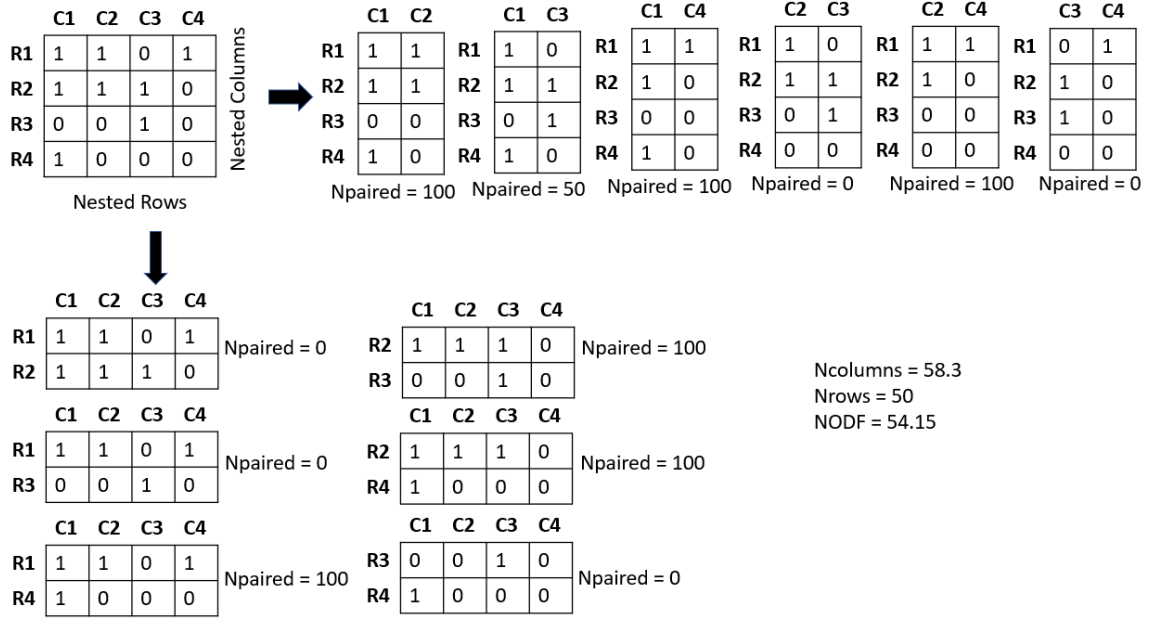


Figure 5: Process for calculating NODF of a hypothetical 4x4 network (top-left, actors R1-4 interacting with actors C1-4). The top-right process shows the column nestedness calculations and the bottom-left process shows the row nestedness calculations. The culmination of which is shown in the bottom right with the overall NODF value.

$$M_{ij} = \begin{cases} 0 & \text{if } c \leq k_j \\ \frac{n_{ij}}{\min(k_i, k_j)} & \text{otherwise} \end{cases} \quad (4)$$

In Equation 4, k_i is the sum of row/column i , k_j is the sum of row/column j , n_{ij} is the total number of entries that match between the two, and c is the number of entries that have a value of 1 in k_j . Finally, equation 5 is the NODF value normalized for the matrix size to better compare different-sized matrices, producing a final NODF value from 0 to 1 rather.

$$\text{NODF} = \frac{\sum_{ij} M_{ij} \text{row} + \sum_{ij} M_{ij} \text{col}}{\frac{m(m-1)}{2} + \frac{n(n-1)}{2}} \quad (5)$$

The NODF calculation process also identifies generalist and specialist actors in the network [30]. Generalist actors will always be closer to the top-left of the matrix, while specialist actors will be closer to the bottom and the right. A nested makerspace network would indicate that students are using a generalist tool first and expanding their use of the space to interact with more complicated and specialized tools. Figure 4 shows a perfectly nested network, with specialist students (for example, S4 and S5) interacting with generalist tools (in this case, T1 and T2). The nested analysis can identify generalists and specialists and how they interact in the network; the underlying causes as to why a network is nested or not may be obvious and would require supplementary investigations.

4.3. Connectance

While both nestedness and modularity analysis can provide valuable insight into a network, it is imperative to see both in combination to understand the network fully. This is because Nestedness and modularity are related, with the primary connection being the network connectance (C , Eq. 4 and a value from zero to one) [30]. Generally, the higher a network's connectance, the higher its nestedness will be, while the lower the connectance, the higher the modularity [30]. However, there are bounds on these trends explored later in the results, which also depend on network size (N_{rows} and $N_{columns}$).

$$C = \frac{L}{N_{rows}N_{columns}} \quad (6)$$

The numerator of Eq. 6 is the total number of network connections, or L (sum of all entries in the matrix $[\mathbf{B}]$). The denominator is the total number of *possible* connections or rows multiplied by the number of columns. A connectance of one indicates that all possible interactions are occurring, meaning that everything is connected to everything. A connectance of zero indicates that no interactions exist in the network. While research has highlighted the importance of analyzing nestedness and modularity together, most work has focused on either specific connectance ranges or the overall importance of nestedness and modularity [30, 51]. The work in this paper expands on the previous relationship. It creates a view of the full range of the relationship between the two metrics with the sample network creation to enhance further the understanding of the relationship between nestedness and modularity.

4.4. Null Models

Determining if a network's nestedness and modularity results are statistically significant requires the generation of null models to check against the nestedness and modularity of a random network of the same size and connectance [9, 30]. A *type-one null model* [9] will explore significance, with 1000 sample networks generated at each connectance value listed. Potential errors associated with empty rows in the random network generation were accounted for by forcing all rows to have a value of 1. This null model modification was previously used in host-phage interaction networks to match the network's dynamics better and maintain the null model network sizes [65]. A *p-value* of 0.05 ($z > 1.96$ or $z < -1.96$) will be used for the network to see whether the resulting

modularity and nestedness values are significantly different from those that would be randomly generated, as determined by the null models.

The procedure for evaluating networks undergoing disturbances compares a network's modularity/nestedness against a null model that uses the network's connectance from *normal* operations. For example, data from Spring 2022 provides connectance values for the makerspaces here during a *normal* semester, against which Fall 2020 and Spring 2021 (when COVID-19 restrictions were in place) are compared. This approach enables a network's modularity and nestedness during disruptions to be understood compared to how the network should operate during its highest connectance semester.

4.5. Relationship between the metrics

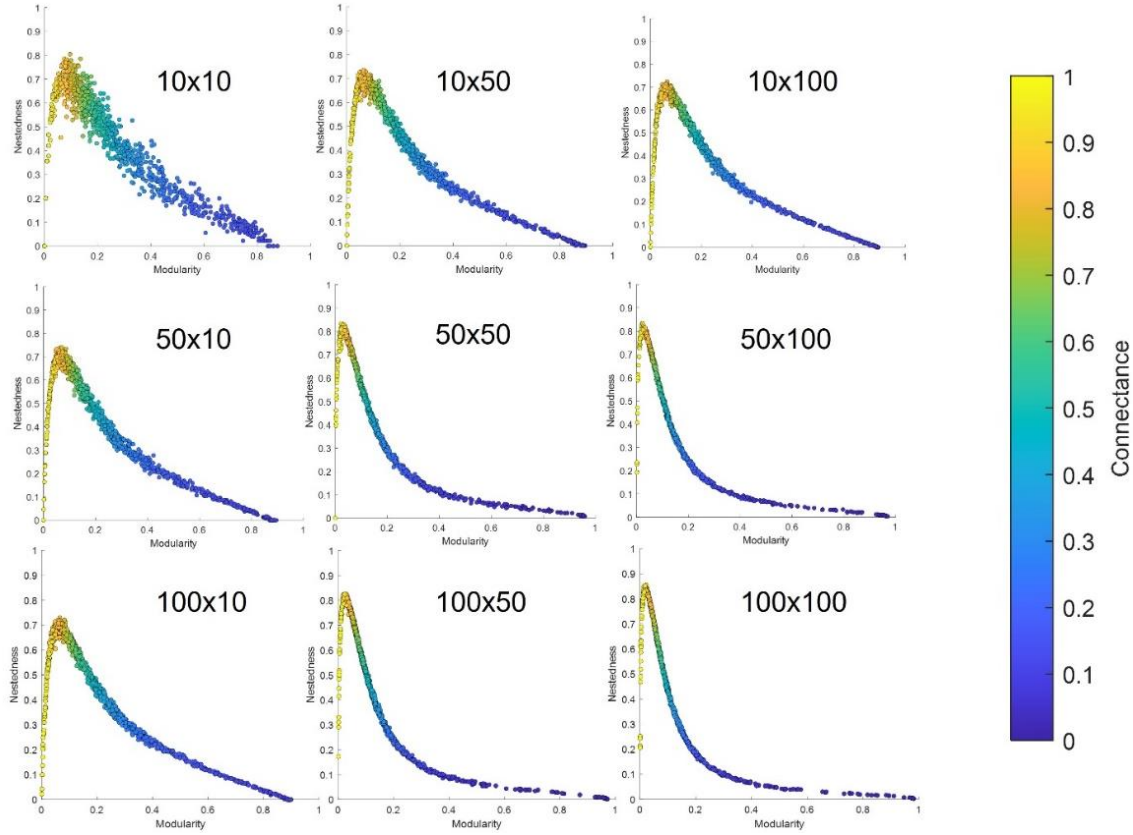


Figure 6: The same curve is shown for a variety of network sizes, describing the impact of network size on the relationship between modularity (x-axis), nestedness (y-axis), and connectance (color scale on the right).

One thousand networks at nine different network sizes, from 10x10 to 100x100, with varying connectance values, were generated to highlight the relationship between nestedness, connectance, and modularity in Figure 6. The results highlight a strong negative correlation between nestedness and modularity for all but the most connected networks (in most cases, a connectance of 0.85 or greater) [9, 30, 65]. In addition, the highlighted connected networks experience a drop in nestedness due to the ideal

“triangular shape” seen in Figure 4 not being achievable [66]. These results suggest that the connectance of a network bounds modularity and nestedness for a specific network size. Increasing or decreasing the modularity or nestedness of a network requires changing connectivity. These findings are consistent with previous work highlighting connectance as a major limiting factor in achieving specific network properties related to degree distribution, like nestedness [56]. However, this is the first visual depiction of the clear relationship between these three metrics. The primarily negative relationship between modularity and nestedness also varies with a network’s size, with larger networks (Figure 6-Bottom Right) more constrained to specific modularity based on nestedness and connectance. These results are critical to guide modularity and nestedness as a network design goal. They clarify that the desired modularity and nestedness are not achievable without a specific connectance.

4.6. Developing a tool to conduct analysis

As the analysis will span several semesters and the open potential for future use with a variety of networks, a network analysis package GUI will be generated that will allow other universities and students to conduct their own modularity and nestedness analysis with ease. The GUI will utilize functions found on the BiMat [64] package as its foundation and create an interface that is easy to interact with. Moving forward, the only items needed to conduct the analysis will be the network of interest in a bipartite network format. The software conducts and calculates all relevant nestedness, connectance, and modularity metrics when provided with the bipartite network. Analysis

in this thesis was generated utilizing the program. The documentation for the package can be found in Appendix F detailing all uses.

4.7. General Results from the Ecological Network Analysis

Across the four semesters studied, School A was found to have higher modularity and lower connectance than School B. A jump in nestedness at School A during the Spring 2022 semester is seen, possibly due to COVID-19 restrictions in the space being lifted (School A had significantly more student use restrictions in the makerspace than School B due to COVID-19). The modularity and nestedness differences between the two makerspace networks can be primarily attributed to differences in connectance (corresponding to student usage of tools). The makerspaces at the two schools have inherent differences in how they are run. The space at School A is primarily staff-run and used to support course curriculums. School B's space is primarily student-run and used for course support and personal projects. School B's space is also set up such that those tools with the most safety restrictions (for example, close-toed shoes, long pants, eye protection) are placed such that students that don't meet these requirements can still enter the space. Safety requirements for the most restrictive tools are used for the entire space. In addition to slight differences in COVID-19 restrictions, these operational differences show up in the network models as differences in connectance, modularity, and nestedness, with Fall 2022 being an outlier for School B. The overall lower connectance this semester can be attributed to the slight changes to the survey gathering methods, with more first time users participating in the survey. The modularity, nested, and connectance values capture this outlier with the survey supplementing the analysis.

Table 3: Network size (rows = students x columns = tools), nestedness (NODF), modularity (Q), and connectance (C) for Schools A and B in Fall (FA) and Spring (SP) 2020, 2021, and 2022. Null models are listed for both the corresponding semester AND for SP22 only.

	Sem.	Size	C	Q	Each Semester's Null Model Q (Z-value)	SP22 Null Model Q (Z-value)	NODF	Each Semester's Null Model NODF (Z-value)	SP22 Null Model NODF (Z-value)
School A	FA20	54x10	0.25	0.34	0.36 (0.32)	0.26 (6.15)*	0.50	0.27 (6.79)*	0.36 (2.46)*
	SP21	178x12	0.18	0.38	0.40 (-1.25)	0.23 (17.3)*	0.33	0.20 (12.7)*	0.36 (-2.33)*
	SP22	77x12	0.34	0.19	0.24 (-3.93)	0.25 (-3.92)*	0.55	0.36 (9.71)*	0.36 (10.1)*
	FA22	80x13	0.23	0.31	0.33(-0.9)	0.23(6.26)*	0.4	0.25 (8.99)*	0.36 (2.30)*
School B	FA20	57x13	0.39	0.18	0.21 (-2.76)*	0.21 (-2.49)*	0.64	0.40 (10.9)*	0.41 (10.1)*
	SP21	94x13	0.34	0.20	0.23 (-2.86)*	0.19 (0.17)	0.61	0.36 (15.0)*	0.41 (11.6)*
	SP22	95x13	0.40	0.18	0.2 (-1.45)	0.20 (-1.91)	0.59	0.42 (12.8)*	0.41 (10.1)*
	FA22	199x13	0.3	0.21	0.24(-3.89)*	0.18(3.28)*	0.51	0.32 (17.4)*	0.41(8.462)*

Table 3 and Table 4 highlight the properties of the networks each semester and their corresponding null models. The modularity and nestedness visualization of the networks at each school each semester can be found in Appendix E. Null models significantly different from the real network at $p > 0.05$ are starred. Table 3 and Table 4 how a strong correlation for the networks highlighting a nested structure for the makerspace. A nested makerspace indicates many students who have minimal tool interactions in the space (these could be the new students or those who are coming in only to use something specific) interact with tools like the 3D or other *generalist* tools [57]. The nested makerspaces also indicate that students with more tool interactions in the space, thereby using a wider variety of tools, are more likely to use tools that fewer students use or *specialized* tools [57]. This trend follows intended use patterns for

makerspaces. A jump in nestedness is seen in Spring 2022 (Table 2 shows that nestedness increased from 0.39 to 0.51 for the specific tool model). The specific tool-based makerspace networks at School B are slightly less nestedness than the general tool network. This decrease is due to the increase in network size resulting in a decrease in connectance (for example, as seen in Tables 1 and 2, Fall 2020, the network's connectance drops from 0.36 in the general network to 0.15 in the specific network). Despite the difference in connectance, the network remains nested in structure compared to its null models.

Table 4: Network size (rows = students x columns = tools), nestedness (NODF), modularity (Q), and connectance (C) for Schools A and B in Fall (FA) and Spring (SP) 2020, 2021, and 2022. Null models are listed for both the corresponding semester AND for SP22 only.

	Sem.	Size	C	Q	Each Semester's Null Model Q (Z-value)	SP22 Null Model Q (Z-value)	NODF	Each Semester's Null Model NODF (Z-value)	SP22 Null Model NODF (Z-value)
School A	FA20	33x27	0.10	0.47	0.53 (-1.45)	0.40 (2.86)*	0.22	0.11 (6.95)*	0.16 (3.27)*
	SP21	122x76	0.06	0.44	0.42 (1.07)	0.22 (37.7)*	0.14	0.06 (23.1)*	0.16 (-4.09)*
	SP22	70x77	0.15	0.22	0.28 (-5.15)*	0.26 (-4.97)*	0.39	0.16 (38.8)*	0.16 (39.9)*
	FA22	78X76	0.10	0.4	0.34(5.83)*	0.25(20.2)*	0.22	0.1(24.0)*	0.16 (9.97)*
School B	FA20	54x45	0.16	0.24	0.30 (-5.09)*	0.24 (-0.19)	0.38	0.17 (20.8)*	0.23 (13.8)*
	SP21	85x76	0.14	0.24	0.26 (-2.50)*	0.19 (10.4)*	0.37	0.15 (40.6)*	0.23 (22.3)*
	SP22	94x71	0.22	0.18	0.19 (-2.00)*	0.19 (-1.89)	0.51	0.23 (44.2)*	0.23 (44.7)*
	FA22	185X79	0.13	0.26	0.22(7.61)*	0.16(32.6)*	0.39	0.14(73.7)*	0.23 (38.1)*

Figure 7 visualizes the significance of each school's modularity and nestedness results each semester. The y-axis is the difference between the null and *general* or *specific* tool network models. Positive difference values indicate significantly more

nested or modular than generated on average by a random network creation of the same size and connectance. A negative correlation indicates that the measured value is significantly lower than the null model. A zero difference, or close to zero values, indicates that the network's nestedness or modularity is similar to what could be randomly generated and is not significant. The nestedness of the spaces at both schools each semester is substantial. The modularity of spaces at both schools each semester is not significant. The significance of this difference is largest for the Spring 2022 semester at both schools when the spaces were back to their normal operations.

The restrictions in place in these makerspaces during the initial COVID-19 pandemic offer a chance to understand the value of modularity and nestedness for understanding disturbance-induced changes over time. Connectance, the number of interactions in the network versus total possible interactions (seen in Tables 1 and 2), clearly highlights the usage changes occurring due to the COVID-19 restrictions. Without COVID-19 restrictions, one would expect the connectance values of the networks to remain relatively similar from one semester to the next. Understanding how the makerspaces were impacted requires comparing the network each semester to what it would be if that semester were normal or using a null model corresponding to the connectance of the normal semester. Spring 2022 is representative of a “normal” semester. Table 3 and Table 4 list both the null model for each semester alongside the null model for the Spring 2022 (SP22) “normal” semester. A significant difference in the z-values at $p > 0.05$ of nestedness to the models is starred. The nestedness (NODF) of the “normal” null models is the same for each semester, as the calculations accounted for

network size when the value is normalized, causing the connectance to be the major driving factor for the null models.

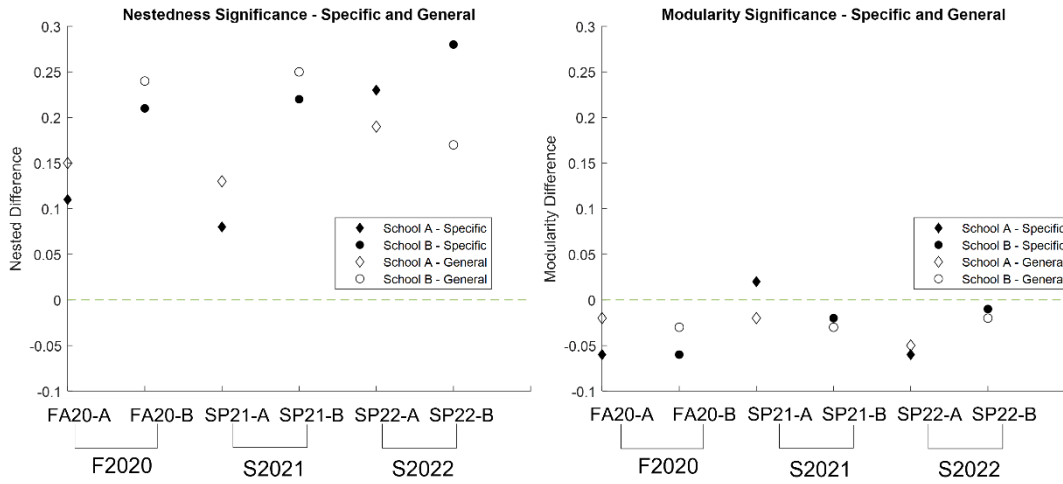


Figure 7: Difference between each semester's null model's nestedness (right) and modularity (left) to the modularity and nestedness of each school, each semester for both the general and specific network models.

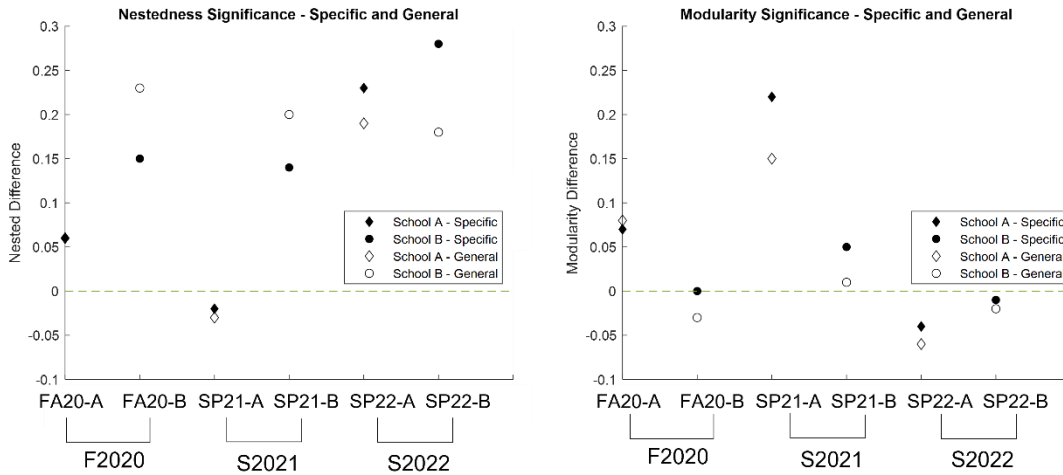


Figure 8: Difference between the normal (SP22) null models' nestedness (right) and modularity (left) to the modularity and nestedness of each school, each semester for both the general and specific network models.

Figure 8 highlights the differences in modularity (left) and nestedness (right) between the “normal” Spring 2022 semester’s null model and each school’s makerspace networks each semester. School A’s (diamond shape) makerspace during Fall 2020 and Spring 2021 has a higher modularity than the null models, indicating that student usage of the space created a significantly modular student-tool interaction network when COVID-19 restrictions were in place. However, School B’s makerspace during Fall 2020 and Spring 2021, compared to the “normal” Spring 2022 semester’s null model, is still significantly nested in both the general and specific tool formats and has an overall lower modularity value. For the Fall 2022 semester for both schools, modularity values were higher, indicating there was a difference to the previous semesters data. For School B, the modularity trended higher when compared to the Spring 2022 semester, likely due to a change in the sample population. It maintains a high nestedness value despite the difference.

4.8. Impact from Initial Nestedness and Modularity Analysis of Space

Nestedness and modularity can identify the current state of a makerspace and any hidden challenges or roadblocks. A healthy makerspace provides an environment where students can explore different ideas, interact with various tools, and have ample resources to make products [5, 68]. University makerspaces must also train students, providing a more hands-on approach to learning course-based material [6]. These goals should result in a nested space, which would indicate that new students are introduced first to general tools while students that have been around longer using a wider variety and more specialized tools. A less nested/more modular makerspace structure would

indicate that students are only using tools associated with their course, creating clusters or modules of student-tool interactions. An extreme version would be an almost perfectly modular network, with few, if any, interactions happening outside the modules indicating that students never explore the space beyond the tools used for class.

The makerspaces of the two schools appear similar in real life (both belong to large R1 schools with significant resources and are used primarily to facilitate student learning in engineering courses). However, the nestedness and modularity analyses used here on student-tool network models provide insight that uncovers significant differences, especially regarding how they function during and after disruptions. The modular structure of School A's makerspace during disruption and the nested structure of School B's makerspace staying consistent throughout the ordeal suggest that differences in makerspace operations are causing large impacts at the network level. The analysis done here and shown in Figure 6 underscores the importance of connectance in a network's modularity and nestedness. The analysis can also point even in normal conditions when something may be affecting the network, as is the case for School B Spring 2022 with more students only interacting with a few tools due to more students interacting with the Vinyl cutter and often being first time students in the makerspace. More on the tool hub analysis will be found in chapter 5.1 of the thesis. The first time students, since they only interact with one tool, lower the connectance as well as increase the modularity of the space.

In the face of perturbations, School B remained static in all its ecological metrics during COVID-19 restrictions. On the other hand, School A drastically changed the

network properties, particularly its connectance and modularity. A static analysis of the space would have likely yielded less valuable information, as the initial null model analysis indicated a consistent trend. However, a method of analyzing how a network performs under different conditions can be created by imposing a higher expected connectance to the network. The potential for the shift of the network based on connectance is also highlighted in Figure 6 with connectance being the main driver to the potential nestedness and modularity of a random network. The importance of connectance thus becomes key when analyzing a perturbation, as it is likely that a network will experience potential lower connections during the duration that could drastically affect the work.

The impact of COVID-19 restrictions at each school can be quantitatively visualized using modularity and nestedness analyses and comparing against the network under normal operating conditions. The class-based use restriction at School A is hypothesized to be the primary driver of the lower connectivity and more modular makerspace use structure. The modules here for School A correspond somewhat with specific courses across the different engineering majors that use the space. Variations could be attributed to more multidisciplinary projects, causing the non-module interactions (the black-colored interactions in the modularity plots of Appendix E).

The makerspace at School B is also intended to supplement engineering courses in the same way as School A. However, it is known that School B's makerspace also has many personal projects occurring at any one time. School B also has arranged its makerspace such that PPE restrictions vary throughout, with the entrance to the space

having almost none to encourage curious students to enter. School A's PPE requirements are significant for the entire space regardless of where you are or what you are doing. The other significant difference between the two schools is that School B's space is entirely student-run, with all the "workers" in the space being paid or volunteering students. School A has some paid student workers but is still a primary university staff-run space. These three major differences have resulted in a modular and less connected space at School A and a nested and more connected space at School B during and immediately after the restrictions. Students are encouraged to explore the space, likely leading to higher interactions documented and an increase in nestedness. The overall nestedness structure of both spaces during normal operating conditions indicates that students are also primarily interacting with the "generalist" tools in the space and specializing further in more advanced tools, with students with fewer interactions primarily working with the "generalist" tools as well.

The modularity and nestedness analyses also make the impact of COVID-19 restrictions visible in both spaces. The decreasing modularity from Fall 2020 to Spring 2022 can be attributed to decreasing COVID-19 related restrictions in both spaces. Fall 2020 and Spring 2021 semesters at School A saw restrictions within the space down to only the most basic class requirements and no student workers, resulting in an increase in modularity and a decrease in nestedness and connectance during the height of COVID-19 restrictions. Starting Summer of 2021, restrictions have eased, and as of Spring 2022, the school reported COVID-19 related restrictions had been completely removed. School B, while they did have some restrictions, did not remove personal

projects or student workers, resulting in their nested structure being lower during the height of COVID-19 restrictions but still present.

The use restrictions at both spaces caused fewer interactions and thus lowered connectance values, but only at School A did that result in a significantly modular structure after the perturbation. School B, although nestedness decreased, it still had dropped so low that the space became modular during the COVID-19 perturbation. The impact of restrictions on the network structure was visible when they were lifted in the 2022 Spring semester. Schools A and B see large increases in how nested their students and tools are. The connection also increases during that semester at both schools.

These results strongly support modularity and nestedness as diagnostic tools for network health. This could especially be useful for networks where equity may be of interest. Energy equity, for example, could be investigated for a power grid network with modularity and nestedness, showing that a more nested structure has better reach to historically underserved users or neighborhoods. Translating modularity values to a water distribution network, for example, could help ensure that the communities have water during disturbances.

The study in Figure 6 highlights the relationship between nestedness, modularity, and connectance. Different networks can often be characterized by their connectance level and fill. Utilizing the sample network plot, a sample operation region can be identified for what the likely modularity and nestedness results could indicate. If the network is high connectance, a positive relationship between modularity and nestedness can be expected as a likelihood of the network showcasing both. This can be useful

when first identifying the network and obtaining overall nestedness and modularity values.

While a makerspace may seek to become more nested, other human networks may want to be more modular. For example, a modular structure in electrical networks has been found to help mitigate the effects of network perturbations, particularly when using microgrids [69]. On the other hand, industrial water networks have been found to benefit from a more nested structure when experiencing disturbances [33]. Modularity and nestedness can also be used as diagnostics tools to see if changes in a network are affecting the network structure positively or negatively.

4.9. Chapter 4 Summary

The three different ecological metrics, connectance, modularity, and nestedness are all applied to the makerspace network models. Null models confirm that the makerspaces are highly nested, indicating that the overall setup of the makerspaces follow a pattern of students first interacting with general tools before working with more specialized tools. Higher connectance values are seen for the makerspaces when the COVID-19 restrictions are lifted. These new values are proposed as a better comparison in the null models and show School A to have a correlation with modularity, indicating that the makerspace restrictions had a large effect on usage the spaces that lasted beyond the semesters when they were primarily in place. Chapter 5 further expands on the analyses of the makerspace network models, focusing more closely on the tool hubs and demographic analyses. Modularity is the primary metric used as it specifically focuses on identification of tool hubs and student demographic grouping

5. NETWORK ANALYSIS TO IDENTIFY HUB TOOLS AND POTENTIAL BARRIERS*

While the ecological network analysis coupled with the survey results provide a holistic view of the structure and functioning of the makerspace, a deeper dive utilizing modularity and demographic survey results here in Chapter 5 provides knowledge about the interactions of the makerspace and breaks down the findings around key hub tools.

5.1. Key hub-tool analysis

The general tool analysis with participation and z-values is generated from the general tool categories outlined in Table 2. The results of the analysis are found in Figure 9.

Various hub tools can be identified within the space for the general tool analysis. Of significant importance across semesters, 3D printing (Tool 1) is a major tool across three different semesters. However, Fall 2022 in Figure 13 shows that 3D printing has significant participation and usage value. While 3D printing remains a hub tool that students use, the drop in usage is one of the reasons overall usages and connectance were down in the space during Fall 2022. Similarly, social activities in the space (Tool 7) was consistently considered a hub tool, despite harsher COVID-19 restrictions in Fall 2020 and Spring 2021 followed by an increase in Spring 2022 once operations returned to normal. The myriad of hub tools in the space coincides with the setup of the space, with the focus of School A's makerspace being supported heavily by the class curriculum.

*Reprinted with permission from “Modularity Analysis of Makerspaces to Determine Potential Hubs and Critical Tools in the Makerspace” by Samuel Blair, Garret Hairston, Henry Banks, Julie S. Linsey, Astrid Layton, 2022, *ASEE Virtual Annual Conference*, Copyright [2022] by ASEE

The class curriculum would thus bolster a variety of hub tools as students used the space that are linked to courses.

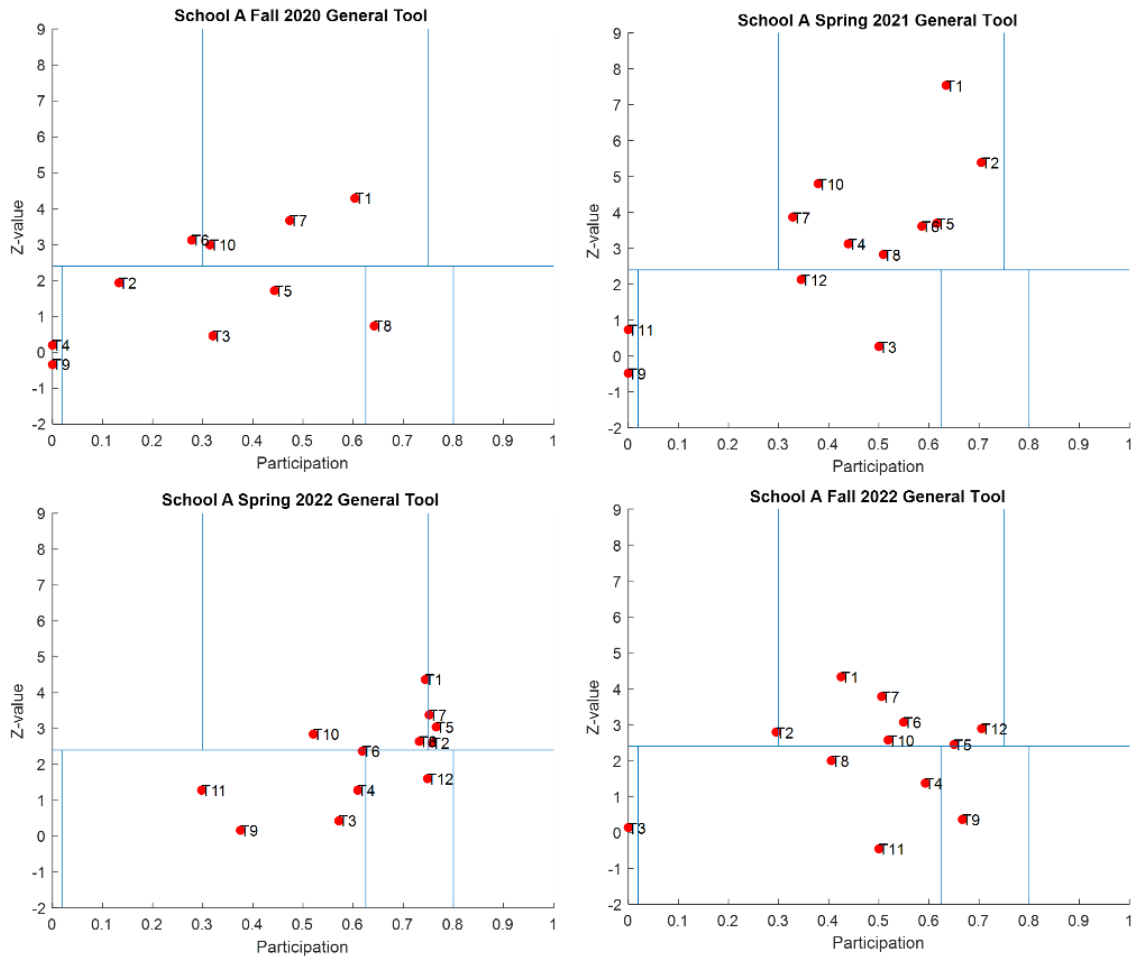


Figure 9: Participation and Z-value analysis for School A across the different semesters. Each point is one of the general tools listed in the survey for School A. Tool numbering matches the names in Table 2.

Participation and Z-value analysis results are generated from the general tool categories outlined in Table 2 and Figure 10 for School B. 3D printing (Tool 1) was a hub tool throughout all the semesters and remained a critical tool within the space. Unlike School A, the laser cutter (Tool 3) was considered a hub tool for most semesters.

The difference in this tool is largely attributed to the laser cutter being a tool taught at School B and students having full access to the tool. At the same time, School A does not focus on this tool as part of the curriculum, and access to the tool is based on request only. School B overall had a lower number of hub tools from the Fall 2020 to Spring 2022 semesters, indicating students primarily interacted with a few key hub tools before interacting with the more specialized tools, as is indicated by the high nestedness values and low modularity values of the space. Fall 2022 deviated from this trend with higher modularity values and lower overall connectance, indicating that students coming into the space often only used a specific tool leading to a more modular design.

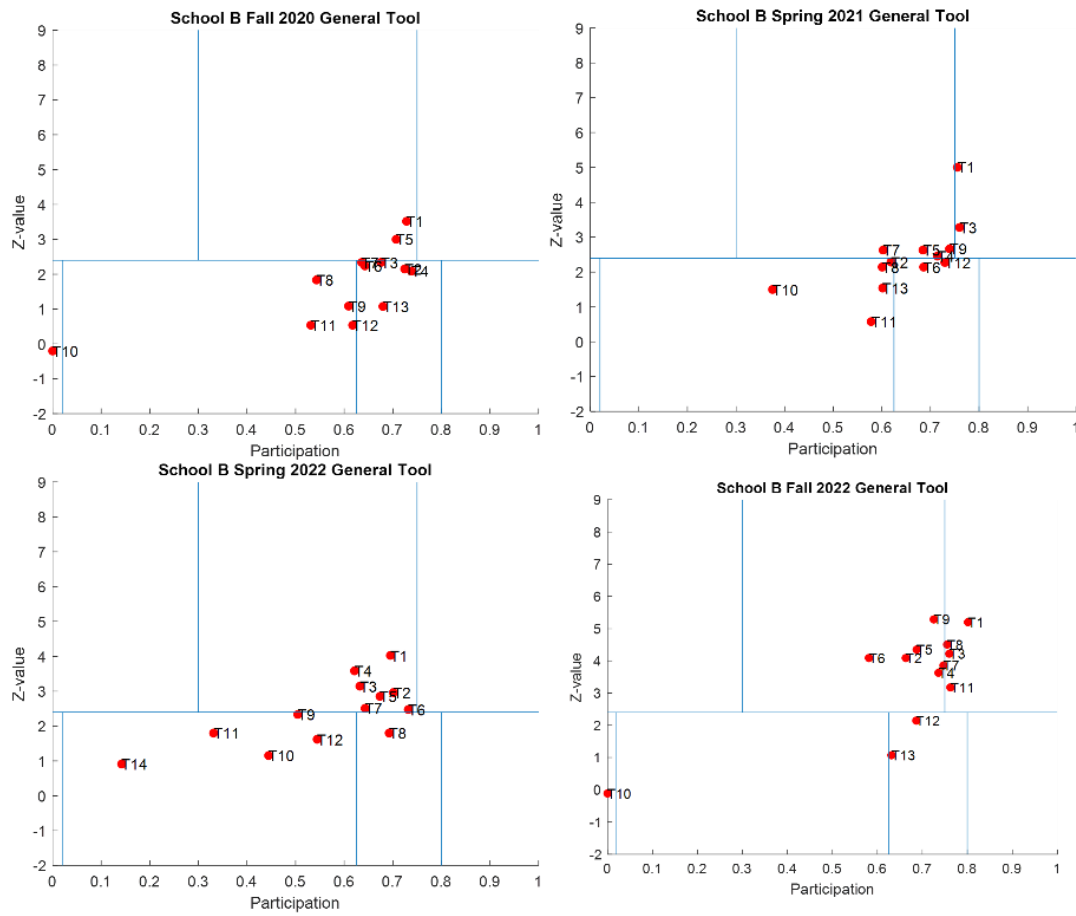


Figure 10: Participation and Z-value analysis for School B across the different semesters. Each point is one of the general tools listed in the survey for School B. Tool numbering matches the names in Table 2.

Results from the general tool analysis provide an overall overview of how students interacted with the space. However, due to the broadness of the categories, several tools can often fall under the hub category due to the large usage numbers by the students. Therefore, to better display which *specific* tools students use in the space, the specific tool category is used to delve deeper. One important item to note in the specific tool analysis is that students are not required to select a specific tool once a general tool is first identified. The higher number of selections for specific tools also leads to a lower

overall connectance, as seen in earlier thesis sections. However, while the usage is overall lower, the specific tool participation and Z-values still yield valuable information about the space.

Results for the specific tool analysis of School A can be found in Figure 11. From the specific tool analysis, individual tools can be spotted and identified as “hub” tools for each semester. For Fall 2020, meeting with a group was still a hub tool despite the increased restrictions in the space. While not a hub, the Ultimaker (Tool 1) had the second highest participation and Z-value. Various 3D printers (Ultimaker, Dremel Digilab) in Spring 2021 were identified as hub tools and both types of mills (manual mill and CNC metal mill). Lastly, for Fall 2022 and Spring 2022 “met with a Group” was the major identified hub tool, indicating students are primarily using the space to work on either project for class or club, as are the restrictions in the space. Spring 2021 deviated from not meeting with a group being a hub tool, possibly due to tightening conditions restricting student group usage of the makerspace at School A.

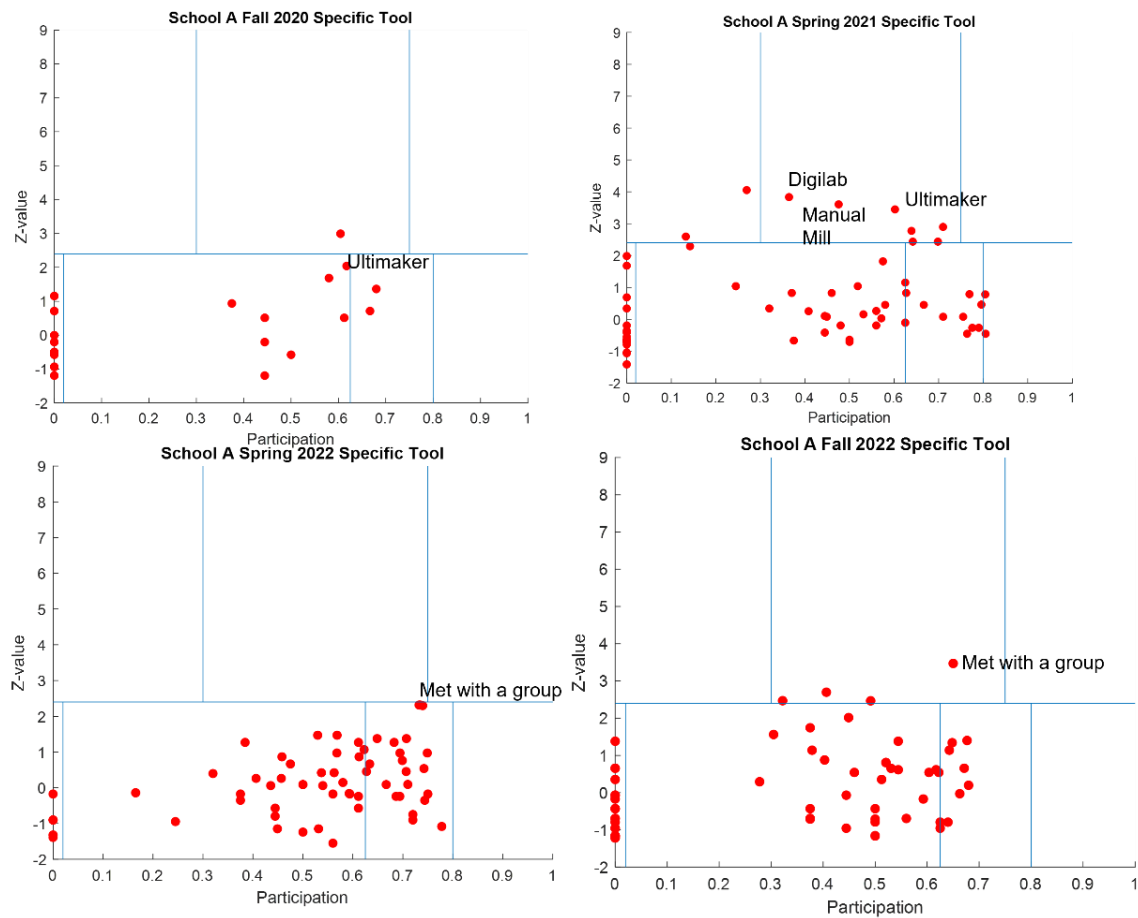


Figure 11: Participation and Z-value analysis for School A for the specific tool categories across the different semesters. Each point is one of the specific tools listed in the survey for School A. For detailed tool labels on each plot, please refer to Appendix C.

Figure 12 shows results for the specific tool analysis of School B. Matching the results from the general analysis across all semesters, the 3D Printing “Ultimaker” was found to be a hub tool. The viny/paper cutter was also found to be a hub tool in Fall 2022 only, hypothesized to be due to changes in the capabilities of creating stickers for students.

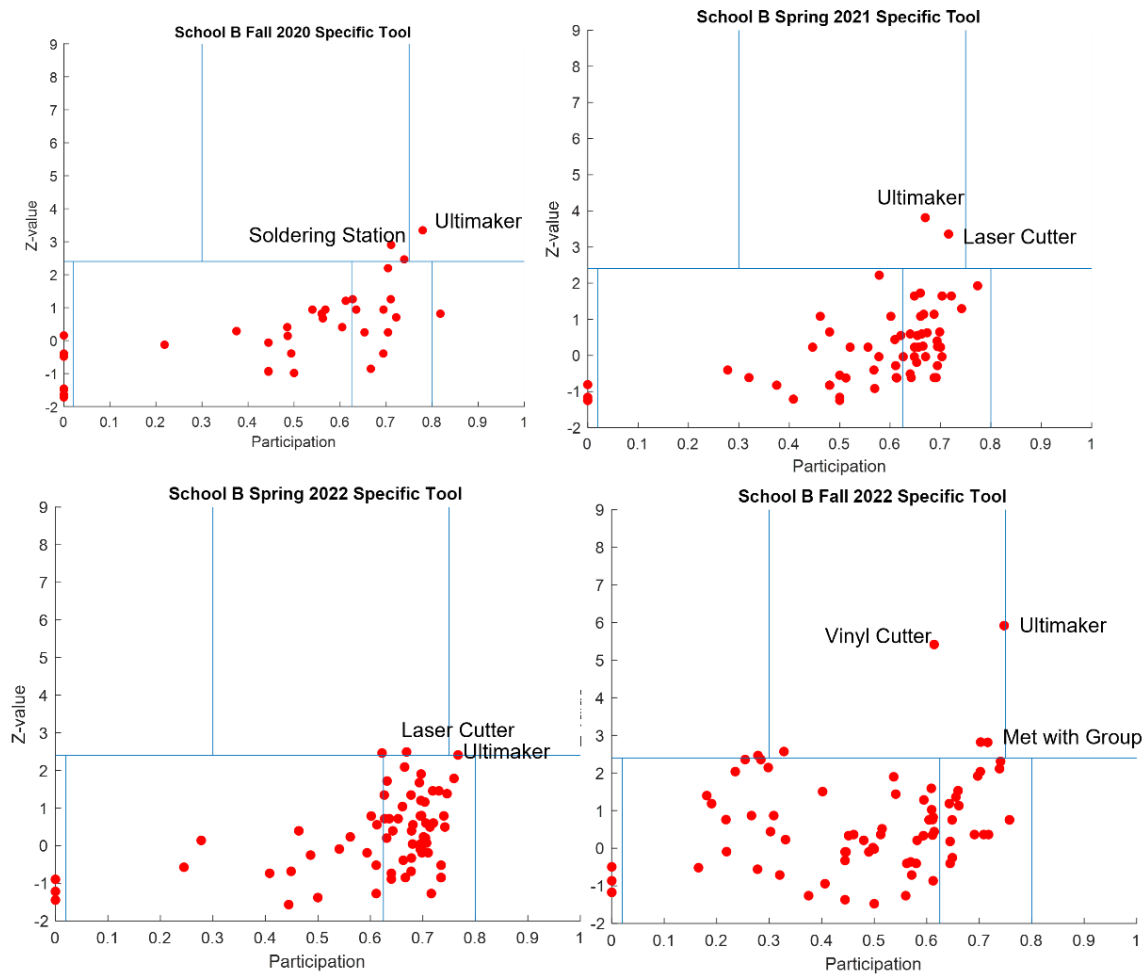


Figure 12: Participation and Z-value analysis for School B for the specific tool category across the different semesters. For detailed tool labels, refer to Appendix C.

At both universities, 3D printing is identified as a key tool, consistent with other research identifying rapid prototyping as a key to space usage [70]. The overall tool usage percentages gathered from the survey are presented in Figure 13 and Figure 14 to validate the tool used for these semesters.

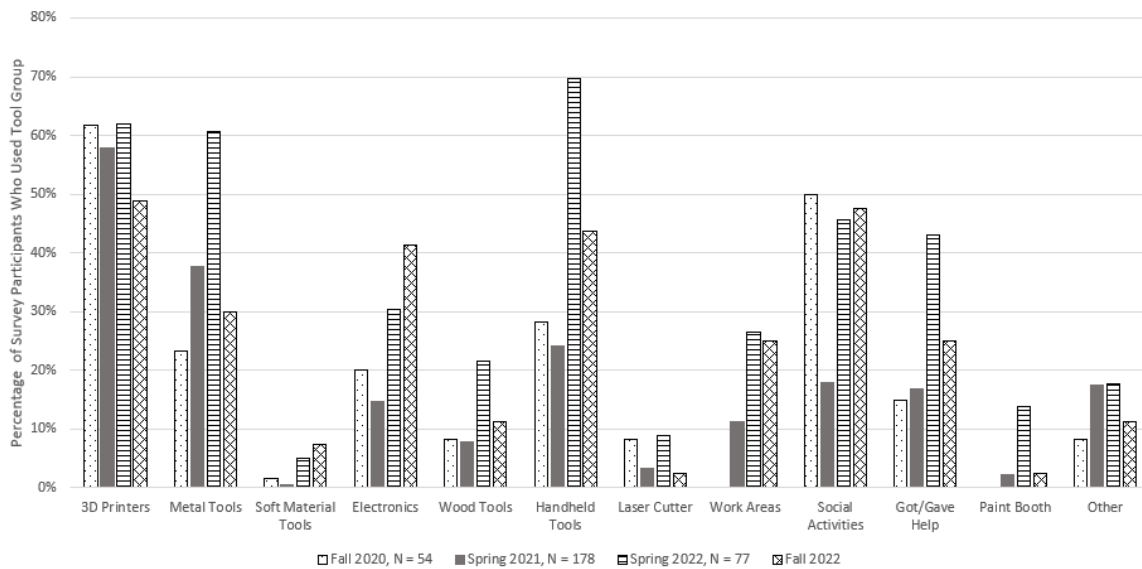


Figure 13: Proportion of students (as a % of the total survey population) at School A that indicated using a tool at least once for each semester.

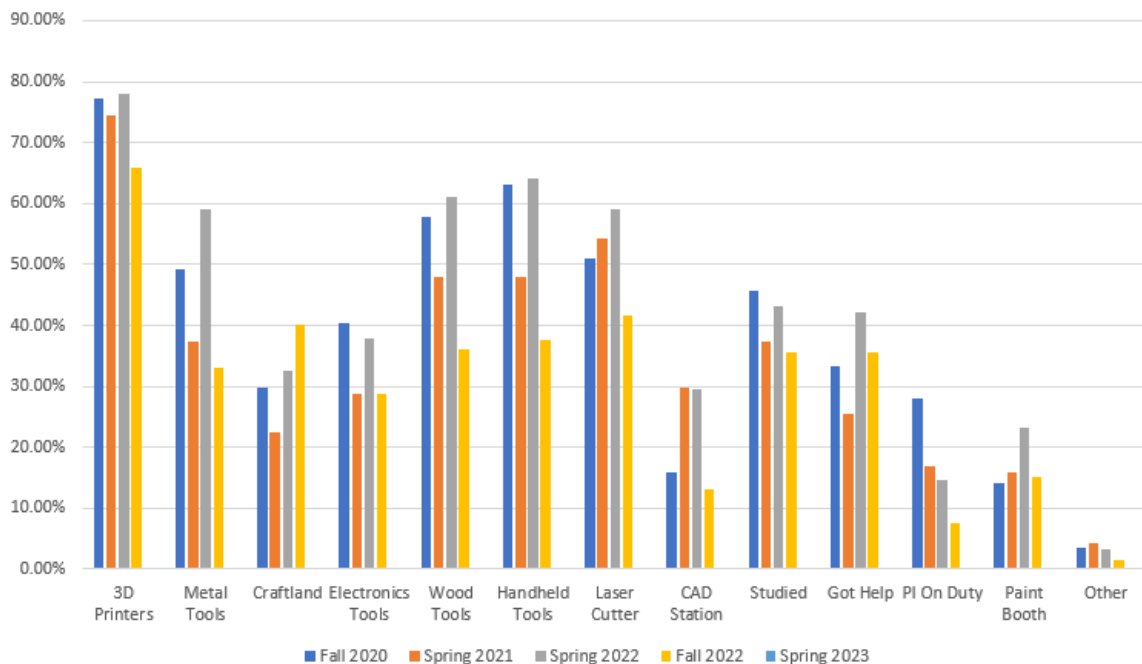


Figure 14: Proportion of students (as a % of the total survey population) at School B that indicated using one of the general at least once for each semester.

The modularity analysis quantitatively characterizes interactions within the makerspace, identifying high-impact tools (hubs) that serve as critical parts of the makerspace and low-impact tools that may need more support to encourage student use. A major advantage of this analysis is its ability to condense a vast amount of data and visualize it instead of relying on more conventional methods that require far more analysis and graphics to convey the same information. With only a few graphs like those in Figure 13, a modularity analysis can provide insight into both usage rates and the significance of tools for the successful functioning of the makerspace. The survey analysis and the modularity analysis showed that 3D printers are a major hub tool at both universities and hanging out in the space for School A was a hub tool.

The modularity analysis for the two schools can also provide insight into the differences between the makerspaces. The tools that were found in the modularity plots to be hubs may be due to their use for specific courses. , Tools used within a course at both schools (for example, the 3D printers, mill, and lathe at School A and the laser cutter at School B) tend to have a higher usage within the space.

Additionally, 3D printing was a major hub for students and a major tool that students first used at both schools. Another key difference is that School A is staff-run, and School B is student-run, possibly causing the overall higher interaction rate at the student-run space of School B. The differences in the layout are further supported by the network analysis in Section 4.7 of the thesis highlighting the higher modularity of School A overall as well as the lower connectance semester of School B.

5.2. Student Demographic Analysis

Table 5 shows a summary of the demographic information. Student percentage use falling below 10% was chosen as a cut off for the demographic analysis (i.e. use less than 10% is not utilized to represent the whole group to avoid one student heavily skewing the results for the full population). Additionally, any student group with fewer than seven individuals was omitted from the analysis. While the usage percentages are still shown in the demographic tables, the following modularity analysis showcasing the interaction network similar to Figure 2 omits student groups for each category due to the small sample size. The modularity network analysis with the different demographic groupings will allow us to see how students interact with tools in the space. The three demographics will be evaluated: gender, race, and major. For a full view of all the demographic breakdowns, please refer to Appendix D.

Summary- School A Spring 2021													
	n	3D Printers	Metal Tools	Craftland	Electronics	Wood Tools	Handheld Tools	Laser Cutter	CAD Station	Studied	Got Help	Paint Booth	Other
General	N = 178	57.87%	37.64%	0.56%	14.61%	7.87%	24.16%	3.37%	11.24%	17.98%	16.85%	2.25%	17.42%
Male	118	59.32%	38.98%	0.00%	16.10%	7.63%	25.42%	4.24%	12.71%	21.19%	16.10%	1.69%	17.80%
Female	57	54.39%	35.09%	0.00%	8.77%	7.02%	17.54%	1.75%	7.02%	10.53%	19.30%	3.51%	17.54%
Hispanic	39	51.28%	30.77%	0.00%	17.95%	7.69%	25.64%	5.13%	5.13%	20.51%	10.26%	0.00%	28.21%
Non-Hispanic	131	60.31%	39.69%	0.76%	13.74%	7.63%	22.14%	3.05%	11.45%	18.32%	19.08%	3.05%	12.98%
White / Caucasian	120	60.00%	37.50%	0.83%	14.17%	9.17%	25.00%	2.50%	12.50%	17.50%	15.83%	2.50%	18.33%
Black or African American	3	33.33%	66.67%	0.00%	0.00%	0.00%	33.33%	0.00%	0.00%	66.67%	0.00%	0.00%	0.00%
American Indian or Alaskan Native	4	75.00%	25.00%	0.00%	25.00%	25.00%	0.00%	25.00%	0.00%	25.00%	0.00%	0.00%	25.00%
Native Hawaiian or Other Pacific Islander	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Middle Eastern	4	25.00%	50.00%	0.00%	50.00%	0.00%	25.00%	0.00%	25.00%	0.00%	25.00%	0.00%	25.00%
Asian	37	54.05%	37.84%	0.00%	10.81%	5.41%	18.92%	8.11%	13.51%	16.22%	27.03%	2.70%	16.22%
Aerospace Engineering Major	8	25.00%	12.50%	0.00%	0.00%	12.50%	25.00%	12.50%	0.00%	25.00%	0.00%	12.50%	37.50%
Biomedical Engineering Major	9	88.89%	0.00%	0.00%	11.11%	0.00%	11.11%	0.00%	11.11%	0.00%	0.00%	0.00%	0.00%
Chemical Engineering Major	1	0.00%	0.00%	100.00%	100.00%	0.00%	100.00%	0.00%	100.00%	100.00%	0.00%	0.00%	0.00%
Computer Engineering Major	4	25.00%	25.00%	0.00%	25.00%	0.00%	0.00%	0.00%	0.00%	50.00%	50.00%	0.00%	25.00%
Electrical Engineering Major	17	35.29%	0.00%	0.00%	70.59%	5.88%	35.29%	0.00%	11.76%	35.29%	23.53%	0.00%	17.65%
Industrial Engineering Major	23	60.87%	60.87%	0.00%	0.00%	0.00%	13.04%	0.00%	8.70%	4.35%	17.39%	0.00%	13.04%
Material Science and Engineering Major	2	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%
Mechanical Engineering Major	90	68.89%	50.00%	0.00%	4.44%	10.00%	26.67%	4.44%	13.33%	14.44%	16.67%	2.22%	13.33%
Nuclear Engineering Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Other Major	24	41.67%	25.00%	0.00%	29.17%	12.50%	25.00%	4.17%	8.33%	20.83%	20.83%	4.17%	37.50%

Table 5: Subset of the full demographic results for School A, Spring 2021. See Appendix D for the full results.

From the demographic table, a modularity analysis breakdown of each category can be obtained. A sample analysis is shown in Figure 15 with the bipartite representation of the network with student-tool modules colored. The general tool category was used for this analysis as it provides the most comparable tool breakdown between the different universities. For a full breakdown of all the different semesters, along with their bipartite student module representation, please refer to Appendix D.



Figure 15: School A bipartite makerspace network and module assignments for various student demographic groupings: A) Gender B) Race C) Major. A connection between a student demographic group and a tool grouping indicates that at least 10% of that demographic interacted.

The bipartite representation, along with the modular analysis, provides a method for identifying how student groups interacted with the space and provides a visual for the interaction that is less easily seen with just the demographic table. In addition, different module colorings allow for usage across the groups, as with the example of School A in Figure 15, highlighting how male students used electronics and CAD stations while female students did not for the semester.

The most consistent module difference among the tool groups is related to the *major*-based demographic breakdown at School A. For Fall 2020, Mechanical engineers were grouped in a module with metal tools, wood tools, and the laser cutter, with the electrical engineers in a module with electronics. The pattern continued for Spring 2021 and Fall 2022, with electrical engineers in a module with electronic tools while mechanical engineers were paired with metal tools in a module. The only semester to

deviate was Spring 2022, with the only difference between electrical engineers and mechanical engineers being the laser cutter usage leading to the difference in modules. The analysis shows engineers often are closely correlated to the tools within their major, supporting the hypothesis that classes play a major role in the usage of the space, but does not restrict them to just those tools as students still used a variety of tools (dark links outside of module).

For School B, the population for each of the majors needed to be increased to show trends across majors due to the space being primarily used by mechanical engineers. The Fall 2022 semester, however, provides a view of various majors. In this semester, different module combinations can be identified. Still, aerospace engineering and mechanical engineers interacting with the CAD station and PI on duty was a major factor in the module creation. Outside of those interactions, majors were connected heavily to all the other tools.

While the bipartite demographic view offers a visual as to how students interact with tools, the analysis is limited by the sample size and reliance on one tool driving the analysis. If two groups use all the same tools except one (as with School A Spring 2022), the two groups will be separated into different modules even if one tool was used more by one student group. Another limitation of the analysis is the sample size, with sample sizes for the survey often not reaching more than seven entries, causing the participant information to be removed. The limitations of this analysis create difficulty when evaluating trends over time and add difficulty for comparing student groups across the university but offer a view at each semester to see how students interacted with the space

and where different tools were used. When combined with traditional survey analysis, differences in semesters can be explored as to why certain patterns emerged. While results are promising as different student group modules can be identified, larger, more diverse sample sizes across multiple semesters would be needed to confirm the analysis found in this analysis.

5.3. Summary of Chapter 5

The participation and Z-value analysis of makerspaces over time highlighted both key and underused tools, singling out hanging out with a group for School A and 3D printing for both schools. The demographic analysis identified student modules, with major classification playing a major role in School A with students in electrical engineering being in the same module as tools commonly associated with electrical engineers and likewise for mechanical engineering students. For other groups, the numbers for a large variety of student groups were not large enough to be represented fully but the visual can identify differences in tool usage by the difference in module assignment. The demographic analysis was able to determine how students interacted with tools in the space and what combinations they were likely to use, however a larger, more diverse dataset is needed to more accurately capture the effects of the different groups more clearly or that did not have a large enough population to be included.

6. CONCLUSIONS AND FUTURE WORK

6.1. Summary

Work in the thesis focuses primarily on utilizing the different ecological network techniques to evaluate the makerspaces at two universities. The three metrics, modularity, nestedness, and connectance, are used in combination first to identify overall network performance and insight, deeper hub-tool analysis, and student demographic breakdown. Differences in the normal operation of and COVID-19 restrictions for the makerspaces at each school provides a unique opportunity to evaluate the makerspaces across time and in different operating environments.

The process for evaluating the makerspace and utilizing the different ecological metrics first consisted of gathering the data in a format that would allow for ecological metrics. The data was gathered utilizing survey-gathering techniques at both universities. A bipartite interaction network with students on the rows and tools on the columns was created from the student-self-reported use of tools.

The varying ecological metrics were introduced and explained with a sample network to show how the metrics would be used to evaluate the space and how the different metrics played a role when used in combination to provide valuable insight. The metrics were then used at each school for each semester, and results were discussed, with the overall makerspace network showcasing a strong correlation for being nested. However, compared to the higher expected connectance, School A showed modular tendencies and overall higher modularity values compared to School B, indicating the restricted use of School A guiding the tool used to primarily class use.

The ecological analysis was expanded by utilizing modularity as the foundation to conduct participation, z-value analysis, and demographic module analysis to identify hub tools and student usage patterns. The hub-tool analysis identified 3D printing as a major hub tool across both schools for most semesters while also providing a visual to rapidly identify the varying tool group usages and key tools across semesters. Traditional survey analysis techniques supported the results. On the other hand, the demographic analysis grouped students by demographic partitions with a 10% cutoff for indicating if a group was using the tool or not. The subsequent modularity analysis provided insight into whether tool usage differed amongst the groups and universities. The analysis showcased major divisions as a major point of different tool usage at School A, while for School B different majors did not have ample numbers to make a substantial comparison.

6.2. Future Work

Future work for this project spans two separate routes to enhance the analysis and understanding of makerspace and utilize the findings to create a positive impact across different makerspaces. In addition, the findings in this thesis and the methods presented should allow for follow-up work.

6.2.1. Enhancing the User Experience

With the identification of hub tools at each university and using different demographics, workshops can be conducted to enhance the student experience. One of the results of the analysis highlighted how the space is nested and how students will typically learn one

tool before expanding to more specialized tools. Introducing students early to the space and showcasing a “hub” tool makes them more likely to return to the space later.

To conduct the workshop, research works closely with the leadership of different organizations that can reach students of different demographics and invite them to the workshop. The workshop would introduce students to different hub tools in the space, allowing students some hands-on experience as well as going over all the potential barriers to entry, so students are aware and more confident when entering the space. To capture whether the students had a better experience, workshop students would be tracked separately from the general population, and their nestedness and modularity values and usage across different semesters be tracked to see if their usage of the space trended higher than students that were not introduced to the hub tools early on. Efforts for conducting these workshops have been implemented at both universities, with initial trial runs conducted at each university. Results from the initial workshops in progress will be used to better understand the effects the workshop had on the student and how they can be improved for future iterations.

Another way to enhance the student experience would be to include hub tools early on in a student’s engineering career curriculum. For example, introducing 3D printing, working in groups in the space, and encouraging the students to use the space earlier on would allow students to become familiar with the space and explore the variety of tools offered. Utilizing the tool analysis, key tools at different universities can be identified, and curriculums can be modified to introduce students better to the space.

6.2.2. Expanding Research to Other Makerspaces

The research presented in this thesis focused primarily on two universities, School A and School B. Both universities had vastly different makeups, restrictions, and focuses for the space and different structures according to the ecological metrics. Expanding this research to other makerspaces would help refine the thresholds for understanding different makerspaces and aid those makerspaces in implanting the findings in this research to improve their makerspaces. By assuring they have key tools that students can use to be introduced to the space and then expanding to more advanced tools, makerspaces can track the growth of the space through the different ecological metrics.

For new spaces starting up, the introduction of new tools and regulations can be closely monitored from semester to semester to visualize their impact on the space. If the space is heavily modular after introducing new tools or regulations, educators and makerspace staff can adjust their approach to the space and improve the user experience. If the space is instead highly nested with low modularity, the new tool can be seen as successful at introducing students to a space.

Additionally, as mentioned in the demographic analysis in chapter 5.2, capturing a larger sample size of varying demographics would aid in the comparisons both between schools as well as between semesters to more definitively visualize how students interact with the space and which groups face challenges. Identifying these potential barriers can aid educators in tailoring curriculums and workshops towards aiding these student groups in the space.

6.3. Conclusions

This thesis's primary focus was to apply ecological network analysis techniques to engineering makerspaces to acquire a deeper understanding of the space and provide measurable metrics to evaluate the health of the space. The primary conclusions of the report highlight the overall nested structure of the makerspace network, with a higher modularity value present in the face of disruptions for School A. The analysis also identified several key tools at both universities, with 3D printers being a major tool in a majority of the semesters at both schools and student social activities being of high importance at School A. Demographic analysis of the space showed the varying population at each university, with major demographic highlighting the more modular structure of School A.

As to the goals of the report to advance different aspects of systems analysis and ecological analysis, a method for evaluating a changing system is presented where a higher standard of connectance is used to generate the null models. The proposed approach allows for the higher modular structure to be identified and for the status of a network to be evaluated. The relationship between nestedness, modularity, and connectance was also explored deeply, providing insight into the network's structure and how a network is expected to behave under certain connectance conditions. This analysis can be expanded into various ecological applications where data is available for a changing population.

For the advancement of human systems, the ecological network analysis provided valuable insight that otherwise would not have been easily accessible or visualized. The conversion of a complex human network into a bipartite graph allows for measurable metrics to be used to evaluate the complex structure of the space. The analysis also allows for key actors to be identified, having far-reaching potential in various human networks where key locations or actors are to be identified.

With the findings, recommendations can be given to engineering makerspaces to create a more inclusive environment that will allow students to delve into various tools and enhance their education. Future work will allow for these recommendations to be applied as well as be tracked at a variety of different universities and locations.

REFERENCES

1. Lou, N. and K. Peek, *Rise of the Makerspace*, in *Popular Science*. 2016.
2. Morocz, R., et al. *Relating Student Participation in University Maker Spaces to their Engineering Design Self-Efficacy*. in *American Society for Engineering Education Annual Conference*. 2016. New Orleans, LA.
3. Smith, R.P. and A. Leong, *An observational study of design team process: A comparison of student and professional engineers*. *ASME Journal of Mechanical Design*, 1998. **120**(4).
4. Meyer, A., *Feminist makerspaces: Making room for women to create*, in *The Riveter*. 2018.
5. Tomko, M., et al., *Observations on guiding principles, or best practices, in university makerspaces*, in *International Symposium on Academic Makerspaces*. 2017: Cleveland, OH.
6. Braga, M. and G. Guttman, *The Knowledge Networks in a Makerspace: the Topologies of Collaboration*. *International Journal of Science and Mathematics Education*, 2019. **17**(1): p. 13-30.
7. Make/Intel, *Maker market study and media report: An in-depth profile of makers at the forefront of hardware innovation*. 2012.
8. Martin, L., *The Promise of the Maker Movement for Education*. *Journal of Pre-College Engineering Education Research*, 2015. **5**(1): p. 30-39.

9. Bascompte, J., et al., *The nested assembly of plant-animal mutualistic networks*. The Proceedings of the National Academy of Sciences (PNAS), 2003. **100**(16): p. 9383-9387.
10. Tomko, M., et al., *Learning in Academic Makerspaces: How Inclusivity Affords Learning for Female Students in Various University Makerspaces*, in *ASEE Annual Conference*. 2018: Salt Lake City, UT.
11. Bean, V., N.M. Farmer, and B.A. Kerr, *An exploration of women's engagement in Makerspaces*. Gifted and Talented International, 2015. **30**(1-2): p. 61-67.
12. Saorín, J.L., et al., *Makerspace teaching-learning environment to enhance creative competence in engineering students*. Thinking Skills and Creativity, 2017. **23**: p. 188-198.
13. Smith, R.P. and A. Leong, *An observational study of design team process: A comparison of student and professional engineers*. 1998.
14. Hilton, E., et al., *Impacts on Design Self-Efficacy for Students Choosing to Participate in a University Makerspace*, in *International Conference on Design Creativity*. 2018: Bath, UK.
15. Hilton, E., et al., *Investigating why students choose to become involved in a university makerspace through a mixed-methods study*, in *ASEE Annual Conference*. 2018: Salt Lake City, UT.
16. Barrett, T., et al., *A Review of University Maker Spaces*, in *American Society for Engineering Education Annual Conference*. 2015: Seattle, WA.

17. Tomko, M., *Developing One's "Toolbox of Design" through the Lived Experiences of Women Students: Academic Makerspaces as Sites for Learning* 2019, Georgia Institute of Technology: Atlanta, GA.
18. Lewis, J., *Barriers to women's involvement in hackspaces and makerspaces*. Access as spaces. Available at: <http://access-space.org/wp-content/uploads/2015/10/Barriers-to-womens-involvement-in-hackspace-and-makerspaces.pdf> (accessed 10 May 2016), 2015.
19. Jens M. Olesen, J.B., Yoko L. Dupont, Pedro Jordano, *The modularity of pollination networks*. Proceedings of the National Academy of Sciences, 2007.
20. Yang, S., F.B. Keller, and L. Zheng, *Social Network Analysis*. 2016, Los Angeles: SAGE Publications. 248.
21. Latapy, M., C. Magnien, and N.D. Vecchio, *Basic Notions for the Analysis of Large Affiliation Networks/Bipartite Graphs*. ArXiv, 2006.
22. Senghore, F., et al., *Using Social Network Analysis to Investigate the Potential of Innovation Networks*. Procedia Computer Science, 2014: p. 380-388.
23. Barber, M.J., et al., *Searching for Communities in Bipartite Networks*. 2008: AIP Conference Proceedings.
24. Guimerà, R., et al., *The worldwide air transportation network: Anomalous centrality, community structure, and cities' global roles*. Proceedings of the National Academy of Sciences, 2005. **102**(22): p. 7794.

25. Fath, B., et al., *Ecological network analysis metrics: The need for an entire ecosystem approach in management and policy*. Ocean and Coastal Management, 2019. **174**: p. 1-14.
26. Foster, A., et al., *Ecological Uniqueness for Understanding Line Importance in Power Grids*. IEEE Texas Power and Energy Conference (TPEC), 2021.
27. Fath, B.D., et al., *Ecosystem growth and development*. Bio Systems, 2004. **77**: p. 213-28.
28. Layton, A., B. Bras, and M. Weissburg, *Ecological Principles and Metrics for Improving Material Cycling Structures in Manufacturing Networks*. Journal of Manufacturing Science and Engineering, 2016. **138**(10): p. 101002-1 – 101002-12.
29. Steffan, S.A., et al., *Unpacking brown food-webs: Animal trophic identity reflects rampant microbivory*. Ecology and Evolution, 2017. **7**(10).
30. Fortuna, M.A., et al., *Nestedness versus modularity in ecological networks: Two sides of the same coin?* The Journal of Animal Ecology, 2010. **79**(4): p. 811-817.
31. Latapy, M., C. Magnien, and N.D. Vecchio, *Basic Notions for the Analysis of Large Affiliation Networks / Bipartite Graphs*. arXiv, 2006.
32. Delmas, E., et al., *Analysing Ecological Networks of Species Interactions*. Biological Reviews, 2019. **94**: p. 16-36.
33. Chatterjee, A., C. Brehm, and A. Layton, *Evaluating benefits of ecologically-inspired nested architectures for industrial symbiosis*. Resources, Conservation, and Recycling, 2021. **167**.

34. Brehm, C. and A. Layton, *Designing eco-industrial parks in a nested structure to mimic mutualistic ecological networks*. Procedia CIRP, 2019. **80**: p. 590-595.
35. Bustos, S., et al., *The Dynamics of Nestedness Predicts the Evolution of Industrial Ecosystems*. PloS one 2012. **7**(11).
36. Mariani, M.S., et al., *Nestedness in complex networks: Observation, emergence, and implications*. Physics reports, 2019. **813**: p. 1-90.
37. Martin, E.A., et al., *Assessing the resilience of biodiversity-driven functions in agroecosystems under environmental change*, in *Advances in Ecological Research*, D.A. Bohan and A.J. Dumbrell, Editors. 2019, Academic Press. p. 59-123.
38. Olesen, J.M., et al., *The modularity of pollination networks*. Proceedings of the National Academy of Sciences of the United States of America, 2007. **104**(50): p. 19891-19896.
39. O'Halloran, B.M., et al., *A graph theory approach to predicting functional failure propagation during conceptual systems design*. Systems Engineering, 2021.
40. Huang, H., et al., *An Ecological Robustness Oriented Optimal Power Flow for Power Systems' Survivability*. IEEE Transactions on Power Systems, 2022.
41. Panyam, V., et al., *Bio-inspired design for robust power grid networks*. Applied Energy, 2019. **251**.
42. Chatterjee, A. and A. Layton, *Bio-inspired Design for Sustainable and Resilient Supply Chains*, in *27th CIRP Life Cycle Engineering (LCE) Conference*. 2020: Grenoble, France. p. 695-699.

43. Chatterjee, A. and A. Layton, *Mimicking Nature for Resilient Resource and Infrastructure Network Design*. Reliability Engineering and System Safety, 2020. **204**: p. 107142.
44. Wilson, T., A. Chatterjee, and A. Layton, *Developing a Supply Chain Modeling Approach to Facilitate Ecology-Inspired Design for Sustainability and Resilience*, in *ASME 2021 International Design Engineering Technical Conferences and Computers & Information in Engineering Conference*. 2021, ASME: virtual. p. 10.
45. Wilson, T., A. Chatterjee, and A. Layton, *Exploring the Effects of Partnership and Inventory for Supply Chain Resilience using an Ecological Network Analysis*, in *ASME 2022 International Design Engineering Technical Conferences and Computers & Information in Engineering Conference*. 2022, ASME: St. Louis, Missouri.
46. Canning, A.D. and R.G. Death, *Relative ascendancy predicts food web robustness*. Ecological Research, 2018: p. 873-878.
47. Ulanowicz, R.E., et al., *Quantifying sustainability: Resilience, efficiency and the return of information theory*. Ecological Complexity, 2009. **6**(1): p. 27-36.
48. Chatterjee, A., R. Malak, and A. Layton, *Ecology-inspired resilient and affordable system of systems using degree of system order*. Systems Engineering, 2021. **25**(1): p. 3-18.

49. Chatterjee, A., R. Malak, and A. Layton, *Exploring System of Systems Resilience Versus Affordability Trade-Space Using a Bio-Inspired Metric*. Journal of Computing and Information Science in Engineering, 2021. **21**(5): p. 1-13.
50. Ulrich, W., M. Almeida-Neto, and N.J. Gotelli, *A consumer's guide to nestedness analysis*. Oikos, 2009. **118**.
51. James, A., J.W. Pitchford, and M.J. Plank, *Disentangling nestedness from models of ecological complexity*. Nature. **486**: p. 227-230.
52. Burgos, E., et al., *Why nestedness in mutualistic networks?* Journal of Theoretical Biology, 2007: p. 307-313.
53. Guimerà, R. and L.A.N. Amaral, *Cartography of complex networks: modules and universal roles*. Journal of Statistical Mechanics: Theory and Experiment, 2005. **2005**(02): p. P02001.
54. Guimerà, R. and L.A. Nunes Amaral, *Functional cartography of complex metabolic networks*. Nature, 2005. **433**(7028): p. 895-900.
55. Heleno, R., M. Devoto, and M. Pocock, *Connectance of species interaction networks and conservation value: Is it any good to be well connected?* Ecological Indicators, 2012. **14**(1): p. 7-10.
56. Poisot, T. and D. Gravel, *When is an ecological network complex? Connectance drives degree distribution and emergin network properties*. PeerJ, 2014. **2**(e251).
57. Blair, S.E., et al., *Bipartite Network Analysis Utilizing Survey Data to Determine Student and Tool Interactions in a Makerspace*. ASEE Virtual Annual Conferense, 2021.

58. Blair, S., et al., *Modularity Analysis of Makerspaces to Determine Potential Hubs and Critical Tools in the Makerspace*. 2022 ASEE Annual Conference & Exposition, 2022.
59. Song Yang, F.B.K., Lu Zheng, *Social Network Analysis*. 2017, United States of America: SAGE Publications.
60. Jackson, M.O., *Social and Economic Networks*. 2008, New Jersey: Princeton University Press.
61. John Moore, P.R., Kevin McCann, Volkmar Wolters, *Adaptive Food Webs*. 2018: Cambridge University Press.
62. Newman, M.E.J., *Modularity and Community Structure in Networks*. Proceedings of National Academy of Sciences of the United States of America, 2006. **103**: p. 8577-8582.
63. Newman, M.E., *Modularity and community structure in networks*. Proceedings of the national academy of sciences, 2006. **103**(23): p. 8577-8582.
64. Flores, C.O., et al., *BiMat: a MATLAB(R) package to facilitate the analysis of bipartite networks*. Methods Ecol Evol. **7**.
65. Flores, C.O., et al., *Statistical structure of host-phage interactions*. The Proceedings of the National Academy of Sciences (PNAS), 2011. **108**.
66. Almeida-Neto, M., et al., *A consistent metric for nestedness analysis in ecological systems: reconciling concept and measurement*. OIKOS, 2008. **117**(8): p. 1227-1239.

67. Matthews, T.J., H.E.W. Cottee-Jones, and R.J. Whittaker, *Quantifying and interpreting nestedness in habitat islands: a synthetic analysis of multiple datasets*. Diversity and Distributions, 2015. **21**(4): p. 392-404.
68. Sawchuk, T., et al., *Understanding Academic Makerspaces through a Longitudinal Study at Three Universities*, in *American Society for Engineering Education Annual Conference*. 2019: Tampa, FL.
69. Mousavizadeh, S., et al., *Resiliency analysis of electric distribution networks: A new approach based on modularity concept*. International Journal of Electrical Power & Energy Systems, 2020. **117**.
70. Stowe, D.T., *Investigating the Role of Prototyping in Mechanical Design Using Case Study Validation*, in *Mechanical Engineering*. 2008, Clemson University: Clemson, SC.

APPENDIX A: NETWORK MATRIXES

Table 6: School A Fall 2020 General Tool interaction matrix

	3D Printers	Metal Tools	Laser Cutter	Wood Tools	Hand Tools	Electronics	Social Activities	Got/Gave Help	Soft Material Tools	Other
s1	1	0	0	0	0	0	0	1	0	1
s2	1	0	0	0	0	1	0	1	1	1
s3	1	0	1	0	0	0	0	0	0	0
s4	0	0	0	0	0	0	1	0	0	0
s5	0	1	0	1	0	1	1	0	0	0
s6	1	0	0	0	0	0	0	0	0	0
s7	0	0	0	0	0	1	0	0	0	0
s8	1	0	0	0	1	0	1	0	0	0
s9	0	0	0	0	0	1	0	0	0	0
s10	0	0	0	0	0	1	0	1	0	0
s11	1	0	0	0	0	0	0	0	0	0
s12	1	1	0	1	1	0	1	1	0	0
s13	0	0	0	0	0	0	1	0	0	0
s14	0	0	0	0	0	1	1	0	0	0
s15	0	0	0	0	1	1	0	0	0	0
s16	1	0	0	0	0	0	0	0	0	0
s17	1	0	1	0	0	0	0	0	0	0
s18	0	0	0	0	0	0	1	0	0	0
s19	1	0	0	0	0	0	0	0	0	0
s20	1	1	0	0	1	0	1	0	0	0
s21	1	1	0	0	0	0	1	0	0	0
s22	1	1	0	0	1	0	1	0	0	0
s23	1	1	0	0	1	0	1	1	0	1
s24	1	0	1	0	0	0	0	0	0	0
s25	1	1	0	0	1	0	1	1	0	0
s26	0	0	0	0	0	0	1	1	0	0
s27	0	0	0	0	1	1	1	0	0	0
s28	0	0	0	0	0	0	1	0	0	0
s29	1	0	0	0	0	0	0	0	0	0
s30	0	0	0	0	0	1	1	0	0	0
s31	1	0	0	0	0	0	1	0	0	0
s32	1	1	0	0	0	0	1	0	0	0
s33	1	1	0	0	1	1	1	1	0	0
s34	1	1	0	1	1	0	1	0	0	0
s35	1	0	0	0	0	0	0	0	0	0
s36	1	0	0	0	0	0	0	0	0	0
s37	1	0	0	0	0	0	0	0	0	0
s38	1	0	0	0	0	0	0	0	0	0
s39	0	0	0	0	1	1	0	0	0	1
s40	1	0	0	0	1	1	1	0	0	0
s41	1	0	0	0	0	0	0	0	0	0
s42	0	1	0	0	1	0	1	0	0	0
s43	1	0	0	0	0	0	0	0	0	0
s44	1	1	1	1	1	0	1	0	0	0
s45	1	0	0	0	0	0	0	0	0	0
s46	1	0	0	0	0	0	0	0	0	0
s47	1	1	0	0	0	0	1	0	0	0
s48	0	0	0	0	0	0	1	0	0	0
s49	1	0	0	0	0	0	1	0	0	1
s50	1	0	0	0	1	0	1	0	0	0
s51	1	0	1	0	0	0	1	0	0	0
s52	1	1	0	1	1	0	1	0	0	0
s53	0	0	0	0	0	1	0	1	0	0
s54	1	0	0	0	0	0	0	0	0	0

Table 7: School A Fall 2020 Specific Tool interaction matrix

	Ultimaker (Combined)	Dremel DigiLab	SLS Formiga (Professional Printer)	Stratasys	Resin	3D Scanner	Studio System Printer (Metal)	Don't Know	Other	Manual Mill	Manual Lathe	Waterjet	CNC Metal Mill	Drill Press	Other	CNC Wood Router	Drill Press	Table Saw	Chop Saw	Sander	Other	Study	Just Hung Out	Met with a Group	Helped by Another Student	Helped by a Staff Member	I helped Someone Else
s1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0
s2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
s3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
s4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
s5	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	1	1	1	1	0	0	0	0	0	0
s6	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
s7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
s8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0
s9	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	1	0	0	1	0	1	0	1	0	1	0
s10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
s11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
s12	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
s13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
s14	0	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0
s15	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
s16	0	1	1	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
s17	0	0	0	0	0	0	0	0	0	1	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	1	0
s18	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0
s19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	1
s20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
s21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
s22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
s23	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0
s24	1	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
s25	1	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0	0	0	1	1	1	0	1	1
s26	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
s27	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
s28	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
s29	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0
s30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	1	0	0	0
s31	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
s32	0	0	0	0	0	0	0	0	0	1	1	0	0	1	0	0	0	0	0	0	0	1	0	0	0	0	0
s33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0

Table 8: School B Fall 2020 General Tool interaction matrix

	3D Printers	Metal Tools	Laser Cutters	Wood Tools	Hand Tools	Electronic s Tools	Social Activities	Got / Gave Help	Soft Material Tools	Work Areas	Paint Booth	Volunteer on Duty	Other
s1	0	1	1	0	0	0	0	1	1	0	0	0	0
s2	1	0	0	0	0	0	0	0	1	0	0	0	0
s3	0	1	0	0	1	0	1	1	0	0	0	1	0
s4	1	0	0	0	1	1	0	0	0	0	0	0	0
s5	0	1	0	0	0	0	0	0	0	0	0	0	0
s6	1	0	0	0	0	0	0	0	0	0	0	0	0
s7	1	0	0	0	0	0	0	0	0	0	0	0	0
s8	1	1	1	0	1	0	1	0	0	0	0	0	0
s9	1	1	0	1	1	1	0	0	0	0	0	0	0
s10	0	0	0	0	0	0	1	0	0	0	0	0	0
s11	0	0	0	0	1	0	0	0	0	0	0	0	0
s12	1	0	0	1	0	0	1	0	0	0	0	0	1
s13	1	1	1	1	1	1	0	1	0	1	1	0	0
s14	1	0	0	1	0	0	1	0	0	0	0	0	0
s15	1	1	0	0	1	1	0	0	0	0	0	0	0
s16	1	1	1	0	1	1	0	0	0	0	0	0	0
s17	0	0	0	1	1	0	0	0	0	0	0	0	0
s18	1	0	1	1	0	0	0	0	0	0	0	1	0
s19	1	1	1	1	0	1	0	0	0	0	0	0	0
s20	1	1	0	0	1	1	1	0	1	0	0	0	0
s21	0	0	0	0	0	0	1	1	0	0	0	0	0
s22	0	1	0	0	1	0	0	0	0	0	0	0	0
s23	0	0	0	0	0	0	0	1	0	0	0	0	1
s24	1	0	0	1	0	0	0	0	0	1	0	0	0
s25	1	1	1	1	1	1	1	1	1	1	0	0	0
s26	1	0	0	0	0	0	0	0	0	0	0	0	0
s27	1	0	0	1	1	1	0	0	0	0	0	0	0
s28	1	0	1	1	1	0	0	0	0	0	0	0	0
s29	0	1	0	0	1	0	0	0	0	0	0	0	0
s30	1	1	1	1	1	1	1	1	0	0	1	0	0
s31	1	0	1	0	0	0	0	0	0	0	0	0	0
s32	1	1	0	1	1	0	0	0	0	0	0	0	0
s33	1	1	1	1	1	1	1	1	1	1	0	1	0
s34	0	0	0	0	0	0	0	0	1	0	0	0	0
s35	1	0	0	1	1	1	0	0	0	0	0	0	0
s36	1	0	1	1	1	1	1	0	1	0	0	1	0
s37	1	1	0	0	0	0	0	0	0	0	0	0	0
s38	1	1	1	1	1	0	1	1	1	0	0	1	0
s39	1	1	1	1	0	0	1	1	1	0	1	1	0
s40	0	0	0	1	1	1	0	0	1	0	0	1	0
s41	1	0	1	1	1	0	1	0	0	0	0	0	0
s42	1	1	1	1	1	1	1	1	1	1	1	1	0
s43	1	1	1	1	1	1	0	0	1	0	1	1	0
s44	1	1	1	1	1	1	1	1	1	0	0	1	0
s45	1	0	1	1	0	0	1	1	0	0	0	0	0
s46	1	1	1	1	1	1	1	1	0	0	0	1	0
s47	0	0	1	0	0	0	0	0	1	0	0	0	0
s48	1	1	1	1	1	0	0	0	1	1	1	1	0
s49	1	0	1	1	1	0	0	1	1	0	0	1	0
s50	1	1	1	1	1	1	0	0	1	1	0	1	0
s51	1	1	1	1	1	1	1	1	0	1	1	1	0
s52	1	0	0	0	1	1	1	1	0	1	0	0	0
s53	1	0	1	0	0	0	1	0	0	0	0	0	0
s54	1	1	1	1	1	0	1	1	1	0	0	0	0
s55	1	1	1	1	1	1	1	1	1	0	0	1	0
s56	1	0	1	1	1	1	1	0	0	0	1	0	0
s57	1	0	0	1	1	1	0	0	0	0	0	0	0

Table 9: School B Fall 2020 Specific Tool interaction Matrix

[illegible]

Table 10: School A Spring 2021 General Tool interaction matrix

[illegible]

Table 11: School A Spring 2021 Specific Tool interaction matrix

Table 12: School B Spring 2021 General Tool interaction matrix

	3D Printers	Metal Tools	Laser Cutters	Wood Tools	Hand Tools	Electronic Tools	Social Activities	Got / Gave Help	Soft Material Tools	Work Areas	Paint Booth	Volunteer on Duty	Other
111	1	0	1	0	1	0	1	1	1	0	0	1	0
112	1	1	1	1	1	1	0	1	1	1	1	1	0
113	1	0	1	1	0	0	1	1	1	1	1	0	0
114	1	1	1	0	1	0	0	0	1	1	1	0	0
115	1	1	1	0	0	0	0	0	0	0	0	0	0
116	1	0	1	1	1	1	0	1	1	1	0	1	0
117	1	1	1	0	1	0	0	0	0	0	0	0	0
118	1	1	1	1	1	1	1	1	1	1	0	1	0
119	1	0	1	0	0	0	0	0	0	1	0	0	0
120	1	1	0	1	1	0	0	1	0	0	1	0	0
121	0	0	0	1	0	0	0	0	0	0	0	0	0
122	1	0	0	1	0	0	0	0	0	1	0	0	0
123	1	0	0	0	0	0	0	0	0	0	0	0	0
124	1	0	0	0	0	0	0	0	1	0	0	0	0
125	1	1	1	1	1	0	1	1	0	1	0	0	0
126	0	0	0	0	1	0	0	0	1	0	0	0	0
127	1	1	1	1	1	1	0	1	0	1	0	0	0
128	1	0	0	0	0	0	0	0	0	0	0	0	0
129	1	0	1	1	1	1	1	1	1	1	1	0	0
130	1	1	1	1	1	1	1	1	1	1	1	1	1
131	1	1	1	1	1	1	1	1	1	1	0	0	0
132	1	0	1	1	1	1	1	1	0	0	0	0	0
133	1	0	0	0	0	0	0	0	0	0	0	0	0
134	0	0	0	0	0	0	0	0	1	0	0	0	0
135	1	0	1	1	1	1	1	0	0	1	0	0	0
136	1	1	1	1	1	1	1	1	0	0	0	0	0
137	1	0	0	0	0	0	0	0	0	0	0	0	0
138	1	1	1	1	1	1	1	1	1	1	1	0	0
139	1	0	0	0	0	0	1	0	1	0	0	1	0
140	1	0	1	1	1	0	0	0	0	1	0	0	0
141	1	0	1	1	1	1	0	0	0	1	1	0	0
142	0	0	0	1	0	0	0	0	0	1	0	0	0
143	0	1	0	0	1	0	0	0	0	1	0	0	0
144	1	1	1	1	1	1	0	1	0	0	0	0	0
145	0	0	0	0	0	0	0	0	1	0	0	0	0
146	1	0	0	0	1	0	0	0	0	0	0	0	0
147	1	1	0	1	1	1	1	0	0	0	0	0	0
148	1	0	1	1	1	1	1	1	0	1	0	1	0
149	1	0	0	0	0	0	0	0	0	0	0	0	0
150	0	1	1	1	1	1	1	0	0	0	0	0	0
151	0	0	0	0	0	0	1	0	0	0	0	0	0
152	1	1	1	1	1	1	0	1	1	0	0	0	0
153	1	0	1	1	1	0	0	0	0	0	0	0	0
154	0	0	0	0	0	0	0	0	0	0	0	0	1
155	0	1	1	1	1	0	0	0	0	0	1	0	0
156	1	1	1	1	1	1	1	0	1	0	1	1	0
157	1	1	1	1	1	1	0	0	0	1	0	0	0
158	1	0	1	0	0	0	0	0	0	0	0	1	0
159	1	0	0	0	0	0	0	0	0	0	0	0	0
160	1	1	1	1	1	0	0	0	0	1	0	0	0
161	0	0	1	0	0	0	0	0	0	0	0	0	0
162	1	0	1	0	1	0	1	0	1	1	0	0	0
163	0	0	1	1	0	0	0	0	0	0	0	0	0
164	0	0	1	0	0	0	0	0	0	0	0	0	0
165	1	1	1	1	1	1	1	1	0	0	0	1	0
166	1	1	1	1	1	1	0	1	1	0	1	1	0
167	0	0	0	0	1	1	0	0	0	0	0	0	0
168	1	1	1	1	0	0	0	0	0	0	0	0	0
169	1	0	1	0	1	1	0	0	0	0	0	0	0
170	1	0	0	0	0	0	1	0	0	0	0	0	1
171	1	1	0	0	0	0	1	0	0	1	1	0	0
172	0	0	0	0	0	1	0	1	0	0	0	0	0
173	1	0	1	1	0	0	0	0	0	0	0	0	0
174	1	0	0	0	0	0	1	0	0	1	0	0	0
175	1	0	0	0	0	0	0	0	0	0	0	0	0
176	1	0	0	0	0	0	0	0	0	0	0	0	0
177	1	0	1	0	0	0	0	0	0	1	0	0	0
178	1	0	0	0	0	0	0	0	0	0	0	0	0
179	1	0	0	1	0	0	0	0	0	0	0	0	0
180	1	1	1	1	1	1	0	1	0	0	0	1	0
181	0	0	0	0	0	0	1	0	0	0	0	0	0
182	1	0	0	0	0	0	0	0	0	0	0	0	0
183	0	0	1	0	1	0	1	1	0	0	0	0	0
184	1	0	0	0	0	0	0	0	0	0	0	0	0
185	0	0	0	0	0	0	0	1	0	0	0	0	0
186	1	1	0	0	0	0	1	0	0	1	0	0	0
187	1	0	1	0	0	0	0	0	0	0	0	0	0
188	0	0	0	1	0	0	1	1	0	0	0	0	0
189	1	0	0	0	0	0	0	0	0	0	0	0	0
190	1	0	1	0	0	0	0	0	1	1	0	0	0
191	1	0	1	1	1	0	0	0	0	1	0	0	0
192	0	1	0	0	0	0	0	0	0	0	0	0	0
193	0	0	0	0	0	0	0	0	0	0	0	0	1
194	1	0	0	0	0	0	0	0	0	0	0	0	0

Table 13: School B Spring 2021 Specific Tool interaction matrix

Table 14: School A Spring 2022 General Tool interaction matrix

	3D Printers	Metal Tools	Craftlands	Electronic Tools	Wood Tools	Handheld Tools	Laser Cutter	CAD Station	Studied	Got Help	Paint Booth	Other
s1	1	1	0	0	0	1	0	1	1	1	1	0
s2	0	1	1	0	0	1	0	0	1	1	0	1
s3	1	0	0	0	0	1	0	1	1	1	0	0
s4	1	0	0	0	0	1	0	0	1	1	0	0
s5	1	1	0	0	0	1	0	1	1	1	0	1
s6	0	1	0	1	1	1	0	0	0	0	1	0
s7	1	1	0	0	0	0	0	0	0	0	0	0
s8	1	1	0	0	0	1	0	0	0	0	0	0
s9	0	1	0	0	0	1	0	1	1	0	0	0
s10	1	1	0	0	0	0	0	0	0	0	0	0
s11	1	1	0	0	0	1	0	1	1	1	0	0
s12	1	1	0	0	0	0	0	0	0	0	0	0
s13	0	1	0	0	0	1	1	0	1	1	1	1
s14	0	1	0	1	1	1	0	0	0	1	1	0
s15	1	1	0	1	0	1	1	0	1	1	0	0
s16	1	1	0	0	0	0	0	0	0	0	0	0
s17	1	1	1	0	0	1	0	1	1	1	0	0
s18	1	1	0	1	1	1	0	1	0	0	0	0
s19	0	0	0	0	0	0	0	0	1	0	0	0
s20	0	1	0	1	1	1	0	0	0	0	1	0
s21	1	1	0	0	0	1	1	1	0	0	0	0
s22	1	1	0	0	1	1	0	1	1	1	1	0
s23	0	0	0	0	0	0	0	0	1	1	0	0
s24	0	0	0	0	0	1	0	0	0	0	0	0
s25	0	0	0	0	0	1	0	0	0	1	0	0
s26	1	0	1	0	1	1	0	1	0	0	0	0
s27	1	0	0	1	0	1	0	0	1	0	0	0
s28	1	0	0	0	0	0	0	0	0	0	0	0
s29	0	1	0	1	0	1	0	0	0	0	0	0
s30	1	0	0	0	1	1	0	1	0	0	0	0
s31	0	1	0	1	0	0	0	0	0	0	0	0
s32	1	0	0	0	0	0	0	0	0	0	0	0
s33	1	0	0	0	0	0	0	0	1	1	0	1
s34	0	0	0	0	0	1	0	0	1	0	0	0
s35	1	1	0	0	0	1	0	0	1	0	0	0
s36	1	1	0	0	0	1	0	0	1	0	0	0
s37	1	1	0	0	0	1	0	1	1	1	0	1
s38	0	1	0	0	0	1	0	0	1	1	1	0
s39	1	0	0	1	0	1	0	1	0	1	0	0
s40	1	0	0	0	1	0	0	0	0	0	0	0
s41	0	1	0	1	1	1	0	0	0	1	1	0
s42	0	1	0	0	0	1	0	0	1	0	0	0
s43	0	0	0	1	0	0	0	1	1	1	0	0
s44	1	1	0	0	0	1	0	0	1	1	0	0
s45	1	0	0	1	0	0	0	0	1	1	0	0
s46	1	0	0	0	0	0	0	0	0	0	0	0
s47	0	0	0	0	0	0	0	0	1	0	0	1
s48	0	0	0	1	0	1	0	0	1	1	0	0
s49	1	1	0	1	0	1	0	0	1	0	0	0
s50	1	1	0	1	1	1	0	0	0	1	0	0
s51	0	1	0	0	1	1	1	0	0	1	1	0
s52	1	1	0	0	1	1	0	1	1	1	1	0
s53	1	0	0	1	0	1	0	1	1	1	0	0
s54	1	1	0	1	1	1	0	0	0	0	0	0
s55	0	1	0	1	1	1	0	1	0	1	0	0
s56	1	1	0	0	1	1	0	0	1	1	0	1
s57	1	1	0	0	0	1	0	1	0	1	0	1
s58	0	1	0	1	0	1	0	0	0	1	0	0
s59	1	1	0	1	0	0	0	0	0	1	0	0
s60	1	0	0	0	0	0	0	1	0	0	0	0
s61	0	0	0	0	0	0	0	0	0	0	0	1
s62	1	0	0	0	0	0	1	0	0	0	0	0
s63	1	0	0	0	0	0	0	0	0	0	0	1
s64	1	1	0	0	0	1	0	0	0	0	0	0
s65	1	1	0	0	0	1	0	1	1	1	0	0
s66	1	1	0	0	0	0	0	0	0	0	0	0
s67	1	1	0	0	0	1	0	0	0	0	0	0
s68	0	0	0	1	0	1	0	0	1	1	0	1
s69	1	0	1	0	1	1	1	0	1	0	0	0
s70	1	0	0	0	0	0	0	0	0	0	0	0
s71	0	1	0	1	0	1	0	0	1	1	0	0
s72	0	1	0	1	0	1	0	0	0	1	0	1
s73	1	1	0	1	0	1	0	1	1	0	0	0
s74	1	1	0	0	0	1	0	0	0	0	0	1
s75	1	1	0	0	1	1	0	0	0	0	0	0
s76	0	0	0	0	0	1	0	1	0	0	0	0
s77	0	1	0	0	0	1	0	0	0	0	0	1

Table 15: School A Spring 2022 Specific Tool interaction matrix

Table 16: School B Spring 2022 General Tool interaction matrix

	3D Printers	Metal Tools	Craftsmans	Electronic Tools	Wood Tools	Handheld Tools	Laser Cutter	CAD Station	Studied	Got Help	Prototyping	Paint Booth	Other
11	1	0	1	0	1	1	1	1	0	0	0	1	0
12	0	1	0	1	1	1	1	0	0	0	0	0	0
13	1	0	0	1	0	0	0	0	0	0	0	0	0
14	1	1	0	0	0	1	0	1	0	1	0	0	0
15	1	0	0	0	1	1	1	0	0	1	0	0	0
16	1	1	0	0	1	1	1	0	0	0	0	0	0
17	1	0	1	0	1	0	1	0	1	1	0	0	0
18	1	0	0	0	1	0	1	0	0	1	0	0	0
19	1	1	1	1	0	0	1	1	1	0	0	1	0
110	1	1	0	0	1	0	0	1	1	0	0	0	0
111	0	0	0	0	1	0	1	0	0	0	0	0	0
112	1	1	0	1	0	1	1	1	0	1	0	0	0
113	0	1	0	1	1	1	1	0	1	0	0	0	0
114	1	0	1	0	1	0	1	0	0	0	0	0	0
115	0	0	0	0	0	0	1	0	0	0	0	0	0
116	1	1	1	1	1	1	1	1	1	1	1	1	0
117	1	0	1	0	1	1	1	1	1	1	1	1	0
118	1	1	1	1	1	1	1	0	1	1	1	1	0
119	1	1	1	1	1	1	1	0	1	1	1	1	0
120	0	0	1	0	0	0	0	0	0	0	0	0	0
121	1	1	0	1	0	1	0	0	1	0	1	0	0
122	1	1	1	0	0	1	0	1	1	0	0	0	0
123	1	0	0	0	1	1	1	0	0	0	0	1	0
124	1	0	1	0	0	0	0	1	1	1	0	1	0
125	1	0	0	0	0	0	0	1	0	0	0	0	0
126	1	1	0	0	1	1	1	1	0	0	0	0	0
127	0	0	1	0	0	0	0	0	0	0	0	0	0
128	0	0	0	0	0	0	0	1	1	0	0	0	0
129	0	0	0	0	0	0	0	1	1	0	0	0	0
130	1	1	0	0	1	0	1	0	0	0	0	0	0
131	1	1	0	1	1	1	1	0	0	0	0	0	0
132	1	1	0	0	0	0	0	0	0	0	0	0	0
133	1	0	1	1	1	1	1	0	1	1	0	1	0
134	1	0	0	0	1	0	1	1	0	0	0	0	0
135	1	1	0	0	1	1	0	1	0	1	0	0	0
136	1	1	1	1	1	1	1	1	1	1	0	1	0
137	1	1	1	1	1	1	1	0	1	1	1	1	0
138	1	1	1	1	1	1	1	1	1	1	1	1	0
139	1	1	0	0	1	0	1	0	0	0	0	0	0
140	1	1	1	1	1	1	1	1	1	1	1	1	0
141	0	0	0	0	0	0	0	0	1	0	0	0	1
142	0	0	0	0	0	0	1	0	0	0	0	0	0
143	1	1	0	0	1	1	0	0	0	1	0	0	0
144	1	1	1	1	1	1	1	0	1	1	0	1	0
145	1	0	0	0	0	0	0	0	0	0	0	0	0
146	1	1	1	1	1	0	1	1	0	1	0	0	0
147	1	1	0	0	1	1	0	1	0	0	0	0	0
148	1	0	0	0	0	0	0	0	0	0	0	0	0
149	1	1	1	0	0	1	1	0	1	1	1	1	0
150	1	0	0	0	0	0	0	0	0	0	0	0	0
151	0	0	0	0	0	0	0	0	0	1	0	0	1
152	1	1	1	1	1	1	1	1	1	1	1	1	1
153	1	1	0	1	1	1	1	0	0	1	0	0	0
154	1	0	0	1	0	0	0	0	0	0	0	0	0
155	1	1	0	1	1	1	1	0	0	0	0	0	0
156	1	0	1	0	1	0	1	0	0	0	0	0	0
157	1	1	0	0	1	1	1	0	0	0	0	0	0
158	1	0	0	0	0	0	1	0	0	0	0	0	0
159	1	1	1	0	1	1	1	0	1	1	0	0	0
160	1	0	0	0	0	0	0	0	0	0	0	0	0
161	1	1	0	0	0	1	0	0	1	0	0	0	0
162	1	0	1	1	1	1	0	0	0	0	0	0	0
163	1	1	0	1	1	1	1	0	1	1	0	0	0
164	0	0	0	0	1	1	1	1	1	1	0	1	0
165	0	1	0	0	1	1	1	0	0	0	0	0	0
166	1	0	1	0	1	1	1	0	0	1	0	0	0
167	1	1	1	0	0	1	1	0	1	1	0	0	0
168	1	1	0	0	0	1	1	1	1	0	0	0	0
169	1	1	1	0	1	1	1	1	1	1	1	1	0
170	0	0	0	0	1	1	1	0	0	0	0	0	0
171	0	1	0	1	0	0	1	0	1	1	0	0	0
172	1	1	0	0	1	1	0	0	0	1	0	0	0
173	0	0	0	1	0	0	0	0	1	0	0	0	0
174	0	0	0	1	0	0	1	0	0	0	0	0	0
175	1	1	1	1	1	1	1	1	1	1	1	1	0
176	0	1	0	0	1	1	0	0	0	1	0	0	0
177	1	1	0	0	1	1	1	0	0	0	0	0	0
178	1	0	0	1	1	1	0	0	1	0	0	0	0
179	1	0	0	0	0	0	0	0	0	0	0	0	0
180	0	0	0	0	1	1	0	0	0	1	0	0	0
181	1	1	0	1	1	0	0	0	0	0	0	0	0
182	0	0	0	0	1	1	0	0	0	1	0	0	0
183	1	1	1	1	0	1	1	0	0	1	0	0	0
184	1	1	0	1	0	0	1	0	0	0	0	1	0
185	1	1	0	0	1	1	0	0	1	1	0	0	0
186	1	1	0	0	1	1	1	0	0	0	0	0	0
187	1	1	1	1	1	1	1	1	1	1	1	1	0
188	0	1	0	1	0	0	0	0	0	1	0	0	0
189	1	1	0	1	1	1	1	1	1	0	0	0	0
190	1	0	0	0	1	0	1	1	1	0	0	0	0
191	1	1	0	0	1	1	0	0	0	1	0	0	0

Table 17: School B Spring 2022 Specific Tool interaction matrix

[illegible]

Table 18: School A Fall 2022 General Tool interaction matrix

	3D Printers	Metal Tools	Crafts	Electronic Tools	Wood Tools	Handheld Tools	Laser Cutter	CAD Station	Studied	Got Help	PI On Duty	Paint Booth	Other
s1	0	0	0	0	1	0	0	1	1	1	0	0	0
s2	0	0	0	1	0	0	0	0	1	1	0	0	0
s3	0	0	0	0	0	0	0	0	1	0	0	0	0
s4	0	0	0	1	0	0	0	0	1	1	0	0	0
s5	0	0	0	1	0	0	0	0	0	0	0	0	0
s6	0	0	0	1	0	1	0	0	1	1	0	0	1
s7	1	0	0	1	0	1	0	0	1	1	0	0	0
s8	1	0	0	1	0	0	0	1	1	0	0	0	0
s9	0	0	0	0	0	1	0	0	0	0	0	0	1
s10	0	0	1	1	0	1	0	1	0	0	0	0	0
s11	0	0	0	1	0	1	0	1	0	1	0	0	0
s12	0	0	0	0	1	0	0	0	0	0	0	0	0
s13	0	0	0	1	0	0	0	0	1	0	0	0	0
s14	0	1	0	0	0	1	0	0	0	0	0	0	0
s15	1	0	1	0	0	0	0	0	0	0	0	0	1
s16	0	0	0	0	0	0	0	0	1	0	0	0	0
s17	0	0	0	1	0	1	0	0	1	1	0	0	0
s18	0	0	0	1	0	1	0	0	0	0	0	0	1
s19	1	0	0	1	0	1	0	0	1	0	0	0	0
s20	1	1	0	1	1	1	0	0	1	0	0	0	0
s21	1	1	0	0	0	0	0	0	1	1	0	0	1
s22	0	0	0	0	0	0	0	0	1	0	0	0	0
s23	0	0	0	1	0	1	0	1	1	0	0	0	0
s24	1	0	0	0	0	1	0	1	0	0	0	0	0
s25	1	1	0	0	0	1	0	1	0	0	0	0	0
s26	1	0	0	1	0	1	1	1	0	0	0	0	0
s27	1	1	0	0	0	0	0	0	0	0	0	1	0
s28	1	1	0	0	0	0	0	1	1	0	0	0	0
s29	1	1	0	0	0	1	0	0	0	0	0	0	0
s30	1	1	0	0	0	1	0	0	0	0	0	0	0
s31	1	1	0	0	0	1	0	0	0	0	0	0	0
s32	1	1	0	0	0	1	0	0	0	0	0	0	0
s33	1	1	0	0	0	1	0	0	0	1	0	0	0
s34	1	1	0	0	0	1	0	0	1	0	0	0	0
s35	1	1	0	0	0	0	0	0	0	0	0	0	0
s36	1	1	0	0	0	0	0	0	1	0	0	0	0
s37	1	1	0	1	0	1	0	0	0	0	0	0	0
s38	1	1	0	0	0	1	0	1	1	0	0	0	1
s39	0	0	0	1	0	0	0	0	0	0	0	0	0
s40	1	0	0	0	0	0	0	0	0	0	0	0	0
s41	1	0	0	0	0	0	0	0	0	0	0	0	0
s42	1	1	0	0	0	1	0	0	0	0	0	0	0
s43	0	1	0	0	0	0	1	0	0	0	0	0	1
s44	1	0	0	0	0	1	0	0	0	0	0	0	0
s45	0	0	1	1	0	0	0	0	1	1	0	0	0
s46	0	0	0	0	0	1	0	1	0	0	0	0	0
s47	1	0	0	0	0	0	0	1	1	0	0	0	0
s48	1	0	0	0	0	0	0	0	0	0	0	0	0
s49	1	0	0	0	0	0	0	0	0	0	0	0	0
s50	0	1	0	0	0	0	0	0	0	0	0	0	0
s51	0	1	0	0	0	0	0	0	0	0	0	0	0
s52	1	0	0	1	1	1	0	0	0	0	0	0	0
s53	0	0	0	1	0	1	0	1	0	0	0	0	0
s54	1	1	0	1	0	0	0	0	1	1	0	0	0
s55	0	0	0	1	0	0	0	0	1	1	0	0	0
s56	1	0	0	0	0	0	0	0	0	0	0	0	1
s57	1	0	0	0	0	0	0	0	0	1	0	0	0
s58	0	0	0	1	1	1	0	0	1	0	0	0	0
s59	0	0	0	0	0	0	0	0	1	1	0	0	0
s60	1	1	1	0	0	1	0	0	1	1	0	0	0
s61	1	1	0	0	0	0	0	0	0	0	0	0	0
s62	0	0	0	0	0	0	0	0	1	1	0	0	0
s63	1	1	0	1	1	1	0	1	1	1	0	0	0
s64	0	0	1	0	0	0	0	0	0	0	0	0	0
s65	0	0	0	0	0	0	0	0	1	0	0	0	0
s66	1	0	0	0	0	0	0	0	0	0	0	0	0
s67	0	0	0	1	0	0	0	0	0	0	0	0	0
s68	0	0	0	1	0	0	0	1	1	0	0	0	0
s69	0	0	0	0	1	1	0	0	1	1	0	0	0
s70	1	0	0	0	0	0	0	0	0	0	0	0	0
s71	0	0	0	1	0	1	0	1	0	0	0	0	1
s72	0	0	0	1	0	0	0	0	1	1	0	1	0
s73	0	0	0	0	0	0	0	0	1	0	0	0	0
s74	0	0	0	1	0	0	0	0	1	1	0	0	0
s75	0	0	0	0	1	0	0	1	0	0	0	0	0
s76	0	1	0	1	1	1	0	1	0	0	0	0	0
s77	1	0	1	1	0	0	0	1	1	0	0	0	0
s78	0	0	0	1	0	1	0	1	1	0	0	0	0
s79	1	0	0	0	0	1	0	0	0	0	0	0	0
s80	0	0	0	0	1	1	0	0	1	0	0	0	0

Table 20: School B Fall 2022 General Tool interaction matrix

ID	Material	Electronic	Wood	Handheld	Laser	CAD	Router	Lathe	3D	Print	Other
Printer	Table	Router	Table	Table	Table	Table	Table	Table	Table	Table	Table
1	1	0	1	1	1	0	0	0	0	0	0
2	1	0	1	1	1	0	0	0	0	0	0
3	1	0	1	1	1	0	0	0	0	0	0
4	1	0	1	1	1	0	0	0	0	0	0
5	1	0	1	1	1	0	0	0	0	0	0
6	1	0	1	1	1	0	0	0	0	0	0
7	1	0	1	1	1	0	0	0	0	0	0
8	1	0	1	1	1	0	0	0	0	0	0
9	1	0	1	1	1	0	0	0	0	0	0
10	1	0	1	1	1	0	0	0	0	0	0
11	1	0	1	1	1	0	0	0	0	0	0
12	1	0	1	1	1	0	0	0	0	0	0
13	1	0	1	1	1	0	0	0	0	0	0
14	1	0	1	1	1	0	0	0	0	0	0
15	1	0	1	1	1	0	0	0	0	0	0
16	1	0	1	1	1	0	0	0	0	0	0
17	1	0	1	1	1	0	0	0	0	0	0
18	1	0	1	1	1	0	0	0	0	0	0
19	1	0	1	1	1	0	0	0	0	0	0
20	1	0	1	1	1	0	0	0	0	0	0
21	1	0	1	1	1	0	0	0	0	0	0
22	1	0	1	1	1	0	0	0	0	0	0
23	1	0	1	1	1	0	0	0	0	0	0
24	1	0	1	1	1	0	0	0	0	0	0
25	1	0	1	1	1	0	0	0	0	0	0
26	1	0	1	1	1	0	0	0	0	0	0
27	1	0	1	1	1	0	0	0	0	0	0
28	1	0	1	1	1	0	0	0	0	0	0
29	1	0	1	1	1	0	0	0	0	0	0
30	1	0	1	1	1	0	0	0	0	0	0
31	1	0	1	1	1	0	0	0	0	0	0
32	1	0	1	1	1	0	0	0	0	0	0
33	1	0	1	1	1	0	0	0	0	0	0
34	1	0	1	1	1	0	0	0	0	0	0
35	1	0	1	1	1	0	0	0	0	0	0
36	1	0	1	1	1	0	0	0	0	0	0
37	1	0	1	1	1	0	0	0	0	0	0
38	1	0	1	1	1	0	0	0	0	0	0
39	1	0	1	1	1	0	0	0	0	0	0
40	1	0	1	1	1	0	0	0	0	0	0
41	1	0	1	1	1	0	0	0	0	0	0
42	1	0	1	1	1	0	0	0	0	0	0
43	1	0	1	1	1	0	0	0	0	0	0
44	1	0	1	1	1	0	0	0	0	0	0
45	1	0	1	1	1	0	0	0	0	0	0
46	1	0	1	1	1	0	0	0	0	0	0
47	1	0	1	1	1	0	0	0	0	0	0
48	1	0	1	1	1	0	0	0	0	0	0
49	1	0	1	1	1	0	0	0	0	0	0
50	1	0	1	1	1	0	0	0	0	0	0
51	1	0	1	1	1	0	0	0	0	0	0
52	1	0	1	1	1	0	0	0	0	0	0
53	1	0	1	1	1	0	0	0	0	0	0
54	1	0	1	1	1	0	0	0	0	0	0
55	1	0	1	1	1	0	0	0	0	0	0
56	1	0	1	1	1	0	0	0	0	0	0
57	1	0	1	1	1	0	0	0	0	0	0
58	1	0	1	1	1	0	0	0	0	0	0
59	1	0	1	1	1	0	0	0	0	0	0
60	1	0	1	1	1	0	0	0	0	0	0
61	1	0	1	1	1	0	0	0	0	0	0
62	1	0	1	1	1	0	0	0	0	0	0
63	1	0	1	1	1	0	0	0	0	0	0
64	1	0	1	1	1	0	0	0	0	0	0
65	1	0	1	1	1	0	0	0	0	0	0
66	1	0	1	1	1	0	0	0	0	0	0
67	1	0	1	1	1	0	0	0	0	0	0
68	1	0	1	1	1	0	0	0	0	0	0
69	1	0	1	1	1	0	0	0	0	0	0
70	1	0	1	1	1	0	0	0	0	0	0
71	1	0	1	1	1	0	0	0	0	0	0
72	1	0	1	1	1	0	0	0	0	0	0
73	1	0	1	1	1	0	0	0	0	0	0
74	1	0	1	1	1	0	0	0	0	0	0
75	1	0	1	1	1	0	0	0	0	0	0
76	1	0	1	1	1	0	0	0	0	0	0
77	1	0	1	1	1	0	0	0	0	0	0
78	1	0	1	1	1	0	0	0	0	0	0
79	1	0	1	1	1	0	0	0	0	0	0
80	1	0	1	1	1	0	0	0	0	0	0
81	1	0	1	1	1	0	0	0	0	0	0
82	1	0	1	1	1	0	0	0	0	0	0
83	1	0	1	1	1	0	0	0	0	0	0
84	1	0	1	1	1	0	0	0	0	0	0
85	1	0	1	1	1	0	0	0	0	0	0
86	1	0	1	1	1	0	0	0	0	0	0
87	1	0	1	1	1	0	0	0	0	0	0
88	1	0	1	1	1	0	0	0	0	0	0
89	1	0	1	1	1	0	0	0	0	0	0
90	1	0	1	1	1	0	0	0	0	0	0
91	1	0	1	1	1	0	0	0	0	0	0
92	1	0	1	1	1	0	0	0	0	0	0
93	1	0	1	1	1	0	0	0	0	0	0
94	1	0	1	1	1	0	0	0	0	0	0
95	1	0	1	1	1	0	0	0	0	0	0
96	1	0	1	1	1	0	0	0	0	0	0
97	1	0	1	1	1	0	0	0	0	0	0
98	1	0	1	1	1	0	0	0	0	0	0
99	1	0	1	1	1	0	0	0	0	0	0
100	1	0	1	1	1	0	0	0	0	0	0
101	1	0	1	1	1	0	0	0	0	0	0
102	1	0	1	1	1	0	0	0	0	0	0
103	1	0	1	1	1	0	0	0	0	0	0
104	1	0	1	1	1	0	0	0	0	0	0
105	1	0	1	1	1	0	0	0	0	0	0
106	1	0	1	1	1	0	0	0	0	0	0
107	1	0	1	1	1	0	0	0	0	0	0
108	1	0	1	1	1	0	0	0	0	0	0
109	1	0	1	1	1	0	0	0	0	0	0
110	1	0	1	1	1	0	0	0	0	0	0
111	1	0	1	1	1	0	0	0	0	0	0
112	1	0	1	1	1	0	0	0	0	0	0
113	1	0	1	1	1	0	0	0	0	0	0
114	1	0	1	1	1	0	0	0	0	0	0
115	1	0	1	1	1	0	0	0	0	0	0
116	1	0	1	1	1	0	0	0	0	0	0
117	1	0	1	1	1	0	0	0	0	0	0
118	1	0	1	1	1	0	0	0	0	0	0
119	1	0	1	1	1	0	0	0	0	0	0
120	1	0	1	1	1	0	0	0	0	0	0
121	1	0	1	1	1	0	0	0	0	0	0
122	1	0	1	1	1	0	0	0	0	0	0
123	1	0	1	1	1	0	0	0	0	0	0
124	1	0	1	1	1	0	0	0	0	0	0
125	1	0	1	1	1	0	0	0	0	0	0
126	1	0	1	1	1	0	0	0	0	0	0
127	1	0	1	1	1	0	0	0	0	0	0
128	1	0	1	1	1	0	0	0	0	0	0
129	1	0	1	1	1	0	0	0	0	0	0
130	1	0	1	1	1	0	0	0	0	0	0
131	1	0	1	1	1	0	0	0	0	0	0
132	1	0	1	1	1	0	0	0	0	0	0
133	1	0	1	1	1	0	0	0	0	0	0
134	1	0	1	1	1	0	0	0	0	0	0
135	1	0	1	1	1	0	0	0	0	0	0
136	1	0	1	1	1	0	0	0	0	0	0
137	1	0	1	1	1	0	0	0	0	0	0
138	1	0	1	1	1	0	0	0	0	0	0
139	1	0	1	1	1	0	0	0	0	0	0
140	1	0	1	1	1	0	0	0	0	0	0
141	1	0	1	1	1	0	0	0	0	0	0
142	1	0	1	1	1	0	0	0	0	0	0
143	1	0	1	1	1	0	0	0	0	0	0
144	1	0	1	1	1	0	0	0	0	0	0
145	1	0	1	1	1	0	0	0	0	0	0
146	1	0	1	1	1	0	0	0	0	0	0
147	1	0	1	1	1	0	0	0	0	0	0
148	1	0	1	1	1	0	0	0	0	0	0
149	1	0	1	1	1	0	0	0	0	0	0
150	1	0	1	1	1	0	0	0	0	0	0
151	1	0	1	1	1	0	0	0	0	0	0
152	1	0	1	1	1	0	0	0	0	0	0
153	1	0	1	1	1	0	0	0	0	0	0
154	1	0	1	1	1	0	0	0	0	0	0
155	1	0	1	1	1	0	0	0	0	0	0

Table 21: School B Fall 2022 Specific Tool interaction matrix

--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

APPENDIX B: TOOL USE SURVEY

Due to size constraints, contained as a separate attachment

APPENDIX C: HUB TOOL ANALYSIS SUPPLEMENTARY PLOTS AND TABLES

Table 22: School A P&Z Values

		Fall 2020		Spring 2021		Spring 2022		Fall 2022	
	Tool	Participation	Z-value	Participation	Z-value	Participation	Z-value	Participation	Z-value
T1	3D Printers	0.60336	4.2888	0.63437	7.5361	0.74386	4.3647	0.42472	4.3323
T2	Metal Tools	0.13265	1.9353	0.70439	5.3882	0.75694	2.5994	0.29514	2.7926
T3	Laser Cutter	0.32	0.46168	0.5	0.26508	0.57143	0.42931	0	0.13538
T4	Wood Tools	0	0.19961	0.43878	3.1241	0.609	1.2824	0.59259	1.3723
T5	Hand Tools	0.44291	1.7184	0.61547	3.6965	0.76562	3.0463	0.6498	2.4505
T6	Electronics	0.27778	3.1241	0.5858	3.6148	0.61806	2.3705	0.54913	3.0681
T7	Social Activities	0.47333	3.671	0.32812	3.8704	0.75154	3.3825	0.50554	3.7821
T8	Got/Gave Help	0.64198	0.73508	0.50889	2.827	0.73183	2.6425	0.405	1.997
T9	Soft Material Tools	0	-0.3408	0	-0.47733	0.375	0.16696	0.66667	0.36113
T10	Other	0.31405	2.9915	0.37877	4.8	0.52041	2.846	0.51852	2.5722
T11	3D Printers			0	0.73508	0.29752	1.2824	0.5	-0.45773
T12	Metal Tools			0.345	2.1313	0.7483	1.6041	0.705	2.8891

Table 23: School B General Tool P&Z Values

		Fall 2020		Spring 2021		Spring 2022		Fall 2022	
T1	3D Printers	0.73	3.52	0.76	5.00	0.70	4.03	0.80	5.20
T2	Metal Tools	0.72	2.15	0.62	2.29	0.70	2.96	0.66	4.09
T3	Laser Cutters	0.68	2.34	0.76	3.28	0.63	3.15	0.76	4.22
T4	Wood Tools	0.74	2.09	0.71	2.46	0.62	3.58	0.74	3.63
T5	Hand Tools	0.71	3.00	0.68	2.63	0.67	2.85	0.69	4.35
T6	Electronics Tools	0.64	2.24	0.69	2.14	0.73	2.47	0.58	4.09
T7	Social Activities	0.64	2.34	0.60	2.63	0.64	2.51	0.75	3.86
T8	Got / Gave Help	0.54	1.84	0.60	2.14	0.69	1.80	0.76	4.51
T9	Soft Material Tools	0.61	1.09	0.74	2.67	0.50	2.33	0.73	5.29
T10	Other	0.00	-0.20	0.38	1.50	0.44	1.15	0.00	-0.11
T11	Paint Booth	0.53	0.54	0.58	0.58	0.33	1.80	0.76	3.18
T12	Work Areas	0.62	0.54	0.73	2.28	0.54	1.62	0.69	2.15

T13	Volunteer on Duty	0.68	1.08	0.60	1.54			0.63	1.07
T14	Prototyping					0.14	0.91		

Table 24: Specific Tool Analysis Participation and Z-Value

	Fall 2020			Spring 2021			Spring 2022			Fall 2022		
Tool Number	Tool	Participation	Z- value	Tool	Participation	Z- value	Tool	Participation	Z- value	Tool	Participation	Z-value
T1	Ultimaker (Combined)	0.62	2.04	Laser Cutter	0.44	0.11	Laser Cutter	0.59	-0.17	Hammers	0.54	0.62
T2	Dremel DigiLab	0.50	-0.58	Vinyl/Paper Cutter			Vinyl/Paper Cutter			Pliers	0.64	1.14
T3	SLS Formiga (Professional Printer)	0.00	1.15	Foam Cutter			Foam Cutter	0.44	-0.80	Vice Grips	0.51	0.35
T4	Stratasys			Sewing Machine			Sewing Machine	0.00	-1.39	Clamps	0.40	0.88
T5	Resin			Paint Booth	0.50	-0.64	Paint Booth	0.17	-0.14	Screw Drivers	0.68	1.40
T6	3D Scanner	0.00	-0.58	All Hand Tools	0.80	0.46	All Hand Tools	0.73	2.32	Hand Drills	0.67	0.66
T7	Studio System Printer (Metal)			Hammers	0.63	0.83	Hammers	0.61	1.27	Angle Grinder	0.50	-0.43
T8	Don't Know			Pliers	0.76	-0.45	Pliers	0.62	1.07	Chisels	0.38	-0.69

T9	Other	0.00	-0.94	Vice Grips	0.45	0.08	Vice Grips	0.61	0.87	Measuring Tape	0.62	0.62
T10	Manual Mill	0.68	1.36	Clams (C-CLAMP or other	0.79	-0.26	Clams (C-CLAMP or other	0.63	0.67	Table Vice	0.00	-0.69
T11	Manual Lathe	0.61	0.51	Screw Drivers	0.80	0.78	Screw Drivers	0.73	2.32	Glue Gun	0.64	-0.79
T12	Waterjet	0.44	-1.19	Hand Drills	0.81	-0.45	Hand Drills	0.75	0.97	Wire Cutters	0.53	0.65
T13	CNC Metal Mill	0.00	-1.19	Angle Grinder	0.38	-0.67	Angle Grinder	0.46	0.26	Hand Saw	0.63	-0.96
T14	Drill Press	0.44	0.51	Chisels	0.00	-0.79	Chisels	0.45	-1.15	Dremel	0.50	-1.16
T15	Other	0.00	-0.49	Measuring Tape	0.76	0.08	Measuring Tape	0.68	1.27	Tap & Dye Set	0.38	-0.43
T16	CNC Wood Router			Table Vice	0.46	0.83	Table Vice	0.48	0.67	Scissors	0.66	-0.03
T17	Drill Press	0.00	0.00	Glue Gun	0.00	-0.55	Glue Gun	0.72	-0.90	Tin Snips	0.00	-1.17
T18	Table Saw	0.00	-0.94	Wire Cutters	0.53	0.16	Wire Cutters	0.71	0.09	X-ACTO Knife	0.38	-0.69
T19	Chop Saw	0.00	-0.94	Hand Saw	0.63	-0.10	Hand Saw	0.44	0.06	Other (hand tools)	0.38	1.14
T20	Sander	0.38	0.94	Dremel	0.78	-0.26	Dremel	0.69	-0.24	Dremel DigiLab	0.28	0.29
T21	Other			Tap & Dye set	0.37	0.83	Tap & Dye set	0.54	0.06	Ultimaker	0.54	1.38
T22	Study	0.58	1.68	Scissors	0.63	-0.10	Scissors	0.74	0.54	SLS		
T23	Just Hung Out	0.00	0.71	Tin Snips	0.00	-1.41	Tin Snips	0.61	-0.57	Stratasys	0.63	-0.79
T24	Met with a Group	0.60	2.99	X-ACTO Knife	0.50	-0.71	X-ACTO Knife	0.74	-0.35	Resin	0.00	0.66

T25	Helped by Another Student	0.00	-0.20	Dremel Digilab	0.36	3.84	Other	0.56	-1.55	3D Scanner		
T26	Helped by a Staff Member	0.67	0.71	Ultimaker S5	0.64	2.78	Dremel Digilab	0.72	-0.75	Studio System Printer		
T27	I helped Someone Else	0.44	-0.20	Ultimaker 3	0.60	3.45	Ultimaker S5	0.56	-0.17	Scanner 3D		
T28				Ultimaker 2+ Extended	0.63	1.15	Ultimaker 3	0.38	-0.17	Don't Know		
T29				SLS Professional	0.00	-0.36	Ultimaker 2+ Extended	0.00		Other	0.00	-0.96
T30				Strasys 3D printer	0.00	0.69	SLS Professional			Band Saw	0.49	2.47
T31				Resin 3D printer	0.56	0.26	Strasys 3D printer			CNC Metal Mill	0.44	-0.07
T32				3D Scanner	0.00	-0.71	Resin 3D printer	0.44	-0.57	Manual Mill	0.38	1.74
T33				Studio System Printer (Metal)			3D Scanner	0.00	-0.90	CNC Lathe	0.44	-0.96
T34				Scanner 3D			Studio System Printer (Metal)	0.00	-0.90	Drill Press	0.00	-0.07
T35				Band Saw (Metal)	0.58	1.82	Scanner 3D			Electric Discharge Machine		

T36				CNC Metal Mill	0.71	2.90	Band Saw (Metal)	0.57	1.47	Surface Grinder	0.56	-0.69
T37				Manual Mill	0.48	3.61	CNC Metal Mill	0.78	-1.08	Injection Molder	0.00	-1.16
T38				CNC Lathe	0.77	0.79	Manual Mill	0.53	1.47	Vacuum Former		
T39				Manual Lathe	0.27	4.05	CNC Lathe	0.38	-0.35	Waterjet	0.00	1.38
T40				Drill Press (Metal)	0.57	0.03	Manual Lathe	0.46	0.87	Hydraulic Press	0.00	-0.79
T41				Electric Discharge Machine	0.00	-0.64	Drill Press (Metal)	0.54	0.42	Metal Shear	0.00	-0.07
T42				Surface Grinder	0.00	-0.64	Electric Discharge Machine			Welding Equipment	0.00	0.66
T43				Injection Molder			Surface Grinder	0.53	-1.15	Other (metal)	0.00	-0.43
T44				Vacuum Former			Injection Molder			Band Saw	0.00	-0.17
T45				Waterjet	0.67	0.45	Vacuum Former			Belt sander	0.00	-0.43
T46				Hydraulic Press	0.00	-1.41	Waterjet	0.38	1.27	Circular Saw	0.00	-0.43
T47				Metal Shear	0.48	-0.19	Hydraulic Press	0.24	-0.95	Miter (Chop) Saw	0.00	-0.69
T48				Welding Equipment	0.00	-1.04	Metal Shear	0.17	-0.14	Jigsaw		

T49				Band Saw (Wood)	0.56	-0.19	Welding Equipment	0.41	0.26	Drill Press (wood)	0.50	-1.17
T50				Belt Sander	0.41	0.26	Band Saw (Wood)	0.56	0.42	Table Saw	0.00	0.35
T51				Circular Saw	0.00	-0.41	Belt Sander	0.67	0.09	Router - shopbot		
T52				Miter (chop) Saw	0.00	-0.19	Circular Saw	0.61	-0.24	Router-hand		
T53				Jigsaw	0.00	-0.64	Miter (chop) Saw	0.50	0.09	sander - hand	0.00	-0.96
T54				Drill press (wood)			Jigsaw	0.00	-0.90	Vacuum Former		
T55				Table Saw	0.44	-0.41	Drill press (wood)	0.50	0.09	Other (wood)	0.00	-1.22
T56				Router - Shopbot			Table Saw	0.69	-0.24	Circuit Board Plotter	0.00	-1.17
T57				Router - Hand			Router - Shopbot			Multimeter	0.41	2.70
T58				Sander - Hand	0.00	-0.64	Router - Hand	0.00	-0.90	Power Supply	0.32	2.47
T59				Vacuum Former			Sander - Hand			Soldering Station	0.45	2.01
T60				Circuit Board Plotter	0.00	-1.06	Vacuum Former			Oscilloscope	0.30	1.56
T61				Multimeter	0.14	2.29	Circuit Board Plotter	0.00	-1.32	Logic Analyzer	0.38	-0.71

T62				Power Supply	0.13	2.60	Multimeter	0.69	0.97	Other (Electronics)	0.50	-0.79
T63				Soldering Station	0.00	1.99	Power Supply	0.32	0.40	CAD Station	0.59	-0.17
T64				Oscilloscope	0.00	1.68	Soldering Station	0.57	0.97	Construction Station	0.50	-0.71
T65				Logic Analyzer	0.00	-1.06	Oscilloscope	0.00	-0.17	Workbench	0.68	0.20
T66				CAD station	0.24	1.04	Logic Analyzer	0.00	-1.32	Mobile HDTV	0.00	-1.22
T67				Construction Station	0.00	0.34	CAD station	0.63	0.45	White Boards	0.00	-1.17
T68				Workbench	0.24	1.04	Construction Station	0.58	0.15	Other	0.00	
T69				Mobile HDTV	0.00	-0.71	Workbench	0.59	-0.16	Studied	0.65	1.34
T70				Whiteboard	0.00	-0.71	Mobile HDTV	0.00	-0.90	Hung Out	0.46	0.54
T71				Studied	0.52	1.04	Whiteboard	0.50	-1.24	Met with a Group	0.65	3.47
T72				Hung out	0.32	0.34	Studied	0.70	0.76	Other		
T73				Met with Group	0.64	2.44	Hung out	0.75	-0.17	Got Help from another student	0.52	0.81
T74				Got help from another student	0.71	0.08	Met with Group	0.74	2.30	Got help from a staff member	0.62	0.54

T75				Got help from staff member	0.70	2.44	Got help from another student	0.65	1.38	Helped someone else	0.60	0.54
T76				I helped someone else	0.58	0.45	Got help from staff member	0.71	1.38	other	0.52	0.81
							I helped someone else	0.71	0.45			

Table 25: School B Specific Tool P&Z table with tool number

	Fall 2020			Spring 2021			Spring 2022			Fall 2022		
#	Tool	Participatio n	Z- valu e	Tool	Participatio n	Z- valu e	Tool	Participatio n	Z- valu e	Tool	Participatio n	Z- valu e
T1	Ultimaker	0.78	3.35	Laser Cutter	0.72	3.36	Lasers	0.67	2.49	Laser Cutter	0.70	2.82
T2	SLS	0.00	-0.39	Paint Booth	0.69	0.40	Paint Booth	0.64	0.72	Paint Booth	0.71	0.36
T3	Formlabs	0.72	0.71	Prototyping Instructor on Duty	0.70	1.64	PI on Duty	0.49	-0.25	PI On Duty	0.65	-0.25
T4	Stratasys	0.00	0.16	All Hand Tools	0.74	1.29	All Hand Tools	0.70	1.91	Hammers	0.18	1.40

T5	FARO Arm	0.44	-0.06	Hammers	0.61	-0.62	Hammers	0.60	0.79	Pliers	0.25	2.36
T6	Don't Know			Pliers	0.62	0.55	Pliers	0.63	1.72	Vice Grips	0.19	1.19
T7	Other (3D Printing)	0.00	-1.49	Vice Grips	0.63	-0.04	Vice Grips	0.70	0.04	Clamps	0.28	2.36
T8	Band Saw	0.82	0.82	Clamps (C-clamp or other)	0.67	1.14	Clamps	0.63	1.35	Screw Drivers	0.30	2.15
T9	CNC Mill	0.44	-0.06	Screw Drivers	0.66	1.73	Screw Drivers	0.62	2.46	Hand Drills	0.24	2.04
T10	Manual Mill	0.00	-1.63	Hand Drills	0.69	1.14	Hand Drills	0.70	1.16	Angle Grinder	0.17	-0.52
T11	CNC Lathe			Angle Grinder	0.48	-0.83	Angle Grinder	0.70	-0.09	Chisels	0.41	-0.94
T12	Manual Lathe	0.56	0.82	Chisels	0.61	-0.62	Chisel	0.64	-0.89	Measuring Tape	0.33	2.57
T13	Drill Press	0.70	0.25	Measuring Tape	0.65	0.55	Measuring Tape	0.67	2.09	Table Vice	0.22	0.76
T14	Injection Molder			Table Vice	0.57	-0.92	Table Vice	0.71	0.20	Glue Gun	0.31	0.87
T15	Vacuum Former			Glue Gun	0.65	-0.04	Glue Gun	0.68	0.04	Wire Cutters	0.27	0.87

T1 6	Waterjet	0.74	2.46	Wire Cutters	0.67	0.26	Wire Cutters	0.71	0.50	Hand Saw	0.33	0.23
T1 7	Other (Metal)	0.50	-0.98	Hand Saw	0.51	-0.62	Hand Saw	0.68	-0.33	Dremel	0.30	0.44
T1 8	Embroidery Machine	0.00	-1.45	Dremel	0.41	-1.21	Dremel	0.70	-0.09	Tap & Dye Set	0.22	-0.09
T1 9	Hot Wire Foam Cutter	0.00	-1.72	Tap & Dye Set	0.38	-0.83	Tap & Dye Set	0.72	-1.27	Scissors	0.40	1.51
T2 0	Sewing Machine	0.22	-0.12	Scissors	0.70	-0.04	Scissors	0.68	1.35	Tin Snips	0.56	-1.26
T2 1	Vinyl/Paper Cutter	0.60	0.41	Tin Snips	0.32	-0.62	Tin Snips	0.73	-0.85	X-ACTO Knife	0.45	0.34
T2 2	Other (Craftland)	0.00	-0.49	X-ACTO Knife	0.58	-0.04	X-ACTO Knife	0.70	0.79	Other (Hand Tools)	0.28	2.47
T2 3	Bandsaw	0.56	0.67	Other (# of times used)	0.44	-2.09	Ultimaker	0.77	2.41	Ultimaker	0.75	5.92
T2 4	Beltsander	0.57	0.94	Ultimaker 3	0.67	3.81	Resin	0.71	0.07	Resin	0.70	2.04

T2 5	Circular Saw			SLS Professional Printer (Formiga)	0.46	1.08	SLS Formiga			SLS	0.00	-1.17
T2 6	Chop Saw	0.54	0.94	Formlabs Form 2 3D Printer	0.69	0.24	Stratasys	0.00	-1.44	3D Scanner	0.00	-1.17
T2 7	CNC Wood Router	0.44	-0.94	Stratasys 3D printers	0.61	-0.28	FARO Arm	0.44	-1.57	Don't Know		
T2 8	Drill Press	0.64	0.94	3D scanner - FARO Arm	0.00	-2.39	Band Saw (Metal)	0.69	1.68	Other (3D Printing)	0.38	-1.26
T2 9	Planer	0.49	0.41	Other			Metal CNC	0.45	-0.68	Band Saw (metal)	0.59	1.29
T3 0	Router	0.49	-0.39	Band saw (Metal)	0.52	0.23	Manual Mill	0.63	0.20	CNC Metal Mills	0.45	-0.10
T3 1	Sander	0.61	1.21	CNC Metal Mill	0.50	-1.25	Manual Lathe	0.66	-0.39	Manual Mill	0.57	-0.36
T3 2	Table Saw	0.69	0.94	Manual Mill	0.61	-0.62	Drill Press (Metal)	0.74	0.79	Manual Lathe	0.57	-0.71

T3 3	Other (Wood)	0.67	-0.85	CNC Lathe			Belt Sander	0.75	1.38	Drill Press	0.59	0.34
T3 4	Circuit Board Prototyping	0.44	-0.92	Manual Lathe	0.69	-0.62	Polishing Wheel	0.59	-0.19	Belt Sander	0.61	0.44
T3 5	Multimeter	0.71	1.26	Drill Press (Metal)	0.56	0.23	Waterjet	0.76	1.79	Polishing Wheel	0.56	-0.40
T3 6	Power Supplies	0.63	1.26	Belt Sander	0.61	0.44	Sheet Metal Break	0.70	-0.19	Waterjet	0.66	1.13
T3 7	Soldering Station	0.71	2.90	Polishing Wheel	0.00	-1.25	Cold Cut Saw	0.73	-0.52	Sheet Metal Break	0.49	-0.10
T3 8	Other (Electronics)	0.50	-0.98	Injection Molder			Metal Shears	0.71	-0.19	Cold Cut Saw	0.58	-0.40
T3 9	CAD Station	0.69	-0.39	Vacuum Former			Band Saw (Wood)	0.70	1.20	Metal Shears	0.48	0.21
T4 0	Workbench/Tables	0.65	0.25	Waterjet	0.70	0.23	Belt Sander	0.66	1.04	Other (metal)	0.44	-1.37
T4 1	Other (Workstations)			Other	0.00	-0.81	Circular Saw	0.70	-0.09	Band Saw	0.61	0.76

T4 2	Got Help (Student)	0.38	0.29	Band saw (wood)	0.77	1.93	Miter (Chop) Saw	0.68	0.56	Belt Sander	0.61	1.59
T4 3	Got Help (Prototyping Instructor)	0.70	2.20	Belt sander	0.70	0.65	Jigsaw	0.64	-0.73	Circular Saw	0.58	0.21
T4 4	Helped	0.49	0.14	Circular saw	0.69	-0.62	Drill Press (Wood)	0.68	0.40	Miter Saw	0.61	0.83
T4 5	Other (Help)	0.38	0.29	Miter (Chop) saw	0.48	0.65	Wood CNC	0.73	-0.85	Jigsaw	0.54	1.44
T4 6				Jigsaw	0.48	-0.83	Hand Router	0.24	-0.57	Drill Press	0.50	0.02
T4 7				Drill press (wood)	0.65	0.23	Planer	0.56	0.23	CNC Wood Router	0.28	-0.56
T4 8				CNC Wood Router	0.38	-0.83	Table Saw	0.63	0.72	Router	0.46	0.36
T4 9				Router	0.28	-0.41	Jointer	0.46	0.40	Planer	0.52	0.52
T5 0				Planer	0.45	0.23	Wood Lathe	0.61	-1.27	Table Saw	0.54	1.90

T5 1				Table saw	0.66	0.23	Embroidery	0.00	-0.89	Jointer	0.51	0.36
T5 2				Other	0.50	-0.55	Hot Foam Wire Cutters	0.00	-1.22	Wood Lathe	0.32	-0.71
T5 3				Embroidery Machine(CN C Sewing Machine)	0.00	-1.25	Sewing Machine	0.54	-0.09	Other (Wood)	0.44	-0.32
T5 4				Hot Wire Foam Cutter			Vinyl/Paper Cutter	0.64	0.40	Embroidery Machine	0.60	0.76
T5 5				Sewing Machine	0.69	-0.28	Button Maker	0.61	-0.52	Foam Cutter	0.61	-0.86
T5 6				Vinyl/Paper Cutter	0.65	-0.19	Circuit Board Plotter	0.28	0.14	Sewing Machine	0.70	1.92
T5 7				Other	0.50	-1.16	Multimeter	0.72	1.46	Vinyl/Paper Cutter	0.61	5.42
T5 8				Circuit Board Plotter	0.00	-1.16	Power Supply	0.70	0.80	Button Maker	0.65	0.76

T5 9				Multimeter	0.64	-0.62	Soldering Station	0.74	0.50	Other (Craftland)	0.50	-0.02
T6 0				Power Supply	0.57	-0.41	Oscilloscope	0.68	-0.68	Circuit Board Plotter	0.64	0.18
T6 1				Soldering station	0.67	-0.04	Logic Analyzer	0.50	-1.38	Multimeter	0.66	1.53
T6 2				Oscilloscope	0.48	-0.83	Function Generator	0.67	-0.85	Power Supply	0.66	1.36
T6 3				Logic Analyzer			CAD Station	0.72	0.60	Soldering Station	0.64	1.19
T6 4				Other			Workbench/Tables	0.71	0.07	Oscilloscope	0.61	1.03
T6 5				CAD Station	0.67	0.63	White Boards	0.41	-0.73	Logic Analyzer	0.00	-0.86
T6 6				Workbench/ tables	0.58	2.22	Studied	0.61	0.56	Function Generator	0.61	0.35
T6 7				White Boards	0.64	-0.51	Hung Out	0.65	0.72	Other (electronics)	0.00	-0.49
T6 8				Other			Met with a Group	0.73	1.46	CAD Station	0.44	-0.10

T6 9				Studied	0.66	1.08	Got help from another student	0.70	0.04	Workbenches/Tables	0.69	0.36
T7 0				Hung out	0.60	1.08	Got help from a PI	0.71	0.60	White Boards	0.64	-0.40
T7 1				Met with a group	0.72	1.64	Helped Someone Else	0.70	0.23	Other		
T7 2				Other			Hung out	0.75	-0.17	Studied	0.74	2.12
T7 3				Got help from another student (not a Prototyping Instructor)	0.66	0.59	Met with Group	0.74	2.30	Hung Out	0.74	2.31
T7 4				Got help from a Prototyping Instructor	0.65	1.64	Got help from another student	0.65	1.38	Met with a Group	0.72	2.82

T7 5				I helped someone else	0.64	0.59	Got help from staff member	0.71	1.38	Other	0.50	-1.47
T7 6				Other			I helped someone else	0.71	0.45	Got help from student	0.76	0.76
T7 7										Got help from Prototyping Instructor		
T7 8										Helped Someone Else	0.72	0.36
T7 9										Other	0.76	0.76

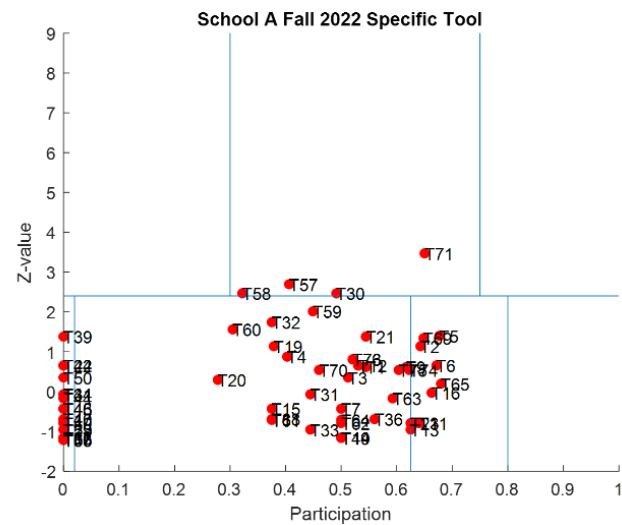
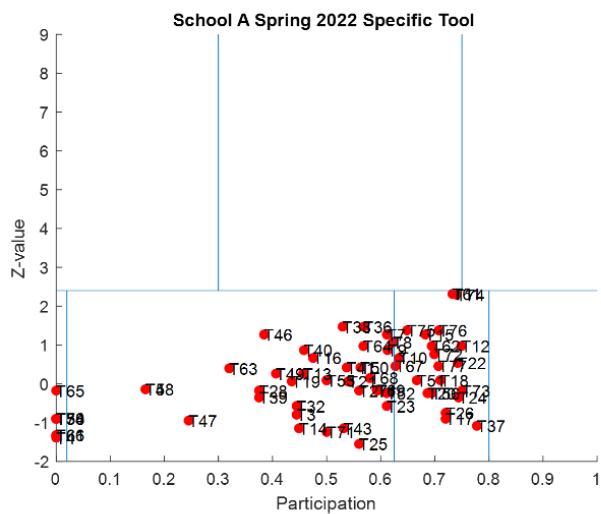
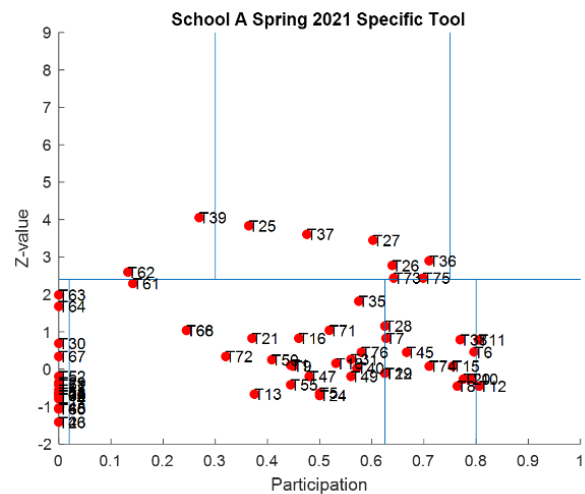
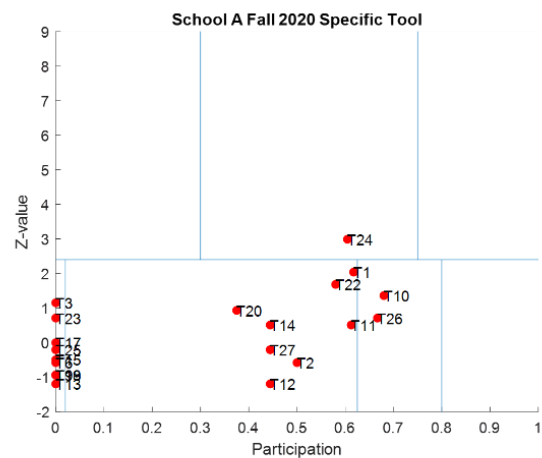


Figure 16: School A specific tool breakdown with labels found in Table 24

APPENDIX D: DEMOGRAPHIC ANALYSIS BREAKDOWN TABLES AND PLOTS

Table 26: School B Fall 2020 demographic data

	n	3D Printers	Metal Tools	Laser Cutters	Wood Tools	Hand Tools	Electronics Tools	Social Activities	Got / Gave Help	Soft Material Tools	Work Areas	Paint Booth	Volunteer on Duty	Other
General	N = 57	77.19%	49.12%	50.88%	57.89%	63.16%	40.35%	45.61%	33.33%	29.82%	15.79%	14.04%	28.07%	3.51%
Male	43	74.42%	53.49%	51.16%	55.81%	62.79%	39.53%	48.84%	39.53%	30.23%	18.60%	11.63%	32.56%	2.33%
Female	13	84.62%	30.77%	46.15%	61.54%	69.23%	38.46%	38.46%	15.38%	30.77%	7.69%	23.08%	15.38%	7.69%
Hispanic	6	50.00%	33.33%	16.67%	50.00%	33.33%	16.67%	16.67%	0.00%	0.00%	16.67%	0.00%	16.67%	0.00%
Non-Hispanic	50	80.00%	50.00%	54.00%	58.00%	68.00%	42.00%	50.00%	38.00%	34.00%	16.00%	16.00%	30.00%	4.00%
White / Caucasian	33	84.85%	48.48%	54.55%	60.61%	60.61%	39.39%	39.39%	30.30%	33.33%	18.18%	15.15%	36.36%	3.03%
Black or African	5	80.00%	60.00%	40.00%	40.00%	80.00%	20.00%	40.00%	40.00%	0.00%	0.00%	20.00%	0.00%	0.00%
American Indian or	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Native Hawaiian or														
Other Pacific	1	100.00%	100.00%	100.00%	100.00%	0.00%	0.00%	100.00%	100.00%	100.00%	0.00%	100.00%	100.00%	0.00%
Middle Eastern	1	0.00%	0.00%	0.00%	100.00%	100.00%	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	0.00%
Asian	22	68.18%	45.45%	45.45%	54.55%	63.64%	45.45%	59.09%	45.45%	36.36%	18.18%	13.64%	27.27%	4.55%
Aerospace	4	100.00%	0.00%	75.00%	50.00%	50.00%	50.00%	100.00%	50.00%	25.00%	25.00%	0.00%	25.00%	0.00%
Biomedical	2	50.00%	50.00%	50.00%	100.00%	100.00%	100.00%	50.00%	50.00%	100.00%	50.00%	0.00%	100.00%	0.00%
Chemical	1	100.00%	0.00%	100.00%	100.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Computer	1	100.00%	0.00%	100.00%	100.00%	100.00%	100.00%	100.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%
Electrical	1	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	0.00%	0.00%	100.00%	0.00%
Industrial	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Material Science	1	100.00%	100.00%	100.00%	100.00%	100.00%	0.00%	100.00%	100.00%	100.00%	0.00%	0.00%	0.00%	0.00%
Mechanical	44	75.00%	52.27%	43.18%	52.27%	61.36%	36.36%	36.36%	27.27%	20.45%	15.91%	13.64%	22.73%	4.55%
Nuclear	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Other Major	3	66.67%	66.67%	66.67%	66.67%	33.33%	33.33%	66.67%	66.67%	100.00%	0.00%	33.33%	66.67%	0.00%

Table 27: School A Fall 2020 demographic Data

	n	3D Printers	Metal Tools	Laser Cutter	Wood Tools	Hand Tools	Electronics	Social Activities	Got/Gave Help	Soft Material Tools	Other
General	N = 54	61.67%	23.33%	8.33%	8.33%	28.33%	20.00%	50.00%	15.00%	1.67%	8.33%
Male	43	69.77%	27.91%	6.98%	11.63%	32.56%	25.58%	48.84%	13.95%	0.00%	4.65%
Female	7	85.71%	28.57%	28.57%	0.00%	28.57%	0.00%	85.71%	14.29%	0.00%	28.57%
Hispanic	8	75.00%	25.00%	12.50%	0.00%	25.00%	25.00%	62.50%	25.00%	0.00%	12.50%
Non-Hispanic	44	68.18%	27.27%	9.09%	11.36%	34.09%	22.73%	54.55%	13.64%	2.27%	9.09%
White / Caucasian	37	81.08%	21.62%	10.81%	8.11%	24.32%	10.81%	54.05%	10.81%	0.00%	8.11%
Black or African	1	0.00%	100.00%	0.00%	100.00%	0.00%	100.00%	100.00%	0.00%	0.00%	0.00%
American Indian or	2	50.00%	50.00%	0.00%	0.00%	50.00%	50.00%	50.00%	50.00%	0.00%	0.00%
Native Hawaiian or											
Other Pacific Islander	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Middle Eastern	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Asian	14	42.86%	42.86%	7.14%	14.29%	50.00%	50.00%	57.14%	14.29%	0.00%	7.14%
Aerospace Engineering	5	100.00%	0.00%	0.00%	0.00%	20.00%	0.00%	20.00%	40.00%	20.00%	40.00%
Biomedical Engineering											
Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Chemical Engineering											
Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Computer Engineering	2	0.00%	0.00%	0.00%	0.00%	50.00%	50.00%	50.00%	50.00%	0.00%	0.00%
Electrical Engineering	16	12.50%	6.25%	6.25%	6.25%	18.75%	62.50%	62.50%	12.50%	0.00%	6.25%
Industrial Engineering											
Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Material Science and											
Engineering Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Mechanical Engineering	29	100.00%	41.38%	13.79%	13.79%	37.93%	3.45%	58.62%	13.79%	0.00%	6.90%
Nuclear Engineering											
Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Other Major	2	50.00%	50.00%	0.00%	0.00%	50.00%	0.00%	50.00%	0.00%	0.00%	0.00%

Table 28: School B Spring 2021 demographic data

	n	3D Printer	Metal Too	Laser Cutt	Wood Toc	Hand Tool	Electronic	Social Acti	Got / Gav	Soft Mate	Work Are	Paint Boo	Volunteer	Other
General	N = 94	74.47%	37.23%	54.26%	47.87%	47.87%	28.72%	37.23%	25.53%	22.34%	29.79%	15.96%	17.02%	4.26%
Male	54	79.63%	44.44%	51.85%	50.00%	48.15%	27.78%	40.74%	25.93%	18.52%	35.19%	12.96%	20.37%	5.56%
Female	32	68.75%	25.00%	62.50%	46.88%	50.00%	34.38%	37.50%	25.00%	34.38%	28.13%	18.75%	12.50%	3.13%
Hispanic	10	70.00%	30.00%	40.00%	30.00%	40.00%	20.00%	30.00%	30.00%	30.00%	40.00%	0.00%	0.00%	0.00%
Non-Hispanic	79	74.68%	37.97%	56.96%	50.63%	49.37%	30.38%	39.24%	24.05%	21.52%	30.38%	17.72%	20.25%	5.06%
White / Caucasian	46	76.09%	36.96%	52.17%	52.17%	54.35%	34.78%	43.48%	30.43%	21.74%	28.26%	13.04%	26.09%	4.35%
Black or African American	1	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
American Indian or Alaskan Native	1	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Native Hawaiian or Other Pacific Islander	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Middle Eastern	2	100.00%	0.00%	100.00%	0.00%	50.00%	0.00%	50.00%	50.00%	50.00%	0.00%	0.00%	50.00%	0.00%
Asian	43	72.09%	39.53%	58.14%	51.16%	46.51%	27.91%	34.88%	23.26%	25.58%	34.88%	23.26%	11.63%	6.98%
Aerospace Engineering Major	22	72.73%	18.18%	40.91%	36.36%	22.73%	13.64%	22.73%	13.64%	9.09%	27.27%	9.09%	9.09%	4.55%
Biomedical Engineering Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Chemical Engineering Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Computer Engineering Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Electrical Engineering Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Industrial Engineering Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Material Science and Engineering Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Mechanical Engineering Major	66	77.27%	45.45%	56.06%	53.03%	56.06%	36.36%	40.91%	25.76%	25.76%	31.82%	16.67%	19.70%	4.55%
Nuclear Engineering Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Other Major	6	50.00%	16.67%	83.33%	33.33%	50.00%	0.00%	50.00%	66.67%	33.33%	16.67%	33.33%	16.67%	0.00%

Table 29: School A Spring 2021 demographic data

	n	3D Printers	Metal Tools	Craftland	Electronics	Wood Tools	Handheld Tools	Laser Cutter	CAD Station	Studied	Got Help	Paint Booth	Other
General	N = 178	57.87%	37.64%	0.56%	14.61%	7.87%	24.16%	3.37%	11.24%	17.98%	16.85%	2.25%	17.42%
Male	118	59.32%	38.98%	0.00%	16.10%	7.63%	25.42%	4.24%	12.71%	21.19%	16.10%	1.69%	17.80%
Female	57	54.39%	35.09%	0.00%	8.77%	7.02%	17.54%	1.75%	7.02%	10.53%	19.30%	3.51%	17.54%
Hispanic	39	51.28%	30.77%	0.00%	17.95%	7.69%	25.64%	5.13%	5.13%	20.51%	10.26%	0.00%	28.21%
Non-Hispanic	131	60.31%	39.69%	0.76%	13.74%	7.63%	22.14%	3.05%	11.45%	18.32%	19.08%	3.05%	12.98%
White / Caucasian	120	60.00%	37.50%	0.83%	14.17%	9.17%	25.00%	2.50%	12.50%	17.50%	15.83%	2.50%	18.33%
Black or African American	3	33.33%	66.67%	0.00%	0.00%	0.00%	33.33%	0.00%	0.00%	66.67%	0.00%	0.00%	0.00%
American Indian or	4	75.00%	25.00%	0.00%	25.00%	25.00%	0.00%	25.00%	0.00%	25.00%	0.00%	0.00%	25.00%
Native Hawaiian or Other													
Pacific Islander	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Middle Eastern	4	25.00%	50.00%	0.00%	50.00%	0.00%	25.00%	0.00%	25.00%	0.00%	25.00%	0.00%	25.00%
Asian	37	54.05%	37.84%	0.00%	10.81%	5.41%	18.92%	8.11%	13.51%	16.22%	27.03%	2.70%	16.22%
Aerospace Engineering	8	25.00%	12.50%	0.00%	0.00%	12.50%	25.00%	12.50%	0.00%	25.00%	0.00%	12.50%	37.50%
Biomedical Engineering	9	88.89%	0.00%	0.00%	11.11%	0.00%	11.11%	0.00%	11.11%	0.00%	0.00%	0.00%	0.00%
Chemical Engineering	1	0.00%	0.00%	100.00%	100.00%	0.00%	100.00%	0.00%	100.00%	100.00%	0.00%	0.00%	0.00%
Computer Engineering	4	25.00%	25.00%	0.00%	25.00%	0.00%	0.00%	0.00%	0.00%	50.00%	50.00%	0.00%	25.00%
Electrical Engineering	17	35.29%	0.00%	0.00%	70.59%	5.88%	35.29%	0.00%	11.76%	35.29%	23.53%	0.00%	17.65%
Industrial Engineering	23	60.87%	60.87%	0.00%	0.00%	0.00%	13.04%	0.00%	8.70%	4.35%	17.39%	0.00%	13.04%
Material Science and	2	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%
Mechanical Engineering	90	68.89%	50.00%	0.00%	4.44%	10.00%	26.67%	4.44%	13.33%	14.44%	16.67%	2.22%	13.33%
Nuclear Engineering Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Other Major	24	41.67%	25.00%	0.00%	29.17%	12.50%	25.00%	4.17%	8.33%	20.83%	20.83%	4.17%	37.50%

Table 30: School B Spring 2022 demographic data

	n	3D Printers	Metal Tools	Craftland	Electronics	Wood Tools	Handheld Tools	Laser Cutter	CAD Station	Studied	Got Help	PI On Duty	Paint Booth	Other
General	N = 95	77.89%	58.95%	32.63%	37.89%	61.05%	64.21%	58.95%	29.47%	43.16%	42.11%	14.74%	23.16%	3.16%
Male	53	77.36%	69.81%	26.42%	47.17%	67.92%	69.81%	56.60%	24.53%	49.06%	47.17%	16.98%	24.53%	0.00%
Female	38	76.32%	44.74%	39.47%	23.68%	52.63%	57.89%	63.16%	34.21%	34.21%	34.21%	7.89%	18.42%	5.26%
Hispanic	15	66.67%	26.67%	6.67%	40.00%	46.67%	53.33%	40.00%	13.33%	26.67%	26.67%	6.67%	13.33%	6.67%
Non-Hispanic	76	78.95%	65.79%	35.53%	36.84%	63.16%	67.11%	61.84%	31.58%	46.05%	44.74%	14.47%	23.68%	1.32%
White / Caucasian	55	80.00%	65.45%	29.09%	32.73%	63.64%	70.91%	61.82%	27.27%	40.00%	43.64%	14.55%	20.00%	1.82%
Black or African American	5	100.00%	80.00%	20.00%	60.00%	80.00%	80.00%	60.00%	20.00%	40.00%	40.00%	0.00%	20.00%	0.00%
American Indian or Alaskan	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Native Hawaiian or Other Pacific	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Middle Eastern	2	100.00%	100.00%	0.00%	0.00%	100.00%	50.00%	0.00%	100.00%	50.00%	50.00%	0.00%	0.00%	0.00%
Asian	28	67.86%	46.43%	39.29%	35.71%	50.00%	57.14%	50.00%	35.71%	46.43%	35.71%	10.71%	25.00%	3.57%
Aerospace Engineering Major	4	100.00%	50.00%	25.00%	25.00%	100.00%	25.00%	75.00%	50.00%	50.00%	50.00%	25.00%	25.00%	0.00%
Biomedical Engineering Major	6	50.00%	16.67%	50.00%	16.67%	50.00%	33.33%	50.00%	50.00%	66.67%	16.67%	16.67%	33.33%	33.33%
Chemical Engineering Major	1	100.00%	0.00%	100.00%	0.00%	100.00%	100.00%	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%
Computer Engineering Major	1	100.00%	100.00%	0.00%	0.00%	100.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Electrical Engineering Major	3	66.67%	66.67%	0.00%	66.67%	66.67%	66.67%	33.33%	0.00%	66.67%	0.00%	0.00%	0.00%	0.00%
Industrial Engineering Major	1	100.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Material Science and Engineering	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Mechanical Engineering Major	63	82.54%	68.25%	30.16%	46.03%	61.90%	77.78%	63.49%	26.98%	44.44%	44.44%	15.87%	23.81%	0.00%
Nuclear Engineering Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Other Major	16	62.50%	37.50%	43.75%	18.75%	50.00%	37.50%	43.75%	37.50%	31.25%	50.00%	12.50%	25.00%	6.25%

Table 31: School A Spring 2022 demographic data

	n	3D Printers	Metal Tools	Craftland	Electronics	Wood Tools	Handheld Tools	Laser Cutter	CAD Station	Studied/Hung Out/Met with a Group	Got Help	Paint Booth	Other
General	N = 77	62.03%	60.76%	5.06%	30.38%	21.52%	69.62%	8.86%	26.58%	45.57%	43.04%	13.92%	17.72%
Male	50	62.00%	64.00%	8.00%	34.00%	24.00%	70.00%	12.00%	22.00%	40.00%	42.00%	16.00%	20.00%
Female	21	66.67%	71.43%	4.76%	19.05%	4.76%	76.19%	4.76%	28.57%	61.90%	38.10%	0.00%	23.81%
Hispanic	18	66.67%	50.00%	11.11%	33.33%	11.11%	66.67%	0.00%	38.89%	83.33%	55.56%	16.67%	16.67%
Non-Hispanic	54	64.81%	66.67%	3.70%	27.78%	22.22%	72.22%	12.96%	22.22%	38.89%	38.89%	14.81%	20.37%
White / Caucasian	47	59.57%	59.57%	6.38%	34.04%	27.66%	74.47%	8.51%	29.79%	53.19%	48.94%	17.02%	21.28%
Black or African American	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
American Indian or Alaskan	2	100.00%	100.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Native Hawaiian or Other	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Middle Eastern	1	0.00%	100.00%	0.00%	0.00%	0.00%	100.00%	0.00%	100.00%	100.00%	0.00%	0.00%	0.00%
Asian	22	68.18%	72.73%	0.00%	13.64%	4.55%	63.64%	9.09%	22.73%	31.82%	36.36%	13.64%	22.73%
Aerospace Engineering Major	3	100.00%	33.33%	0.00%	0.00%	66.67%	66.67%	0.00%	33.33%	33.33%	33.33%	0.00%	0.00%
Biomedical Engineering Major	4	75.00%	25.00%	25.00%	25.00%	0.00%	50.00%	0.00%	0.00%	75.00%	0.00%	0.00%	25.00%
Chemical Engineering Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Computer Engineering Major	1	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Electrical Engineering Major	9	33.33%	11.11%	0.00%	44.44%	22.22%	55.56%	0.00%	33.33%	55.56%	66.67%	11.11%	22.22%
Industrial Engineering Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Material Science and	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Mechanical Engineering Major	56	66.07%	80.36%	5.36%	30.36%	23.21%	78.57%	10.71%	30.36%	42.86%	46.43%	17.86%	19.64%
Nuclear Engineering Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Other Major	4	50.00%	0.00%	0.00%	50.00%	0.00%	50.00%	25.00%	0.00%	75.00%	25.00%	0.00%	0.00%

Table 32: School B Fall 2022 demographic data

	n	3D Printers	Metal Tools	Craftland	Electronic s	Wood Tools	Handheld Tools	Laser Cutter	CAD Station	Studied	Got Help	PI On Duty	Paint Booth	Other
General	N = 199	65.83%	33.17%	40.20%	28.64%	36.18%	37.69%	41.71%	13.07%	35.68%	35.68%	7.54%	15.08%	1.51%
Male	110	74.55%	40.91%	31.82%	32.73%	46.36%	45.45%	46.36%	14.55%	38.18%	38.18%	7.27%	18.18%	2.73%
Female	59	47.46%	23.73%	54.24%	20.34%	22.03%	23.73%	38.98%	13.56%	35.59%	35.59%	6.78%	10.17%	0.00%
Hispanic	11	54.55%	9.09%	9.09%	36.36%	36.36%	27.27%	54.55%	0.00%	9.09%	18.18%	0.00%	27.27%	0.00%
Non-Hispanic	174	65.52%	34.48%	42.53%	27.59%	36.78%	38.51%	42.53%	14.37%	37.93%	38.51%	8.05%	14.37%	1.72%
White / Caucasian	94	64.89%	34.04%	37.23%	28.72%	37.23%	38.30%	45.74%	9.57%	37.23%	34.04%	8.51%	19.15%	2.13%
Black or African American	11	63.64%	18.18%	36.36%	27.27%	18.18%	45.45%	45.45%	9.09%	18.18%	36.36%	0.00%	0.00%	0.00%
American Indian or Alaskan Native	1	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%
Native Hawaiian or Other Pacific Islander	1	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%
Middle Eastern	3	66.67%	33.33%	0.00%	66.67%	33.33%	66.67%	66.67%	0.00%	0.00%	33.33%	0.00%	0.00%	0.00%
Asian	83	62.65%	34.94%	45.78%	28.92%	38.55%	34.94%	40.96%	18.07%	38.55%	44.58%	7.23%	14.46%	1.20%
Aerospace Engineering Major	15	86.67%	60.00%	33.33%	26.67%	53.33%	73.33%	53.33%	20.00%	26.67%	33.33%	13.33%	26.67%	0.00%
Biomedical Engineering Major	9	77.78%	33.33%	44.44%	44.44%	33.33%	22.22%	22.22%	22.22%	22.22%	44.44%	0.00%	0.00%	0.00%
Chemical Engineering Major	7	28.57%	0.00%	57.14%	14.29%	14.29%	14.29%	42.86%	0.00%	42.86%	42.86%	0.00%	0.00%	0.00%
Computer Engineering Major	7	85.71%	0.00%	28.57%	57.14%	0.00%	14.29%	0.00%	0.00%	28.57%	28.57%	0.00%	14.29%	0.00%
Electrical Engineering Major	13	69.23%	30.77%	15.38%	53.85%	23.08%	15.38%	38.46%	15.38%	38.46%	23.08%	7.69%	15.38%	0.00%
Industrial Engineering Major	6	33.33%	33.33%	33.33%	0.00%	16.67%	0.00%	16.67%	16.67%	16.67%	0.00%	0.00%	0.00%	0.00%
Material Science and Engineering Major	4	0.00%	25.00%	25.00%	25.00%	0.00%	0.00%	25.00%	0.00%	0.00%	0.00%	0.00%	0.00%	25.00%
Mechanical Engineering Major	75	77.33%	42.67%	40.00%	36.00%	49.33%	50.67%	52.00%	20.00%	46.67%	36.00%	14.67%	17.33%	1.33%
Nuclear Engineering Major	2	50.00%	50.00%	0.00%	50.00%	0.00%	50.00%	50.00%	0.00%	50.00%	50.00%	0.00%	0.00%	0.00%
Other Major	61	54.10%	22.95%	49.18%	13.11%	31.15%	31.15%	37.70%	4.92%	29.51%	42.62%	1.64%	16.39%	1.64%

Table 33: School A 2022 Fall demographic data

	n	3D Printers	Metal Tools	Craftland	Electronics	Wood Tools	Handheld Tools	Laser Cutter	CAD Station	Studied	Got Help	PI On Duty	Paint Booth	Other
General	N = 80	48.75%	30.00%	7.50%	41.25%	11.25%	43.75%	2.50%	25.00%	47.50%	25.00%	0.00%	2.50%	11.25%
Male	53	47.17%	28.30%	5.66%	41.51%	11.32%	37.74%	3.77%	26.42%	47.17%	22.64%	0.00%	1.89%	16.98%
Female	23	52.17%	39.13%	8.70%	39.13%	13.04%	56.52%	0.00%	21.74%	52.17%	30.43%	0.00%	4.35%	0.00%
Hispanic	21	42.86%	33.33%	9.52%	28.57%	9.52%	42.86%	0.00%	9.52%	47.62%	14.29%	0.00%	9.52%	9.52%
Non-Hispanic	56	50.00%	30.36%	7.14%	48.21%	12.50%	46.43%	3.57%	32.14%	48.21%	28.57%	0.00%	0.00%	12.50%
White / Caucasian	55	49.09%	34.55%	5.45%	34.55%	7.27%	41.82%	1.82%	25.45%	56.36%	30.91%	0.00%	3.64%	10.91%
Black or African American	3	0.00%	0.00%	33.33%	66.67%	33.33%	66.67%	0.00%	33.33%	66.67%	33.33%	0.00%	0.00%	0.00%
American Indian or Alaskan Native	1	100.00%	100.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Native Hawaiian or Other Pacific Islander	1	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Middle Eastern	3	66.67%	66.67%	0.00%	66.67%	66.67%	100.00%	0.00%	33.33%	33.33%	0.00%	0.00%	0.00%	0.00%
Asian	14	57.14%	21.43%	7.14%	57.14%	0.00%	50.00%	7.14%	35.71%	21.43%	21.43%	0.00%	0.00%	14.29%
Aerospace Engineering Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Biomedical Engineering Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Chemical Engineering Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Computer Engineering Major	3	66.67%	0.00%	33.33%	0.00%	0.00%	0.00%	0.00%	0.00%	33.33%	33.33%	0.00%	0.00%	33.33%
Electrical Engineering Major	29	10.34%	0.00%	6.90%	79.31%	6.90%	41.38%	0.00%	27.59%	68.97%	37.93%	0.00%	0.00%	13.79%
Industrial Engineering Major	1	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Material Science and Engineering Major	1	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	0.00%	0.00%	0.00%	0.00%
Mechanical Engineering Major	39	76.92%	58.97%	5.13%	23.08%	17.95%	56.41%	5.13%	25.64%	33.33%	15.38%	0.00%	2.56%	10.26%
Nuclear Engineering Major	0	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Other Major	7	42.86%	0.00%	14.29%	14.29%	0.00%	14.29%	0.00%	28.57%	42.86%	28.57%	0.00%	14.29%	0.00%

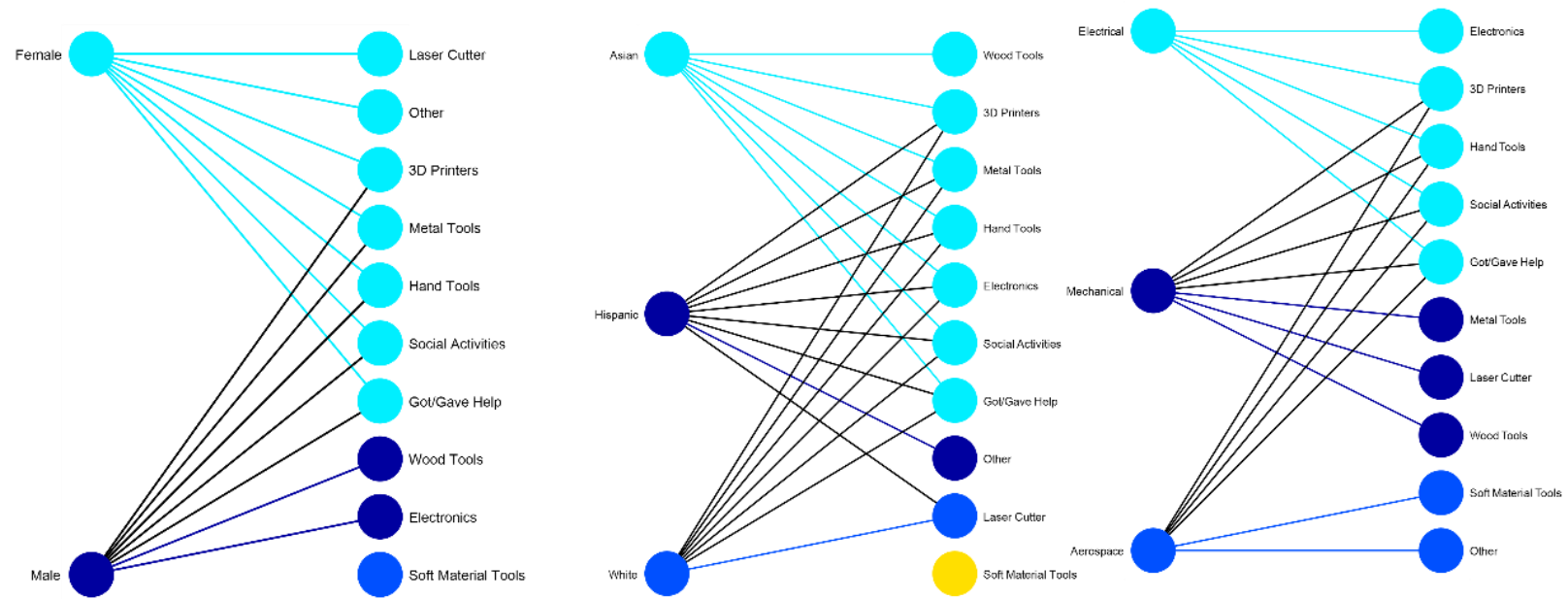


Figure 18: Demographic analysis School A Fall 2020

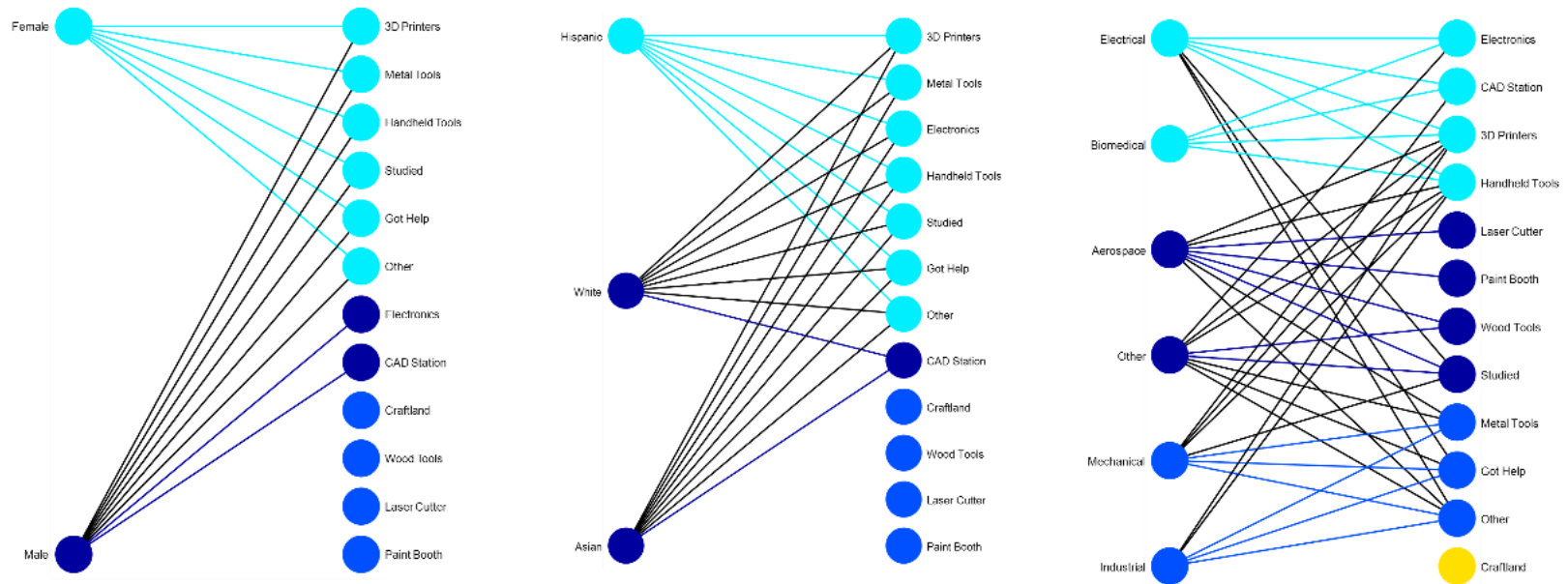


Figure 19: Demographic analysis School A Spring 2021

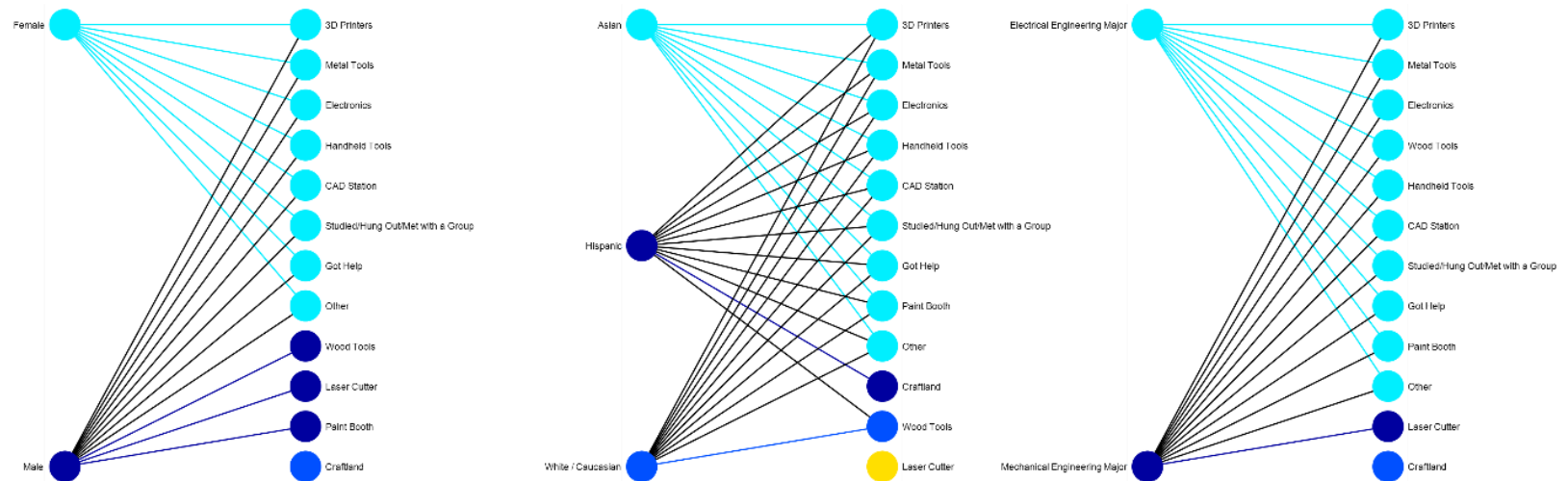


Figure 20: Demographic analysis School A Spring 2022

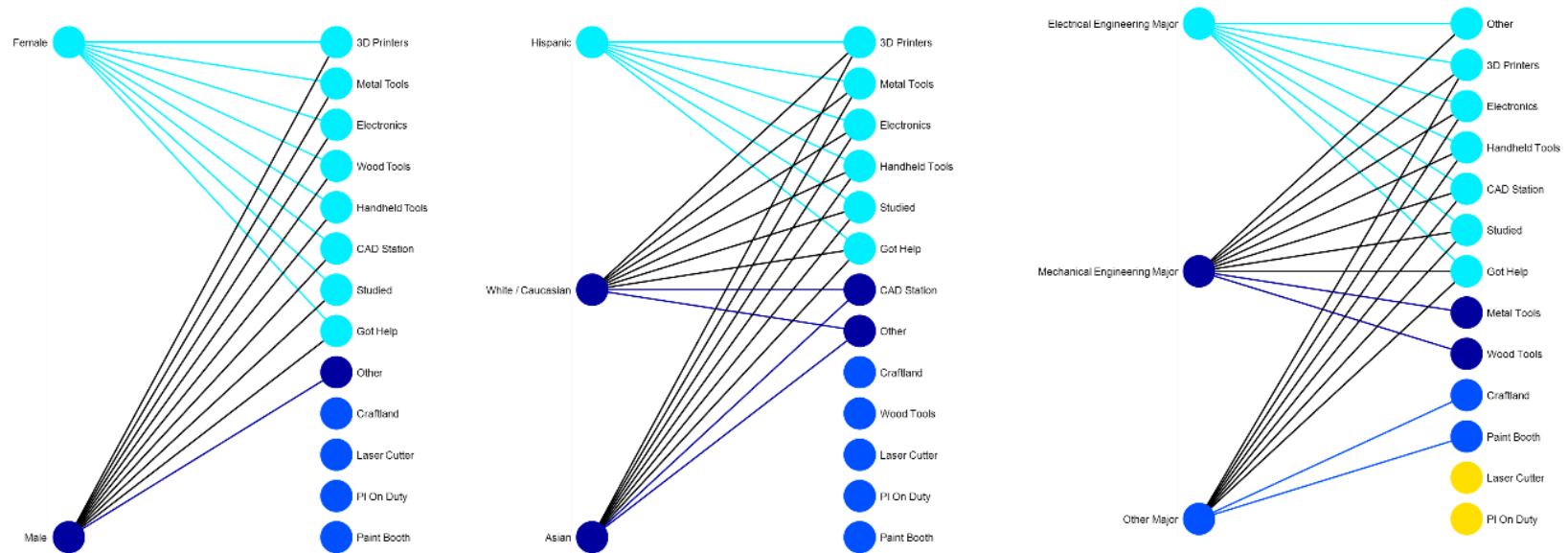


Figure 21: Demographic analysis School A Fall 2022

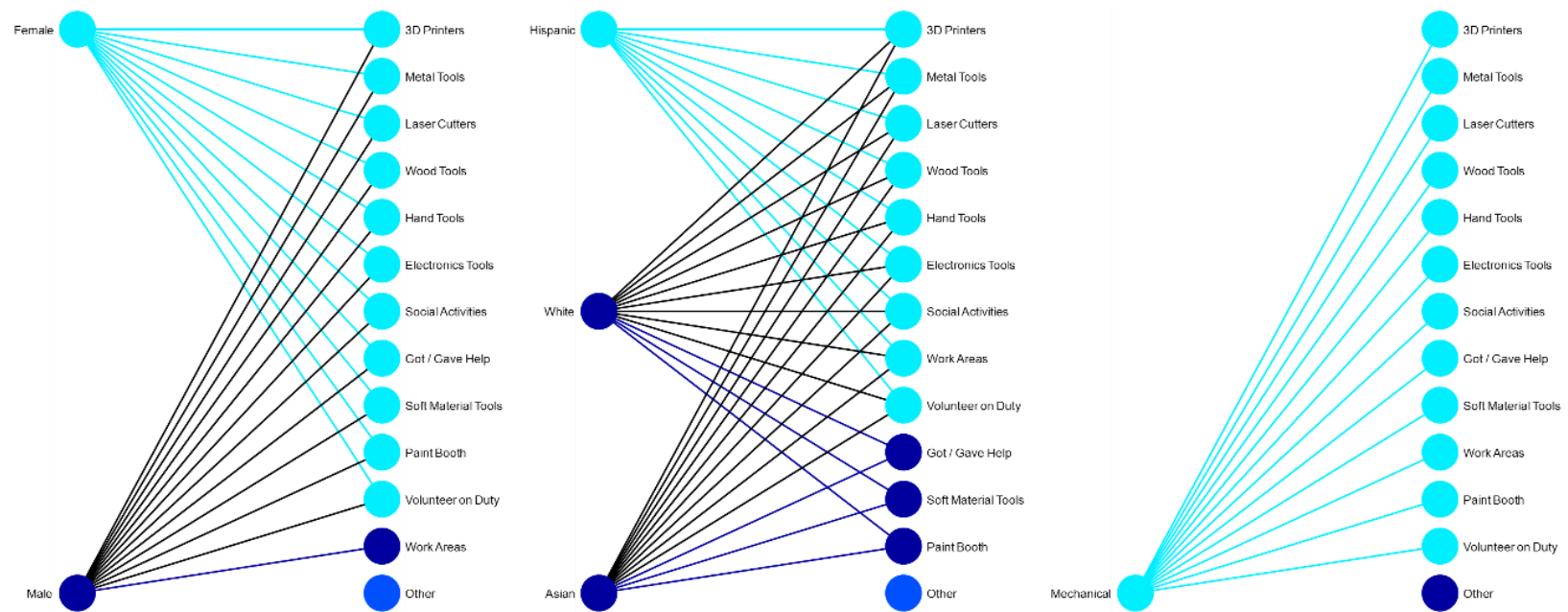


Figure 22: Demographic analysis School B Fall 2020

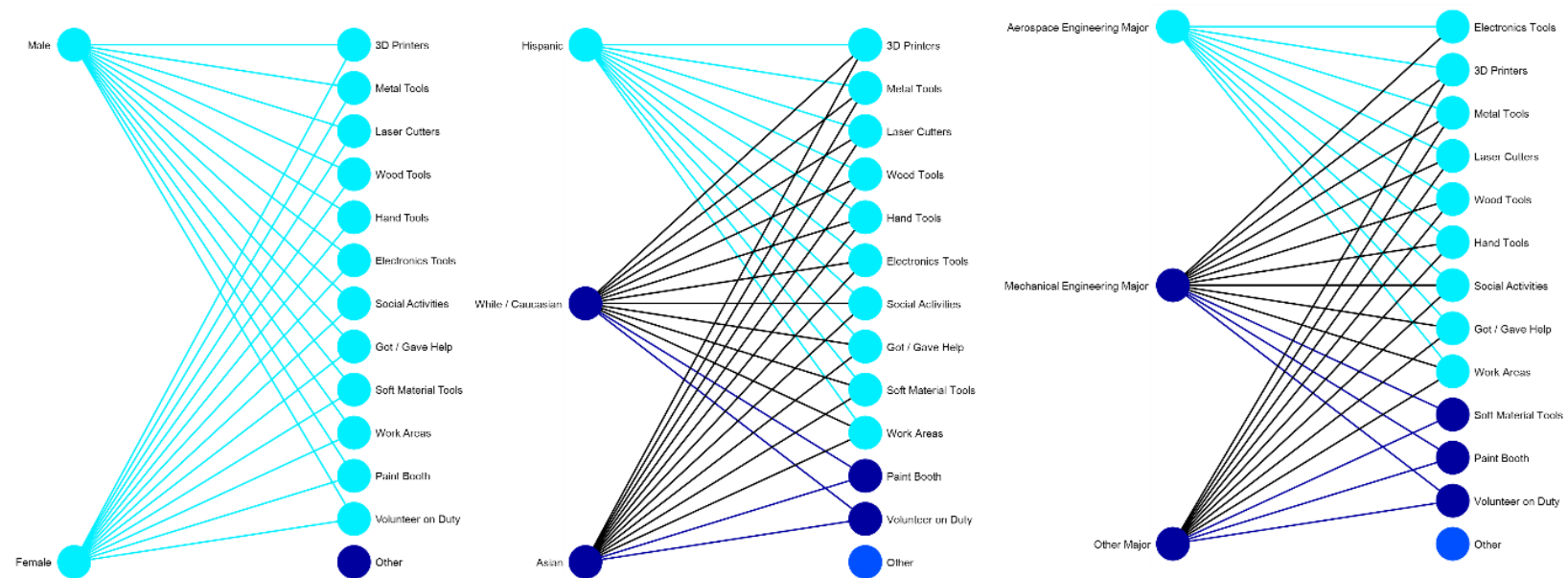


Figure 23: Demographic analysis School B Spring 2021

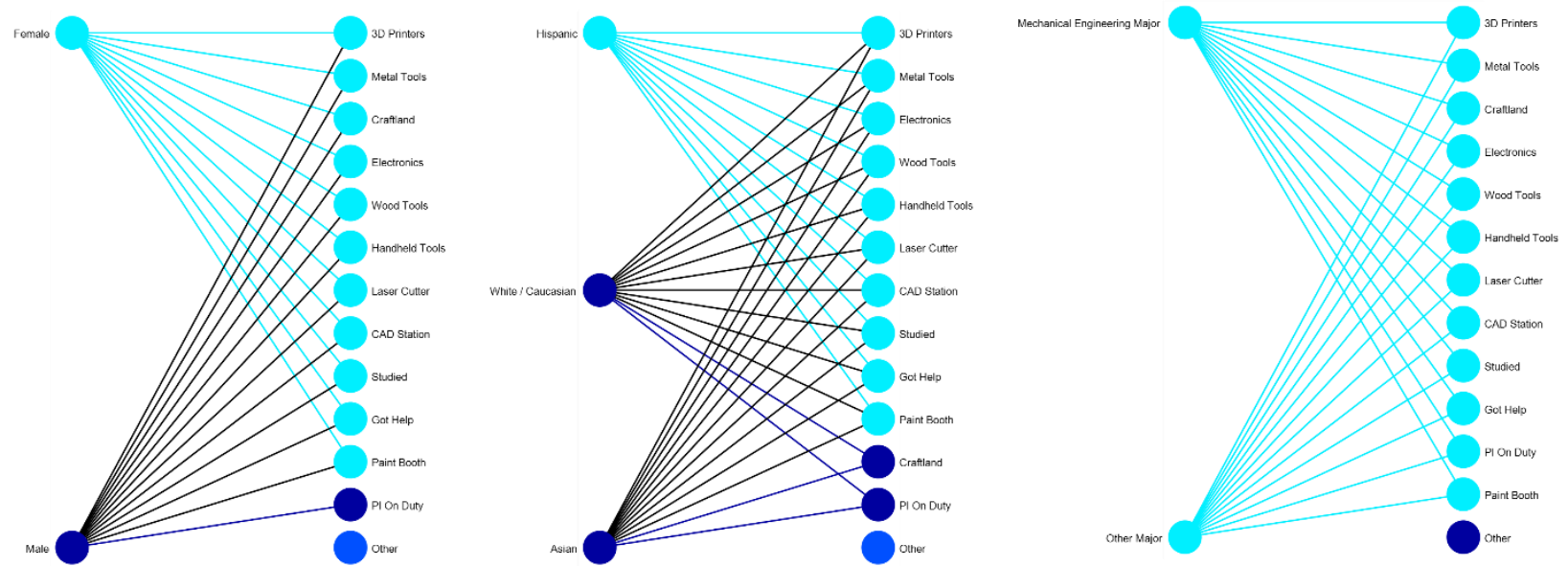


Figure 24: Demographic analysis School B Spring 2022

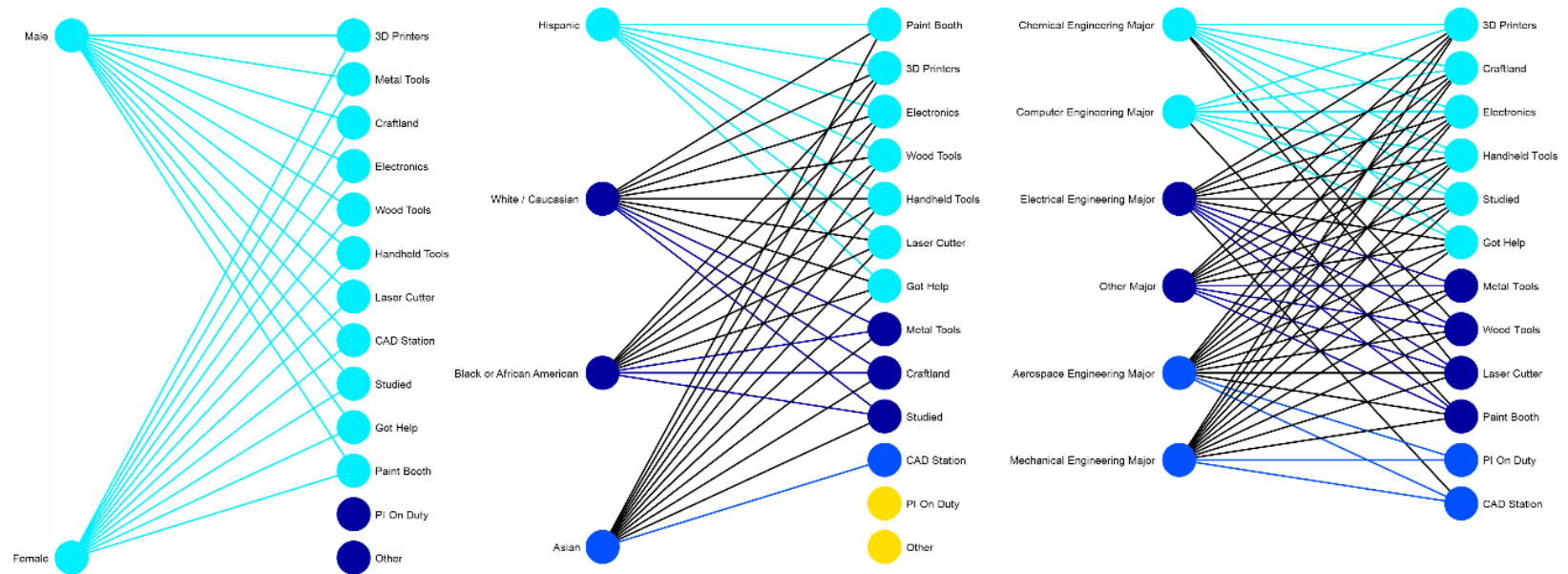


Figure 25: Demographic analysis School B Fall 2022

APPENDIX E: MODULARITY AND NESTEDNESS PLOTS

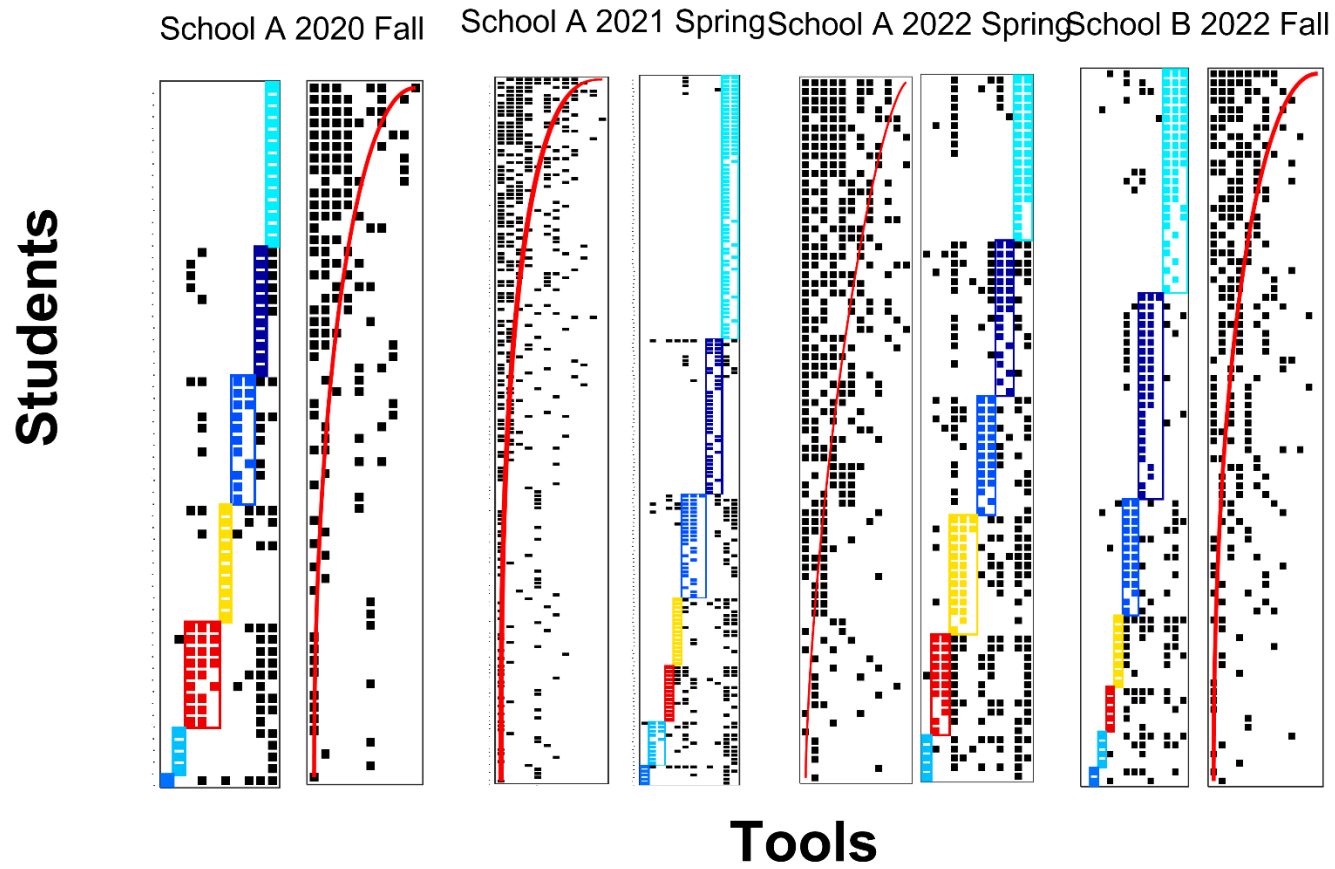


Figure 26: School A modularity and nestedness plots for general tool network

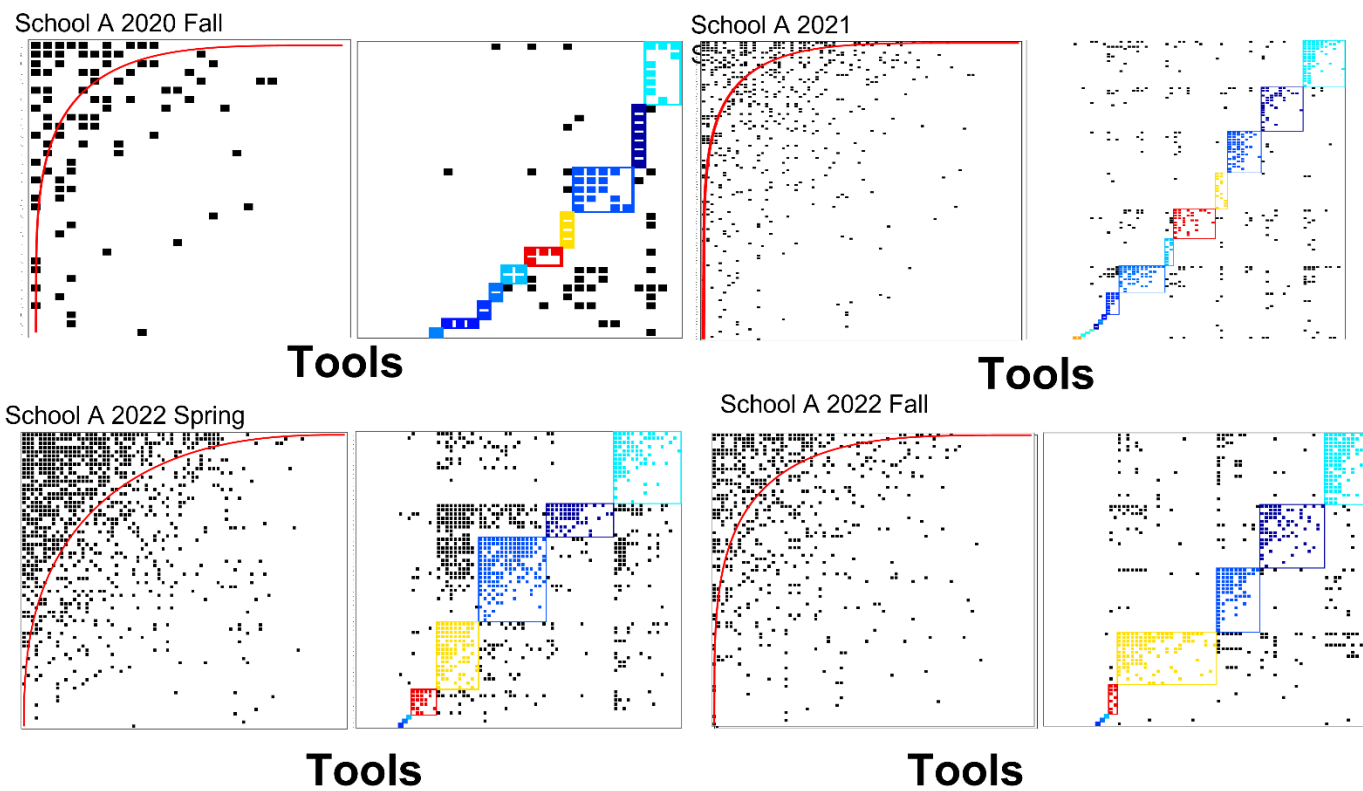


Figure 27: School A modularity and nestedness plots for specific tool network

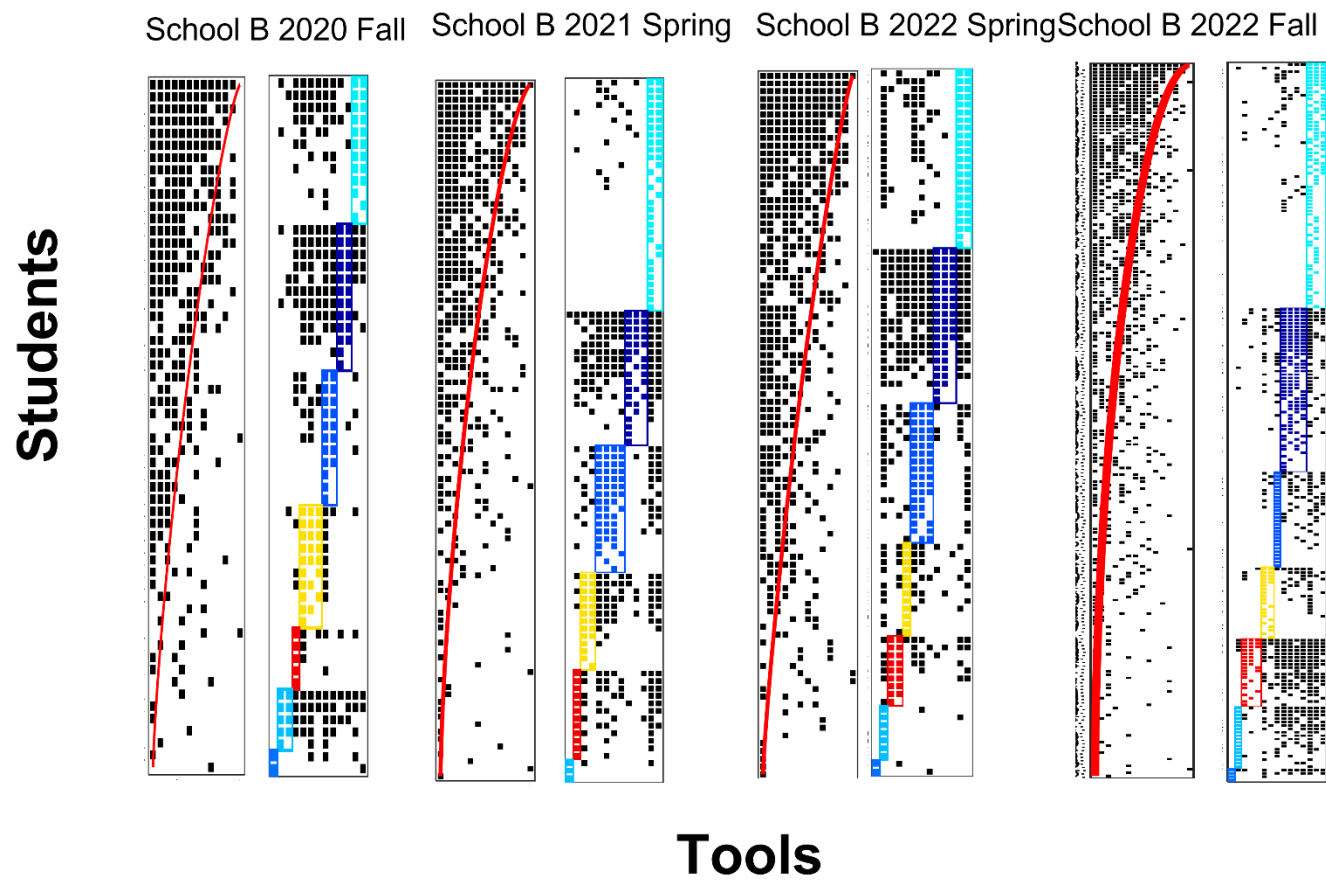


Figure 28: School B modularity and nestedness plot for general tool network

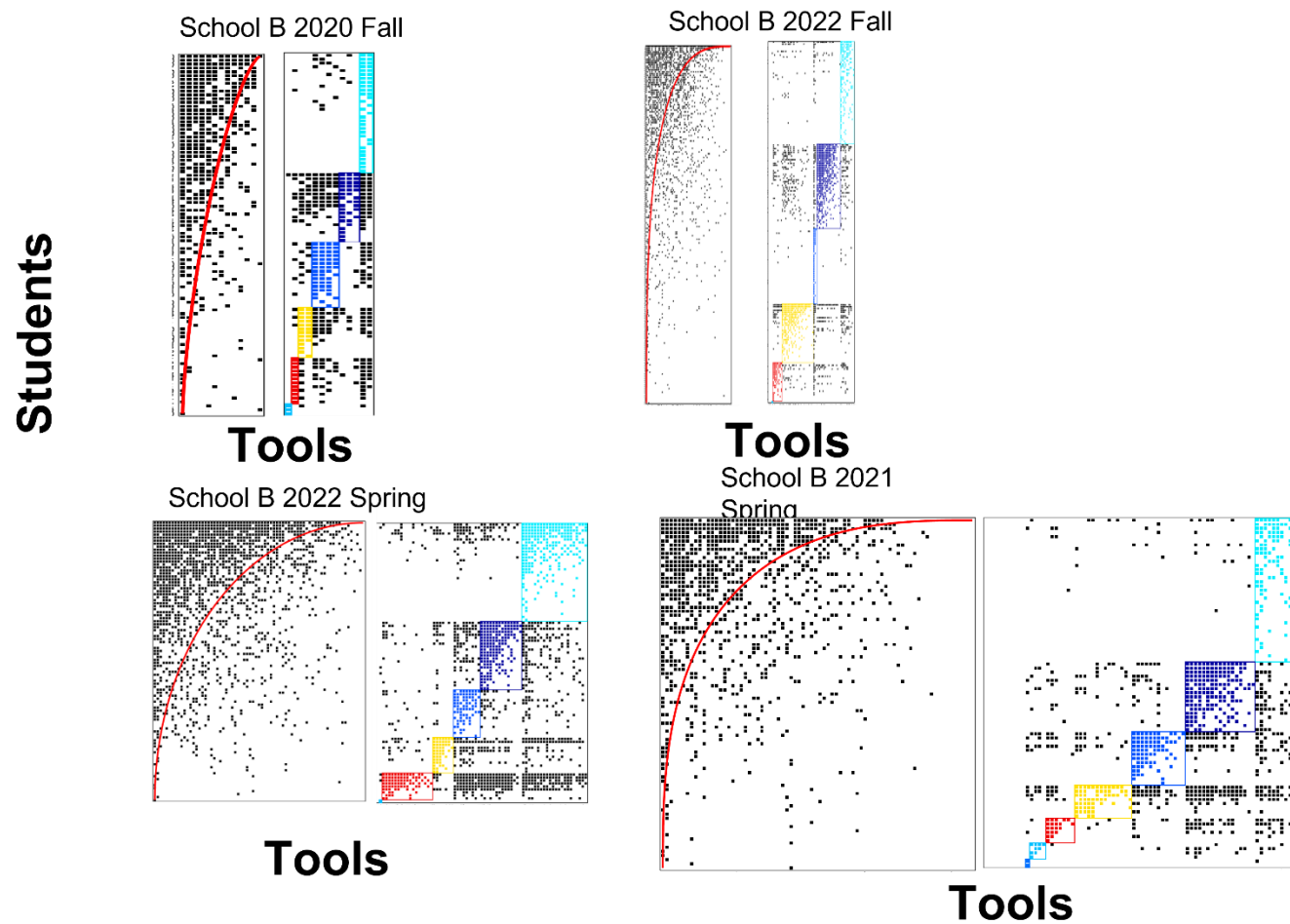


Figure 29: School B modularity and nestedness plot for specific tool network

APPENDIX F: NETWORK ANALYZER SOFTWARE DOCUMENTATION

Included as a supplementary file due to size.