Design and Analysis of an IoT Usage Tracking and Equipment Management System Within a University Makerspace

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Dedication

For my family
In memory of my father
For Alli and our future
And for myself

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ABSTRACT

This dissertation provides an account of the design and analysis of an IoT usage tracking and equipment management(UTEM) system. A motivation to both increase safety and user awareness in the emerging learning environments of academic makerspaces drove the development of this technology. It was designed with three stakeholders of academic makerspaces in mind; the students who use the resource for fabricating course projects, staff responsibility for its operation, and the faculty who consider these makerspaces in their pedagogy. The system combines a centralized database, a web interface, and RFID controlled equipment terminals to provide administrative control of connected fabrication equipment and collect data on the usage of those resources. The system was installed on six equipment stations in a university makerspace in fall 2016 as a pilot study implemented to assess it's performance.

The UTEM system was assessed on system performance, usability, and influences on the host learning environment. Interactions with the system were examined through observation and interviews with design stakeholders: students, staff, and faculty who work with the makerspace. It captured over 1,022 hours of use on the attached stations, provided a useful interface for interacting with the database, and provided a barrier to use of equipment unless properly trained and approved. All through the use of open-source software and less than $85 per safety interlock terminal.

The pilot study found that the UTEM system improved stakeholders relation-

ships with the makerspace through its ability to provide safety interlocks to equipment, create a central repository of organizational information, and track usage of attached resources within the makerspace. Faculty saw value in the information it provided but did not make use of it. Staff used the technology to maintain user and station information as well as permissions and referenced usage data in their organizational discussions. Staff also featured the safety features in administrative reporting and opened up extended non-supervised hours for equipment connected to the system. Students enjoy greater access to the makerspace and those resources due to the safety interlocks. The UTEM system achieved its design criteria and met its goals to provide stakeholders with an increase of safety a makerspace as well as collect data on equipment use and through those attributes, improve stakeholder experiences within the makerspace.

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The CEEO innovation fund enabled me to take this idea and turn it into something tangible, something real. I will always appreciate that seed that allowed the UTEM system to grow. It also enabled me to hire William Dolan. His abilities and creativity pushed my design in interesting and innovative ways.

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Part I

Introduction

I begin this dissertation by providing an introduction to the technology I developed as part of my doctoral research. The motivation behind this effort comes from my involvement in academic makerspaces and examining those learning environments. That interest resulted in the technology that is described within this document as well as the efforts to assess its performance.

Chapter 1

Introduction

1.1 Motivation

My involvement in developing educational makerspaces, studying these learning environments, connecting with other similarly interested researchers, and meeting with a variety of educators made me particularly aware of the barriers and concerns involved in starting up a makerspace and establishing the community within. For those unfamiliar with this term, a makerspace is a collaborative work space that exists for its users to make with the variety of resources made available within these spaces. I had the opportunity to develop and run a makerspace at my university's main campus library, converting a conference room into a temporary makerspace for the summer of 2014. That space then transitioned to one of the university's centers to become a greater academic resource in support of engineering courses, workshops, and students' prototyping (Vavra 2014). I have also attended several official Makerfaires, even presenting at the New York Maker Faire (O'Connell 2015), as well as makerspace development workshops and academic conferences focusing on making in education.

Through these experiences, I recognized that although makerspaces take on a wide range of formats and purposes, they do maintain a few commonalities among them, particularly in their uptake. Developers must consider cost, accessibility, resources, and safety when taking on the planning and design of a makerspace. They must also keep in mind that these spaces answer to a variety of stakeholders with a wide range of expectations in regards to the makerspace, particularly in an educational setting.

Most individuals interested in developing these spaces do not see them as simply empty rooms, they see them as bastions of fabrication resources and collaborative design. Those resources cost money, particularly the more high end, desktop fabrication equipment like 3D printers, milling machines, and laser cutters. Even the space itself has a value within an institution with limited available square footage. Once that space is acquired and tools purchased, resources such as staff and material replenishment need addressing. Those commodities of money, space, and resources need to be allocated for these environments to begin their formation and require some sort of authority to sign off on such expenditures.

For instance, in an educational setting there are administrative entities that need to be involved. They are the ones to approve those initial resources, but typically need some convincing to allocate them first. An understanding of how the space will be beneficial must be somehow communicated. In my experience, this has been primarily achieved through advocacy by influential members of the faculty. They see the value in having a makerspace as resource for their students in both supporting a desire for more project based pedagogy but as a general resource for students to engineer and develop their own projects, not just class assignments. The information backing that advocacy though has mainly been experiential and informal, lacking hard data to corroborate that experience.

There is also the matter of the ongoing support necessary to maintain a makerspace. The staff involved want to know what happens within the space, how it is being used. This isn't just for reporting usage up the hierarchy but also to ensure it is being used safely. Ensuring that the risk to injury is minimized takes a high priority since these educational spaces service so many young, inexperienced students. Injuries in similar settings have led many campus fabrication shops to take on a "no" is the safest response mentality. This conflicts with the student desire for access to the resources of the makerspace. I have staffed an educational makerspace and been a student attempting to use them. I have even taught courses that expected my students to utilize the available makerspaces on campus and observed that desire and the resulting actions from each of those perspectives. Students expect all available resources to meet their needs and have minimum barriers to their use, to be open when most convenient for them and contain all the tools they need to fabricate their projects.

My experiences as a student, a staff member, and a faculty member drove me to engineer a solution to some of the issues I have come across. Administration wants simple reasons to know that a campus makerspace has value. Faculty want to utilize them for their courses. Staff want the resources to be useful to students but to be used in a safe manner. Students want to have as much access to the makerspace as possible. These concerns motivated me to design a system which could address some of these issues. For this iteration, my primary goal was for the system to increase safety around equipment use. I also wanted the product to provide data on equipment usage that may inform faculty of what their students are doing for just-in-time help and also provide staff with more information about the usage of the space for their decision making and reporting.

1.2 The UTEM System

The IoT[1] usage tracking and equipment management(UTEM) system was developed with those experiences and concerns in mind. I identified three main stakeholder groups by their likely interests into the installation of a makerspace at their institution, each a role I had some personal experience in: makerspace staff, university faculty, and university students. These stakeholders were in mind throughout the process. The UTEM system consists of a network of devices that communicate with a central server. These devices, the RFID terminals, interact with the equipment at each connected workstation, prohibiting use until an approved user disables the interlock. Users interact with the terminals with personal RFID tags, identifying them to the system's database. The UTEM system and its component parts will be described in greater detail in chapter 4 on page 23.

My goal in this work was to develop the following features as the main user level attributes of the UTEM system:

1. Automatic equipment safety interlock
2. A centralized database of system information
3. Logged usage tracking data and visualizations
4. help button on each station terminal
5. photo button on each station terminal

These attributes are features that have some direct and noticeable effect on stakeholder experience. This effect was expected to be more sociocultural in nature rather than examined through a quantifiable metric. Therefore qualitative methods were also used in the assessment of the pilot study.

[1]Commonly used acronym for 'Internet of Things'

1.3 Pilot study

The analysis of the UTEM system was achieved by examining it as a technology-in-practice installed in the learning environment. The study depends mainly on qualitative methods. The design intended for the user level attributes of the IoT usage tracking and equipment management system would have positive influences on stakeholder relationships with an academic makerspace. Success of this technology would require evidence connecting the use of the UTEM system to a positive change in stakeholders' outlook on the makerspace and how they interact with it. That interest in the UTEM system's use and cultural interaction within a specific makerspace influenced the formation of the pilot study and its methodology as well as established a bounded system. As part of the study, I collected qualitative data from observations, interviews, and artifacts collected as well as quantitative information from the system itself. These data were examined for evidence giving insight into the cultural environment and what noticeable relationships exist between the design attributes and stakeholders' experience.

The overall objectives of the pilot study was to analyze the UTEM system during the initial semester of its implementation to assess its performance and, considering the technology a socio-technical system, understands how it fits within the culture of that makerspace. This effort was to make an assessment of whether the new technology met its initial design expectations with regards to the 5 user level attributes. Qualitative methods from both educational studies of makerspaces and from ethnographic studies of technologies were used for their ability to provide a deep understanding of the cultural environment, not towards the generation of any learning theory but to best understand the makerspace and the technology's relationships within.

Chapter 2

Background

2.1 Makerspaces

Makerspaces encourage and enable wide ranges of creative outlets and empower personal agency within the maker. They serve as the physical embodiments of the Maker Movement, the growing community of amateur to professional individuals who share a do-it-yourself mentality. These informal fabrication and collaboration spaces have attracted the interest of artists, scientist, engineers, educators, and many more. Their users design and build with varying complexity in both the physical and the digital realms, each personal to the individual maker (Anderson 2012; Dougherty 2013).

For many years now, the maker movement and makerspaces have garnered a growing interest around the world (See figure 2.1). The total number of spaces internationally has grown 14 fold since 2006(Lou and Peek 2016). This growth in physical locations designed to encourage making is consistent with the greater adoption of the maker movement. Chris Anderson (2012), former editor of Wired Magazine, refers to the movement as ”a new industrial revolution” and ascribes it three defining characteristics: taking the opportunity to exploit digital desktop tools,

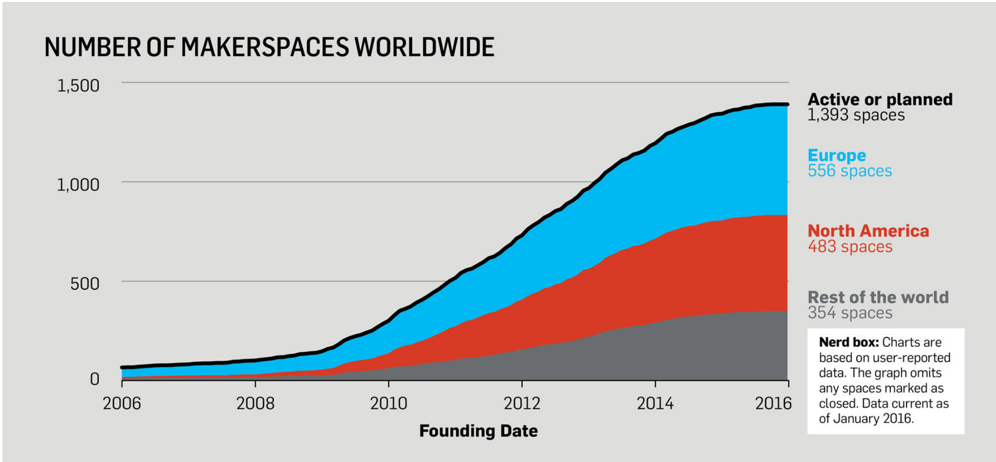


Figure 2.1: Number of makerspaces over time

source: Lou and Peek (2016)

established cultural norms of sharing and collaboration, and adoption of growing design standards and common resources which facilitate that collaboration and design iteration.

It is that sharing and collaboration that has contributed to the growth of makerspaces in many communities. Informal groups of makers organically come around shared ideas and interested then constructed their own small makerspaces. These grew into larger entities such as Artisan's Asylum in Somerville, MA and even chains of professional makerspaces such as TechShop (Hatch 2014). This widespread adoption by hobbyists, tinkerers, and professionals have allowed makerspaces to permeate a vast number of cities around the world. The creation of these professional and community built makerspaces paved the way for their integration into other, already established edifices of the community (Lou and Peek 2016; Dougherty 2012).

Libraries and museums were some of the first to welcome the maker movement and establish their own makerspaces (Abram 2013; Brahms 2014; Honey and Kanter 2013). Once these museums and libraries began to showcase the value of makerspaces, educators and their administrations took notice (Dougherty 2012;

Sheridan et al. 2014). The leap into makerspaces as learning environments was not a difficult one. Being traditionally informal learning environments in and of themselves, there was a logical progression to the transition of these fabrication environments into more formal educational institutions.

2.2 Learning Environments

Halverson and Sheridan (2014) noted that the role of making in learning has been talked about far before the term ”making” was coined. The nature of activity within makerspaces is essentially personal engagement with construction, an inherent tenant within Papert's constructionism (Papert and Harel 1991). This learning theory advocates discovery learning centered around the student and enabling them to build their knowledge with their already existing knowledge and new experiences. Project-based learning enables them to make connections between their ideas and new areas of knowledge. Researchers have suggested this learning theory established the theoretical backbone to the movement, creating a clear connection to education for these environments (Halverson and Sheridan 2014; Martinez and Stager 2013). This is of particular interest for engineering education, a discipline that traditionally encourages such hands on engagement as part of pedagogy and values creativity and innovation as essential engineering skills (National Academy of Engineering 2004, 2005). These environments encourage design and prototyping as well as perform similar functions as many existing school fabrication shops. After the growth in popularity of these spaces, many colleges and universities having taken notice of their value. They have installed and developed these makerspaces of their own[1] to support their engineering students desires and their academic needs. Many issues need to be addressed though before installing a makerspace in such a setting.

[1]Or re-brand existing, similarly functioning spaces as makerspaces.

The educational institutions installing their own makerspace must consider cost, accessibility, resources, and safety; the latter being one of the primary concerns (Jariwala et al. 2014). There are liability interests at the upper echelons of the institution that must be reflected in the practices of each hierarchical level. Makerspaces typically establish protocols, safety procedures, as well as codes of conduct to address most safety concerns. Tools deemed unsafe often become sectioned off in a secure portion of the space or locked away, only to be used under proper supervision during certain hours since to difficult to control access otherwise. This is counter to the defining characteristic of a makerspace is its community of openness and accessibility though (Anderson 2012). That characteristic is difficult to maintain while still adhering to the safety requirements of an educational institution. There is also the matter of resource awareness and control, something important to reporting use and cost to an administration but difficult to maintain in a free use setting (Jariwala et al. 2014; Sheridan et al. 2014; Wilczynski 2015; Blikstein and Krannich 2013; Doorley, Witthoft, et al. 2011). These concerns are not limited to institutions of higher education though. Industry faces similar concerns in their professional settings and developed many of their own solutions to such problems.

Industry takes advantage of a wide range of technologies to generate solutions to their concerns, particularly regarding tracking of resources and data collection. Population tracking is probably a familiar one for most. Employers typically provide their employees ID badges that either contain a mag strip, a bar code, or an RFID. Various readers around facilities connect to centralized databases that keep track of who is allowed where. Doors have their own scanners that employees swipe or tap to gain access to the room, allowing the company to know who enters what areas when. This method is popular in most industries to control employee access to vulnerable or unsafe areas. Hospitals are a particular example since they also use these types of technology to track more temporary visitors, patients in particular.

Some also use similar access control of pharmaceutical substances, providing more detailed information and automated on such concerning materials (Angelo, Christensen, and Ferreri 2005; Oswald and Caldwell 2007). Material control and tracking is another common industry concern with various technical solutions. Machine shops utilize vending machines for their resources, enabling them to automatically calculate replacement rates on bits and other tools as well as who uses them. The may even be attached to work pieces and scanned at each step of their manufacturing process, to maintain a record of work for the part. Large scale equipment can be set on keyed power as part of a safety protocol as well, ensuring use can't occur without being issued a physical key or code (Collins and Aulert 2016; Kennedy 2016).

These are all industrial scale solutions to problems that makerspaces similarly face. They carry with them industrial scale prices for such resources though. With the advent of more and more open source options for personnel identification such as open-source RFID cryptographies and more inexpensive communication and interlock control hardware, many of the functional features of those systems can be recreated at a smaller scale for these educational makerspaces (Seidle, K., and Cavis 2016; Smith 2010). This technology can be developed and implemented within a makerspace. Measuring the success of such a new system in such a learning environment though is not as straight forward.

2.3 Qualitative Research in Engineering

Makerspaces are learning environments that contain a great many interconnected variables; equipment, materials, space, students, staff, faculty, self-directed activities, course-driven ones, official procedures, established norms, etc. Each of these variables influences and is influences by others, making it difficult to isolate and evaluate their individual influences. Linn and Songer (1988) criticized comparative approaches in studying innovation integration into an educational setting; you can not simply look at just real-time data collection and ignore the influences of a technology on the culture of the setting. It has an effect on standard routines and other cultural aspects that influence its use. She also warns that causal attributions become problematic when many aspects change. Implementation of a new technology system within a university makerspace would fall into that category of concern. This means that the study can not limit its scope to just single interactions and outputs of the technology, that you must consider the extended effects of those interactions. The moments that follow that moment of interaction are also of interest in understanding the technologies effect.

In makerspaces, the technologies involved serve as part of the culture of the system, bounded by the physical space but also by the extended community connected to it (Anderson 2012). Learning and teaching are also social processes at a fundamental level. Research in an educational makerspace and any of its components needs to especially consider those social constructs (Lee et al. 2014; Halverson and Sheridan 2014). This, combined with the communal aspects of a makerspace, requires that somewhat of a situative perspective be adopted for examining these spaces. The environments are partially defined by their social connections, particularly to that of the maker movement (Dougherty 2012; Anderson 2012). These spaces establish hierarchy of experience among its users with a range of available technologies along a spectrum of difficulties, providing more knowledgeable others to interact within a zone of proximal development (Vygotsky 1978). Learning processes in a makerspace are intimately connected with those social interactions. The available resources, particular the technologies, affect those situations though. So recursively, the interactions with the technologies must be considered in the context of the overall learning activities as well (Greeno 1998; Rusk 2016).

Makerspaces have been a research topic of interest for a number of years. Many of the studies that examine them do take into account the cultural aspects of such learning environments. They directly address the importance of understanding the social interactions and utilize appropriate qualitative methodologies to gain a deeper understanding of the research subjects and directly state. Slatter and Howard (2013) conducted a series of one-on-one interviews with librarians in Australian makerspaces, identifying many benefits of these spaces as well as challenges similar to what have already been mentioned. In higher education classrooms, other researchers reported on their integration of making into their curriculum and utilizing craft technologies as part of a maker course by analyzing student interactions, artifacts, and course comments (Wardrip and Brahms 2016; Fields and Lee 2016). Sheridan et al. (2014) spent a year examining the various artifacts produced within three makerspaces and interviewing their members to produce a comparative case study. Their findings were much broader, finding meaningful shared themes among them with implications for the study of makerspaces; their multidisciplinary nature fuels engagement and innovation, a diversity of learning arrangements dependent on the learner, and the learning is strongly rooted in the experience of making. Such ethnographic approaches served those researchers well in gaining a better understanding of the makers and their relationship with their respective makerspaces.

More modern researchers have also advocated ethnographic methods be utilized in design and design education research for its ability to capture and represent the larger story (Litts 2015). That ideal can be seen in many studies of designers and engineers (Vinck 2003; Nguyen et al. 2006). Candy and Edmonds (1996) studied the past outputs of an expert designer through historical records, design documents, and the designer's reflective accounts. Cross (2003) examines experts in their professional design settings through observation and interview to gain insight into their creative strategies. *Design Studies* spent an issue delving deeply into the topic of ethnographic studies in design and the various approaches (Jagodzinski, Reid, and Culverhouse 2000).

Qualitative methods have not just been used in the examination of design practices but also in the validation of various technologies, particularly those socio-technical in nature. Orlikowski and Baroudi (1991) considers the research perspective to be the most important concern for the study of technology systems. They argue that all potential data sources and methodologies be considered, especially qualitative methods if the context of the technology's implementation requires it. For instance, they examined 155 studies on informational technology and found that many utilized ethnographic methodologies and relied heavily on the qualitative data. Those studies also took into account the quantitative findings, typically from the examined system, but the qualitative findings simply were more effective in speaking to the full scope of implementation. In those cases and many since, researchers argued that a full understanding of the effectiveness and agency of a technology can not occur until it has been understood while as a technology-in-practice (Orlikowski 2008). This is particularly understood with the implementation of various medical devices (Timmermans and Berg 2003). Edmondson, Bohmer, and Pisano (2001) examined the effect of a new cardiac surgery technique on 16 surgical teams' routines and behaviors with site visits, observations, and over 100 interviews. Qualitative methods served in examining customization features in medical devices by nursing staff in 3 hospital settings (Randell 2003). Custom organizational software has been similarly investigated before formal release, examining both the piloting of the technology for its effectiveness and to establish lessons for future developments and pilot programs (Schwabe and Krcmar 2000). The common thread being the acknowledgement of these technologies being socio-technique, that their use has an inherent social context and therefore their evaluation and acceptance required inclusion of the social element.

The cultural aspect of a makerspace is one of their defining characteristics. Learning environments also have inherent social processes involved in the curricular engagement between students, instruction, and that setting established for those teaching purposes. Installing a technology into such a space and then attempting to evaluate that technology requires understanding of that cultural dynamic. The UTEM system is installed in an educational makerspaces that sees significant use by the university students both for their personal projects but also since various courses take that advantage of that resource as part of their coursework. Students interact with it as they make use of the equipment and it was designed with many of those social contexts of the space in mind. To examine the effectiveness of this technology and make any determination about its use, it must be examined using an approach that can assess the culture of its host makerspace and consider the situation it is installed.

Part II

Design

This portion of my dissertation presents the design and assessment of the IoT usage tracking and equipment management system. The development of the technology, the resulting features, the pilot study that examined its initial implementation, and the resulting performance of the system are provided. Each of these items are described in detail in their own chapters within this part.

Chapter 3

Design Criteria

I began developing the IoT usage tracking and equipment management system in the Spring of 2015 through a grant by the Center for Engineering Education and Outreach Innovation Fund. The first motivation was to create an added safety measure for makerspaces to help ensure their safe use and, through that encourage greater adoption in academic settings. The second was to provide a data collection method to provide information on how the makerspace is being utilized. I considered three stakeholders as the groups most affected by the UTEM system: staff, faculty, and students. The design resulted in a system consisting of a centralized database, a web framework, and RFID terminals with either a sign-in function or full safety interlock capabilities. I installed this system in a university makerspace in August 2016. At the request of the staff, the installation was limited to six fabrication equipment stations and one sign-in station on their largest fabrication area. The fall 2016 semester served as the pilot study to examine the system's performance in its intended socio-technical setting, leading to design improvements informed by user interactions[1].

[1] Interactions which led to improvements are discussed within the performance analysis in chapter 6 on page 89

3.1 Identifying the Main Stakeholders and their Design Archetypes

I took into consideration three major stakeholders when designing the UTEM system: staff, faculty, and students. They were selected based on their involvement or interest in the implementation and management of an academic makerspace. These three stakeholders arose from discussions at experiences includes attendance and presentation at events such as the 2012, 2013, and 2014 New York Makerfaire as well as presenting in an educational forum at the 2015 New York Makerfaire (O'Connell 2015). Attendance of Artisan Asylum's 2013 How to Make a Makerspace workshop enabled conversation with a wide range of individuals interested in implementing a makerspace (Artisan's Asylum 2013). Helping start makerspaces at Tufts University and through the Center for Engineering Education and Outreach provided many opportunities to meet with educators, administrators, and researchers experienced with makerspaces as well as those simply interested in their adoption. These pursuits also involved the establishment and management of a makerspace, Jumbo's Maker Studio, in Tisch Library during the summer session of 2014 and its transition to the Center of Engineering Education and Outreach that fall (Vavra 2014).

That prior experience along with visits to both academic and public makerspaces in the United States of America and Queensland, Australia including discussions with their management, staff, and users informed the stakeholder archetypes and the design criteria. Those archetypes are also informed by several publications on makerspaces and echo their common concerns, such as staff's concern for safety and cost and faculty seeing makerspaces as a student resource (Burke 2014; Anderson 2012; Slatter and Howard 2013; Abram 2013).

These archetypes serve as tools for design, emphasizing characteristics necessary to consider in developing with these stakeholders in mind. These are not generalizations of their actual personalities. These are simply items that are needed to be understood to meet design goals within an academic makerspace. In the same way that child safety locks do not believe that small children want to drink cleaning supplies under the sink, they need to consider the worst case scenario that the stakeholder is likely to engage in.

3.1.1 Staff

The people responsible for the day to day operations of the makerspaces, for decisions regarding the overall design of the makerspace, determining what resources and equipment should be available within, and what operational hours should be are the first set of stakeholders in the design. Staff typically concerns themselves with ensuring that the space functions well and in accordance with their values and policies. Those values and policies are typically set by both the host of the makerspace, in this case a university, as well as the interests of the staff. In this academic setting, that was considered to be primarily attending to the needs of the students as a learning environment and maintaining a safe environment. As for day to day concerns, staff maintain the equipment, ensure consumable stocks are available, and actively pursue safe use of the equipment through oversight and training, which they may either adopt from existing source such as the equipment's manufacturer or developed themselves. Some staff members have more administrative items to consider in their decision making: the available budget for the makerspace, amount of equipment use, and visitation. That information serves staff in making administrative decisions as well as in promoting the space and seeking further funding.

3.1.2 Faculty

I considered the faculty as a secondary user of an academic makerspace since they were thought more likely to consider it regarding its service to their pedagogy, not considering it for their own fabrication and creativity but rather mainly for their students' fabrication and creativity. This stakeholder wants feedback on how their students make use of the makerspaces, particularly with regards to the assignments given in their coursework. Ideally, faculty would see an added data source as a resource for their pedagogy and useful in making just-in-time teaching decisions.

3.1.3 Students

The students are the primary intended user of an academic makerspace. I saw their use as a consideration by the other stakeholders along with their own. They recognize that the purpose of an academic makerspace, especially one intended as a learning environment, is to service the students' needs. Students maintain an expectation of availability of resources. If they find it available to them, they will use it. They desire all resources to serve their needs in the most convenient way, providing them with the tools and equipment they need to complete their course work as well as their own personal projects. Their do exist some students hold little concern for policies if it is easy to circumvent them[2]. I consider them to likely be the minority but the efforts of those individuals will most greatly effect the functionality of the UTEM system so that consideration for students must be kept in consideration during the design.

[2]This last point of the archetype was considered to a far lesser degree prior to implementation. Updates in response to events during implementation forced it to be a primary consideration in those redesigns.

Table 3.1: Design Criteria

Design Criteria	Importance	Requirement
Safety	Primary	Ensure/encourage safe use of attached equipment
Data	Primary	Automatically collect usage data on attached equipment
Cost	Secondary	Minimize cost of implementation
Delay in Access	Secondary	Minimize delay in use
Interface	Secondary	Useful means for users to access data

3.2 The design space constraints

With these three stakeholders in mind and along with the initial motivations for this project, I established several design criteria. The two primary criteria were a means to collect equipment usage data and a means to inform and possibly ensure safe use. Data made available should be done so in a useful interface for the interested stakeholders. The expectation was that staff and faculty would be the only stakeholders with an interest in the usage data, to inform their managerial decisions of the makerspace or pedagogical decisions within their courses. The design must also inherently encourage or ensure the safe use of any equipment it interfaces with, alleviating a major concern for the staff in allowing open access to perceived dangerous tools (Moorefield-Lang 2015; Burke 2014). These two aspects serve as the primary features of the UTEM system and required criteria for acceptance of the design. The secondary design criteria includes minimal cost, maximized accessibility, and useful data interface; they serve as beneficial components to the system to encourage adoption and improve use (See table 3.1). Secondary only denotes these criteria in relationship to the primary criteria. For instance, if safety is negatively affected by a positive change in cost, then that change in cost will not be implemented.

Academic makerspaces are becoming more and more popular and a desired feature in many schools (Halverson and Sheridan 2014; Blikstein 2013). In spite of calls for national support of such efforts (The White House 2014), budgets for most public schools are tight and typically adding new resources is difficult. The cost of many of the resources typically associated with makerspaces also come with a hefty price tag, MIT's Fab Foundation (2016) recommends budgeting $25-65k in capital equipment and about $15-40k in consumables. With that in mind, I set a design criteria of minimal cost and prioritized use of commercial-off-the-shelf(COTS) open source components before design of custom components. This was arbitrarily set to less than cost of less than the least expensive station. In this case it was the soldering irons which retail for $100.

The primary users of the equipment (students) desire access to the equipment with minimal hurdles or delays to that access. The means by which the system identifies and approves individuals should be minimally invasive, adding minimal steps into the users process of interaction with the equipment[3] . The time required for the system to make an access check should also be minimized. Students should also see secondary benefits of increased access due to the safety considerations enabling staff to allow for increased access.

The final design consideration was the user interface. Some means to access the data in the database is necessary for the stakeholders to make use of it. Considering the staff and faculty as the stakeholders who would make use of any captured usage data, interfaces need to be available that enable that access and clearly display that data. The stakeholders should also be accessing data informative towards their concerns within the makerspace, so displayed data objects need to consider those potential desires.

[3]This assumes the students follow all the appropriate policies before attempting to use the equipment.

Chapter 4

The IoT Usage Tracking and Equipment Management System

I considered data collection, safety, minimized cost, maximized equipment accessibility, and data interface in the development of this new technology. It combines an open-source object relational database system, a python web framework to enable interaction with the database, and a set of interlocks controlled by RFID access terminals constructed from majority open-source COTS components, costing less than $55 in functional hardware each. It utilizes Mifare CLASSIC ISO 14443A identification standard hardware, Raspberry PI ZERO microcomputers as unit controllers, a Python based web framework, and an object-relational database.

Users interact with the system through web interfaces to access and input information within the database (See figure 4.1 on the next page). They also interact with the system through the RFID terminals using their personal RFID tags. Those terminals communicate with the database through another web app, checking for user permission status. When access is granted, interlocks disengage so the user can make use of that resource. That usage can then be seen by other users through the web apps.

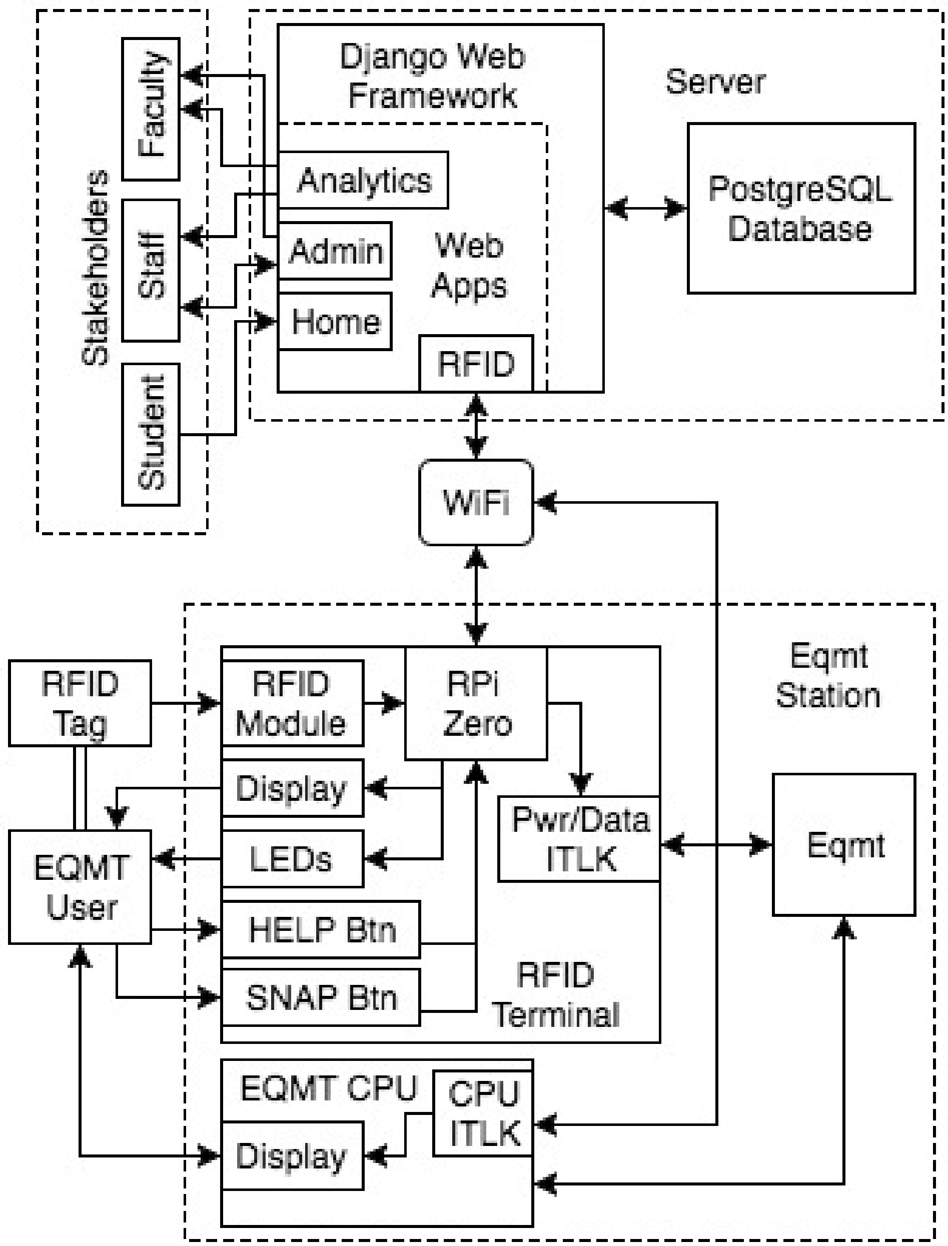


Figure 4.1: Schematic of the IoT Usage Tracking and Equipment Management System

4.1 Database - PostgreSQL

PostgresSQL(commonly referred to as Postgres) is an open-source object-relational database system with a strong support following (PostgreSQL Global Development Group 2015). Active development has been maintained since the initial release in 1995 and the architecture has proven reliable and secure. I examined this option on the recommendation of a colleague. It is well documented by its development group with several strong support communities (MediaWiki contributors 2017; Stack Exchange Inc 2017; PostgreSQL Community 2017). That strong community support as well as my colleague's recommendation led to its selection as the database for this system. The database is installed on the central server for the system.

In an object-relational database, data is collected into objects of stored values and then those objects are organized into established relational tables. Accessing and manipulating that data occurs through object queries in a query language. The UTEM system integration will be discussed further in section 4.2. This section discusses the architecture of the database.

I held a design meeting with colleagues in the summer of 2015 and there we argued what data would be of interest to the stakeholders, identifying the initial data objects. With the help of a focus group, we developed on that set of data tables.

Some changes have occurred since then but the the overall architecture and the majority of the available data objects have remained constant (See table 4.1 on the following page). Additional object fields were added and reorganized as required during development. We determined that the data of perceived value were those pertaining to users, stations, permissions, and logs of usage and organized into tables which reflected that grouping.

I organized all user specific information into the table 'users' (See table 4.2)

Table 4.1: Data Objects and Relational Tables Identified During Design Review

Users	Stations	Permissions	Locations	Log
User ID # -	Station ID # -		Location ID # -	Log # -
(Unique Serial Key)	(Unique Serial Key)		(Unique Serial Key)	(Unique Serial Key)
User Name (Unique)	Station Name	User (ref ID#)	Name	time
First Name	Description	Station (ref ID#)	Description	User ((ref ID#)
Last Name	Location (ref ID#)	Access (Boolean)	Address	Station (ref ID#)
Email (Unique)	Setup Date	Access Date	# of Primary Users	Request (Ask or tell)
rfid (Unique)	Last Maintained	Last Use		Response (Boolean)
Registration Date	Maintenance Period	Total Uses by User		Returns
Department	Last Use	Total Hours by User		
Class Year	Total # of Uses	Notes		
Birth Year	Total # of Hours			
Last Visit	Materials			
Expiration Date	Notes			
Primary Loc. (ref ID#)				
Notes				

When a users signs up for the RFID interlock system, they are automatically assigned a unique identifer ('uid') for reference by other tables in the database. They are required to select a username ('uname') and provide their first name ('fname'), last name ('lname'), preferred email ('email'), Tufts University email ('temail'). The uname, email, and temail are required to be unique within the database. All are essential to the system's general function and therefore required. The user has the option of providing their department ('dept'), class year ('class'), relationship to the university ('rel'), and birth year ('byear'). These serve purely as demographic information for analysis of trends. The 'rfid' field stores the hexadecimal unique identifier of the user's rfid tag.

The rest of the user information is controlled by server side functions. The registration data ('reg_date') records the date a user signs up for the system as its default value. The ('exp_date') stores a calculated date for user's expiration as a member of the space, although currently the field is unused to affect permissions. The user's last visit is recorded in the 'lvis' field and updated with each visit. The primary location ('prim_loc') is determined by the most often visited location within the system. The boolean administrator ('admin') field stores whether or not a user has administrator rights in the system.

The stations table (See table 4.3 on page 30) contains all information related to the various location sign-in and equipment interlock stations. These are created through another user interface feature and are each assigned a unique station identifier ('sid') for reference by other aspects of the system. When an administrator creates a new station, they input the type of station ('type1' and 'type2')[1], its name ('name'), a more detailed description ('description'), the location in which it is being setup ('loc'), a time interval to serve as the maintenance period ('maint_interval'), a time interval to serve as the expiration time for user access ('access_exp'), any ad-

[1]The type refers to functional type. This cross references to another table of values such as 'woodworking','metalworking','hand tool','CNC', etc.

Table 4.2: Data Objects in Table ’users’

Column	Type	Function
uid	integer	Table’s Unique Identifier for each row (a user) Auto-generated by database from a serial key
uname	citext	User Name field is unique and case insensitive
fname	text	First Name
lname	text	Name Name
email	citext	Personal Email Address field is unique and case insensitive
temail	citext	University Email Address field is unique and case insensitive
rfid	bytea	Unique Identifier of User’s RFID Tag/Card
reg_date	date	Registration Date Auto-generated when user information entered
exp_date	date	Expiration Date Intended to auto-purge old users. Not currently used.
dept	integer	User’s Dept. Affiliation References serial key of table of University Depts
class	integer	User’s Expected Graduation Year For calculating a student user’s class level
byear	integer	User’s Birth Year For calculating a user’s age
lvis	date	Last date that the user interacted with system Auto-updated by the Django RFID app
prim_loc	integer	Primary Location. Not currently used.
rel	integer	Relation to University References serial key of table listing possible options
admin	boolean	Administrator Status Indicates if users has administrator rights
notes	text	General notes for administrative comments

ditional notes about the station ('notes'), and what the default user access should be ('defaccess'). The 'loc' field references a reference table of locations within the system.

The remaining fields are controlled by server side functions. The 'setup_date' is assigned the date which the station was created in the database. The database calculates the next maintenance date ('maintenance') from the 'maint_interval' field. The time of the station's last use ('luse'), the number of user interaction with the station ('uses'), and the total time in hours and minutes that a user has used equipment connected to the UTEM system ('hours') are constantly updated upon every use. The 'curr_used_by' field shows whether the station is currently in use and by what user, indicated by 'uid' from the users table.

The relationship between users and the stations is recorded and controlled within the permissions table (See figure 4.4 on page 31). The table references the stations 'sid' and the users 'uid', forcing a unique requirement within the table on that relationship (ie meaning only one row is allowed for each combination of 'sid' and 'uid'). The user's access to that station is stored in the 'access' field. Whenever a new user or a new station is created, the database automatically creates a new permission for that user and each station (or that station and each user) and each permission is assigned a unique identifier ('id'). The permission access is a boolean type and set by the station's 'defaccess' from the stations table. Whenever a permission is set to 'true', either by default or manually by an administrator, the database sets the registration date ('reg_date') to the current date and calculates the expiration date ('exp_date'). Similar to the stations table, the last use ('luse'), the total number of uses ('uses'), and the total time of use ('time_used') are updated each time the station is used but in this table that information is specific to the individual user instead of the station. The average time of use ('avg_use) and time between uses (avg_period) are calculated for each individual the station periodically by an

Table 4.3: Data Objects in Table 'stations'

Column	Type	Function
sid	integer	Table's Unique Identifier for each row (a station) Auto-generated by database from a serial key.
type1	integer	The primary type of equipment at station References serial key of table listing possible types
type2	integer	The secondary type of equipment at station References serial key of table listing possible types
name	text	Station's Name
description	text	More detailed description of station
loc	integer	Location where station is at References serial key of table listing locations
setup_date	date	Setup Date. Auto-generated when station information is entered
maintenance	date	Last maintenance data of station. Auto-generated from 'main_interval' but not currently utilized in practice.
maint_interval	interval	Days between required maintenance
access_exp	interval	Interval between required retraining. Intended to auto-purge old users. Not currently used.
luse	timestamp	Last time the station was used Auto-updated by the Django RFID app
uses	integer	Total number of times the station was used Auto-updated by the Django RFID app
hours	interval	Total time the station has been used Auto-updated by the Django RFID app
curr_used_by	integer	Indicates the current user at the station References serial key of users table Auto-updated by the Django RFID app
defaccess	boolean	Default access status given to new permissions
notes	text	General notes for administrative comments

Table 4.4: Data Objects in Table 'permissions'

Column	Type	Function
id	integer	Table's Unique Identifier for each row (a permission) Auto-generated by database from a serial key.
sid	integer	Station that this permission applies to References serial key of stations table
uid	integer	User that this permission applies to References serial key of stations table
access	boolean	User's permission status for station default value auto-populated from station:defaccess field
reg_date	date	Registration Date. Auto-generated when permission is set to 'True'
exp_date	date	Expiration Date. Auto-calculated from reg_date and station:access_exp Intended for training updates but not currently used
luse	timestamp	Last time the station was used by this user Auto-updated by the Django RFID app
uses	integer	Total number of uses of this station by this user Auto-updated by the Django RFID app
time_used	interval	Total time the station has been used by this user Auto-updated by the Django RFID app
avg_use	interval	Avg time of use of this station by this user Not currently maintained
avg_period	integer	Avg time between use of this station by this user Not currently maintained
notes	text	General notes for administrative comments

administrator triggered script[2].

The permissions table is automatically populated using internal triggers in the database. These triggers engage during certain events in the related tables, users and stations. For the permissions table, two events will trigger population of the table (See algorithms 4.1 and 4.2 on page 33). When a new user in the table 'users'

[2]This is not yet automatic due to reliability issues with the RFID module. This will be discussed more with the events table but the issue is the RFID terminal created multiple events for a single use due to occasional read errors. A system clean is necessary to determine actual number of events and their durations otherwise the average use would be greater and the average time of use will be shorter than reality.

is created, one permission will be created for that new user and for each existing station in the table 'stations'. The reverse occurs whenever a new station in the table 'stations' is created.

The previous tables dealt with mainly static system data objects; the users that are generated by a new member signing up and entering their information, the stations which are generated by an administrator inputting a new station in the system, and the permissions which are auto-generated upon the creation of a user or station. Those data may change but will only have that one associated row. I consider the usage data differently due to how it is created and how it is stored. Usage data is created internally by the UTEM system whenever a user interacts with the physical components of the system. It also compiles, creating a new log each time and never going back to alter any previous data. Those data are stored within the usage log (see table 4.9a on page 50) and the use event (see table 4.6 on page 34) tables.

The usage log keeps a record of every interaction between a user and the RFID terminals. The unique identifier field for this table is the 'log'. The exact time of interaction is recorded in 'time' with a time zone aware timestamp. The 'uid' and 'sid' of the user making the request and of the station sending that request are used to reference pertinent information from the users, stations, and permissions table in responding to the request. The 'req_type' field records the type of request being

Algorithm 4.1: Creation of new permissions for new user

input : New 'user' in table 'users'
output: Multiple new entries to table 'permissions'

Algorithm triggered by creation of new 'user' in table 'users'
'user' ← SELECT New 'user' in table 'users';
foreach *'station' **in** table 'stations')* **do**
  Create new 'permission' in table 'permissions' –
   Set 'permission' values (uid, sid, access) =
   (user.uid, station.sid, station.defaccess);

Algorithm 4.2: Creation of new permissions for new station

input : New 'station' in table 'stations'
output: Multiple new entries to table 'permissions'

Algorithm triggered by creation of new 'station' in table 'stations'
'station' $\leftarrow$ SELECT New 'station' in table 'stations';
foreach *'user'* ***in*** *table 'users')* **do**
    Create new 'permission' in table 'permissions' –
    Set 'permission' values (uid, sid, access) =
    (user.uid, station.sid, station.defaccess);

made[3]. The system's response ('response') is also recorded. The 'info' field is used for any notes on that log. The IP address ('ip') is also recorded for confirmation purposes.

The usage log is for individual moments of interactions with the system such as starting at equipment station or leaving an equipment station. The use event table records the entirety of a user's time at an equipment station, similar to a calendar instance recording time spent on equipment with a start and a finish. The events in this table are generated internally by the database, with each action upon them triggered by the creation of logs in the usage log (See algorithm 4.3 on page 35).

That event has a unique identifier ('event') and records the user ('uid') and station ('sid') of the request's origin. The log ('ref_start') which generated the event, as well as the timestamp ('e_start') for that log, are recorded. The same is done for the log that closes the event (ref_end, e_end). The duration ('duration') is the time interval between the event's start and end. The 'closed' field is a convenience measure for sorting through events which are incomplete (a logged use has yet to end it) or been completed.

There is also a 'valid' field that indicates the event has been checked and confirmed. Confirmation of the events occurs periodically and is triggered by an administrator. This process consolidates events from the table 'use_events_dev' that

[3]These will be discussed in greater detail in the section on the RFID terminals.

Table 4.5: Data Objects in Table ’usage_log’

Column	Type	Function
log	integer	Table’s Unique Identifier for each row (a log) Auto-generated by database from a serial key.
time	timestamp	Time of event being logged
sid	integer	Station that made the request triggering this log References serial key of stations table
uid	integer	User that made the request triggering this log References serial key of stations table
req_type	integer	Type of request being made of RFID app
response	text	Response given by RFID app
info	text	Any additional info provided with request
ip	inet	IP address of terminal making the request

Table 4.6: Data Objects in Table ’use_event_dev’

Column	Type	Function
event	integer	Table’s Unique Identifier for each row (an event) Auto-generated by database from a serial key.
sid	integer	Station from the log that started this event References serial key of stations table
uid	integer	User from the log that started this event References serial key of stations table
ref_start	integer	Log that started the event References serial key of usage_log table
ref_end	integer	Log that ended the event References serial key of usage_log table
e_start	timestamp	Time that event starts Recorded from time of log in ref_start
e_end	timestamp	Time that event ends Recorded from time of log in ref_end
duration	interval	Duration of the event
closed	boolean	Event ended without system error
valid	boolean	Event has been validated Default value is ’True’
notes	text	General notes for administrative comments

Algorithm 4.3: Creation and Update of Use Event

```
input : New Row 'log' in table 'usage_log'
output: Create or update 'event' in 'use_event_dev'

Algorithm triggered by creation of new entry into table 'usage_log';
'log' ← SELECT New entry from table 'usage_log';
if log.req_type = 1 then
    /* User placed their RFID at an interlock station */
    Create new 'event' in table 'use_event_dev' –
      Set 'event' values (uid, sid, e_start, ref_start, closed) =
      (log.uid, log.sid, log.time, log.log, 'f');
else if log.req_type = 2 then
    /* User removed their RFID from an interlock station */
    Identify latest 'event' where uid = log.uid and closed = 't';
    Update that 'event' in table 'use_event_dev' –
      Set 'event' values (e_end, ref_end, closed) = (log.time, log.log, 't');
    Calculate and set the duration of the 'event' –
      Set event.duration = (event.e_end - event.e_start);
else if log.req_type = 3 then
    /* User tapped their RFID in at a sign-In station */
    Create new 'event' in table 'use_event_dev' –
      Set 'event' values (uid, sid, e_start, e_end, duration, ref_start, closed) =
      (log.uid, log.sid, log.time, log.time + 5 min, 5 min, log.log, 't');
```

occur within 2 minutes of one another. Cleaned event data gets copied into a secondary table ('use_event' is identical to 'use_event_dev) which is primarily used for data analysis and not for user interface reports (See algorithm 4.4). The selection of 2 minutes is because the computer interlocks check for a user every 30 seconds. If a user inadvertently moves their RFID or the terminal misreads or misses the next user check, that gives the user one cycle to be informed of the error by the terminal and a second cycle to reposition their RFID. This is long enough for the system to note the removal but if replaced in that time, it is assumed that the removal was not intended by the user.

Events in the 'use_event' table with durations over 2 hours are double checked manually since this was thought to be a long time for a user to be active at a single station. The occurrence was rare enough, 63 occurrences out of 1457 events

Algorithm 4.4: Validation and cleaning of use event data

```
input  : events from table 'use_event_dev'
output: Consolidated event in 'use_event'
'old_event' ← Select earliest event from 'use_event_dev'
  WHERE notes IS NULL;
'new_event' ← Initialize event in 'use_event' –
  Set 'new_event' values (uid, sid, e_start, ref_start) =
  'old_event' values (uid, sid, e_start, ref_start);
'events' ← Select all events from 'use_event_dev'
  WHERE notes IS NULL AND
  ref_start in range ref_start.old_event to += 12 hours;
'log' ← empty array;
'log' ← append 'old_event';
foreach i,'event' in enumerate('events') do
    'last' ← event[i-1];
    'time2' ← last.e_end ;            /* End of the last event */
    'time1' ← event.e_start ;          /* Start of this event */
    'time_diff' = time1 - time2;
    if 'time_diff' < 2 minutes then
        /* Assume the break between events is not
           intentional                                    */
        'log' ← append 'event';
    else
        'new_event' ← update event ending from 'event' –
          Set 'new_event' values (e_end, ref_end) =
          'event' values (e_end, ref_end);
        set event.notes to "Consolidates all items in" + str('log');
        Set 'new_event.duration' = 'new_event.e_end' -
          'new_event.e_start';
        break;
Mark all events in 'log' as replaced by 'new_event';
if 'new_event.duration' < 2 hours then
    Set 'new_event.valid' = true; foreach 'log' in 'logs' do
        Set 'log.valid' = true;
else
    /* Events over 2 hours currently require manual      */
    Leave 'new_event.valid' = NULL; foreach 'log' in 'logs' do
        Leave 'log.valid' = NULL;
    print 'new_event' and log' for use in a manual double check;
```

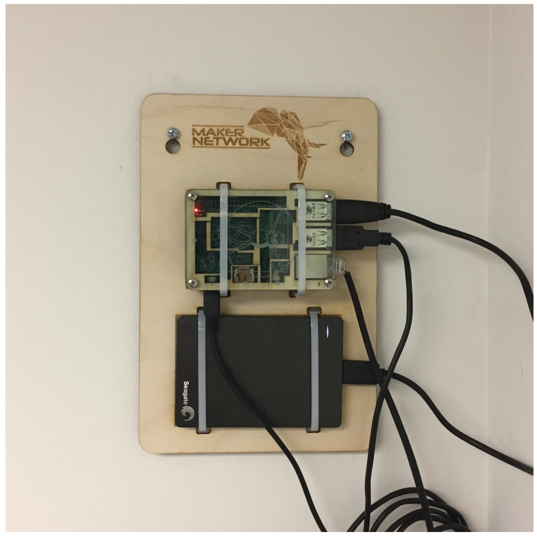


Figure 4.2: The UTEM System - Server

in the fall semester or 4.3%, that manually checking was thought to be less time consuming than automating the task. Only 5 were marked invalid due to other user interactions taking place during that time, such a that user's UD logged at another station. The other instances were assumed to be an RFID accidentally forgotten at a station by the user but that scenario can not be confirmed at this time.

4.2 Web Interfaces

The web interface for the UTEM system serves mainly as the communication system between the database and the rest of the world. The server runs on a Raspberry Pi 2 Model B given a static IP address on the university campus. The interface is built on a python based web framework, Django. This handles all communication from the terminals on the system, communicating through a RESTful API. It also provides the graphical web interfaces for user interactions with the database.

4.2.1 Server and Django

The server is on a Raspberry Pi 2 Model B (Raspberry Pi Zero 2014) running version 9.1.19 of Raspbian (Raspbian 2016), a free operating system optimized for the Raspberry Pi hardware. It is based on Debian systems (Debian Developers and Debian Maintaners 2016) and uses a Linux kernel (The Linux Kernel Organization 2016). An external 500 GB USB storage drive is used as the hard drive to avoid some of the limitations and overwrite issues of an SD card, which typically serve as the primary hard drive for Raspberry Pis (See figure 4.2 on the previous page)

The web-framework selected for this system was Django (Django project 2016), a free and open-source high-level Python based framework designed for rapid development and pragmatic design. In this case, the framework uses its own development server to aide in debugging. Django follows a push-based model-view-controller (MVC) architecture. The MVC paradigm is a separation of the web application components into three parts (See figure 4.3 on the following page). The model is the application's independent behavioral component, an object-relational mapper that negotiates between data models and the PostgreSQL database in this implementation of Django. The view is the representation of the information, Django's processing of HTTP requests into web pages based on various HTML templates or direct HTTP responses for the communication with the RFID terminals. The final portion is the controller that accepts inputs and converts that information into commands for the model or the view, a regular-expression-based URL dispatcher in this case. Simply put, this part takes an HTTP command sent to server, parses out all information from it, pushes it to the appropriate view layer based on the URL for processing.

Django applications are structured into a directory of python scripts; the big three of each app are 'models.py','urls.py', and 'views.py'. There also exists 'forms.py'

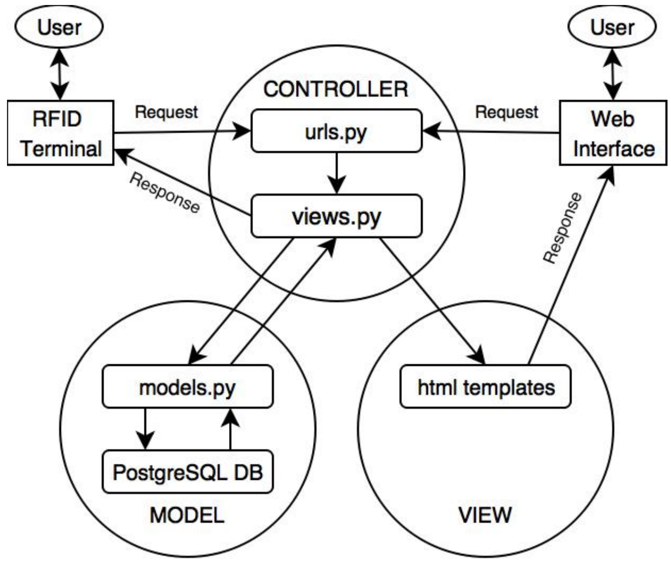


Figure 4.3: Django's Model View Controller

and HTML templates for aiding representing information in web pages. Django apps can have a hierarchy of apps and these can share scripts and reference one another to reduce redundancy. Those scripts correspond to that MVC pattern in their primary function. 'models.py' contains and manages the data structures. These are referred to as 'models' and are created as Python classes based on the tables with each field mapped to the corresponding data object in the database. Handling and cleaning functions exists within those classes to assist in maintaining data quality. A manipulation of any of these model class fields will query and update corresponding information in the database. 'urls.py' serve as the top layer of the controller, capturing the URL patterns for processing, recognizing the data objects within the HTTP command, and directing that information to the proper executable. For instance, if the URL 'http://¡server ip address¿/analytics/usagelog/2/' is called, the higher level 'urls.py' will recognize .../analytics/... and know to direct it to the analytics app. That app will recognize .../usagelog/2/ and direct it to the proper function within 'views.py' with the input '2'. 'views.py' interprets that information, queries and manipulate the models, and then determines what data will be presented. That information is passed along to HTML templates that determine how the information is presented in the web interfaces. Django's forms class aids in direct user manipulation of the models through the view.

There are several applications within the UTEM system's Django implementation, each handling different aspects of the interface. The 'RFID' app handles all views involving interactions with the RFID terminals. Administrative functions are taken care of by the 'admin' app. Items like usage data and calendar views of use events come from the 'analytics' app. The rest of the interface requirements, like the homepage and user sign up, are handled by the 'home' app.

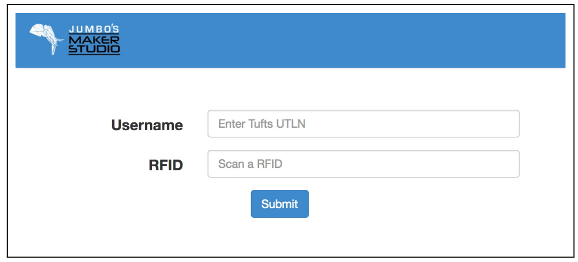
4.2.2 RFID App

I set up the RFID app to handle all queries from the RFID Terminals. The terminals communicate with the database in the form of an HTTP request. These come in the form 'http:// <server address> /RFID/ <req> / <sid> / <rfid> / <info> /'. 'Req' is the request type. These can indicate the start of a user event, the end of a user event, a sign-in tap, a request for help, and a request for a photo. 'Stid' is the station's unique identifier. 'rfid' is the 8 character hexadecimal unique identifier of the user's RFID tag or card. The 'info' field is for any information passed with the request such as a request clarifier. Embedded within the header of the HTTP request is the IP Address of the client, i.e. the RFID terminal making the request in this case. Algorithm 4.5 on the next page shows, assuming no input errors, how these are handled by the app. In non-ideal cases, e.g. if the user ID has no owner or misreads or if the image doesn't take properly, the HTTP response from the server is the system error response and the action is still logged although any missing fields aren't saved in the 'log'. As an example, if an RFID without an attached user is attempted, the resulting response is 'ERROR: No user in database' and 'uid' is saved as NULL in the log.

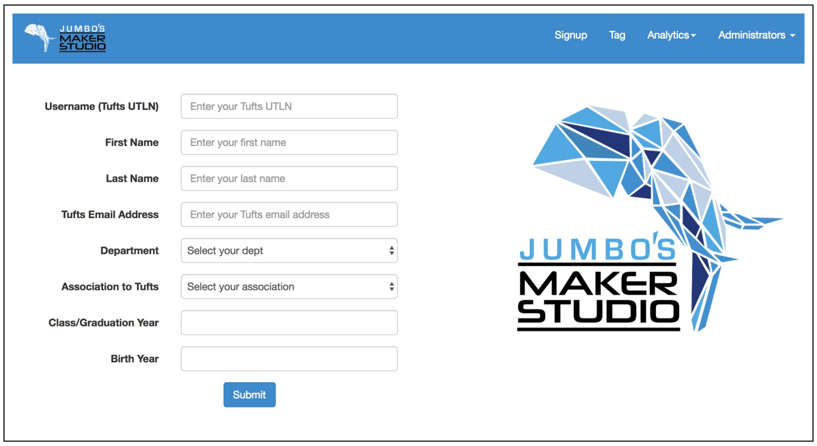
Algorithm 4.5: Django handling of /RFID/ requests

```
input  : HTTP Request from an RFID Terminal
output: HTTP Response
(client IP, req, sid, user's rfid, info) ← HTTP request;
'user' ← Query model 'users', filter by 'rfid';
'station' ← Query model 'stations', filter by 'sid';
switch the value of 'req' do
    case 1 or 3 do
        /* RFID tag placed down on interlock station(1)    */
        /* or tapped at sign-in station(3).                */
        'access' ← Query model 'permissions', filter by 'uid' AND 'sid';
        if 'access' = True then
            /* Update database usage fields                */
            Set 'station.luse' and 'permission.luse' to current time;
            Increment 'station.uses' and 'permission.uses' by 1;
            Set 'station.curr_used_by' to 'user.uid';
            Response ← "True, 'First Name'";
        else if 'access' = False then
            Record action to 'usage_log';
            Response ← "False, 'First Name'";
    case 2 do
        /* End of a use event. RFID tag taken away.        */
        Set 'station.curr_used_by' to NULL;
    case 4 do
        /* Help Button has been pushed                     */
        if 'info' == 'help email' then
            Send 'station' help resources to 'user.email';
        else if 'info' == 'Contact Admin' then
            Contact administrator;
    case 5 do
        /* Photo Button has been pushed                    */
        Upload photo taken by the RFID terminal;
        Send photo to 'user.email';
if Response is None then Response ← "ok";
Create new 'log' in 'Usage_Log'–
  Set 'log' values (uid, sid, req_type, response, ip) =
  (user.uid, sid, req, response, info, client ip);
Send 'Response' as the HTTP response
```

(a) Home Page



(b) Attach RFID Tag to User



(c) User Sign Up

Figure 4.4: UTEM System User Interfaces for the Home app

4.2.3 Home app

I placed all general public interfaces within the home app. Public interfaces refers to the home page, the user sign up, and the interface for assigning an RFID tag to a user. The home page is a simple welcome page with a standard navigation bar, universal to all pages. The navigation bar offers links to the home app interfaces and the other apps as drop down menus (See figure 4.4a).

The user sign up page makes use of Django's modelform class, simplifying adding infomation to the database by linking the resulting html forms to the database. In the same way models are generated from the corresponding database's table fields, the modelform class directly relates to those field types through the preloaded Django model and the appropriate information through the Django model. It auto-generates the appropriate HTML form fields when the view loads this form to the page. Fields that cross reference other tables upload those choices into a drop-down select element as well.

This class also offers the added value of performing cleaning operations before accepting the form data's upload and warns of any errors that require corrections. This takes into account the data types and format set by the model as well as any relational constraints. For instance, since the 'Username' field is specified as case-insensitive UNIQUE in the database (ie that each object within that column must be unique independent of any character's case.) then if a user tries to select 'JSmith01' as their username but 'jsMiTh01' already exists, the form will not upload to the database but rather inform the user of the issue and require them to change that field before resubmitting. This internal awareness of the requirements of the database as it relates to user input helps ensures data integrity and validity.

The tag attach page uses a generic form class since the enterred information doesn't directly transfer into the database (See figure 4.4b on the previous page). Since the RFID tags are not human readable, an RFID Mifare Card Reader 14443A Emulation Keyboard is used to input their unique identifier into the field. The particular emulators we selected output the data formatted as a 10 decimal integer while all other aspects of the system deal in 8 character hexidecimals. Therefore preprocessing is required to format that information before entering it into the database. Specifically, a function within the views converts the 10 decimal integer to an 8 character hexidecimal then encodes it for the model field. A custom cleaning operation checks the now properly formatted information against the database similar to that of the 'ModelForm' class.

4.2.4 Admin app

The admin app user interfaces intended primarily for administrative purposes. These include creating new stations, granting and updating user permissions, and check-

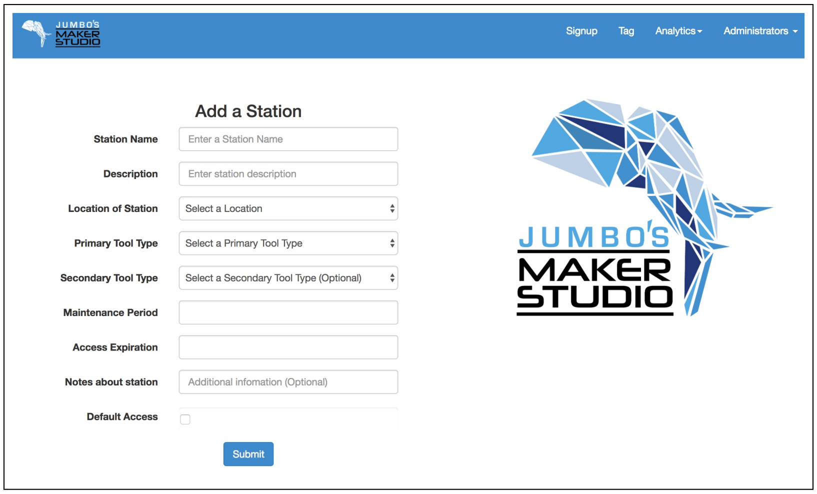
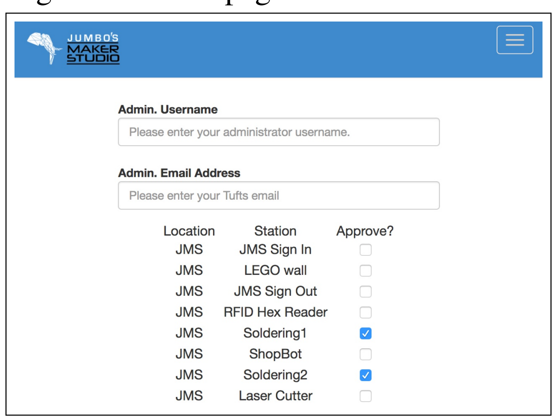
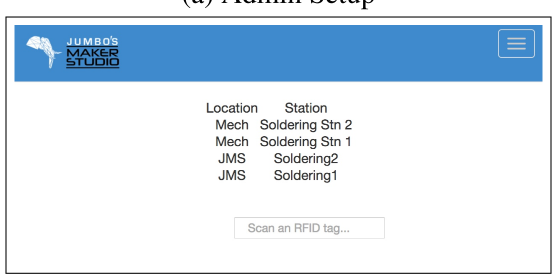


Figure 4.5: Web page to add a new station



(a) Admin Setup



(b) User Interface

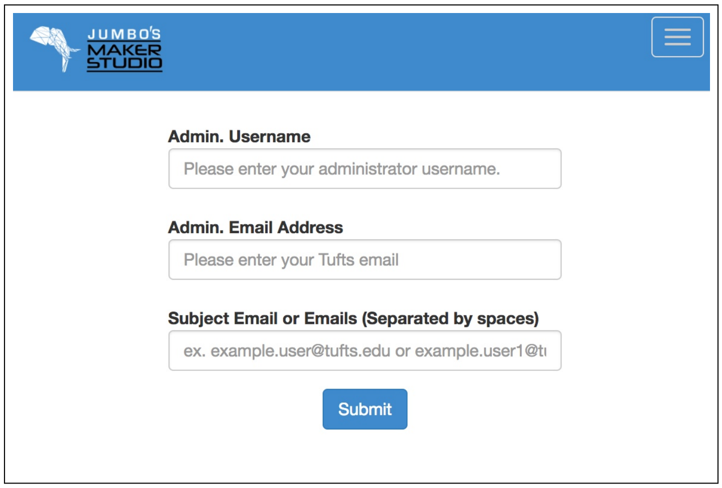
Figure 4.6: Permission Approval by RFID Tag

ing and editing user information. The interfaces include a page for creating a new station, a manual permissions editing page, one for granting permission by RFID tag, and a user information page. Each requires an administrator to enter their username and email address to access. Full password protected administrator authentication was not implemented for this version due to it being a highly limited implementation with close developer oversight.

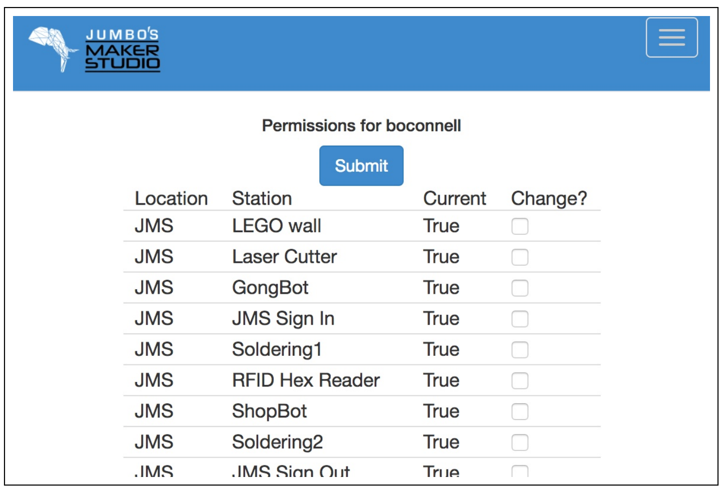
The web page for creating a new station functions similar to the new user creation page (See figure 4.5 on the preceding page). It also uses django's ModelForm class to create the page's form. It performs clean operations against the database station table before acceptance to help maintain database integrity.

There are a few options for editing user permissions. One interface allows for users to update their page with a swipe of their RFID tag (See figure 4.6 on the previous page). An administrator must set it up by entering their information and then selecting the station permissions to be updated (See figure 4.6a on the preceding page). Users can then swipe their RFID on a keyboard emulating reader to update their permission to 'True' for the selected stations (See figure 4.6b on the previous page). Like when attaching a tag to a user, the page identifies the user by their RFID tag and updates the 'permissions' model to grant access. It refreshes after each entry, confirming the change and allowing for the next RFID tag's input. This feature was generated to aid in updating permissions right after a training; allowing the trainer to set up the page and then all users can form a line then quickly update their permission. Previously, the administrator had to update permissions manually, using the manual permission pages explained below. This did not necessarily occur directly after the training, leading to a time delay between a training and a user's actual ability to use the equipment.

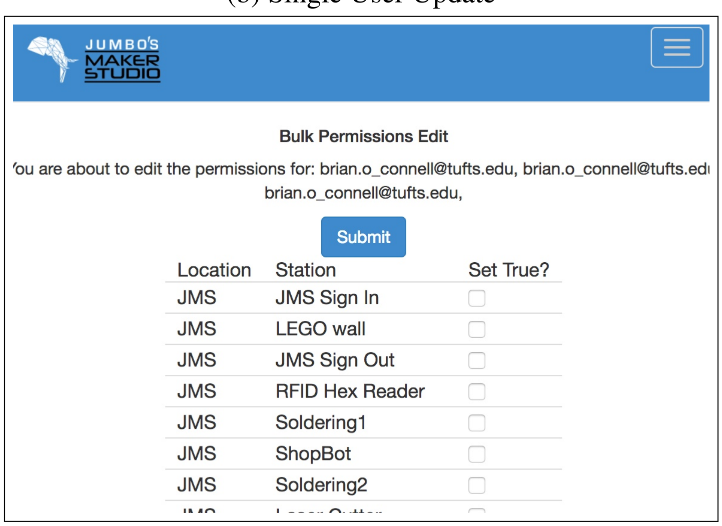
The manual permissions page serves two purposes. When a single user's email address is entered, a page loads that includes their presents their permission status



(a) Permissions Log In and User Info Input



(b) Single User Update



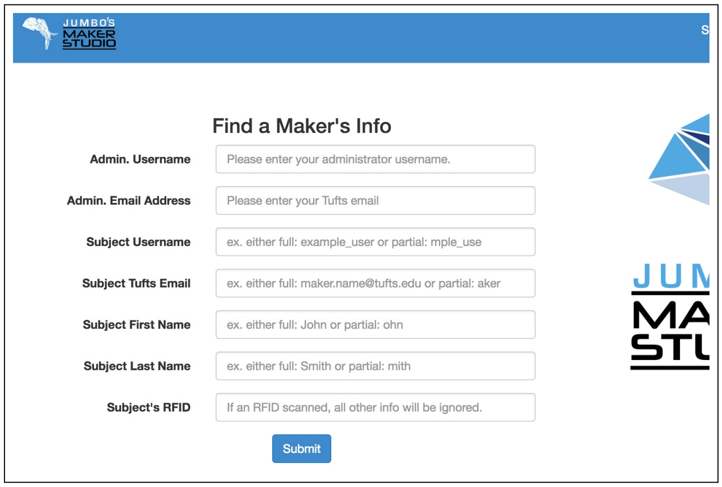
(c) Permissions - Multiple User Update

Figure 4.7: Manual Permissions Editing

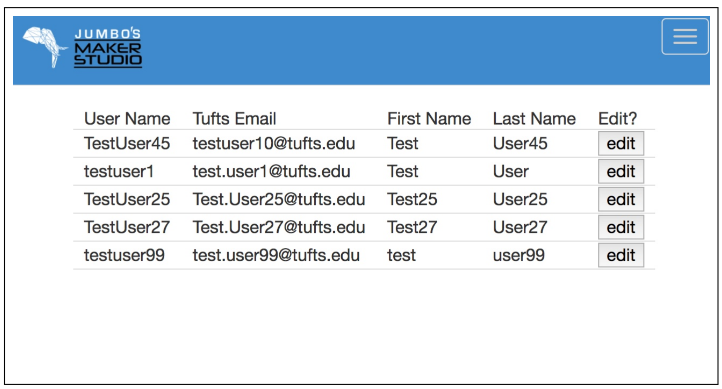
for all available stations (See figure 4.7b on the preceding page). An email address is used since it is a unique field in the 'users' table so a valid selection criteria to determine a single user and it is information readily provided by users. Each row shows the station, its location, and the user's current status for that station. This allows staff to check the permissions of a specific user. A radio button is also part of that tabel and when selected, it indicates that an administrator wants to switch that status. There is an 'Submit' button that, when pressed, switches the permission status for each selected station.

I also included a permissions options to update multiple users' permissions at the same time. A tab or comma delimited list of user email addresses can be enterred into the 'subject email' field (See figure 4.7c on the previous page). In this case, a similar list of permissions come up but the radio buttons is labeled 'True?'. When the 'Submit' button is pressed, each selected permission is set to 'True' for all users inputted.

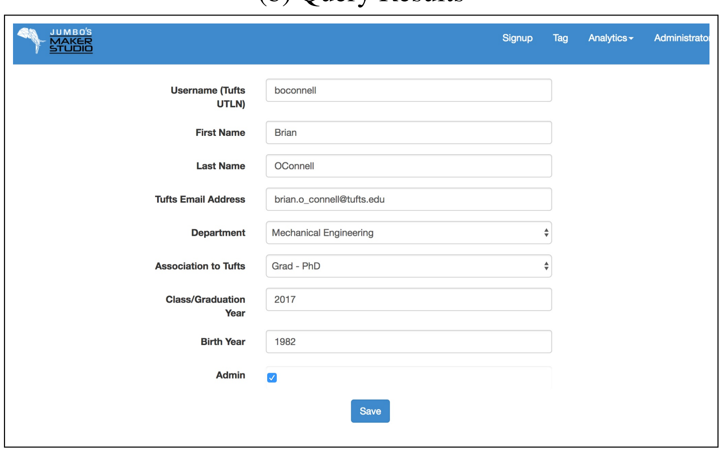
The 'maker info' page is the user information page. It serves to allow administrator's access to user information from the database and update that information. The fields allow for searches based on partial values of either a user's user-name, email address, first name, or last name. This is to aid in finding a user if they accidentally misspelled something while sign-ing up. For instance, if Alexander Hamilton entered his name as 'Alexnder Hamliton', they could be recovered by entering 'lex' as the first name or 'ton' as a last name. An RFID tag can also be swiped and inputted to identify a user. Once submitted, the resulting page list all users who match the search criteria. Each has an 'edit' button. This opens up a new page with pre-populated user information fields, again using the modelform class. The administrator can edit that information in those fields then save the changes to the database.



(a) Maker Info Search



(b) Query Results



(c) User Info Edit

Figure 4.8: User Info Interface

4.2.5 Analytics app

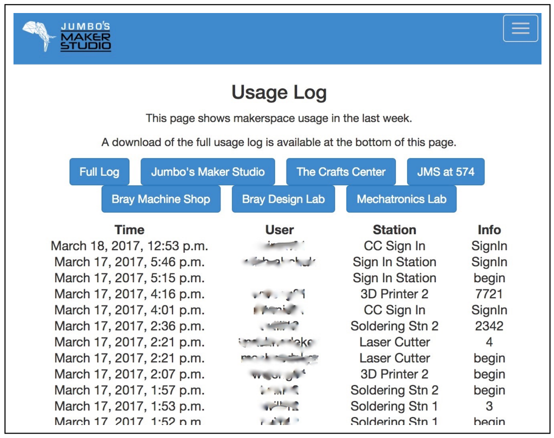
The analytics app handles displays usage information. The most verbose is the usage log. It provides a scrollable list of all logs within the 'usage_log' table. Events from 'use_event_dev' are graphically represented in calendar form in two other web pages. One is organzed by user and the other is organized by station.

The usage log page provides a list of all logged activity for the previous 7 days (See figure 4.9a on the following page). This list can be reduced to all logs for a single location by selecting its corresponding button on the top of the page. The time of the log, the station, the user, and the log's info are the information displayed. There is also a download option that provides all columns of the 'usage_log' table. There are three options for this format: that day's log, the past week's log, and the entire log.

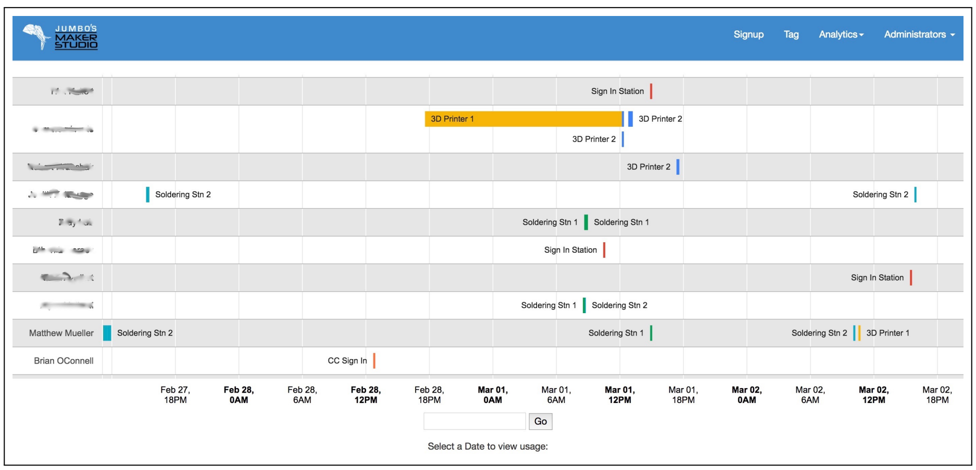
For a more visual indication of equipment usage, there are the calendar views available of the use events organized by user or by station (See figures 4.9b and 4.9c). This feature utilizes the timeline feature of Google's chart tools to provide the visualization (Google Developers 2016). These pages display usage over the course of 3 days. On the initial load, it displays the last 3 days but if a new date is selected, it displays that date plus and minus a day. Hovering over the event displays the specifics of that event: the user's full name, the station, and the specific start and end time.

4.3 RFID Terminals

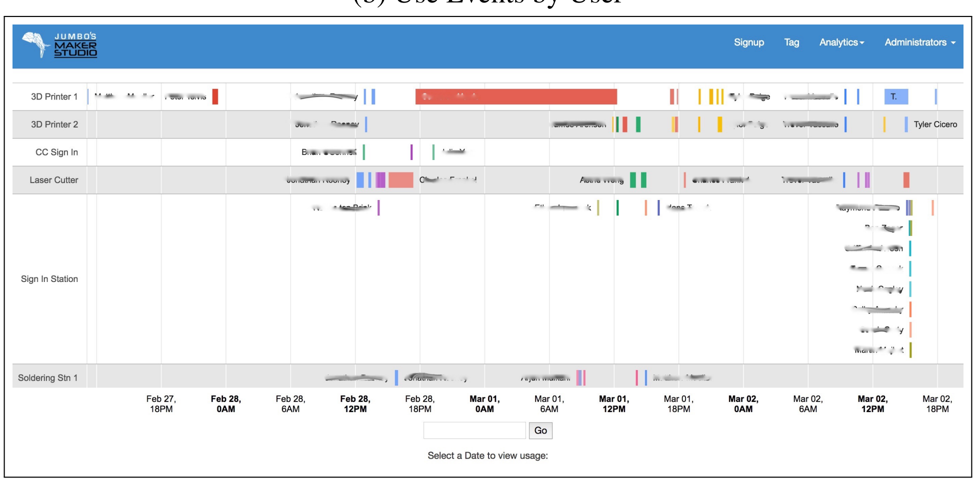
I designed the RFID terminals to be the physical interfaces of the UTEM system (see figure 4.10 on page 52). They serve as a barrier to unauthorized use of attached equipment by identifying the user through their RFID and checking for that user's permission in the database. The terminal will grant access for as long as



(a) Usage Log



(b) Use Events by User



(c) Use Events by Station

Figure 4.9: Usage Interfaces

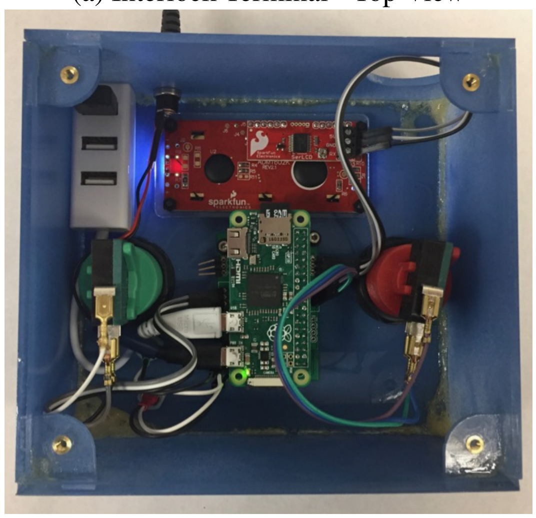
the user leaves their RFID on it. There is also a sign-in version that is a tap only interface, just checking noting that a user has entered an area. The components of the terminals were sourced based on their low cost and availability and I selected open-sourced components where available. An RFID module capable of reading the MiFare ISO 14443A standard tags is installed in the center of the terminal. For the interlock terminals, this is surrounded by a tray to rest RFID cards or tags in. There is just a protective cover to tap against in the case of the sign-in version. A 16 character LCD provides some user feedback and instruction. A red and green LED provide visual feedback about a user's permission status. A Raspberry Pi ZERO serves as the controller of each terminal and was configured to access the university's network through a USB wifi dongle, connecting the terminals wirelessly to the main server.

The interlock version has additional components for added capabilities. Two large buttons on either side of the terminal face labeled 'SNAP' and 'HELP' either take a photo or make a help request. An access hole on the rear allows access to 3 wire leads for controlling any interlock hardware: a 5V, GND, and Signal cable. There is an exposed USB port on the rear for attaching a USB camera.

The terminals run two variation of the software depending on their function as either an interlock station or a sign-in station. The software runs automatically when the terminals are booted up, taking advantage of start up capabilities of the Raspberry Pi. A bash script is called from Pi's rc script[4]: `sudo sh <path>run_rfid_IP.sh`. This script configures the terminal with it's station ID, a required command line argument that matches the 'sid' from the table 'stations' in the database. It also determines whether it will run as an interlock terminal or as a sign-in terminal. The default is for it to run as an interlock terminal but if the argument `-SI` is included, it will run as a sign in station.

[4] An rc script is an initialization process run during a Debian system's boot up.

(a) Interlock Terminal - Top View



(b) Interlock Terminal - Rear View

(c) Sign In Terminal - Top View

(d) Sign Terminal - Rear View

Figure 4.10: RFID Terminal

Algorithm 4.6: Terminal Software

```
input  : RFID input
output: Station Access

The terminal's interlock feature is engaged by default and the terminal
  continuously checks for an RFID Tag or Card every .5 secs
An RFID tag/card is Detected;
RFID1 ← Read the unique manufacturer ID from the tag/card;
if RFID is None then Display "RFID read error, Try again";
else
    Send type 1 HTTP request →
      http://<server_address>/RFID/1/<sid>/<rfid>/<info>/;
    RESP, NAME ← HTTP response: "<permission> <user's first
      name> (See Algorithm NEED THE NUMBER);
    if RESP is True then
        Turn On RED LED;
        Display "Welcome <NAME>";
        while STATUS is True do
            Disable Equipment Interlock;
            RFID2 ← Check for an RFID tag/card every .5 sec;
            if RFID2 ≠ RFID1 then
                Engage Equipment Interlock;
                Send type 2 HTTP request →
                  http://<server_address>/RFID/2/<sid>/<rfid>/<info>/;
    else
        Flash RED LED;
        Display "Insufficient credentials, Get approved at <Makerspace's
          website>";
```

The bash script calls up the appropriate version of the executable[5], inputting the terminals 'sid'. There is a configuration step that determines the IP address of the terminal then displays the station ID and then the IP address for the user. This was to easily find the terminal's IP address so I could SSH into them if any issues occurred. Once up and running, the terminals perform a periodic check for an RFID tag or card every half second, disengaging any equipment interlock depending on the server's response to the new user (See algorithm 4.6). Once found and read, that RFID unique identifier is sent to the server and the response is used in determin-

[5]Written in C due to the availability of libraries for the RFID reader in that language.

Algorithm 4.7: Terminal Software - Help Button

```
input  : SNAP Button pressed
output: Photo uploaded

admin_help ← Resets to False between users
HELP button pressed;
if No User Present then
    Send type 4 request → HTTP GET request
      "http://<server_address>/RFID/5/<sid>/none/"contact_admin"/";
else if A User is Present then
    if admin_help is False then
        admin_help ← Set to True to indicate first button push Send type
          4 request → HTTP GET request
          "http://<server_address>/RFID/5/<sid>/none/"help_email"/";
    else if admin_help is True then
        Send type 4 request → HTTP GET request
          "http://<server_address>/RFID/5/<sid>/none/"contact_admin"/";
```

ing whether or not to grant access. The primary difference between this function between the two terminal types is that the SignIn stations send a type 3 HTTP request instead of an initial type 1 HTTP request and it does not send a Type 2 HTTP request after the tag or card is taken away. SignIn terminals also do not include interlock components to engage or disengage. The HELP and SNAP buttons functionality are are only included in the interlock terminal software (See algorithms 4.7 and 4.7).

4.3.1 RFID Terminal Hardware

The terminal hardware was selected from readily available, open-source components (See table 4.7 on the next page). The advent of certain low cost, open source hardware enabled the development of the UTEM system. The RC522 MiFare RFID module is a $7.99 read/write module that takes advantage of NXP Semiconductors maintaining their earlier versions of the MiFare RFID technology as open-source. The release of the Raspberry Pi ZERO provided a $5 option for a fully functioning

Algorithm 4.8: Terminal Software - Photo Button

```
input  : SNAP Button pressed
output: Photo uploaded

SNAP button pressed
if No User Present then
    Nothing happens;
else if A User is Present then
    TempFile ← Image taken with attached USB camera;
    Send type 5 request → HTTP Push request
     "docfile=<File Path to TempFile>
     http://<server_address>/RFID/5/<sid>/<rfid>/TempFile/";
```

Table 4.7: RFID Terminal Hardware

Part	Description	Source	Avg Cost
RFID Module	RC522 13.56MHz MiFare ISO 14443A RFID Read/Write Module	Multiple	$7.99
Display	Serial Enabled 16x2 monochrome LCD	SparkFun	$24.95
Pi ZERO	Raspberry Pi ZERO	Raspberry Pi	$5.00
WiFi Dongle	150mbs 802.11 B/G/N WIFI USB 2.0 Adapter	Multiple	$8.99
Power Supply	5V 2A UL Listed switching power supply	Multiple	$7.95

computer operating the individuals terminals. Previous versions utilized low cost Arduino microcontrollers but, although they worked, those limited the capabilities of the system and the Wifi option for Arduino was unreliable. The availability of a relatively low cost LCD display enabled options for visually engaging with the user through text. This component is not entirely necessary if a further cost saving is required. I continue to include it though because it enables a personalization aspect in that it welcomes users by name and allows for communicating instruction if an error occurs. The WiFi Dongle and the Power Supply are standard parts and necessary to overall functionality.

The rest of the hardware is standard hardware and not entirely necessary for the primary function. They serve to add nice-to-have features such as visual indicators

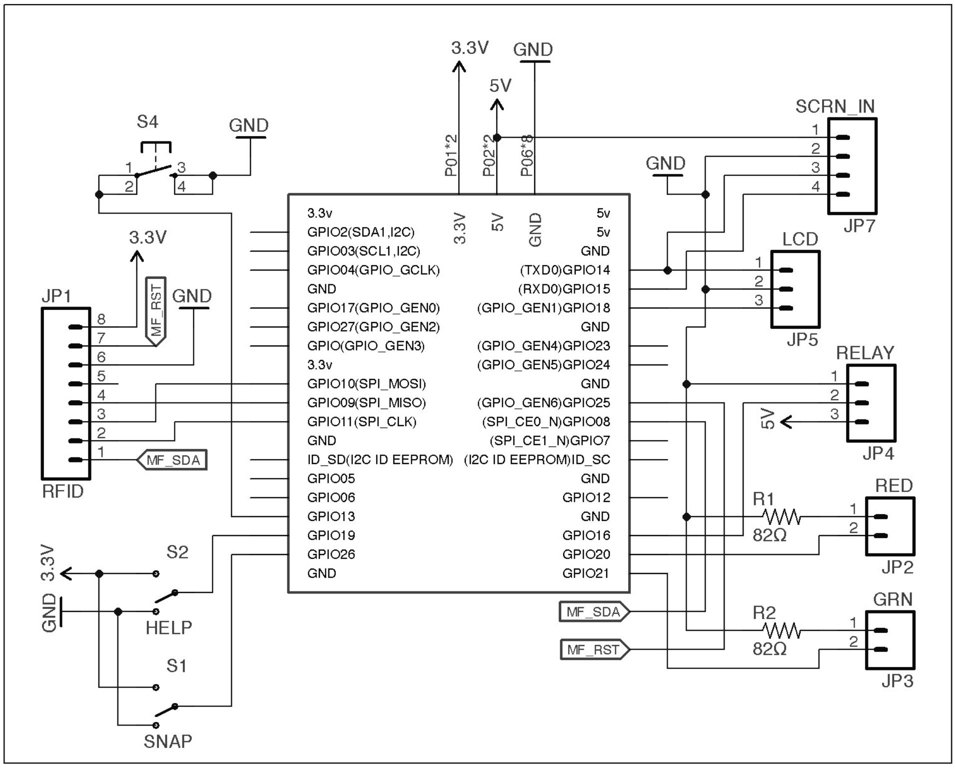
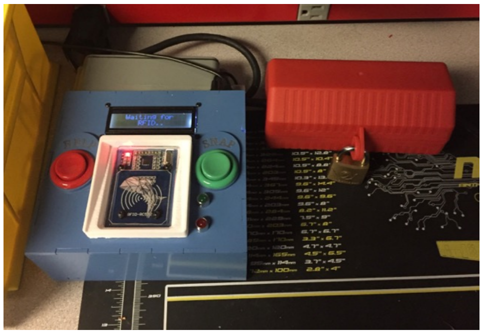


Figure 4.11: RFID Terminal Schematic

and user requests via button press (See ref des S1, S2, R1, R2, JP1, and JP2 in figure 4.11). The indicator lights (JP2,JP3) are standard 5mm 1.8-2.2VDC forward drop 20mA max LEDs. I selected large arcade style buttons but they are just a style of single pole double throw momentary switches (S1,S2). A panel mount 2.1 mm DC barrel jack connector serves as the connection for the power supply(5V,GND). The enclosures are fabricated from laser cut acrylic with thermal set threaded inserts to bolt components in place.

4.3.2 Power Interlock

The power interlock functions by controlling a relay to cut off power to the attached piece of equipment. The control leads out the back connect to a relay board developed by an open source electronics retailer and developer. The relay board uses a single pole double throw normally open relay (SPDT-NO) with a 5V control logic



(a) RFID Power Interlock Terminal

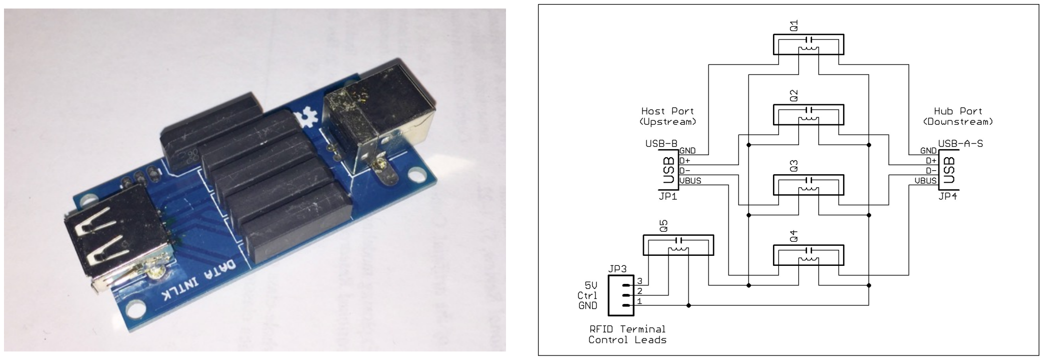
(b) Lockout Box to Dissuade Bypass

Figure 4.12: RFID Power Interlock Terminal

rated for up to 20A and 220V. For safety purposes, the power interlock hardware is enclosed in a UL rated conduit box. The plug and outlet exit the conduit box from one end while the other fits through the access hole. The control leads connect to the relay board through that fitting. The terminal can then be plugged into the wall and the station equipment then plugged into the relay's outlet. To keep users from unplugging the equipment and plugging into an un-secure power source, a COTS lock out box is installed. This option is for any hardware that can be quickly power cycled without delaying use, such as soldering irons. Equipment with a boot up cycle are better serviced through either the data interlock or the computer interlock.

4.3.3 Data Interlock

The data interlock works similarly to the power interlock but instead of interrupting the power, it interrupts the data stream. The device has a USB class A and USB class B port connected through 4 relays, one on each pin of the connectors. These relays are reed style single pull single throw normally open (SPST-NO) relays rated for up to 12V and 500ma triggered by 1V to 9V. These types of relays physically engage and disengage two wires internally to open and close the connection, making them ideal for maintaining data integrity.



(a) Data Interlock Board

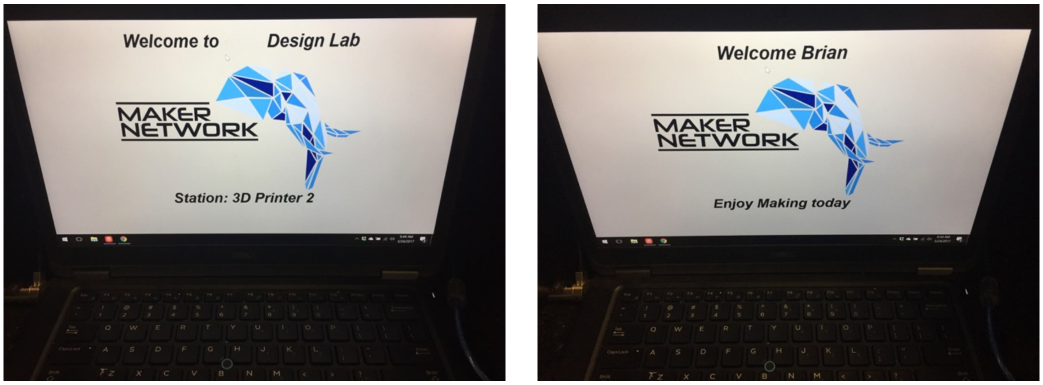
(b) Data Interlock Schematic

Figure 4.13: UTEM System Data Interlock Board

4.3.4 Computer Interlock

The computer interlock is a companion application that runs on the dedicated computer for a station outfitted with an RFID terminal. When an approved user places their RFID tag or card on the RFID terminal, it marks the station as currently in use by updating the stations 'curr_used_by' field with the user's 'uid'. The computer interlock queries the database every 30 seconds for that field. When populated, the application knows a user is at the RFID terminal and it disengages. The application is currently only windows compatible although does have an non-field tested mac compatible version. When engaged, the computer interlock takes over the computer's screen. No other application can be accessed through the computer interface. Those other applications are still running though. For instance, if a user sets up a job for a 3D printer, they can take their RFID to move onto other work and allow the computer application to continue running the job behind the computer interlock.

The application does not have an accessible icon or an application menu, instead requiring a special key combination to exit. The application also disables the windows hotkeys so a user can not close out the application with standard key combinations. When first installed and run, the application creates a configuration file



(a) Computer Interlock Main Screen (b) Computer Interlock Welcome Screen

Figure 4.14: UTEM System Computer Interlock

for an administrator to set the station's 'sid'. This can be reset by recalling the configuration window with a another preset key combination. When disengaged, the application greets the user and hides the application. If credentials are insufficient, the screen remains but a warning appears to inform the user of the issue.

Chapter 5

Pilot Study

In this chapter, I discuss the development and execution of the pilot study involved in the qualification of the UTEM system. I present the reasoning for using qualitative methods in the assessment of this technology and presenting those findings in case studies. The selection of the bounded system and the participants within are described in detail. This chapter also includes the data sources, their collection methods, and the examination of those data.

5.1 Reasoning

My goal in the development of the UTEM system was have positive influence on stakeholders' experiences within the makerspace through their interaction with the five user-level design attributes. A positive influence would be the technology providing a meaningful, for the stakeholder, contribution to achieving or promoting their priorities or values regarding the makerspace. Meaningful is considered as a direct acknowledgement of that contribution by the stakeholder or their acknowledgement of improvement of another facet of their relationship with the makerspace that is directly connected to the UTEM system, although the stakeholder may not be aware of that connection. To assess that goal, understanding of the the stakeholders' relationship with the makerspace and its change over the course of the pilot study was necessary. Qualitative methods were used to evaluate those relationships and understand the influence of the following design attributes:

1. Automatic equipment safety interlock
2. A centralized database of system information
3. Logged usage tracking data and visualizations
4. help button on each station terminal
5. photo button on each station terminal

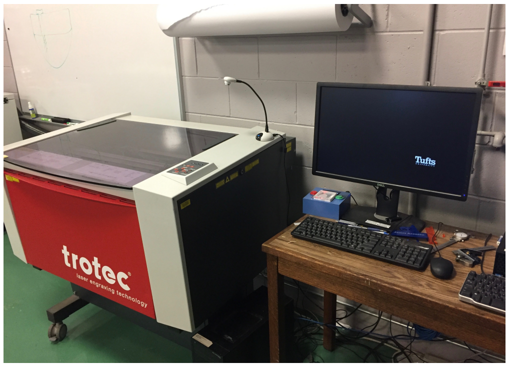
I envisioned this technology as a socio-technical system, influencing its environment through the performance of a technical base. The initial design of the UTEM system and these attributes does not push social interactions as directly as originally envisioned but I still examined the social connections to the system to better understand the attributes as opposed to a simple 'does it work or not' style analysis. Also, Data pertaining to usage and user feedback on the space was unavailable, limiting my ability to compare performance metrics such as number of users or hours of use. The time to collect such data on the makerspace without the installed UTEM system as a control then implement the technology into a now understood and controlled system would extend the research study beyond a reasonable time scale and there was also no guarantee of no major future changes that would disrupt a comparison.

With the system installed into an academic makerspace that had undergone both major physical and administrative changes in the previous year, I determined that consideration for the influence on the socio-cultural aspects was required. This led to the selection of a ethnographic case-study approach to establish an understanding of the makerspaces cultural aspects and the influences of the UTEM system. It allows for in-depth understanding of a situation and the social context (Merriam 1998). As noted in chapter 2, this approach has been successful in examining socio-technical systems previously and has been successful in examining makerspaces as well. The UTEM system functions as both a single unit and as a swarm spread throughout the installed environment. This led to setting the focus of the case to include the entire academic makerspace, both physically and socially. Stakeholder participants were selected from that environment.

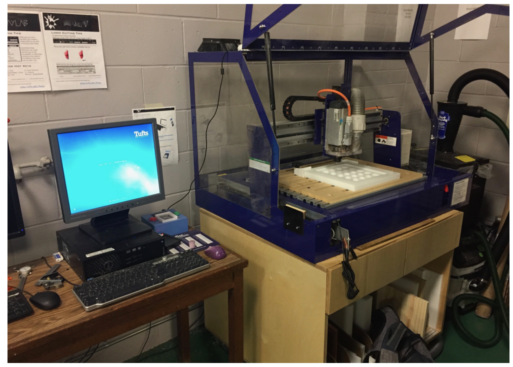
The pilot study focuses on user interactions with the mechanical engineering department's primary makerspace with particular focus on interactions involving aspects of the UTEM system. Data was actively collected from August 2016 to February 2017.

5.2 Implementation

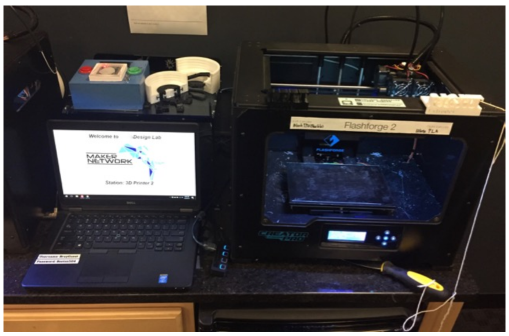
The UTEM system was installed into the department of mechanical engineering's makerspace during August 2016, before the start of the university's fall semester. This space also served as the focus of the pilot study, creating a physical boundary to concentrate observation upon as well as a social construct to recruit participants from (Discussed further in section 5.3 on page 65). I met with the staff on multiple occasions in the months prior to inform them of the capabilities of the system and to organize the installation of the UTEM system. Once made aware of the full capabilities of the physical system and given an overview of the interfaces, the makerspace staff made all decisions about which equipment the RFID terminals would be installed. As the creator, I turned over the technology for their use as another tool within the resources of the makerspace. In that rule, I did advocate for more RFID terminals to be installed to a small degree. As the developer as well as researcher of its uptake and performance, I felt this was ultimately the staff's decision and how they used it could be considered part of their use of the system, another data point for the pilot study.



(a) 1 Laser Cutter Station



(b) 1 CNC Router Station



(c) 2 3D Printer Stations
(1 Shown)

(d) 2 Soldering Station

Figure 5.1: Stations Connected to the UTEM System

RFID terminals were installed in the makerspace's collaborative fabrication area and design space in August 2017. The collaborative fabrication area contains industrial size machining equipment, medium duty standing power tools, several workbenches with an assortment of hand tools. The space also contains a 40W laser cutter and a desktop CNC 2 1/4hp router. Computer interlock terminals were set up on the laser cutter and the desktop CNC router (See figures 5.1a and 5.1b). A sign in station was installed by the main entrance to that portion of the makerspace.

The design lab is set up for idea generation and collaboration. There are tables, chairs, drawing supplies, and white boards. The room also contains two dual extruder head 3D printers (See figures 5.1c). These are connected to the UTEM system with a computer interlock terminal each.

Another room in the makerspace services electromechanical projects. It houses various mechanical hardware and electrical components as well as various other prototyping supplies. There is a desktop CNC wirebender and a PCB/Small part CNC router. Two power interlock terminals were installed on the two soldering stations in that space (See figure 5.1d on the previous page). These were not installed until October 10th, 2016. This was at the request of the staff, having originally decided to hold off on their implementation but requested their addition in late September. The staff were provided with 2 RFID 13.56 MHz Mifare ISO 14443A[1] Card Reader Emulation Keyboards and 1000 13.56 MHz Mifare Compatible ISO 14443 A RFID sticker tags.

Another reason for the lack of push for more RFID terminals installed was that their implementation was sufficient for the needs of the pilot study. Equipment was connected in 3 out of the 5 rooms of the makerspace, 2 of which offered extended unsupervised hours. 4 different types of tool were connected, providing some range of variation to examine. This appeared sufficient in the establishment of a pilot study so further effort in expanding the UTEM system's implementation was not pursued at the time.

5.2.1 Positionality

The pilot study began with the understanding that pre-existing relationships existed between myself and the potential research participants. I have worked with one of the faculty participants on prior research studies. One of the staff members was a member of my research group when she was still a student. The faculty manager of the makerspace has already been research participant in another researcher study[2]. Many of the mechanical engineering students recognized me as a long standing graduate student in the department. Many have engaged with me within the univer-

[1] The same frequency and cryptographic standard as the RFID terminals

[2] Study is ongoing and currently unpublished. Faculty manager sat for a single 1 hour interview in that study.

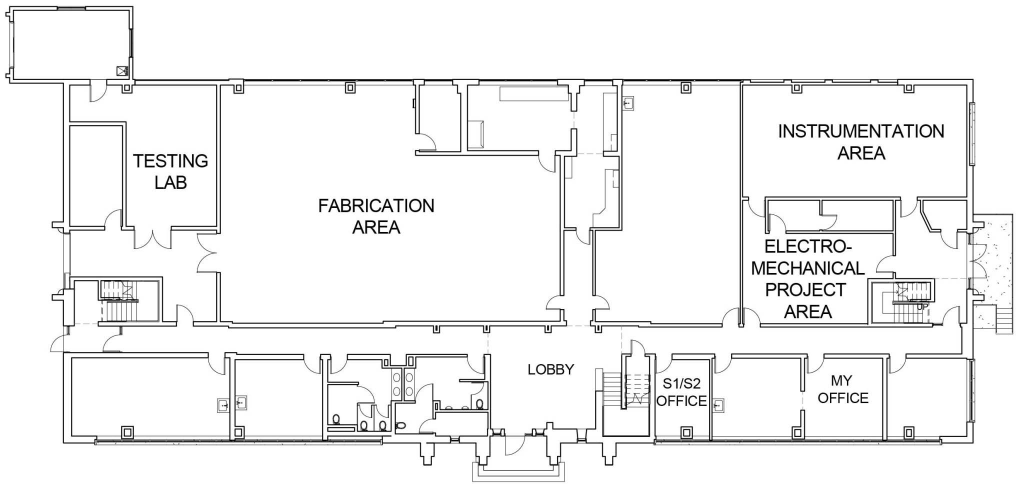
sity makerspaces or had worked with me as undergraduate researchers during the summer sessions. The staff were also involved in the adoption of UTEM system and the selection of which equipment it would be installed.

I took these considerations of positionality into account in understanding participant reactions and interpreting the data. Openness about prior relationships and bias inform both the collection and interpretation of any data (Hartas 2015). During the consenting process, recruitment scripts made clear the voluntary nature of the study. Great effort was put into minimizing any negative effects of these prior relationship to the study during interviews as well, discussed in further detail in section 5.4.4. Requests for any artifacts were made with clarification that they are not required to provide those items.

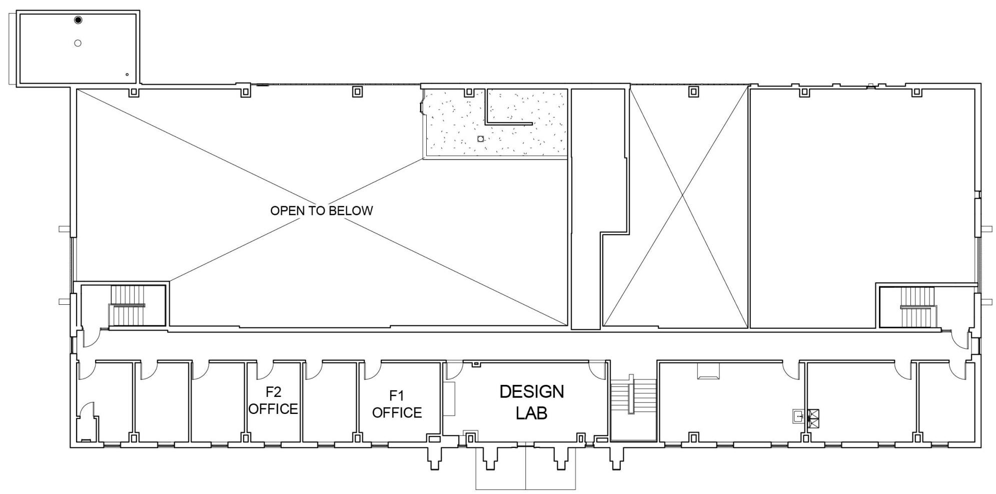
5.3 Bounded System of the study

The bounded system refers to the physical, social, and temporal constraints that create the limits of focus within a case study (Smith 1978; Stake 1978). These were selected to limit the scope of the study. In the most general terms, the academic makerspace in which the UTEM system was involved served as the bounded system for this research study and the primary subject of the resulting case studies. Keep in mind, that for the purposes of this study, a makerspace is considered both a physical location and social construct. This helped in situating the stakeholder design criteria and developing the design features but also helped in the identification of research participants within that definition.

The physical bound was the building containing the academic makerspace of the mechanical engineering department, clearly defining a physical system of interest (see figure 5.2 on the following page). The makerspace is fully staffed with a faculty member as the manager of the space, 2 full-time staff members, and several



(a) Floor 1



(b) Floor 2

Figure 5.2: Building Containing the Makerspace

undergraduate part-time staff members. All members of the university community may access the space during normal business hours and members of the department of mechanical engineering enjoy extended access hours. Several courses actively encourage the use of the equipment available as part of their course assignments, 6 class sessions within the mechanical engineering department. This accessibility as well as encouraged use created a potential that a large community of users would form the social aspect of the makerspace.

The makerspace being so accessible with a potentially large number of users, the scope of the study focused that pool down to participants of interest within the learning environments. Participants of interest were identified for their membership in one of the stakeholder groups considered in the design of the UTEM system; staff, faculty, or students. The primary participant from the staff were the faculty manager and the two full time staff members. These were the individuals involved in selecting the equipment to be connected by the UTEM system and identified as most likely interested in the UTEM system's performance and data. For the faculty and students, the Senior Capstone Design course (ME43) served to narrow the number of potential research participants. The course was selected since it historically has been the primary user of the fabrication resources of the department. It was led by two faculty members of the department of mechanical engineering, each leading their own section. The students in the class are split into 13 design teams[3]. To limit the scope further, conceptual bounds were applied to narrow the pool of design teams. I selected two groups from each section to follow as primary student participants throughout the semester based on similarities between them, one pair had selected the same project and one pair had both selected projects with university makerspaces as clients. The selection of a design course as a social limiter also offered a temporal constraint of the university's fall semester.

5.3.1 The Makerspace

The makerspace is housed within an engineering laboratory building on the main campus, spanning several rooms within the building. Notices are posted in each of the rooms informing users of ongoing research and who to contact for further information about the study or any concerns. In prior years, accessibility to the space was fairly limited, primarily just to those students in a sophomore level machining course and in the senior design course and primarily M-F 8:00-16:00. Even then,

[3] 6 for one section and 7 for the other

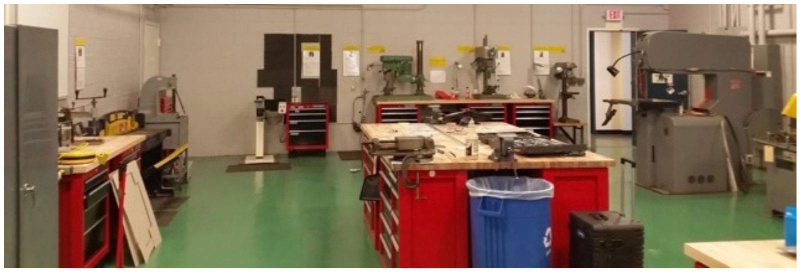
staff did the majority of machining for students. This year, the space acquired more rapid desktop CNC prototyping resources and more space within the building, and the staff changed.

The largest portion of the makerspace is the collaborative fabrication area (See figure 5.3a on the next page), equipped with the all of the larger industrial equipment. The room also contains several workbenches with a large number of hand tools, separate zones for powered fabrication tools and that industrial scale equipment, as well as the RFID terminal equipped laser cutter and Shopbot. A testing lab with equipment for advanced mechanical testing is also available to students (See figure 5.3b on the following page). These are only accessible during staffed hours of M-F 9AM-6PM.

The other spaces maintain extended unsupervised access hours. An instrumentation area exists that has equipment for data collection and analysis (See figure 5.3c on the next page). It is set up to primarily serve as an instructional space. One of the makerspace's rooms is stocked and equipped for the development of electromechanical projects and other technologies. This space contains the soldering stations equipped with power interlock RFID terminals. The design space is set up for collaboration and ideation with tables, white boards, and drafting paper. The 3D printers are installed in this room with UTEM system computer interlocks installed on the computers and include the accompanying RFID terminals at those stations. These ares are open M-F 6:00-20:00 for the general university community and mechanical engineering students may access it from 6:00-23:00 7 days a week.

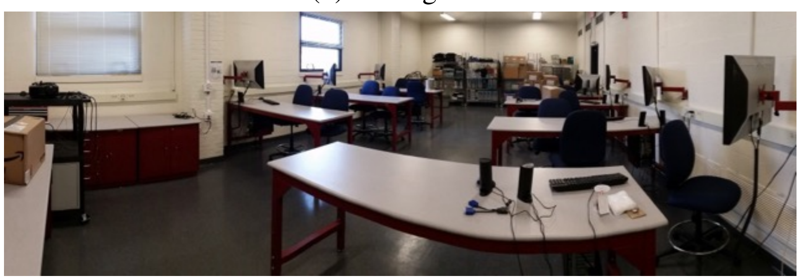
5.3.2 Staff

The participant staff members were involved in the adoption of the UTEM system in the makerspace. They approved installation of the system and made all decisions about which equipment the RFID terminals would be connected too. Recruitment

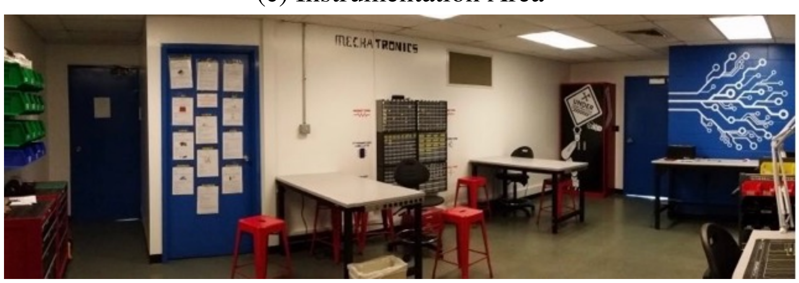


(a) Fabrication Area

(b) Testing Lab



(c) Instrumentation Area



(d) Electromechanical Project Area

(e) Design Lab

Figure 5.3: The Makerspace

was discussed prior to the start of the research study since their permission and support was a necessity for this study to take place.

5.3.2.1 Faculty Manager

Management of the makerspace is the responsibility of one of the department's faculty. He took over the responsibility the year prior to this study upon the retirement of the two staff members holding that responsibility. He has been at the university for 26 years. Prior to that, he had experience as a mechanical design engineer and quality control engineer. As the faculty manager, he overseas the running and equipping of the makerspace to facilitate the fabrication needs of the department, primarily those of the students in the execution of their course and research work. His goals for the makerspace drove many of the policies which opened it up in welcomeness, functionality, and accessibility. He will be referred to as the 'F1' in this document.

5.3.2.2 Makerspace Coordinator

The makerspace Coordinator started in the department 7 months prior to the start of this study. Prior to that, she was a graduate student in the department and graduated with an M.S. in human factors. Her research was primarily in the development and study of makerspaces. She consults on the design of educational makerspaces as well. She is responsible for much of the day to day operation of the space. She will be referred to as the 'S1' in this document.

5.3.2.3 Fabrication Supervisor

The fabrication supervisor also started at the beginning of the year. Prior to this position, he had been a junior fabricator in the aerospace industry. He also had some experience in a design firm and has a degree in industrial design. His responsibilities include much of the higher level equipment training and assisting students in their academic fabrication. He will be referred to as the 'S2' in this document.

5.3.3 Capstone Design Course

ME43 is the university identifier for Senior Design Project, a senior level design course. This course serves as the capstone design experience for students in the program and is required for all seniors. It was selected as a social bound for the research study since capstone design is a subject of interest among design and engineering education (Dutson et al. 1997; Cooper et al. 2015). Within this department, it has historically been the primary user of the student fabrication resources. The curriculum was recently changed as well to take into consideration the updates to the makerspace and encourage greater personal fabrication and prototyping from the students.

Researchers have examined these course types extensively, producing literature on curriculum, recommendations for practice, and the effectiveness of such design courses. They have found these courses to be extremely diverse in their implementation but similar in their desire to provide a real-life engineering design experience (Dutson et al. 1997). Many studies have looked into student practices and pedagogical decisions for such courses. A common subject of interest has been design skills and interdisciplinary teams. Several methods have been used to examine such phenomena within the course's context, particulary ethnographic and case study for social and cultural concepts of Capstone design courses (Newstetter 1998; Harper and Nagel 2014; Cooper et al. 2015; Mohedas, Daly, and Sienko 2014).

There are two sections of this course offered every fall. Each is led by their own instructor. It expects the students to design and present a client based project over the course of a semester. Traditionally, the students would perform some of their own fabrication but most was offloaded to the former staff member in charge of the machine shop. The major changes to the course were to utilize more local clients, including on campus sources, for the course projects and to update expectations with regards to students and the departmental resources. The updates to the makerspace allowed for students to do more of their own fabrication so that was factored into the course's redesign. There was also a shift away from formal lecture time to more group activity including course time being spent in the makerspace. The course will be referred to as 'ME43' in this document.

5.3.3.1 Instructor 1

The faculty manager, F1, of the makerspace also served as the instructor for one of the sections of ME43. He holds a B.S, M.S., and Ph.D. in mechanical engineering. Some of his research interests are in materials processing and the characterization and design of automated systems. In interviews, he notes that during his time at the university, he has focused effort in applying design skills in interdisciplinary teams as part of his research and as part of his instruction. These interests and experiences are typical of the activities that takes place in a Capstone design course. He stated that he has taught the course "seven to ten times or more."

5.3.3.2 Instructor 2

The second faculty member involved is a first time instructor of this course. She holds a B.S. in mechanical and aerospace engineering, an M.S. in aeronautics and astronautics, and a Ph.D. in science education. A few of her research interests are in engineering education, community-based engineering, discourse practices in engineering, and engineering teaching. Her research interests run parallel with some of the design practices and engineering collaboration focused upon in the course. In interviews, she noted her "interest in how people learn how to design" as a factor in wanting to lead a section of this couse. She also saw the course as an opportunity to bring "issues of societal responsibility in design" to the curriculum. She will be referred to as 'F2' in this document.

5.3.4 Design Teams

During the first meeting of each session for this course, I recruited potential student participants. It was made clear that participation would have no affect on their standing within the course and that specific findings would not be shared with instructors until after the course was completion. Consent documented was provided and collected during the next course session. Only student teams with full consenting members were considered for participation.

In ME43, the students separated into design teams, each team working on their own clients' project. This occurred by the end of the second week of the semester. 4 groups were selected, 2 from each section. This formal selection didn't occur until week 6. The delay was to allow general observation of all teams during class sessions and to gain some feedback from the instructors before selecting the 4 design teams. These groups were selected due to a perceived value as research participants. These would be participants interested in fabrication, typically responsive to inquiry, selection of a project relevant to research interests, and the recommendations of the faculty participants. This will be described in more detail for each group. Tables 5.1 and 5.2 on the following page summarizes reasoning for selecting certain design teams and ruling out others.

5.3.4.1 Milk Tag

One of the clients was a local dairy vendor who was looking for an automatic method to apply hang tags[4] on the company's dairy products. One team from each section selected this project, lending it value to comparing teams across classes.

[4] Promotional tags that hang from the top/spout of a dairy container. They are applied by tying them on with a string.

Team	Mbrs	Reason Selected
Milk Tag S1	3	Comparison team in other class.
Milk Tag S2	4	Comparison team in other class. Prior knowledge of 1 students' responsiveness.
3D Wire Bender	5	Subject makerspace as the client. Prior knowledge of 2 students' responsiveness and interest in fabrication.
Water Table	4	Youth makerspace as the client. Prior knowledge of 1 students' responsiveness and technical literacy.
	(16)	

Table 5.1: Participant Design Teams Reasoning for Selection

Team	Mbrs	Reason Ruled Out
Wind Tunnel	2	Overly constrained project
3D Print Rec.	5	Aware of several pre-existing solutions
Bike Storage	4	Lack of complexity to design problem and aware of several pre-existing solutions as well
Vaccum Former	3	Aware of several pre-existing solutions
Pet Rewarder	5	Small scale project with little use of system attached equipment according to early team discussions
Wheelchair Mod	3	Early client issues limited teams ability to get started on project
Airport Chlg	3	Students were leaning towards primarily digital solution
Bio-robotics Kit	2	Small scale project with little use of system attached equipment according to early team discussions
Smog Simulator	5	Early client issues limited teams ability to get started on project
	(32)	

Table 5.2: Reasoning for Ruling Out Design Teams

This served as the primary reason for selecting these teams[5]. Members of these team will be referred to by 'MT1#' for members of the team from F1's section and by 'MT2#' for members of the team from F2's section.

5.3.4.2 3D Wire Bender

The third team of interest selected a project to design a desktop automated wire bender capable of creating 3D objects. The client for this project was the makerspace itself. They already had a 2D CNC wire bender as one of the available desktop fabrication resources and were interested in advancing that capability. Their project intended to be a similar, makerspace type piece of equipment. Since their project revolved around equipment in the space and was looking to make a fabrication resource for the makerspace, they were selected. Prior knowledge of two of the members interest and experience with fabrication and makerspaces was also a factor in selecting this group. One has been an undergraduate researcher in my group two summers prior to this study so I had knowledge of their interest in fabrication and some knowledge of their design skills. The other was a student I didn't know by name but had used equipment I had previously been responsible for on occasion, enough to recognize him and have a sense of his comfort level with desktop fabrication resources. Members of this team will be referred to by '3DW#.'

5.3.4.3 Water Table

The final team worked on a project for two graduate student researchers in the university's department of child development. The clients were developing a children's makerspace and sponsored two projects for the course. I personally knew the clients and had prior knowledge of their interests and some sense of their expectations for

[5] One of the team members of the group from F2's section was a summer undergraduate researcher at the same center I worked in. I did not directly work with the individual but did hear encouraging things about his work ethic, responsiveness, and capabilities as an engineer through personal correspondence. This was not a major factor but a small influence on the decision.

these projects. The project was to design a water table that serves as a hands-on instructional analog to electricity for young students to work with to gain a better understanding of electricity. This project was selected because it had a makerspace aspect to it, making it in line with a general interests of the study. It was selected over the other project since that project, a vacuum former for that young student makerspace, already had many real world equivalents so the water table was personally thought to be the more interesting design challenge. One of the students was also a student of mine in a course about design and fabrication the previous fall so I had prior knowledge of her fabrication, design, and technical literacy skills. Members of this team will be referred to by 'WT#.'

5.4 Data Collection

Several different data sources were available within the bounded system (See table 5.3 on the next page). These will be discussed in greater detail in their subsequent sections. I was the primary collector of these following data. As an overview though, field notes were taken in the makerspace and during the class sessions taught by the faculty participants. Academic artifacts submitted as part of ME43 were also collected. Usage data from the fall 2016 semester collected by the makerspace's UTEM system was another data source. Interview data was also collected during that time and was most used in the assessment of the UTEM system's performance due to the direct statements of stakeholder outlook which it provided. The other data informed interview protocols, triggered interviews with a participant, and was used as discussion prompts during interviews though. Participants of interest were scheduled to be interviewed several times throughout the data collection window, as individuals and in groups.

The entire data collection period occurred from August 2016 to February 2017,

Table 5.3: Data Collected as part of the Pilot Study

Data Type	Source	Details
Field Notes	Classroom Observations	Occurred during faculty participants class sessions. Both sections of ME43 and one section of ME42.
	Makerspace Observations	Occurred weekdays at random times and weekends when fabrication area was opened. Field notes recorded if event observed.
Course Artifacts	Curriculum materials	Course provided resources created by faculty. Collected through course website and in-class handouts.
	Student Artifacts	Prototypes, final reports, and presentations. Provided by students or collected with their permission.
	Communications/ Feedback	Teams used publicly accessible team messaging service. Course feedback provided by faculty.
Usage Data	UTEM System's Logged Usage Data	Data queried from the database after completion of the fall semester. Collected without reference to an individual by team usage, station usage, and usage by time intervals.
Interviews	Staff Participants Student Participants Faculty Participants	Interviews occurred throughout the semester with follow-ups after its completion. Protocols informed by prior data.

but all activities took place the fall semester from August 28th, 2016 to December 25th, 2016. These dates encapsulate the weeks in which students officially had access to the learning environment of interest for the University's fall semester. For organizational purposes, data collection is coded by both date and by week, with week 1 being the first week of the acknowledged fall semester[6].

Data was collected into a qualitative data analysis software, NVivo, to aide with organization. This step was not taken until after the data collection was completed though. Prior to this, data was kept in a field journal and digital information, such as transcripts, coursework, and UTEM system data, were stored on a secure hard drive.

5.4.1 Field Notes

I took field notes using methods described by Wolfinger (2002) and Burgess (2003). Earlier field notes employed a comprehensive note-taking approach, trying to capture as much of the action occurring within the classrooms or the makerspace. Particular focus was given to comments or actions that referenced or related to the makerspace. These early notes informed later interviews and more directed observations. Over time, I gained a better understanding of the behavioral norms within the classroom, particularly regarding student interests and interactions. This better informed my tacit knowledge about the research participants and the meaning of observable actions within the classrooms and how those relate to the study. For instance, recognizing that rarity of a quiet student participating in class or noticing a student team struggling in the makerspace and knowing how the issue had been brought up in prior classes. This allowed for the use of a salience hierarchy note taking approach, noting only items of salience based on a large deviation from prior observed behavior, emphasis by the instructor, popular uptake by the class or group,

[6]Sunday August 28th, 2016 to Saturday September 3rd, 2016

or in relation to the greater bounded system (Wolfinger 2002). This transition occurred after the first interviews with the instructors occur. They provided a measure of feedback on observations made during the class session.

I attended both sections of ME43 to take field notes. These class sessions took place in classrooms outside the makerspace building but were observed due to the selection of the course as part of the bounded system of the study. Participants were observed in this setting since actions and instructions during the class sessions of a course that considered the makerspace in its curriculum would at some points address the makerspace, particularly in the context of the course. This would potentially provide insight into how participants relate to the makerspace as students or instructors, decide on actions they take within the space, inform some queries within the interview protocols, and provide insight into those responses.

I attended 20 out of 24 classes of session 1 of ME43 and 23 out of 26 classes of session 2. Class sessions lasted for 1hr 15min each, totaling 53 hrs 45 min of observation in that setting. F1 was also teaching a session of a machine design course (ME42) with an expectation of student fabrication in the makerspace. Due to the shared instructor and a lesser but still existing expectation of student interaction with the makerspace as part of curriculum, I took field notes in 43% of the class sessions for that course[7] I attended 11 out of 26 classes, primarily in the first 3 weeks of the course then checking in every other week for the rest. This was a convenient sample due to the time it met and the opportunity for comparison observation of one of the instructors.

I made several efforts to minimize my influence within the course. I would typically position myself at the rear of the classroom and offer minimal participation. I did occasionally ask a question for clarification and there were some occasion when my prior experience as a mechanical engineer in industry was pertinent to a lecture

[7] Students were informed of the research study during the first class session. Consent forms were distributed in that class and collected in the second class.

point or activity. I would confirm with the instructor before adding input. I would try not to add information that pertained to the makerspace, particularly not directing anyone towards that, nor would I put forth inquires that may instigate a student to reference the makerspace. The in-class observations were meant to gain insight into participant perspective from ME43 and therefore in-class intervention on my part was minimized. During small group discussions or work, I would walk around the classroom to observe and would record anything of note upon sitting back down in order to minimize discomfort of the participants[8].

In the makerspace, field notes were taken in a similar fashion but there was less concern for interaction with participants. Cultural norms within the makerspace encourage asking about what others are working on and, by both being within the makerspace, I felt safe in assuming they were aware of the makerspace. Occasional simple prompts for clarification[9] were used to derive greater information from the observations. Any more specific questions would be prefaced for a request for an interview, since I felt more direct questioning and a longer discussion changed the nature of the data collection from observation to actively participating in an interview. For the same reason as in classrooms, observations typically were not recorded directly ”over the shoulder” of research participants. Any salient actions or interactions would be recorded outside of direct physical proximity from the participant or participants. These observations were undertaken daily at random times throughout the day. Typically they involved a walk through the makerspace, similar to the path described later in the makerspace vignette on page 130. Field notes were recorded if any salient events were observed: a student struggling with the UTEM system, an ME43 design team working together or separately throughout

[8]This was a specific decision to not be standing over students writing in a notebook, an action which may have made myself more conspicuous than desired. I have no methodological reasoning for this behavior. As a research participant in past studies, I have been made uncomfortable by someone writing in a notebook over my shoulder. I decided to not risk perpetuated that discomfort.

[9]ex: ”What are you working on?”, ”How long have you been working on this?”, ”Is this for class?”

the makerspace, an instance of UTEM system bypass, or other notable interactions involving the pilot study participants or the UTEM system.

5.4.2 Course Artifacts

Course artifacts refers to any collectible material pertaining to participant participation in ME43, including both the faculty and the students. The materials available included all curricular materials, student artifacts, and communications/feedback. The curricular materials refers to resources provided by the instructor for course assignments or for student reference. The course syllabus and design project descriptions informed selection of participants and early interviews. Most faculty provided resources were collected through the university's proprietary online learning environment and course management system. Student artifacts were any artifacts produced as part of course curriculum. The team prototypes were a means to observe their progress and were discussed in interviews along with the final report and presentations. Those collected assignments, both before and after faculty feedback, were typically received directly from the students. Before making a request to faculty for copies of student work though, I informed student participants of the intended request and asked for permission beforehand. The course used an online team messaging service, Slack, to enable public[10] communication between team members and class members organized into various channels. These channels were monitored using notification features within the web application. For the message streams of the 4 design teams, Keywords were flagged for email notification Push notifications to the phone app were setup for general activity[11]. The course feedback from the students was requested and provided by one of the faculty members.

[10]Message streams were viewable to all students in the course, not just the individual design teams.

[11]The terms selected as keywords were <Name of makerspace>, 'lab', 'data', 'fabrication', 'machining', 'printing', 'acrylic', 'PLA', 'meet', 'meeting', and 'library'. This selection was arbitrary but produced enough notifications to ensure checking the message feed several times a week.

5.4.3 Usage Data

All UTEM system data reviewed came from the fall semester. Usage data was the primary focus though for informing interview protocols and observing participant behaviors. The primary queries focused on the following data:

- Usage data by ME43 team
- Usage data by station type
- Usage data outside of the official access hours

Searches were performed without request for user specific information. I made all database searches without reference to any items from the 'users' table include in the output results, always starting with "SELECT event, sid, e_date, e_start, e_end, duration, ref_start, ref_end FROM use_event WHERE ...". Note that the 'SELECT' criteria does not include 'UID', the database's user identification number. Data was checked semi-regularly during the collection window, typically before an upcoming interview. It was downloaded for figure development after the fall semester had completed.

5.4.4 Interviews

Interviews were held throughout the data collection period and served as one of the primary data sources for analysis. The main use of the prior data was to inform the protocols for the research interviews. Those with the staff and instructors took place before classes began, in the middle of the semester, and after the completion of the semester. Student participants were not selected until after the start of fall semester courses began and they had formed design teams. The majority of interviews were scheduled ahead of time. (See table 5.4 on the following page for a list of interviews).

Table 5.4: Interviews

partic	Stake-holder	type	Loc	Prot	Date	Wk	Dur (min)
S2	Staff	indv	Office	Pre	8/30	1	18
F2	Faculty	indv	Office	Pre	8/31	1	43
S1	Staff	indv	Office	Pre	8/31	1	35
F1	Faculty	indv	Office	Pre	9/1	1	33
F2	Faculty	indv	Office	Mid	9/26	5	28
F1	Faculty	indv	Office	Mid	10/4	6	40
MT1	Student	grp	Design Lab	Mid	11/4	10	17
MT2	Student	grp	Design Lab	Mid	11/4	10	22
3DW	Student	grp	Design Lab	Mid	11/7	11	15
WT	Student	grp	Design Lab	Mid	11/16	12	27
S1	Student	indv	Mechatronics	N/A	12/5	15	12
F1	Faculty	indv	Office	Mid	12/6	15	55
F2	Faculty	indv	Office	Mid	12/7	15	28
S1	Staff	indv	Office	Mid	12/8	15	43
S2	Staff	indv	Bray Shop	Mid	12/14	16	34
3DW1	Student	indv	My office	Post	1/13	20	15
F2	Faculty	indv	Office	Post	1/13	20	39
S1	Staff	indv	Office	Post	1/18	21	28
F1	Faculty	indv	Office	Post	1/20	21	36
MT21	Student	indv	Bray Lab	Post	1/20	21	14
MT24	Student	indv	Mechatronics	Post	1/23	22	18
S2	Student	indv	Office	Post	1/23	22	26
WT2	Student	indv	My office	Post	1/23	22	15
3DW4	Student	indv	My office	Post	1/24	22	43
MT12	Student	indv	My office	Post	1/24	22	19
WT2	Student	indv	My office	Post	1/30	23	19
MT13	Student	indv	Skype	Post	2/1	23	17
MT23	Student	indv	Mechatronics	Post	2/1	23	15
WT1	Student	indv	My office	Post	2/1	23	18
3DW3	Student	indv	Mechatronics	Post	2/2	23	18
MT11	Student	indv	Mechatronics	Post	2/2	23	13
3DW2	Student	indv	Mechatronics	Post	2/3	23	26
WT4	Student	indv	Mechatronics	Post	2/10	24	11

A total of 14 hours of interview data were collected. All interviews were semi-structured and conversational in nature, guided by pre-determined interview protocols (See appendix B on page 200), and informed by clinical interviewing practices (disessa 2007; Ginsburg 1997). The initial protocols were developed for IRB application and evolved as experience and observations cumulated throughout the study. The protocols only served to guide the interview participant's attention towards the matter of interest to the study, the participant's relationship with the educational makerspace. I relied heavily on open ended prompts to allows participants the most opportunity to voice their full thoughts on the subject. More direct questions typically served to allow the participant to confirm or reject a previous statement, some inferred meaning from a field note, or an interpretation of a statement from a prior interview[12]. Interviews were treated more like conversation and that style of interaction was noted and encouraged at the start of each interview. This was intended to allow topics of interest to the interviewees to emerge (Brinkmann 2015). These lines of dialogue would be pursued as long as thought to be beneficial, typically ending when interviewee no longer had comment on the subject. At that point the next item in the protocol would be brought up.

The previously discussed data sources not only informed protocols but were at times used as discussion prompts within the interviews. For instance usage data and observations of student interactions with the equipment were commonly discussed with staff participants during these exchanges. All interviews were audio recorded and transcribed[13].

Interviews are inherently a social interaction between individuals with their own identities (Rapley 2001; Heyl 2007). The researchers and participants each held identities that in some ways overlapped and in other ways created differences in

[12]Typically questions like ”Can you clarify that point?” and ”When you said [this], did you mean [it in this way] or [in that way]?”

[13]The exception being the S1 week 1 interview when an error with the recording equipment occurred.

authority. There also existed social relationships, either established by the individuals or through those identities. Due to these considerations, the researcher functioned within a scenario where their interactions regularly shifted between studying us, studying sideways, and studying down (Bowman 2009), constructs which aptly address the scenerio. As a graduate student, there is an awkwardness in having participants in faculty roles (studying up). My relationship with the staff members is more one of colleagues (studying sideways). I assume students view me in some role of authority because of my status within the makerspace and the oversight I have over an aspect of the space, the UTEM system (studying down). This awareness informed how interviews were framed and the level of awareness given to that framing. I gave the greatest amount of consideration for student framing of the interviews.

All interviews began with a description of the intention for that interview. I would explain the style I use and how I allow for conversation through guiding questions. With the staff and faculty, prior endeavors had already established relationships as well as interview rapports, giving confidence for valid responses. In situations where students began to hesitate in answering, say if they were concerned about criticizing the course, I emphasized my position as a independent researcher and that they were welcome to speak freely. Making clear that our discussions would remain simply as part of the protected data set and will not be reported directly to anyone perceived as having authority over them. All participants knew that my interest was in the UTEM system and that I had put a significant amount of time and effort into its development. To avoid an interviewee's eagerness to provide socially desirable feedback influencing responses, I was clear and consistent in assuring the participants that I, as both a researcher and the technology developer, desire the honest opinions on the system and reporting of its effectiveness. These efforts to empower respondents into a more informative and collaborative frame as well as maintaining a reflexivity to ease interview pressure while still pursuing pertinent information are believed to help achieve the most valid responses in those scenarios (Heyl 2007) (See appendix B on page 200).

5.5 Analysis of the data

As mentioned, data collection and analysis occurred concurrently, influencing one another throughout the study through concurrent collection of the data, its analysis, and its influence on the subsequent data collection. Efforts later in the study utilized prior data to inform approaches to its collection and improve my understanding of the saliency of observations. I took advantage of follow up opportunities to confirm that prior date with more pointed questions in the interview protocols.

Data was analyzed with the goal of forming a meaningful assessment of the UTEM system's performance within a sociocultural environment that typically holds strong ties between the resources and the culture, ie academic makerspaces. Towards that end, data was analyzed using inductive methods used in grounded theory(Glaser and Strauss 1967) as well as deductive approaches that focus on identifying data that corresponds to a-priori codes created from the items of interest, the user level design attributes. This was not undertaken with an expectation of developing learning theory around the use of the UTEM system within an academic makerspace. The appropriate levels of rigor were not considered for that purpose. These methods were simply used to enable me to gain an understanding of the culture of the makerspace, the influences of the UTEM system, and to assess the connections within.

As I mentioned, I used two separate approaches to review and assess the data. This was done in a repeating pattern as new data accumulated, taking in the new data as well as reviewing the old. The first pass was an inductive pass using open-coding practices, ignoring the design and other considerations to gain insight into what arose from the data without influence of desired outcomes. This involved a constant comparative approach being applied to the data to find natural themes within the data and axial coding to focus those (Boeije 2002; Glaser and Strauss 1967). Due to time constraints and the goals of the study, an extensive inter-rater reliability process was not pursued. This phase was primarily to take full advantage of the hypothesis generating nature of qualitative data to identify themes that could inform future interview protocols within the study as well as more learning centered studies in the future (Merriam 1998).

My focus during this study was to identify how the UTEM system affected stakeholder relationships with the makerspace through the user level attributes. The second pass of data took that focus into account for a more deductive examination of the data. This provided a premise to identify the a-priori codes of the 5 attributes for coding the interview transcripts. Some label pertaining to those attributes were pre-selected to assist in searching and examining the interviews:

1. Safety, equipment, or access (Automatic equipment safety interlock)
2. Database or system information (A centralized database of system information)
3. Usage Data or Logging (Logged usage tracking data and visualizations)
4. help or assistance (help button on each station terminal)
5. snap, photos, or documentation (photo button on each station terminal)

Situational labels were also pre-selected since it was expected that data would hit upon topics such as the makerspace itself, the courses, and the other stakeholders.

The inductive pass did produce similar labels as the a-priori codes but that was expected since the purpose of the study and bounded system influenced and directed data collection. The deductive approach is still considered a separate methodological approach applied to the dataset since more directed, often computer aided through NVivo, searches within the data were used during that process. The influence of the hypothesis on the collection protocols also allowed for a pre-identification of regions where deductive coding may be applied such as portions of interviews stemming from direct queries relating to a code.

Chapter 6

Performance

6.1 UTEM System Use for Fall 2016 Semester

The final configuration of the IoT usage tracking and equipment management system consists of an open-source database and web-framework connected to a system of RFID terminals constructed from open or readily sourced software and hardware. All software was developed using open-sources without licensing fees. The hardware costs were kept to a minimum. I used open-source items whenever possible as well as readily available COTS components. The final cost for the core components is less than $55.00 (See table 6.1). All auxiliary items are also readily available or provided as open source in this document (See appendix A on page 199).

The UTEM system allows for safety control of equipment stations as well as

Table 6.1: Base RFID Terminal Cost

Main Component	Avg Cost
MiFare RFID Module	$7.99
Serial Enabled LCD	$24.95
Raspberry Pi ZERO	$5.00
USB WiFi Adapter	$8.99
5V 2A Power Supply	$7.95
Total	$54.88

Table 6.2: Events Logged by UTEM System

Events	Station	Total Use (hr:min)
796	3D Printers	533:56
323	Laser Cutter	428:33
149	Soldering Irons	49:22
24	Desktop CNC Router	10:48
103	Sign In	N/A

data collection through the terminals. The base units can be equipped with a power interlock, data interlock, and computer interlock options. The web-based user interface allows staff to interact with the database information including user information and station permissions. They can also use it to view up-to-date usage information for all equipment connected to the UTEM system.

Over it's initial semester in the makerspace, the UTEM system logged 1395 events for all equipment it was connected to (See 6.2). To clarify, an event is a single user interaction with the system and not a job in a shop sense. A user may interact with the system to set up a job and then return a few times to check on that job, leading to a ratio of multiple events per job. The UTEM system can not specifically track number of jobs yet, currently focusing more on the user interaction than the actual resource use. 202 new users were registered in the database during that time as well. 289 had already been registered before the beginning of the semester over the course of the UTEM system's development and as part of prior courses. Of those users, the UTEM system logged usage from 115 unique visitors to the makerspace during that fall semester, 87 of which had been users who registered during the fall semester.

6.2 System Stability

Once installed, the RFID terminals were continually in place and powered on. The terminals were taken off-line in late October to be reformatted and upgrade their malware protection. This was due to a DDoS attack which targeted IoT devices infecting the RFID terminals. Otherwise, some of these devices have been on for long periods of time without restarting since that incident, well over 3 months as of this writing. With the exception of one terminal requiring a hardware replacement, the RFID terminals are capable of running continuously for long periods of time without crashing. The exact amount of time is unknown though since staff occasionally unplug the devices when maintaining or cleaning the equipment station. There were also occasional instances where a user's RFID would not work and they would reset the RFID terminal but the fault was actually with a damaged RFID tag. The terminals do not log times when they startup and shutdown and when simply unplugged, a proper shutdown procedure can not occur to trigger a log. Therefore the number of these occurrences was not tracked. True run times are unknown and estimated based on conversations with staff and observations of their actively running daily.

6.3 User Interface Assessment

Several interfaces for interaction with the UTEM system and its information were developed. To assess these items, I worked with one of the staff participants, the makerspace coordinator, to assess the user interfaces through a heuristic evaluation. This examination is based on the expertise of that one user. A set of heuristics developed by Nielsen (1994) was used for analysis.

1. Visibility of system status

2. Match between system and the real world

3. User control and freedom
4. Error prevention
5. Consistency and standards
6. Recognition rather than recall
7. Flexibility and efficiency of use
8. Aesthetic and minimalist design
9. Help users recognize, diagnose, and recover from errors
10. Help and documentation

6.3.1 Heuristics

Visibility of system status

This heuristic refers to the interfaces abilities to keep users informed of system activity with the caveat that the feedback be appropriate and given within a reasonable amount of time. Each web interface contains titles describing its function. The inputs are all labeled for the information being inputted and its proper format. When actions are taken, the system provides a notification of the completed action or that the action did not occur due to an error.

According to the participant, the interface succeeded in keeping the user informed about what is going on with each interface. She noted it provides feedback when an action has been successfully or unsuccessfully completed.

Match between system and the real world

The system should speak the users' language. Phrases and concepts that are already within their vernacular, avoiding system-oriented terms. Real-world conventions should also be used, providing information in a natural and logical order. To achieve this, conventions standard to the university were used for the username, Tufts' UTLN(Universal Tufts Login Name) which was the standard at the time of development. Information is arranged with the username and name fields at the top of any form with auxiliary information placed below. The calendar views include clear labels giving the station's colloquial name and user's full name.

The participant noted that the system uses common wording throughout. She did have issue with the use of Tufts UTLN. Some of the students do not recognize the term. She recommends changing the system to use Tufts username instead. This would actually bring the system into agreement with the university's current terminology, a change that occurred just before the start of the pilot study.

User control and freedom

This heuristic refers to a users ability to fix a mistake, the system's inclusion of functions that enables the user to leave an unwanted state and return to the previous or desired state without going through an extended dialogue. The web interface has a navigation on top of all the web-pages, linking to all available web apps within the system. The only page without this option is the one to attach an RFID. Due to the steps required and non-standard input device needed to use this page, it was excluded to minimize distractions from the desired process.

S1 agrees that all pages are accessible through the navigation bar so it is easy to return to a desired page if another is clicked in error. General users have less access but only on pages where there are singular functions so the inability to easily mistakenly exit helps. Admins can access all pages at anytime though, which is appropriate for them. She also noted, unprompted, that the exclusion of the navigation bar for that attach RFID page was appropriate for the purposes of that page and the users who interact with it.

Error prevention

The design should not only warn users of errors but to prevent such issues from occurring in the first place. Error-prone conditions should be minimized, checks for errors included, and confirmation options given before actions are committed. This system includes underlying checks of all information before inputting or retrieving information from the database. For instance, partial search terms still produce matches and all items are case-insensitive to avoid errors due to their use. When information which violates some internal rule, such as attempting to overwrite an RFID value for a user who already has a registered RFID tag, a confirmation window informs the user of the action about to be taken and asks if they are sure they would like to continue.

S1 noted one issue that violates this heuristic, going too far in its error prevention. For that example of overwriting an RFID, the error message produced states ”user already has an RFID, override errors?” Users have expressed to her a fear about overriding an error in the system, causing them to not register a new RFID and find a staff member instead. She recommends eliminating the error message since users rarely want to find their old RFID rather than simply replace it. Even if they find it, they can just overwrite it again.

Consistency and standards

Consistency and standards means that users shouldn’t have to wonder if different words, situations, or actions carry similar meanings. That conventions fall within platform standards. This was addressed by the same considerations which address the heuristics ’match between system and the real world’ as well as ’error prevention’. Use of ”UTLN” and ”override errors” are the only aspects of the system that violate this heuristic. Otherwise, S1 believes that the UTEM system uses proper consistency and standards in the conventions used to communicate function.

Recognition rather than recall

The users' memory load should be minimized by making objects, actions, and options visible in the interface. The user should not be expected to remember information between one part of the interface to another. Instructions should be clearly included or easily retrievable when appropriate. The UTEM system uses their assigned username from the university, so a new username is not necessary. All forms include instructions within the fields as well as examples of properly formatted information so users don't have to remember functions or formats.

S1 notes those features as items that address this heuristic. They can easily remember the username since its the same for all university services. All relevant information is included within each page and no information is hidden from the user.

Flexibility and efficiency of use

Typically accelerators are included within an interface to address this heuristic. They often speed up expert user interaction and remain unseen by the novice user. These enable the system to cater to users on various level of access experience or need. They also allow users to tailor frequent actions. Currently, the UTEM system is weak on this matter. Admin pages require inputting admin information but an administrative login with subsequent system state has not yet been developed.

S1 referenced those shortcomings for this heuristic. She noted that admin commands do require that information input each time, which can be taxing to continually type in. Especially if the admin user needs to deal with these interfaces multiple times during a day or even in a row. She recommends doing away with these added steps. The security is minimal and the user base is small enough that it is unnecessary at this time. A proper admin side of the interfaces with login would be useful but until then, the added steps do not buy security since the information used is easily found out so should be done away with.

Aesthetic and minimalist design

Dialogues should not contain irrelevant or rarely necessary information. All information in the interface competes for visibility. Each detail included needs to be relevant otherwise it diminishes from the actually relevant information. For that reason, the interfaces were kept simple, with a blue navigation bar and plain white background. Information is limited to that necessary to accomplish the function of that interface. The majority of web interfaces also perform a single function each. The only exception is the permission edit page which provides two variations of the permission edit function, by group or by individual. That page leads to separate interfaces, each designed for those variations on the function though.

The participant thought the design to be esthetically pleasing and simplistic. She stated that it enables the admins and users to quickly understand the page and its purpose. She also noticed that each page is designed for one function, eliminating confusion by not requiring a user to be concerned with multiple actions at once.

Help users recognize, diagnose, and recover from errors

This heuristic refers to error recovery measures within an application. Error messages should use plain language rather than numerical or internal error codes. They need to precisely indicate what the problem is and suggest a constructive solution. The error messaging within the system does not use numerical error codes, rather describing them in plain language such as ”This is a required field.” or ”User name not in system.” Solutions are not explicitly provided, assuming that the information is enough and that instructions such as ”This is a required field. Please fill in the field.” are implicit in the error message ”This is a required field.”.

S1 refers back to the issue with the Add an RFID pages overwriting error message and the already mentioned confusing instruction to continue with overwriting. Otherwise, the other error messages clearly state the issue and there is no confusing in addressing them.

Help and documentation

Sometimes various forms of help or documentation are required. Such information should focus on the tasks, be easily searched, and not be unnecessarily large. Staff were introduced to the UTEM system and given a short, information training on the various interfaces as they became available. Formal documentation was not created due to the simplistic interface and staff's easy use of the system made it a low priority item.

S1 echoes that statement, affirming that documentation is not needed for the UTEM system. She finds the system easy to use and documented instruction would not simplify or improve use.

6.3.2 Interface Usability

The UTEM system user interfaces provide an easy to use means to access and interact with the database and usage information. They meet requirements of heuristics which have been a commonly used design tool in human factors (Nielsen 1994). System statuses are provided upon each action. Common language is used, the only variation is due to a change in the university terminology it was meant to be in agreement with. The interfaces are clearly labeled and easily navigated. Underlying functions check inputted information and provide feedback if errors occur and what those are. The simplistic and clean aesthetic, single function per page design, and appropriate information provided makes for an easy to use web interface without need for documentation.

The makerspace coordinator agrees with those conclusions about the interfaces usability. She noted several issues that are not in line with the identified heuristics. The majority were minor issues that caused some confusion rather than outright issues. She recommended many solutions to address those heuristics, the majority easily implemented. The web interfaces provide an easy to use interface to the UTEM system.

6.4 UTEM System Design Attributes

The UTEM system has 5 user level design attributes. These were intended to interact with the user and, through that use, have a positive influence on stakeholder experiences within the makerspace. These being:

1. Automatic equipment safety interlock (Section 6.4.1)
2. A centralized database of system information (Section 6.4.2)
3. Logged usage tracking data and visualizations (Section 6.4.3)
4. help button on each station terminal (Section 6.4.4)
5. photo button on each station terminal (Section 6.4.5)

The automatic equipment safety interlock actively inhibits user access to the station at times, if they do not have the proper training and therefore proper permission within the system. The centralized database stores system information on users, stations, and permissions and are accessible by users through the various web interfaces. The usage data is automatically logged and made available to certain users in multiple formats. The access terminals also have two buttons on either side labeled 'HELP' and 'SNAP' serving as the help button and photo button. Pushing these buttons will either serve as a request for help by the user or trigger a photo taken of the station and emailed to the user.

It is for the assessment of these aspects of the design that drove the approach and many of the methodologies, to gather and examine information that would speak towards the cultural aspects of the makerspace. The pilot study data was deductively coded using a-priori codes from the design attributes to identify their influences on the stakeholders' experience. That analysis is presented in greater detail in part III on page 128 as vignettes describing stakeholder experiences noting the interactions with and influences with the UTEM system. For this section, the information is more focused and organized around the individual design attributes to assess their performance within its sociocultural setting.

6.4.1 Safety Interlock

The safety interlock is arguably the most noticeable attribute of the system due to it's interface with the equipment. This attribute refers to the UTEM systems ability to provide a safety measure against misuse through the interlocks integrated within the RFID terminals. It also includes the reassurances that this barrier provides stakeholders, that conception of safety provided by having such a technology in place.

6.4.1.1 Staff

The initial design expectations for this attribute, like all, varied for the different stakeholders (See table 6.3 on the next page). With regards to staff, this attribute of the UTEM system served as a measure of reassurance. Its intention, as a functional feature, was to provide staff some peace of mind with regards to safe use of the equipment through its ability to inhibit unauthorized access. That hurdle created by the inclusion of an automatically controlled interlock provides confidence that unauthorized use of the various equipment is minimized, if not fully eliminated.

Table 6.3: Attribute: Safety Interlock

	Design Expectation	Stakeholder Expectation	Observed Reality	Success
Staff	Reassure that equipment is being used safely	Have confidence that equipment is being used as desired	Featured UTEM system in administrative safety reviews	✓
	Provide reasoning for expanded access	Expand accessible hours for equipment on system	Kept equipment in areas in expanded hours	✓
Student	Provide a barrier to remind students of safety and policy procedures	Not applicable [a]	Consistently attempted to bypass the system. When those attempts failed, they did pursue proper channels.	✓
	Prohibit access to untrained or unapproved students	Not applicable	Inhibited students attempts at bypassing the system	✓
Faculty	No intended direct consideration by faculty	Not discussed in pre-semester interviews	No observed concern or interaction	-

[a] Students not formally interviewed about expectations prior to the semester's start.

Unauthorized use, more specifically that by individuals not trained and approved by staff, was a major concern for the staff going into the semester. In the pre-semester interview with S2, he was especially verbose in his concern. He had past experience with unsafe working environments and the injuries that resulted. He provided the following statement during our interview, giving evidence that the staff believed this attribute of the system will provide them with confidence that equipment is being used as desired.

> Being able to set up a shop and be in charge of the safety and everything and all the documentation that's going to the safety office and everything, makes me feel really comfortable in the shop because I know that, this shop is run a lot better than any other shop that I have worked in before, um, which is good, and I think your system is just gonna help us keep everyone in line.

He reiterated that value and became more specific in that help in response to a later question. This time he was asked about access control in past shops.

> I mean having these kind of gates that stop people from, who aren't supposed to be doing something from doing something, it's gonna help a lot[1]

That sentiment is shared among the rest of the staff, each referring to the terminals as "gates", "barriers", "reminders", and other figurative comparisons to their ability to either protect the equipment from unauthorized use or remind students of makerspace policies around equipment use.

These attitudes followed through the semester. They mentioned the safety aspects of the terminals in all subsequent interviews. In discussing misuse of equipment of hand tools, S2 noted "luckily, your system [was] implemented on safe tools,

[1] Filler and repeated words removed. The complete quote is "I mean having, having these kind of gates that stop people from, who aren't supposed to be doing something from doing something, you know, is the, it's gonna help a lot" Similar edits taken with other quotes.

hands-off tools". When going through reporting information to the university safety department and providing tours on the matter, the RFID terminals were featured as part of the space's safety protocols. They voiced interest in trying to find a way to utilize this safety interlock with more equipment, including hand tools.

The safety interlock had another purpose with regards to staff, to provide reasoning for expanded access hours to attached equipment. During pre-semester interviews with S1, she made clear that it was important to her that the makerspace be open to the greater university community including expansion of the accessible hours of the space. The faculty manager shared that sentiment as well with statements such as "Looking to be more accommodating, saying 'Yes you can' use equipment more".

The clearest evidence came from S1 when I asked her directly if the safety interlocks were the reason they allowed certain equipment to be in the extended access hours. She provided a direct answer on whether the safety interlocks served as enough of a safety measure to expand equipment accessibility: "Yes, that equipment is available in those extended hours spaces because that equipment has RFID terminals with the safety interlocks." Expanding that without those interlocks, they would have placed that equipment in a part of the space accessible only during staffed hours or disabled/stored them at nights.

The equipment stayed in those areas for the duration of the semester. Other equipment of concern, the soldering stations, had RFID terminals with safety interlocks added mid-way through the semester. There has been talks about adding sign-in stations to the other spaces eventually to capture some of the passive after hours use and to expand the system to cover more equipment in the upcoming semester. As of the writing of this document, safety interlock terminals have been added to the professional grade 2D printers in the Testing Lab.

6.4.1.2 Student

The initial design expectation of the safety interlock with regards to the students was echoed in some of the discussion with the staff. Their comments about it being a barrier and reminder are consistent with its original intent. I had specifically designed that feature thinking that it could serve as a reminder to students of the safety and policy procedures. The priority of safety held by staff works in some conflict with student priorities though. For staff this attribute provides a barrier to use to ensuring only those trained to safely use the equipment can while students just want to use the equipment. Due to safety being an initially motivating factor, the student desire for open access had to be specified to open-access after training and in accordance with policies set by staff. Since student participants had not been selected until after the semester's start, they were not interviewed before it began so design expectation were not recorded for those stakeholders.

Student initial treatment of the RFID terminals quickly made clear that the existence of the terminals did not initially serve as a policy reminder. There were some students[2] that would first attempt to bypass the RFID terminals to get access to the equipment. If successful, they would typically leave it bypassed[3]. I will note that we assume that the majority of students abide by policy. Even those who used a bypassed equipment station were not always aware that it had even been bypassed at that time.

Figure 6.1 shows instances where either the soldering stations or the 3D printer stations in the areas with extended access hours were bypassed in someway. The first instance of this occurred early in the semester with the computer interlocks

[2]An exact number is not available due to the tool that would record that being bypassed by that subset of users.

[3]Evidence of bypass was consistently finding the RFID terminal unattended and bypassed. Due to the number of those occurrences, staff and myself believe it unlikely that a user would bypass the system then re-enable it once they were done but, due to the nature of the incident and the available data sources, do not have more than circumstantial evidence towards that opinion.

for the 3D printers being bypassed through an unforeseen hot-key combination enabling anyone to close out the application. The power interlocks of the soldering irons were quickly bypassed, in their initial configuration, and each upgrade intended to dissuade that behavior was met with resistance.

The number of instances of student's bypassing the system speaks directly to the design expectation that the terminals would remind students of policies. The fact that some students did bypass the system, indicates that they either were not aware of their purpose or the policies involved and simply proceeded to make use as the believed they were allowed, or if they were aware of the policies but did not report the bypass, the terminals did not remind them strongly enough to abide by them and they used the equipment in spite of that.

There was an incident with the soldering stations in which the student who disabled the safety feature was still there when it was discovered and they were also willing to discuss the matter (See figure 6.2). This is further illustrated in section 10.2 on page 174, which describes in more detail an interview with the only student I came across in the act of damaging an interlock feature to bypass the UTEM system. His response to why he physically damaged the RFID terminal to gain access was, without any hesitation, "Cause no one's in right now and like, I need the solder for robotics"[4]. As the conversation progressed, I learned that although this was the first time he had destructively bypassed the system, he had knowingly used it while it had been bypassed in the past. Throughout the interview, he showed an awareness of the system, it's purpose, and some of the policies around it. He showed no hesitation in physically damaging a feature so that he could use the equipment though, citing his perceived urgent need due to an upcoming deadline and the inconvenience of staff being out to lunch. Based on my interactions with other students and their resistance to taking the appropriate steps to gain access as

[4]The project was due the following afternoon.

Figure 6.1: Timeline of System Bypass Events

Wk	Day	stn	
1	Sun	-	First week students have general access to makerspace.
2	Tue	-	Classes Start.
4	Tue	3d	Computer interlock application found to be closed out, allowing open access.
6	Mon	sld	RFID Terminals put in place, not connected, with warning and information signs.
6	Fri	3d	Informed that an unforeseen hot-key feature had been used to bypass computer interlock.
7	Mon	sld	RFID terminals enabled, plugging the equipment into the power interlock.
7	Sat	3d	First version of computer interlock with hot-key security installed.
8	Tue	sld	Zip ties installed to secure power connection to power interlock.
9	Fri	sld	Zip ties discovered cut and equipment plugged directly into the wall power.
10	Mon	sld	Zip ties reinstalled. Staff added more signs.
10	Fri	sld	Zip ties cut again. Pattern repeated every few days. Began looking for better solution.
12	Tue	3d	Installed final version of computer interlock with hotkey security.
14	Mon	sld	Zip ties checked daily.
15	Mon	sld	Steel wire cage used to secure power connection to power interlock.
15	Mon	sld	Steel wire cage cut by a student. That student was interviewed.
15	Tue	3d	Computers reformatted. Computer interlock forgotten to be reinstalled.
15	Fri	3d	Computer interlock reinstalled.
15	Fri	sld	Installed lockout boxes on the power connections.

well as the number of required re-installation of the cable locks, he is not a unique case among student stakeholders.

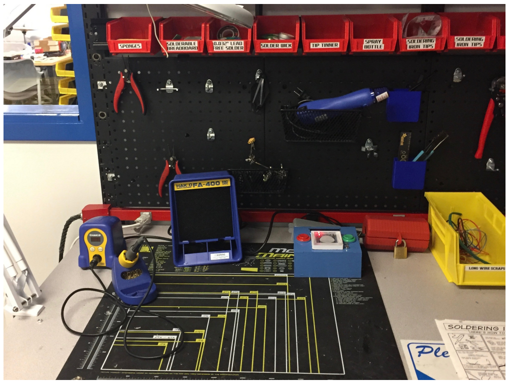
The previous observations also spoke to the second design expectation regarding students, the safety interlocks ability to prohibit access to untrained/unapproved students. Initially these would indicate a failure regarding that attribute, but those instances also fed back into the systems design, leading to improved interlock features. The dates of these improvements are included within the timeline provided in figure 6.1 and also noted in the usage data tables.

Figures 6.3 and 6.4 show the duration of use per day by semester week for those equipment types[5]. Some of the events can be noticed in the data. The 3D printers saw consistent use throughout the semester for both personal and academic projects. The data shows limited use early in the semester though. There are gaps of a few days throughout the semester, but they occur more often towards the beginning. Those gaps reduce after the first upgrade with hot-key protection to the computer interlock is installed. They also return when a new hot-key workaround is discovered, reducing again when the final version was installed[6].

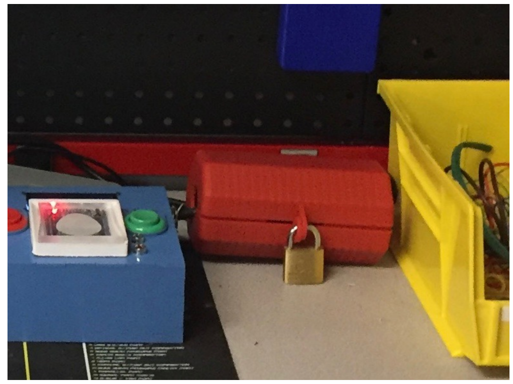
Similarly in figure 6.4, usage data does not start until week 8, after the zip-ties are installed, providing some small barrier to simply unplugging from the terminal and plugging into the wall. Consistent usage is not clearly observable until later in the semester, when the zip ties began to be checked daily and replaced as needed. After the lock out boxes were installed, no instances of the soldering station terminals being bypassed was observed for the reminder of the data collection period.

[5]Values that far exceed the average duration are likely due to an RFID left on the terminal, forgotten to be collected by the user once they were finished. These instances are still included in the data though because they can not be confirmed as a forgotten RFID tag.

[6]The gap in week 13 was due to a staff member reformatting the 3D printer station computers but forgot to reinstall of the computer interlock.



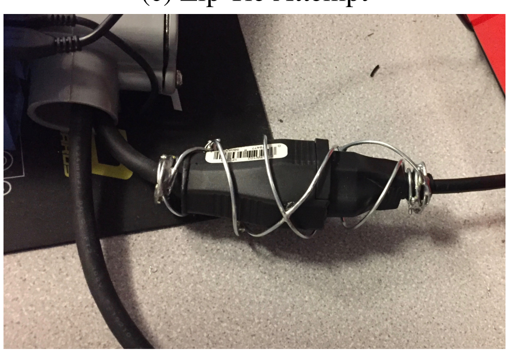
(a) Layout of the Soldering Station



(b) Currently Using a Lock Out Box

(c) Zip Tie Attempt

(d) Zip Tie Bypassed



(e) Steel Cage Attempt

(f) Steel Cage Bypassed

Figure 6.2: RFID Terminal Lockout Features

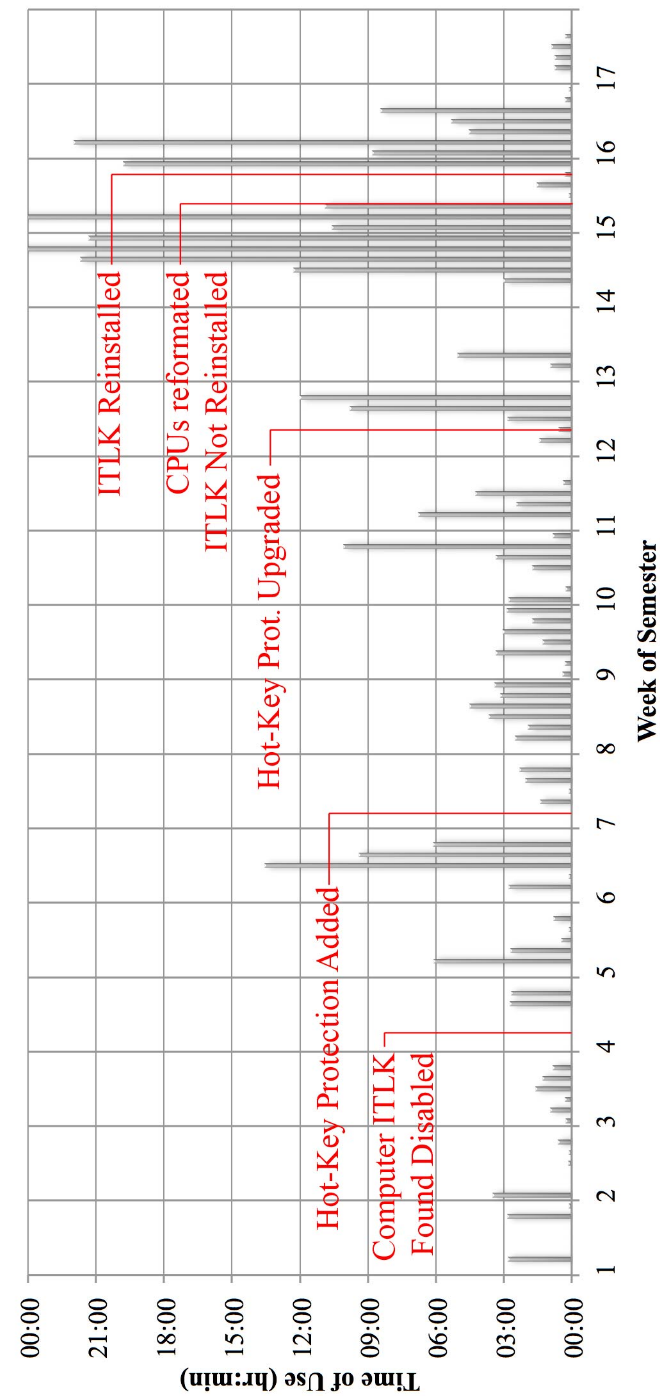


Figure 6.3: Daily Duration of Use for the 3D Printer Stations

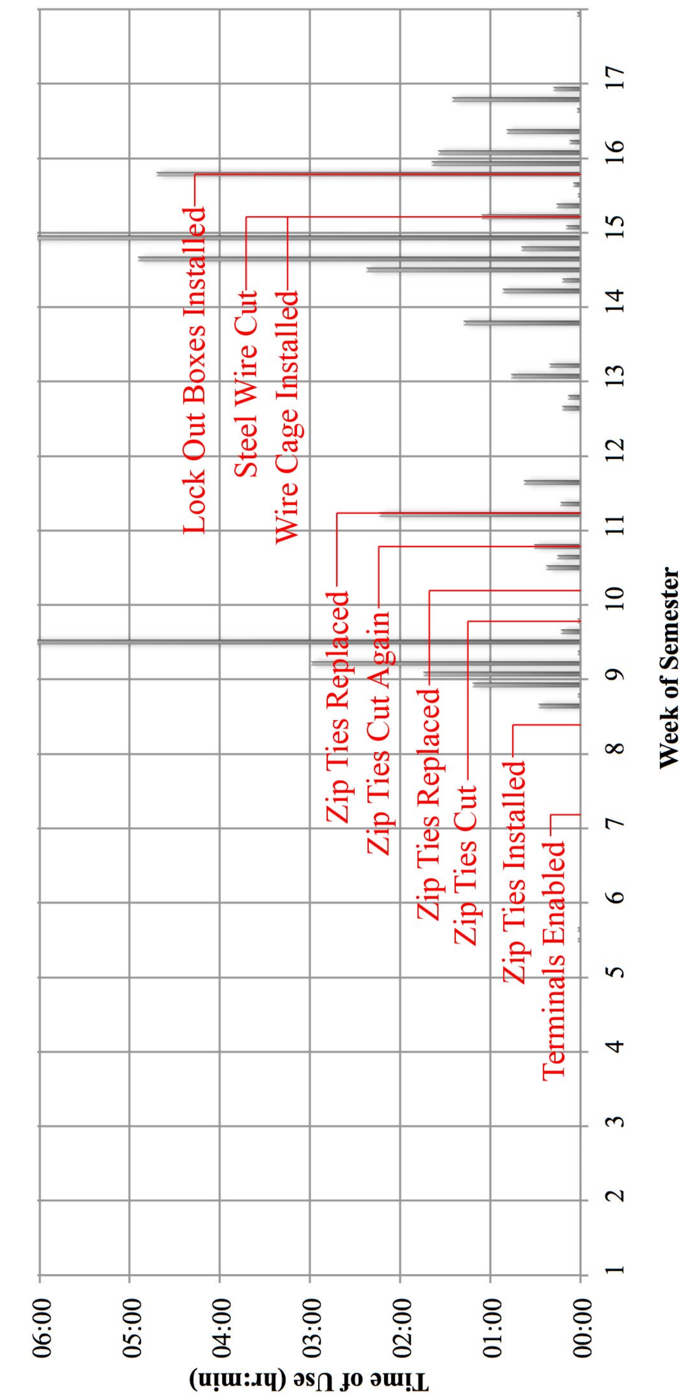


Figure 6.4: Daily Duration of Use for the Soldering Stations

6.4.1.3 Faculty

As noted in table 6.3, faculty were not considered to be a stakeholder who would make use or have interest in this attribute as described in chapter 4. There was no considerations for them in the initial design of this attribute. It was not discussed, as a concern from a faculty perspective, in the pre-semester interviews. No following observations or interviews indicated an association with this attribute for the faculty.

6.4.2 Centralized Database

A centralized database within the system stores all the pertinent information for the UTEM system to function. This includes information pertaining to the stations, the users, and the relationship between those stations and users, the permissions. Users may access it through the web interfaces to either check, edit, or add information to those data tables.

6.4.2.1 Staff

The database and its interfaces were designed for the staff to be able to store and track information pertinent to the organization of a makerspace and the access to its equipment. This was initially considered to be user information, permission statuses, and training information (See table 6.4). The staff members were made aware of the capabilities of the database and types of information they could use it for when the system was being implemented. They initially considered the database to be a useful centralized location for organizing and access user and permissions information as required.

This expectation was mainly addressed by S1 in our pre-semester interview. Prior to the implementation of the system, she had been tracking user, training, and permission information using spreadsheets. She saw the new database and user

Table 6.4: Attribute: Centralized Database

	Design Expectation	Stakeholder Expectation	Observed Reality	success
Staff	Provide centralized location to store and track information on users, permissions, and trainings	Track user information with the database	Tracked user information and gave feedback leading to better interfaces for that purpose	✓
		Track permissions via existing documentation and on the system for access control	Tracked permissions fully through the database	✓
		Track training via existing documentation	Maintained training through existing documentation	X
Student	Not considered for this iteration of the system	Not applicable	Requested means to know when equipment was being used [a]	+
Faculty	Check access statuses of students	Not a concern	Never checked	X

[a] The request could be serviced by this attribute with further development.

interfaces as a better way to track user information and be accessible by all staff members. At that time, they were still tracking training sign-ups and permissions through an excel document. She did not discuss in detail transitioning that information over to the database though, indicating it would remain in place. Permissions would have to be inputted into the database though for access control to function[7].

In those pre-semester interviews and early in the term, she made several recommendations leading to improved web interfaces such as a better web layout, new user sign up form, and improved permissions interfaces. Those improvements helped lead to a transition away from those excel documents as the semester progressed. Staff use the databases for keeping track of student information. Recommendations by the staff even lead to improved interfaces for searching user information and updating that information. Instead of then transferring that information to the excel documents, the database became the main repository for that information. Training organization and scheduling moved to the makerspace's website using a Wordpress plugin for event management.

Training information and their scheduling did remain in wordpress. There were several conversations about ways to accommodate this function through the database though. It has the internal structures to organize training information, but the front end interfaces were not fully developed. It is capable of online quizzes for lower barrier equipment or other types of automatic post-training test authentication. Development of these required greater input from the staff, specifically a determination of the actual content of those interfaces. The topic was brought up several times with S1 and S2 but staff never prioritized developing the necessary information for implementation. Instead, existing interfaces were expanded or developed upon to more easily update user permissions during a training.

[7]Error occurred with the voice recorder during the pre-semester interview so no direct quotes available. These statements, based on observations captured in notes during the interview, were confirmed with the participant when the recording error was found.

6.4.2.2 Students

The database information was intended to be a tool mainly for the staff. There was no predetermined design aspect of this attribute which considered the students as direct users. During interviews with the student groups though, they were asked about the UTEM system and how they thought it could better serve them. The most common request was some means for knowing when equipment was in use. This is a request that may be accommodated by this attribute.

6.4.2.3 Faculty

This attribute was supposed to also be able to provide information to the faculty. Specifically it was thought they may utilize it to check in on student access statuses for their courses. This was not of a concern to the faculty during the pre-semester interviews or throughout the semester. In post semester interviews, they admit to never have accessed the database for this information outside of the earlier interviews when I presented the interfaces to them.

6.4.3 Usage Data

One of the primary progenitors for the UTEM system was a desire for automated data collection on how these spaces are being used in real time. This attribute differs from the previous attribute in that while the database attribute focuses on static but malleable information in the system, the usage data is a growing log of archived information. This is where every user interaction with RFID terminal enabled equipment is captured and stored.

6.4.3.1 Staff

For the staff, this attribute expected to inform staff about user activities through logging equipment use events (See table 6.5). This information is accessible through the web interfaces in either a listed log with options for downloading as a spreadsheet or in a calendar view organized by user or by equipment. The listed log can export a csv formatted spreadsheet, intended for the staff to be able to take the information and utilize it for their own purposes. The visual representation of the data provides a calendar view for them to have an at-a-glance ability to look over the data.

The staff saw this attribute in a few different ways. The simplest to present is that of S2.

> I think [the UTEM system is] a safety feature... cause I'm not gonna do anything with any of the data. I'm just gonna enjoy that someone who's not trained on something can't have access to it so they can't hurt themselves.

With regard to the logged data itself, S2 noted "I don't know what I would do with it". This sentiment lasted throughout the semester both in conversations with him and observations of his use of the system. He did note that S1 "probably has some ideas". She and the faculty manager had similar expectations for how they would use that information.

In the pre-semester interview, S1 admitted interest for the data[8]. She was interested in using it to justify costs by having some quantitative information speaking to equipment use and the number of students making use of the facility. The faculty

[8] Faculty made no specific mention of the type of information that interested him was provided in that conversation, just referring to it as ”data” as opposed to ”usage log” or ”user information”. They had been briefed that the system logs each user interaction with the UTEM system through an RFID terminal.

Table 6.5: Attribute: Usage Data

	Design Expectation	Stakeholder Expectation	Observed Reality	success
Staff	Provide access to usage logs for more complex analysis	Employ the usage data to track users and equipment use for reporting and decision making, possibly informing material purchasing	Used usage log output mainly for discussion input on equipment use and traffic. Some use for external reports.	✓
	Provide visual representation of usage	Not applicable[a]	Used calendar usage view for at a glance usage analysis without further prompting by me and for awareness of usage outside of allowed hours	✓
Student	Not applicable	Not applicable	Requested means to see trends in equipment use to aid in planning	+
Faculty	Make pedagogical decisions based on just in time usage data	Check assumptions about team dynamics against the usage data	Never checked	X
		Check team claims of effort and activity against the usage data	Never checked	X

[a] Visual representation added after start of semester

manager had similar thoughts when asked about his thoughts on having user and equipment specific usage data:

> I think I got multiples perspectives on that, because obviously I'm overseeing kind of the space and the two people that are running the spaces, and so from that perspective I want to be able to show people at the management level, "this is an incredibly important space, all these, spaces, uh, we need to focus resources on people who use these kinds of spaces" so I want to show that there are a ton of people coming through, a lot of the equipment that we have down there that we've spent money on that we have in place that actually take resources and money to actually maintain and so forth, are the right tools

He speaks directly towards wanting this data for justification of the space, and by extension, the funding it cost and continues to require.

They also saw ways that the data will help them in the internal decision making of the space. S1 voiced interest in what the data may show in regard to usage trends, possibly effecting what sections they make available during what hours and what is placed in those spaces. The faculty manager echoed this sentiment, noting that that equipment trends could help inform staff scheduling. Directly following the last quote though, the faculty manager began discussing his perspective on the data's relevance to equipment decisions.

> and on the flip side maybe we can start to learn that some of the tools are not the right tools, you just talk about [the] 3D printers that are down there. We have three large 3D printers that if we had them all up and running and all under maintenance contracts it could easily be 15,000 dollars a year just on maintenance because maybe the data is showing us that we're not using the heavier printers

He makes clear the value he placed on such information by ending his overall response on the matter with “I think it’s very powerful to actually have real data.” in reference to both the ability to justify, with real data, internal decisions and departmental funding.

As the semester progressed, the staff reported that data was being used in the expected ways but not to an extent indicated in earlier conversations. S1 ended up being the primary user of the usage log data. She noted late in the semester that “it allows us to have discussions and discussions using real data as opposed to hypothetical data”. She continued that thought saying

> Because we make a lot of inferences I think on how the space is being used and what’s happening, that I don’t think are necessarily true, and I do this all the time, like you know I kind of try, I do the best that I can to kind of think about how I think the space is being used and student’s safety but I don’t actually know for sure. And so it’s nice to be able to kind of point to data that clearly indicates it

In the post semester interview, she commented that she still maintains an interest in the data, but she used the training data from the word press site to inform training procedures. She did pull data from the usage log and used it for reporting purposes, even at one point requesting I pull more specific information directly from the database for a report to the department. Her reasoning for not fully relying on the usage data was due to the issues with users bypassing the terminals and their final development coming later in the semester, leaving some of the data from earlier in the semester suspect; She did notice a similarity between the two sources though.

> Because I think that they ended up getting developed towards the end of this semester, and so the data logs I think were a little bit inaccurate, although they kind of followed the trend of what I was seeing,

She does remain hopeful about this attribute, now that the interlocks have been continually successful in their function

> And so I think the UTEM system will be useful this time, this semester kind of to see, one how many people do we have trained on the equipment, and then how many people are actually using it, and then compare pieces of equipment to each other

6.4.3.2 Students

The usage data collection was not designed for student interaction. Like the database attribute though, several students mentioned that, along with knowing when equipment is being used, it would be useful to know what the trends in use are to assist them in planning. Similar to the calendar view and the listed usage log, the usage data could be used to meet that unforeseen expectation.

6.4.3.3 Faculty

For the faculty, the design expectation for the usage data attribute was to provide information that may inform just in time pedagogical decisions. Both professors indicated an interest in having this information. The faculty manager compared the data to a resource like Slack which allowed him to observe some of the organizational chatter of the design teams. He saw value in seeing what their usage was like.

> It becomes harder for me to have those interactions with the students, to be able to say ”ey, I’m gonna sit it on a meeting of yours, so I can see how things are going” and things like that, so... going more to a model, trying it for the first time in 43, Using Slack, a way to sort of see what the conversation is like, even if we’re not physically present. And tied to that also is to see how the fabrication chatter is going, so if

> I can get a sense that I've had these students, those teams, re-using this equipment in that space, it's useful. So I like that, so we'll see how that shows up, I don't want it to be seen though as big brother watching out for them but I don't mind a little.

He also made note of an issue he seemed to deal with in the past, student excuses of not having enough time in the space. If a student tries to argue against an assessment claiming not enough time to work on the project, the usage data allows him to say "I can show you the open hours I can show you the amount of time you actually did avail yourself." to counter those arguments.

F2 also had some ideas for how they would use the data in her position as an instructor teaching the other section of ME43. She suggested it may help her make assumptions about team dynamics

> I would imagine there's gonna be some teams that gel, that appear to me to be working more smoothly together, and just appear to be more dedicated to the task than others...I might be able to check those assumptions that I'm making by looking at the data from who's in the machine shop doing what, so that might be one way I use it

She also makes reference to her interests as a learning scientist, noting the types of behavior she may be interested in. Specifically she suggests that, in this course, student participation in the prototyping process may be of interest to her.

> I imagine just because of my interests I'm gonna be, I imagine I might be noticing people who just seem disconnected from the prototyping experience, based on the way they're talking, reporting in class, right? ... I think I would be able to tell by what they're bringing in class who's not participating in the physical prototyping or the testing, you know, are there people in groups who are, seem to be only engaged in the

> like, desktop research and the writing, and I would like to try to push those people to participate in the prototyping and the physical testing, and so I can imagine the database being a helpful source of information to confirm whether or not it's true that they're really not being like the shop people on the team.

Neither followed through on these interests, admitting that it was not something they had taken up the habit of considering. Proceeding interviews in the semester showed they still maintained an interest in the data, albeit not as specifically. When updates to the tools were presented, they received them positively and noted an interest. They did not report continuing to use those tools though.

6.4.4 Help Button

The help and photo buttons serve as attributes enabling the user to make simple and quick requests of the UTEM system through pushing a button. The help button puts in a request for help in two stages. A single press emails you help information and a second press contacts a staff member that help is needed at that station. This feature was used once by a student and not one in ME43.

6.4.4.1 Staff

The Help Button was included with expectations for all stakeholders in mind. For the staff, this attribute would enable them to better provide assistance at stations which are not in line of site (See table 6.6). With stations in separate rooms within the building, this allows them to offer assistance in those spaces as required. S1 and S2 saw the benefit of this feature in their pre-semester interviews. The former noted it would allow for them to be notified in the case of major issues quickly or give a direct method for students locked out and unaware of the procedures to contact the right people. The latter provided a similar sentiment when we interviewed in his office. “so the thing about that is, if I’m in the shop they should just grab me, if I’m not in the shop that’s perfect, cause like my phone’s been in [my office with me] all day.”

Interestingly, the students did not use the feature so they were never able to respond. There was one instance of a student using the feature but they were previously unaware of the feature. They saw a button labeled ’HELP’ and assumed it had something to do with getting assistance. This lack of use and general unawareness of its function was possibly an issue of the trainings, where staff gave no explanation of this attribute nor did they note it as a system attribute during tours, or one of labeling, although the one student who used it referenced the label as why he did so.

6.4.4.2 Students

This attribute was designed to be noticeable, using an oversized labeled button, to provide students with assistance in the makerspace, particularly when in an area without staff readily available. All primary students research participants were asked about the feature. They reported not being aware of it. As stated above, the one student who did use it was not aware, just assumed the button marked ’HELP’ had something to do with getting help. That student was also not one of the primary student research participants.

6.4.4.3 Faculty

This design attribute logs to the listed usage log to provide information about when and how often students request help. These data were expected to be informative for the faculty, that they may find it of interest in their lesson planning and other pedagogical decisions. Prior to the semester’s start, they agreed, like the staff, that this information could prove useful but after its introduction into the interview, they

Table 6.6: Attribute: Help Button

	Design Expectation	Stakeholder Expectation	Observed Reality	success
Staff	Enable better responsiveness to students in need of help at any station	Respond to students requesting help	Did not promote the feature in trainings or tours	X
			Feature was not used	X
	Provide log of help requests as part of the usage log	Use information along with the other usage data	Feature was not used	X
Student	Provide resources for assistance upon first press. Contact staff for assistance on the second press.	Not applicable	Reported not knowing about the feature or its function	X
Faculty	Provide log of help requests by their students to inform planning	Thought to be a nice-to-have for consideration in lesson plans	Feature was not used	X

then it into conversation about the the usage data, not considering separate to that information. Since they did not make use of the usage data though, it is unlikely they would have made use of the help request data.

6.4.5 Photo Button

The second button on the RFID terminals is the photo button, labeled 'SNAP'. The photo button on camera enabled terminals requests a photo be taken of the workspace, emailed to the user, and stored in the spaces repository. The story of this attribute runs very similar to that of its neighbor on the terminal's face.

6.4.5.1 Staff

The photo button was included to enable images of student work to be easily captured 6.7. For the staff, the design expected that these images could serve as visual feedback of student work in the space, possibly providing information about space use or an option for promotional items. The staff members, specifically S1, thought this feature would be useful, particularly for adding adding examples to reports and for promotion.

Like the help button, those expectations of use were not observed. Again, the students did not take advantage of the feature so no repository of images was created. In the post semester interviews, the staff admitted that they neglected mentioning the feature in the trainings or during tours.

6.4.5.2 Students

The inclusion of the 'SNAP' button was intended to enable students to take photos of their in-process work to aide in the documentation of their projects. Students also reported not knowing about this feature. A few noted that there is no real time

Table 6.7: Attribute: Photo Button

	Design Expectation	Stakeholder Expectation	Observed Reality	success
Staff	Collect and provide images of student work for visual feedback of space use and promotion	Use the collected images of in-process work for reporting and promotion	Did not promote the feature in trainings or introduction to the system	X
			Feature not used so could not utilize images	-
Student	Take photos of in-process work pieces for documenting the project	Not applicable	Reported not knowing about the feature	X
			Concerns over no real-time view	X
			Used cellphones to take picture of work pieces, typically off-equipment	X
Faculty	Faculty would not have direct access to repository	Thought to be a nice-to-have time lapse of ME43 projects for final reports	No images were taken using the feature	X
		Considered it to at least serve as a documentation reminder	No images were taken for	X

view of the camera feed, so you don't know how the image will look beforehand. That if the workstation had a feed from the camera, they would have been more likely to be aware of it and use it. I did observe students taking pictures of their work throughout the semester but typically using their personal devices to do so.

6.4.5.3 Faculty

The faculty were not intended as direct users of this attribute due to no access to the photo repository. They noted that it would be good to have better documentation of student projects in ME43 and that it could be useful to have a reminder about documentation as part of the process. The attribute was not discussed in the post-semester interviews since no photos existed to trigger discussion.

6.4.6 Summary

The first three attributes, those having to do with the motivating factors of safety and data acquisition, had some positive effects on stakeholder's experiences within the makerspace. For the staff, each of these provided some value. It provided them with a level of safety as well as the reassurance of having those barriers in place. Data was used to inform their operation of the makerspace. Students enjoyed greater access to the makerspace and the equipment due to the inclusion of the safety interlocks. Faculty saw value in the database and logged usage attributes but did not utilize them. This was not because they didn't see utility in those features but rather due to its inability to easily integrate into their daily routine. See table 6.8 on the next page for a summary of this assessment.

The help button and photo button attributes were not taken up. Staff and faculty saw value but they were never used. It was not referenced in trainings and not promoted at all. Students reported not even knowing about the features, let alone their function. Only one student used the help button, but admits to not knowing

Table 6.8: The UTEM System Assessment

		Stakeholders		
		Staff	Student	Faculty
User Level Attributes	Automatic equipment safety interlock	✓	✓	+
	A centralized database of system information	✓		o
	Logged usage tracking data and visualizations	✓		o
	help button on each station terminal	o	o	o
	photo button on each station terminal	o	o	o

✓ Met design expectations
- Negatively effected stakeholder
+ No design expectation but saw positive value to attribute
o Did not meet design expectation, neutral effect on stakeholder

its function and made an assumption that it would provide him some form of help. Since these features were not used, that usage information did not make it into any of the logs, so no determination could be made on how that information would inform decisions either managerial or pedagogical. The existence of the features did not have a negative impact on any stakeholder experience though.

Responses to the attributes ranged from positive to neutral. None had a negative effect on a stakeholder's experience within the makerspace. Even students who took umbrage with the safety interlock features, saw more benefits of access due to the freedoms granted by staff due to the safety interlocks. Based on this feedback from the pilot study, I consider the performance of the attributes of the safety interlock, centralized database, and logged usage tracking to be more successful then not. They did not perform perfectly in line with design expectations but enough so to consider them successful for this iteration of the design. The help button and snap button did not meet design expectations, therefore they are not successful in their performance. Their neutral effect though means they can not be considered failed attributes. They need further use before a true decision can be made and likely redesign of some aspect of the UTEM system to encourage that use to enable that eventual assessment.

Part III

Socio-technical Vignettes

I include the following vignettes as a narrative of the stakeholder experiences and to illustrate the social interactions of the UTEM system. They highlight the individual arcs experienced by stakeholders within this academic makerspace. Connections to the UTEM system are emphasized though. I describe the individual experiences of the staff participants, one about general student experiences as well as one focusing on students bypassing the system, and a final stakeholder vignette about the faculty's arc. These are informed by observations made during the pilot test and the stakeholder interview responses. I also attempt to provide context about the makerspace itself through the experience of walking through the space and its story of change in a short time.

Chapter 7

The Makerspace

The makerspace was central to the understanding of the UTEM system's function. It served as the implementation site for the pilot test of the study and the socio-cultural setting that complete the UTEM system. It is the setting where all of the stakeholders interacted with my technology and continue to do so. It is a complex environment consisting of many rooms, lots of equipment, and dozens of users passing through daily. A first hand understanding of the space is not fully necessary in order to understand the social contexts. In that regard it is likely similar to many other makerspaces in that it involves a community which has adopted it as a place of their own due to its availability of resources. I think a more detailed understanding will help with the following stakeholder vignettes though and this chapter intends to serve that purpose.

Let me preface these makerspace vignettes by saying they are primarily experiential, informed by my experiences within the space to provide some context and shared experience for the reader before the continue on to vignettes about stakeholder experiences. It is purely an exercise in description and informed by my personal experiences of the makerspace. This reiterates some earlier descriptions but adds more detail to build a setting and foundation for the narrative of the following vignettes.

7.1 Entering the Space

The makerspace lives within an old brick building that provides the mechanical engineering department with lab and office space. It sits on a part of campus considered off-campus, or at the very least out of the way, by the general population of students. Even mechanical engineering students think of this building, which is less than 100 yards away from the building that houses the majority of their classes and the main office for their department, as ”down the hill”, separating it from the primary campus.

The building is two stories tall and long. It could best be described as a very utilitarian styled central block with wings. A long hallway runs its length on both floors with the main entrance and lobby in the center of the building. It is essentially split into two parts although not very disconnected due to the small, architecturally inornate lobby. When entering through that lobby, you'll see signs made from acrylic laser cut in the makerspace direct you to the various rooms.

If you the path in figure 7.1 on the following page, you'll first walk past projects built within the makerspaces, currently artifacts from Fall 2016 courses. The first door on the right, practically at the end of the hall, enters into a loading dock zone. This space has been co-opted as spillover for the makerspace, set aside for any wood working to keep sawdust out of the main fabrication area and includes some shelves for project storage. There is a long carpenter's bench to the left along the loading area wall for students to work with wood. Storage shelves sit to the right of the entrance, primarily for specific course projects due to limited availability. This area also serves as an entryway to the fabrication area and the testing lab.

Those two parts of the makerspace become unlocked when the makerspace co-

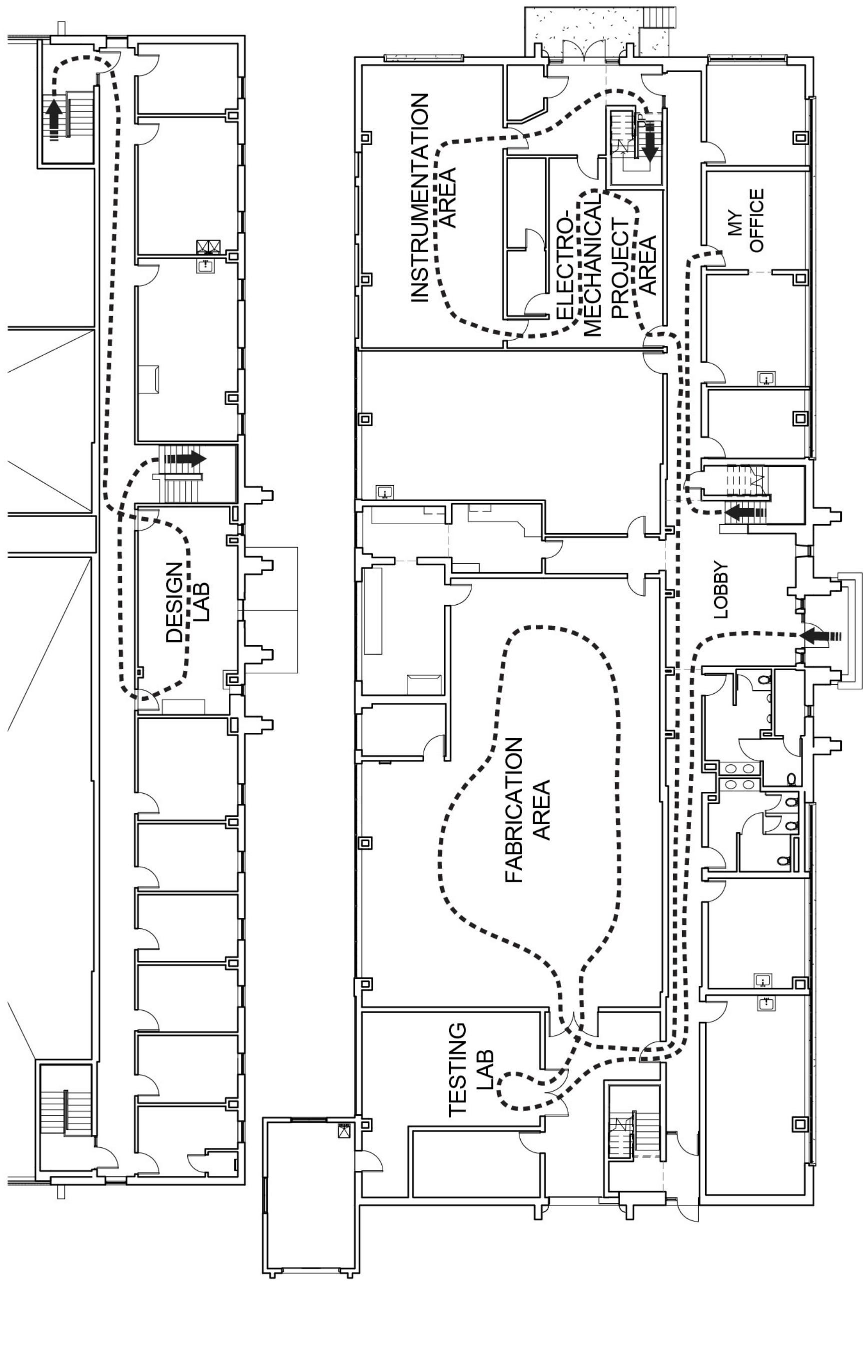


Figure 7.1: Daily Walk Through the Makerspace

ordinator comes in at 9 and are locked again when the fabrication supervisor leaves at 6. The testing lab contains equipment for mechanical testing of parts, a tensile tester and a drop tower straight across from the entrance. To the right stand two industry scale 3D printers. Other tools for measuring and calibration are organized into tool chests and computers stations are set up for using this higher level equipment. This equipment requires some added permission and staff oversight to use. This part of the space is more specialized than most, serving specific testing requirements and providing finer 3D prints when the makerspace's other resources are insufficient. The room is clean, pure white, and filled with expensive equipment; it very much feel like a lab space.

The fabrication area contrasts that starkly. The floor is primarily green but painted red under the larger, industrial machines. This helps separate the zones within the space. You enter into the hand tools zone, named due its primary content. There is a computer station for people to sign-up in the UTEM system and to get themselves an RFID. A UTEM system sign-in RFID terminal is also located there. More project racks are near the entry way and the laser cutter and cnc router stations are to the right. Three large butcher block tables with tool chests as legs serve as work tables and span the green painted floor in front of you. These provide users work surfaces and contain a wide range of hand tools. Outlets descend from the ceiling above each bench.

If you look up past those outlets, you'll see a sign of rules and regulations delineating the start of the power tools zone. Another larger workbench sits in the middle of a horseshoe of industrial power upright tools: drill presses, band saws, jump shears, chop saw, and more. Yellow signs above the equipment inform you about the tools use and provide safety warnings. This area is separated since you could really hurt yourself if misusing any of this equipment.

The final zone in the fabrication area is the precision machining zone. It is the portion of the area with the floor painted red. Large mills and lathes, both cnc and manual, are kept in this area. They are under key-lock control by the fabrication supervisor. Staff separated these equipment and decided on key-lock level control since these machines could kill you if not used properly. There is a logical organization to this area with regards to tool capability as well as safety concern.

If you return to the hallway and walk towards the other side of the building, you come to a room with a large window looking into the hallway. This is the electro-mechanical project area. Rolling racks of spare parts are tucked away until needed. Cabinets and bins contain a variety of prototyping supplies. Two tables for collaboration are against the wall opposite the mirror with a large selection of electrical components separated into small parts cabinets. To the right of the doorway are two soldering stations, outfitted with a wide assortment of soldering supplies and organized to a professional quality. Effort was clearly put into making the room useful yet interesting with vinyl labels on all walls and an PCB inspired design on one wall. Below that visual touch sits the cnc wire-bender and small part router. Organization is again showcased as a priority through the clearly defined layout and thoughtful labeling.

Passing through the electro-mechanical project takes you to instrumentation area. This room is accessible by students at most hours but serves as classroom a few times a week. There are 7 lab benches with computers. These face a white-board with projector classroom front. In the rear of the room are racks of various testing and instrumentation hardware. It is the result of a few decades worth of accumulated National Instruments data acquisition hardware. Theses resources have been maintained to enable students better means to develop and examine their projects.

If you pass through the instrumentation lab and head upstairs, the design lab is half way down the hall. They set this up with a few tables surrounded by chairs. Along one wall are white boards with a projection screen installed on another. There is a large assortment of writing utensils supplied to the room and the tables have rolls of paper for sketching out ideas. Two desktop 3D printers with dedicated computers sit on one wall of the space. The emphasis of this room is collaborative design, with seating around sketching spaces and walls for sharing and combining ideas.

I am typically one of the first people to enter the building, arriving around 8:00 AM. It has been open though since 6AM, automatically unlocked every Monday through Friday. The building has remained quiet in that time though. Other than the occasional student swinging in to pick up a print that had run overnight or setting up one to run all day, student activity during those early hours doesn't really occur until late in the semester with deadlines looming. The full-time staff and other faculty in the building start arriving around the same time as I do. The undergraduate staff for the makerspace typically begin coverage between 9 or 10. Other students begin making use of this resource, coming in and out at all hours of the day.

The students make great use of the makerspace. I typically see most use of the fabrication area in the afternoons, with students typically on the laser cutters or at the various tables finishing parts and assembling their projects. Some work spills out into the loading dock area, even pushed out if it involves woodworking. Staff putter around this area, helping whenever needed and trying to keep up with cleanliness and organization. The fabrication supervisor is a strong presence in the room, working on projects for the makerspace and students, performing general maintenance and cleaning, as well as keeping an eye out for students who seem to need help or a little extra guidance on the machines. He never prohibits students from working, once trained, but does keep a watchful eye and offer help if he thinks it's necessary:

> S2: I don't want someone thinking, which is a problem with a lot of the students around here is that they're a little too smart for their own good, and they think they know what they're doing when they don't have the experience to do everything as confidently as they're doing it.

Classes meet throughout the week in the Instrumentation Area. When not being used as such, students are on the computers or using the tables to meet and work on their projects. The back of that room quickly became a storage area for projects, as with a lot of the other free space within the building. These crowd the various rooms but students attempt to minimize their footprint, but more often to protect their work:

> we've had a lot of people just constantly building in here, so there's always kind of projects laying around the different rooms, so we've had some issues with like cleanliness, but they haven't been as bad as I thought they were, so mostly students kind of push their projects off to the side cause I think they don't want to get them broken.

These projects move around the makerspace as students progress through the various stages of their development. Larger scale fabrication of parts and assemblies happening within the Fabrication Area, assembling them as a team on the tables in the Instrumentation Area, working on the electronics in the Electro-Mechanical Project Area. Their location dependent on project needs and availability of surface area. The design lab has some presence at most hours of the day. At times, large groups crowd the space to work on homework, designing their projects, or troubleshoot ideas. At others, there is a single person waiting just watching their 3D print slowly form.

Cleanliness and organization is an issue for the makerspace, especially as the semester progressed. Through general use, items moved throughout their various rooms. Occasionally resources made their way from one room to another but the staff would do their best to make sure items regularly returned to their home. Overall, these issue do not get to the point were safety or usefulness were compromised. It has all the indicators of a well-organized space with clear signage throughout, organizational hardware in every space, dedicated stations, and labels everywhere. It also has all the indicators of a well-used space with tools left out on tables, projects in every nook and cranny, and the sounds of machines running or students working throughout the day.

7.2 Recent Changes

The difference between this makerspace and its prior incarnation within the department are quite drastic. This makerspace consists of several rooms in the building that served different purposes less than a year prior. Even just the physical changes to those areas themselves are extreme.

The simplest conversion would be the design lab. This was a lock-and-key access controlled conference room for the department, simply a standard long table setup. The projector and white-boards are all that remain now. The layout and resources of the room have completely changed, drastically altering its intent and utility. The testing lab had been space used by one of the extracurricular design challenge teams, filled with their prototypes and tools. The team moved to another location, the room was cleaned out, repainted, and the testing tools and industrial 3D printers moved in.

The instrumentation area was previously two rooms. One served as a small overflow storage area with some of the faculty's tools and experimental setups. Another extracurricular group inhabited the larger of the two. It was functionally similar to the electro-mechanical project area, supplied primarily for robotics projects. That room was the antithesis to all the organization and planning that had gone into its current incarnation though. Those faculty moved to new lab spaces in other buildings, taking their equipment. That group was removed, having finally lost the space in part due to the remodel but the state of it did not help. The wall between the rooms was knocked down and work tables and storage racks were moved in. Computer stations installed at each table as well as a projector and white boards. It quickly became a purpose built engineering lab based classroom with the instrumentation to support student work.

The electro-mechanical project area was another room previously a faculty lab space. That also moved to a new building, freeing up the room to be claimed by the makerspace. The room was cleaned out, repainted, and filled with the cornucopia of tools and supplies it now is.

The fabrication area was the department's machine shop. It was run by the previous fabrication supervisor and focused primarily on industrial grade equipment. It was set up to accommodate teaching a class of students general machining on the mill and lathe. Much of the same equipment has remained in that space although the majority of duplicate tools have been removed to make room for the work benches and rapid prototyping resources. Access was limited by the fabrication supervisor and to the hours he was there, to the extent that if he took a personal day then the space would not be open to students.

The largest change in the departments mentality towards these resources would be their outlook on access and availability. Prior to this year, safety was maintained through a policy of 'no':

> F1: Versus the old way of doing things was basically you would say "no, you can't come here," and as a utility to saying "no", you'd know your facility would be up and running, you would actually have your tools in good order, you'd have a really good safety record, that's cause

> no one's using it.

In previous years, tool access was highly limited. Students would more often draft parts and have them machined by the fabrication supervisor than do it on their own. This was something the department wanted to change, to provide students more experience fabrication on their own:

> F1: One of the motivations for shifting from the way the shop was oriented away from traditional metal removal with just mill and lathe work and be able to have students, in a safe way, be able to much more fully use that space. So we could have more students in there, we can actually have them do more of their own fabrication, instead of being overly concerned about them being in hazardous situations

The inherent restrictions within the old layout and policies created a burden on students. The machine shop, where the majority of machining equipment and hand tools resided, would regularly not be open, effecting student ability to plan use or requiring them to wait another day for parts that they needed for their coursework. This had driven students to work on projects in their dorms or apartments, a known issue among the faculty:

> F1: [Now] work was being done in a facility that was much more geared toward that work, rather than them working in a dorm or on a table somewhere else, so that was a huge thing,

These issues drove the expansion of the physically available student fabrication space as well as increased accessibility. The staff members now responsible for these resources wanted to expand access to fabrication resources and space to provide a better learning environment for the students:

> F1: You know our environment here was always so restrictive in terms of how many people could use the facility and our ability to train and

> I knew that we could break free of that because obviously other places can actually accommodate more things and more activities and um, allow uh students to use it more

Within a year, this facility transitioned from one which suffered a reputation for being unwelcome and inaccessible to becoming one of the primary places for mechanical engineering students to meet and work any day of the week. This time span falls within the tenure of the students within ME43. They have experienced the prior machine shop and its policy of 'no'. This year will have been the first of their college career where they have comparatively unrestricted access to these types of resources for both their personal projects and their coursework, where they've been given this amount of trust around these types of tools.

Chapter 8

Staff

I choose to describe the three staff participants experiences individually in this chapter. Each experienced the UTEM system differently, through the lens of their individual responsibilities regarding the makerspace as well as their differing prioritizing of their values due to those roles. Therefore, their stories are more simply told individually then trying to organize them into a exemplar faculty experience.

8.1 The Faculty Manager

The faculty manager was one of the driving forces for change within the makerspace. He has been with the department for many years and had interacted with the machine shop as both a researcher needing to use it for development and an instructor needing it to service his curriculum. When the opportunity to make changes came about, he took on that responsibility and pushed for this new incarnation as an open-access academic makerspace. He wanted students to really experience and use the space instead of outsourcing the work to the staff, as had been the previous practice:

> we basically act as facilitators there in the shop so that is a departure

> from what we've done in the past...be able to have students, in a safe way, be able to much more fully use that space, so we could have more students in there, we can actually have them do more of their own fabrication.

One of the underlying influences in his motivations, as generous as they are for the student access, is continually considering "in a safe way" in each of their policy actions.

Every consideration and privilege he put forth included that caveat:

> the level of trust we have is gonna be greater but I hope the level of safety is gonna be as good if not better.

Upon taking up the reigns, he made moves to improve access and steer the space away from purely traditional machining. He hired a makerspace coordinator and fabrication supervisor similarly interested in establishing a risk adverse environment but one that still enables students to utilize it fully. There was high encouragement for inclusion of a wide range of desktop tools, typical makerspace style hardware more about easy adoption and rapid prototyping than increasing precision capabilities. His experience with many of the ME courses in the past as well as leading two in the upcoming fall semester ensured their consideration in the updates to the makerspace.

The nature of his position is not day-to-day management of the makerspace though. Those responsibilities are passed along to the other staff members. He remains more of a thought leader within the space, having say over the overall themes and mentalities that influence the policies of the makerspace, and a large voice in what is put into the space. He was a major voice in adopting the UTEM system, although not the first. The system was brought to him by the department head and by his makerspace coordinator but his approval was needed before installation. It was not a difficult sell. He saw value in collecting data in the space, recognizing its need in justifying and expanding any budgets as well as in enabling them to make better decisions about the space. He saw that things like material, equipment needs, and even operational hours would benefit from hard data on the day-to-day use of the makerspace:

> so I want to show that there are a ton of people coming through, the equipment that we have down there that we've spent money on... are the right tools, and on the flip side maybe we can start to learn that maybe some of the tools are not the right tools...that is a ton of money, that shows up on the radar screen... that's the kind of thing I would need to be able to present data to other people and make the argument that it is necessary...
>
> I want to be able to show donors and other people that I want to approach and say "I need a hundred thousand dollars for a new x", um, I want to be able to justify why it's x and why we need that kind of money, and to show them for the money you already gave me, here's the kind of uses that we actually have out of this, other than just artifacts which I could show. I think it's very powerful to actually have real data.
>
> So I'd love to see, also, from an operational point of view, what hours should we keep? Should [S2] come in at 10 am and leave at 6 pm or should he come in at 6 am and leave at 4 pm or 3 pm, right? So... uh, I think I know what the result's gonna be in the morning hours, but I'm really interested in seeing what happens between the hours of say, 3 pm and 10 pm, um... how dominant is sports versus other activities, and maybe we're not gonna hit the mark quite right so we can actually use the data to actually help us...

Although he saw great use in the data, part of that was overridden by that initial desire to provide student's more trust in using the space. Concerns over perceptions of "big brother sitting on your shoulder at all times" limited the implementation of the UTEM system to high use equipment not isolated within various zones. For example, the power equipment in the yellow zone of the fabrication room is not connected to the UTEM system. Items with safety and misuse concerns, such as the 3d printers and the laser cutter, were connected to the UTEM system.

Once the semester began, his role fully transferred to a more managerial presence. His involvement in the operation of the space became second to his other faculty responsibilities. Activities within were typically communicated to him through his staff as needed and his office location and instruction of ME43 ample opportunity for observation of the makerspace and its happenings. Most interactions with his own staff were due to his role as an instructor in the department rather than as their manager though. Even our first interview during the semester ended up being purely about his faculty role as the instructor of ME43.

This is not to say he was unaware of some of the operations going on in the building. The popularity of the makerspace does not escape his notice. The shear amount of projects being created under the walls he finds impressive, but it does bring up a variety of considerations:

> I see a lot of things that are really positives around the building, around the facilities, and then some negatives that I worry about, so I worry about how many people we have using the facility, and I don't know what the tipping point is of having too many people actually using it.

He views it as both a good thing and something of a concern. He was no longer recognizing all of the students since the space was attracting students from outside the department. He worries about organization, cleanliness, availability of space, materials, and other concerns of a well-used environment. These problems persist throughout the semester but remain manageable due to the efforts of his staff.

When we next met for an interview, two instances really showcased some of his worries about the makerspace. I first talked with him about some of the bypass issues, specifically the bypassing of the soldering irons[1]. This activity concerned him enough that he brought up installing cameras in the area to aide in monitoring usage, a drastic turn from his previous concerns of too much oversight.

> F1: I'll make note of who's down there, well one thing, way around this is a security system where you can actually see people, right, I hate to get to that point but that, I think would help, would it not?
>
> Interviewer: Yeah... I know we talked about this over the summer, you didn't want to get to the big brother level,... but I do think that might have some deterrence to it, but I also don't know what the student's feelings would be on that
>
> FM: Well, I mean I could see some interesting survey coming up, you should ask questions like would you prefer to have no access to soldering irons, or have access to soldering and other tools, but there be a video system in place, that could record your usage of it, I think I know the response to that, everyone would say that they would be okay with the video system.

Other ideas such as requiring university ID swipe access to the doors of the electromechanical project area and the design lab 24/7 instead of allowing them to remain open. I informed him of the incoming lock-out boxes, a professional grade solution to these types of bypass attempts. He was slightly assuaged by this but continued to hypothesize about what students may do, about what steps they might take or lines they may cross in pursuit of their needs.

[1] This interview occurred later in the day I had ordered lockout boxes to address this issue.

When presented with the new calendar view of use events, he recognized the utility of the ability to examine usage at-a-glance, particularly since the tool made him aware of an all-nighter which occurred the night before. Seeing how this feature provided a quick way to identify unauthorized events triggered in him ideas of how it could help reinforce policy beyond what he had previously seemed comfortable with. His first example was a blanket lockout where interlocks or door locks would not disengage during off-hours. He also speculated that this may just drive students to more drastic measures though, putting forth questions like would they cut the power cable and reattach it or wondering at what point do students break a window to access equipment?

Those thoughts were purely speculative though and remained within that conversation, he made no follow up or pursuit of these changes or sought some of these ideas integrated into the UTEM system. He continued to provide students with the level of trust they had been given all semester, although aware of how some had pushed the limits of that trust. Day-to-day operations remained with the staff and he continued along very focused on his instructor role, particularly since the end of the semester and major project due dates were approaching.

He continued to make note of operational items, those that worked and those that needed improvement throughout the semester:

> I thought our fabrication went very well compared to a year ago, I could see room for improvement but the students don't realize, and I don't know what kind of feedback you'd get from them. Just the access and the ability to use [electro-mechanical project area], the [instrumentation area] behind it, and we just organically saw that they were building their projects in there and just allowed that. That wasn't the intent but that was a huge benefit to the students even though they may not have articulated it that way, cause I know they met up there for a lot of

> fabrication and work was being done in a facility that was much more geared toward that work rather than them working in a dorm or on a table somewhere else, so that was a huge thing.

With the semester completed, he can now articulate some of those observations and work with his staff towards addressing many. He hopes to re-examine hours to better accommodate student schedules with some either late night or weekend coverage of the spaces. He sees a large amount of low-precision work and wants to find ways to encourage more mill and lathe work. He asks questions about the culture and in how do you develop these behaviors and a respect for the makerspace and the policies which enable it to remain free and open for the students? That line of questioning is partially fueled by student attempts to bypass the system:

> I was disappointed in, as you know, there's a relatively simple experiment of just putting soldering irons on our RFID and then just actively going around the safeties, multiple times, disappointed with the people who did that and then the people who participated without saying anything... so that's a problem for a couple of reasons, one is, I'm trying to keep the safety people happy, and so us laying out that plan of having our RFID and saying you need a certain level of training on paper, it looks great, but I don't know how to respond to them if they find out then that people in the crunch time cut it, so they actually use, so we'll have to figure that out cause I do not want to just ban soldering irons and I do not just want to say it has to be supervised time, so that actually is a big concern of mine, cause I would have loved if it had worked great, I would have loved to go to different equipment, on that as well, I don't know what the next level of I would go to, but I don't know if we'll go to a drill press, but I would think about a drill press

He feels the UTEM system is partially a failed experiment for that first half of the semester semester due to the bypassing issues. He does recognize the improvements made to the system towards what he had hoped it would be. It needs more time before he is 100% comfortable with the performance of the UTEM system, but he does see usefulness in it.

> Interviewer: did you ever make use of the usage logs I showed you or the visualization stuff that...
>
> F1: I did not. I would do it now... I think one of the reasons was I was thinking it was tainted, right cause we had these outliers where [someone has] their RFID on there for twelve hours and he's not there for twelve hours, other people are piggy-backing off of that, so it was hard to know what I'm gonna glean from that information, but I like the idea, and so if I actually knew we had a really robust system and I can know how many people are logging in after midnight, how long people typically are on the machine and it actually is robust, I think I would have that minimum as a report at the end that we would look at.

Staff has recommended its expansion to other equipment and he has approved that, such as the higher fidelity 3D printers. Follow through is with them now and future upgrades to the technology may also improve his use of it as well. He specifically recommended event triggered emails to staff or weekly overview emails to put the data right under their noses, giving those upgrades a high priority in the next version.

His interaction with the UTEM system during the fall semester was that of a short views, quick glances through the wide focus of his conversations with staff mainly. His positioning in the makerspace allowed him to observe much of the activity, examining things up close but not always in great detail. He relied on his staff to bring salient details to him but continually made observations of his own. His dual role within the space pulled him away from directly addressing some of the management responsibilities, delegating that to his staff, so he experienced the UTEM system as more of an outside observer of its function. Interactions with it were few and data was primarily presented to him, reactions to it were within those moments. His overall acceptance of the system though comes from a broader view of the technology, his understanding of its actual use, and in how its potential aligns with his desires for the makerspace.

8.2 The Fabrication Supervisor

The fabrication supervisor joined the department's staff in January of 2016, taking over the responsibilities of the recently retired shop manager. He came from the realm of industrial design, having studied it in college and then working in a design firm after that. His most recent job had been as a fabricator in the aerospace industry though. He gives his official responsibilities as being a student resources to help with fabricating for class projects, training students to build on their own, and maintaining the tools and machines. He hopes to pass along some of his design knowledge and experience to the students as he works with them in the makerspace, possibly teaching some design more formally at some point.

One of his primary concerns though is maintaining a safe environment and minimizing students' risk of injury. A strong influence to that drive is his past shop experiences:

> I've gotten hurt before, I've gone to the hospital for stitches and things like that but at the company I worked for our motto was like, "safety third." It was not a safe place to work, people got hurt there.

He easily could have taken up with policies of 'no' and 'off-limits' to save students from similar experiences, a not atypical response in risk-management of similar resources and one the prior incarnation of the shop used extensively. Not once in my experience with him did he even suggest that route though. Even having faced events that would drive others in that direction, he approached this issue more positively than most. He maintained an interest in enabling students' making but never ignoring the realities:

> We had an injury last semester where someone came in at midnight and brought their own drill, didn't clamp down the piece well enough and ... they had to get stitches and it was nasty, it sucked, but it was at midnight, they shouldn't have been here. I can't lose sleep over that but I'm just waiting on the day where it does happen ... I'm gonna beat myself up about it but I'm gonna have to come back in the next day and keep doing my job

In spite of that worry, he remains comfortable in the shop. The preparation they put into the makerspace and all of the concern given to policy enables that ease:

> Being able to set up a shop and be in charge of the safety and everything and all the documentation that's going to the safety office and everything, makes me feel really comfortable in the shop because I know that this shop is run a lot better than any other shop that I have worked in before, which is good, and I think your system is just gonna help us keep everyone in line.

That was the lens he took for seeing the utility of the UTEM system, focused on the safety and reassurance it provides. He saw the RFID terminals as safety aides helping him in creating a safe environment for students through their ability to block misuse:

> I mean having, having these kind of gates that stop people from, who aren't supposed to be doing something from doing something, you know, is gonna help a lot...

He saw this tool for that one attribute, not concerning himself with the data or other features since those were not of his professional concern. In the scope of his responsibilities, he never saw how that information would be useful for him:

> I think it's a safety feature, any data that it can give to you or anyone else, to me it's a safety thing, cause I'm not gonna do anything with any of the data. I'm just gonna enjoy that someone who's not trained on something can't have access to it so they can't hurt themselves

His behavior reflected this outlook. The majority of his time was spent in the fabrication area: assisting students with parts fabrication, training them on the various tools, and maintaining the equipment. Students would continually ask for his help and he was very aware of that time, trying to be efficient in assisting them so they could get their work done and he could move onto helping the next student.

As part of this assistance efficiency, he developed a habit of leaving his RFID tag on the laser cutter's RFID terminal, "ninety percent of the time that thing's on there, it's not me cutting" This was simply a time saving matter for him. Students would complain about the terminal not recognizing their RFID but he never had issue with it. Instead of trouble shooting the issue or seeking out why their RFID wasn't working, the simplest solution was to place his RFID there so they could get to cutting. He was around to monitor who used the laser cutter so he didn't mind the students using his RFID to access the equipment. This resulted in large chunks of time in the system showing him using the equipment, averaging 4 hours 51 minutes per use for the semester.

The effect this would have on the data, not tracking exactly who used the equipment or for how long they were there, did not concern him in those moments:

> I know that from your data, you'll see that I've been on it most of the days, all the time, and that's just because my card's been on it. It's

> mainly to allow students to work cause they've forgot their RFID, it doesn't work, or either this or that.

That accommodation was never provided for other equipment though. He never simply unlocked the larger, more dangerous equipment while he was in the room to save the time of a student asking him before using it. His RFID never rested for hours on equipment that was not directly within his ability to monitor by sight. He simply continually experienced the makerspace through the lens of wanting to efficiently help students while still prioritizing safety. He took precautions towards that end and created conveniences where he believed risk was not increased.

There does come a point where this behavior stopped though. This change did not come from a great concern for lost usage information or the system registering his presence instead of those actually using the laser cutter. The motivation remained the same but the circumstances altered the best solution:

> The system just became reliable later in the semester. All the upgrades and the new sign-in station with it's own computer made it so the students' RFIDs worked wore often and if they didn't or they forgot them, we had a station were they could replace it on their own. So I didn't have to worry about my RFID, the students could get back to work without needing a lot of help or guidance, and I could help people who needed actual fabrication assistance.

Upgrades to the UTEM system increased reliability in his view. Students were no longer bringing to him issues of failed attempts to access with their RFID. For the scenario where students had forgotten theirs, the dedication of a computer station for general user interface with the UTEM system made it easy for students to get a new RFID tag and created a space for him to direct students to help themselves. His value of the UTEM system did not change, the way in which the makerspace utilized it and its increase in robustness just made those convenience moves no longer necessary in his mind.

8.3 The Makerspace Coordinator

The makerspace coordinator holds the most day-to-day responsibilities in the department's makerspace. She manages the various rooms which make up the makerspace as well as the undergraduate staff that helps to maintain and provide assistance in those spaces. She trouble shoots machines when they go down; orders new parts, tools, or materials as required; and acts as one of the point people for dealing with student issues. These responsibilities are shared with the fabrication supervisor as well as delegated to her undergraduate staff when possible but these are the items she must concern herself with as part of her position. That breadth of responsibilities forces her to view the makerspace through a multi-faceted lens; to see all parts of it, how they interact, and how those interactions move towards the desired function of the makerspace.

She joined the staff part-time in January of 2016, transitioning to full-time in June. She spent that spring and summer re-evaluating the layout and policies of the makerspace, working with the faculty manager and fabrication supervisor to create an environment more welcome to student use as a resource in the development and realization of their engineering solutions and other projects. Trainings were established for the various resources within the makerspace and she created a website where students could get information about the makerspace and sign up for those trainings. She kept track of these using that website, excel sheets, checklists, as well as copying the information to the UTEM system.

She was one of the biggest advocates for adoption of the UTEM system. Her experiences throughout the country examining and studying makerspaces had given her some insight into the power of such a tool:

> Every time I mention [the UTEM system] to somebody, they always get really excited, so I'm going down to New York City to visit NYU's like tandem engineering school, and their makerspace there, and I contacted the woman who runs the space and gave her a link to our website, and her reply back to me was "oh great, I'd love to have you visit, hey by the way I see this RFID system, can you tell me more about it?"...
> I think there's just so many people out there with this problem, and everybody's trying to come up with a solution and there's no solution there and I think we have the best solution that I've ever seen.

On top of her research experience with makerspaces, she came into this position with experience establishing and running makerspaces. This informed a lot of her planning for the makerspace and the types of problems she expected to occur. Part of that preparation was the installation of the UTEM system. Not only did she desire the data it provides but she also credits it with allowing greater access to equipment and areas:

> The fact that we can keep this room open and keep the downstairs room open to students is purely because [the UTEM system] exists. I think that there would be people who would be very uncomfortable with letting students use the space and operate the machines, not necessarily also hurting themselves but also hurting the machine, but just knowing that there is some kind of tracking system in place is very helpful.

Once the semester began, her preparations went into effect. Trainings began for a wide range of students, mainly those taking engineering courses that intended to use the makerspace for their assignments. As word of the space began to expand, her staff and she began noticing an influx of students from other schools in the university. The increased traffic created a surprisingly busy semester. Maintaining and stocking the equipment took up time. The constant influx of people made cleanliness more of an issue for the staff. They put a lot of effort into signage and advertising but students continually asked questions whose answers were thought to be clearly posted. These became an issue they would continually try to address. One of the more surprising aspects for her was enforcement:

> We're having to put a lot more, kind of, enforcement in place than, and having to be much more strict, than I would have thought, so I think that was a kind of surprise for me.

She was aware of many of the issues that pushed the limits of the makerspace policies. This surprisingly came not only from her own observations or data in the UTEM system but also through the students:

> Yeah, what I also think too is interesting is that when students do these things, like they don't think that they did anything wrong, like they'll tell their friends, they'll tell me, they'll be like oh yeah I just cut it.

Students admit violations easily, which came across as an oddity to her but in some ways was helpful for her job. She similarly finds out about issues in with the machines or supplies through the students version of 'telephone' which eventually finds it way to her or a staff member. She handles these issues and the violations as they come to her attention.

In spite of some of the unforeseen issues, she continuously worked on and improved the space. Updating their setup and policies in response to the experience the semester provided. That effort led to many of our conversations throughout the semester. We shared many discussions about how students were engaging with the UTEM system and ways in which it could be upgraded. Some of them were policy and setup changes, a greater emphasis on use of the RFIDs:

> I think training-wise and with the RFID's, I want to create multiple RFID stations or a couple more RFID stations so we have one in the shop, one in the instrumentation lab, and then possibly one here, where we have extra RFID cards and an area where people can kind of connect them to their account ... and I think, I want to try and do a big push for next semester, is to really make it mandatory RFID's, we've been a little bit flexible this semester since we've been kind of doing repair work on the machines and [the UTEM system], so sometimes [the RFID terminal] isn't always on.

She made several efforts to ease how students interacted with the UTEM system, following through on a dedicated station.

Other conversations involved recommendations that led to better interfaces for students and staff. These also involved some upgrades to the RFID terminals, hammering out bugs discovered by students. Her involvement was integral to the UTEM system's increase in robustness:

> So the system is working and working better and better and we're using it more and more.

These enabled her and her staff to better utilize the system and put more trust into the data.

The UTEM system allowed her to have conversations reinforced by real data. She used the various web interfaces to collate information to bring to her discussions with the rest of the staff:

> What's nice is that, what's great with this system is that, it allows us to have discussions and discussions using real data as opposed to hypothetical data, because we make a lot of inferences I think on how

> the space is being used and what's happening, that I don't think are necessarily true.

This allowed for confirmation of their observations about equipment use. Previously they could only infer from observation and material use that a station was being used:

> It's nice for you to track how much, what tool is being used, cause again I make, I believe that the laser cutter is getting used the most, you know, out of tools, but it's nice to be able to actually have data that does show that that's the case.

They suspected that students had been using the space in off-hours, staying later than they were allowed. Data points in the use events confirmed those suspicions:

> A lot of times when [we] have discussions, a lot of it is just things that we think, aren't sure so we think the students are using the equipment [outside of allowed hours] and but we're not really sure, and so it's amazing to kind of have the data that spells it out clearly, yes there is a student that tagged in and used the soldering irons at 2am, you know from like 2 to 2:30.

The UTEM system aided her in viewing trends in the space and discussing them. Issues earlier in the semester caused some of the data to be viewed as suspect for hard influence on their policy at the time but it did have influence on their discussion and action.

The makerspace coordinator examined the makerspace through a multi-faceted lens, trying to keep track of a wide range of concerns. Some of those facets focused on the UTEM system, informing her about usage in the space and providing means to verify their observations. For this semester, those lenses were filtered through an awareness of early issues with students bypassing the system and faults, eventually addressed, with the system itself. Those filters have since been removed. She is eager to see what the data will provide going forward:

> I think the RFID system will be useful this time, this semester kind of to see how many people do we have trained on the equipment, and then how many people are actually using it, and then compare pieces of equipment to each other.

8.4 Faculty Lenses

The faculty each valued the UTEM system differently, focused through their responsibilities within the makerspace and in how it fit within their priorities. The makerspace coordinator made the grandest use of the system. She used the data in discussions with the staff and confirming her observations. It informed her awareness of safety as well as provided the safety needed for her to push for certain accommodations within the makerspace. The fabrication supervisor concerned himself primarily with safe use of the equipment, concerning the students, and used the UTEM system as a tool to help with that concern. He saw it's utility purely from a safety viewpoint. The faculty manager held multiple roles and their priorities adjusted throughout the semester. He mainly interacted with the system's data second hand, when any information of interest would be brought to him in discussion with his staff.

Their stories were separated due to these differences but they highlight the major aspects of the UTEM system. The technology provided them with reassurances of safety, enough that policy decisions were effected by it. They used system data, with an asterisk set upon it, to inform their operational conversations. The extent to which the information or reassurance influenced the makerspace is indeterminable at this point and future study would have to be implemented to answer those questions. These vignettes simply highlight an impact to the social interaction between the makerspace and the staff due to their utilization of the UTEM system.

Chapter 9

Faculty

The faculty made little use of the UTEM system. They saw utility in the various features when they presented to them during interviews. The constraints and limitations of a semester leading one of the larger, more involved courses of the department though made passive adoption of a new technology difficult. They were already juggling many changes and other new experiences in co-teaching this course.

9.1 A Faculty Experience

Senior capstone design was instructed by two faculty members in fall of 2016, each leading their own section. One had many years experience teaching the course. The other was doing so for their first time. They made the decision to update the course, working together to institute changes that would take advantages of their combined experience and the department's resources to improve student experiences in this defining course of their senior year.

They worked during the summer of 2016 to update the curriculum to address past issues and incorporate their desires into the course. The major changes of the makerspace enabled some of changes. Students would be expected to do more fabrication now that the resources and policy enabled them to rapid prototype and access other tools. Local clients were selected from within the university and surrounding community. This provided predetermined, focused problems with accessible information sources as well as a flavor of community engagement and accountability:

> F1: So last year I went with a theme and allowed the students to kind of flesh out their own problem that they might tackle within that theme, and that was good for some students but surprisingly didn't work well with many students where they didn't know how to focus and were very tentative.

> F2: and so then another idea was, you know can I find clients just within the Tufts community so we feel like we're designing for, you know, our neighbors, our colleagues, our organizations here at Tufts?

They also decided to move their instruction away from a lecturer role and into a more facilitator of ideation and design development at times. They planned time to take the students out of the classroom and use the makerspace as meeting place occasionally:

> F1: Then during the semester their class is when we basically act as facilitators there in the shop using it. That is a departure from what we've done in the past... because we have that resource, I feel good about not having traditional lectures for every class and then have you down there [to] use it.

New research and design process tools were integrated into the lessons. Their collaboration over the summer set them on a path to keep both sessions on the same page in the fall:

> F1: We're very much on the same page in terms of our overall structure it comes in down this white board here, we decided to go with a series

> of concepts and sort of class goals based on this research that [F2] had found that I actually really liked... so I think that's really conducive to doing that um, so just, just that her pushing those, that card stack and me taking a good look at it, I think we're on the same page and it looks like a really good framework for us.

They entered the semester with a variety of expectations as any instructor would. This was informed by their experience in other courses, their collaboration, as well as this being one of the major courses of students' undergraduate careers. They understood students would put in a lot of their time although maybe more so when deadlines approach.:

> F2: I expect them to be in there working on their projects independently... I do think this is the kind of course where they're gonna be, like ten hours a week outside of class, on the project, maybe not at the beginning but, at the end for sure, I don't know that they'll be in the shop, I don't think everyone from every team will be in the shop for ten hours a week.

Another hope for the two faculty members was that the makerspace would turn out to be a useful resource for their students. Their curriculum planned for their students to be making use of it:

> F1: I hope that means that students will actually see this as a locus of resources so therefore it will be much more heavily used.

They were experimenting with using Slack as a communications resource. They thought it would help their students organize but also provide them another window into how the design teams are working together and what their project statuses were.

The UTEM system also had potential for use. They had concerns about students engaging in the prototyping process. They saw it as a way of passively seeing that students were working on the projects and a spot check to see if all students were all engaging with the fabrication resources they had considered in their curriculum planning:

> F1: So if I can get a sense that I've had these students, those teams, re-using this equipment in that space, it's useful. So I like that, so we'll see how that shows up, I don't want it to be seen though as big brother watching out for them but I don't mind a little.
>
> —
>
> F2: I would like to try to push those people to participate in the prototyping and the physical testing, and so I can imagine the database being a helpful source of information to confirm whether or not it's true that they're really not being like the shop people on the team.

Classes began and the started instructing the students of the Senior Capstone Design Course. They pushed forward with the curriculum, curious about how these many intersecting changes would work out. Some habitual lecturing styles had to be suppressed to move into a more facilitator role for this class:

> F1: I definitely have been doing things differently during class which is to, [I] see the struggles of trying to get out of the mode of just lecturing at and more giving some instruction and then trying to facilitate.

They kept up to date on students progress through reportings in class and monitoring the message feeds in Slack. The semester began as expected, without much issue in getting the students separated into design teams and started upon a path to developing their solutions.

They maintained contact with one another to make sure things are progressing similarly between their sections, meeting not as often as during the summer but trading emails back and forth. They established habits of trying to gauge student participation outside of class time through the occasional walks throughout the makerspace to see what activity could be observed:

> F1: I'm doing more of that now so I'm wandering to the instrumentation lab, helping one team but I can see what other people are working on at the same time, and I'll start making late night runs down there.
>
> —
>
> F2: When I come in in the morning, I look to see what's going on in the shop, what's put out, you know... it's a huge difference in terms of the number of students that are around in the past week than previous, in an ideal situation I would spend more time in the shop...

Students took advantage of this availability often. The instructors stayed responsive to those issues and arising needs of student design teams, using those observations in their feedback.

Late in the semester they were presented with the UTEM system's calendar view. They saw some value in this feature, in being able to glance and see who was in the space when. They did not know how they would use it but did conceptually appreciate it:

> F1: This is a great display, I like this, I'd like to have access to this.

They did note that a focused display, one with a longer time span and specific to their students would be preferably. They were given the tool anyways, another item in their arsenal to keep tabs on the course. Walks and Slack remained their primary means, outside of class time and submitted assignments, to gain insight into student progress and engagement with the prototyping process.

They were aware of an increase in activity as the dates for design review and final design presentations approached. Extended hours, including some made available on Saturdays, in the fabrication area were organized and supervised by the faculty manager. They wanted to give the ME43 students more opportunities to produce their project components using those resources, noticing and getting word that the hours of that space conflicted with many other courses. Course time was also given over to prototyping and team meetings with the instructors in these late stages. They saw their students through the design reviews and the final presentations for the projects two weeks later, and through the completion of their senior capstone design course.

Reflecting on the semester, they saw many positives from their changes and confirmations of their expectations with evidence from the students:

> F2:The in-class practice of design process techniques were valuable to the students based on what they wrote in their course evaluations, what they said to me orally and what they wrote on the various written reflections I had them do in class

This year, evaluations were more concrete than in the past. Their collaboration produces metrics to give weight and consistency to their assessments, a difficult task with many disparate groups and projects needing to be fairly compared:

> F1: and this is actually, this semester is the most quantitative we've been able to get to, and it's [F2]'s influence, where she was helping work out what metric we'd use and we'd really specified okay: here are the key deliverables, here's the percentage, it includes participation which specifically said slack usage, so when I assigned grades, I had justification for knocking grades down for participation.

Soon after turning in those grades, ideas began forming for the next iteration of this course.

They want to address issue of students waiting until late in the semester to prototype as well as not all students gaining experience with fabrication. Ideas quickly formed to address some of these issues in future courses while others need more thought to address:

> F2: One thing I'm gonna do is give them some money to spend that they can only spend in the first like two weeks of working on their project. I want them to fail more and sooner... I also witness you know, some students being there from teams and other students not at all, and so I have not figured out what the action is to take, but I need to do something, so that there's some individual requirement to learn something about fabrication

In spite of having some areas they would like to work on, they feel successful in their changes. They incorporated new design concepts and a greater expectation of fabrication. All of the student groups ended up with prototypes. They were able to follow the groups' activity through coursework and classes but also through their online conversations and their own observations within the makerspace. The UTEM system was seen as a potentially useful tool for these purposes as well but never made it into their daily activity routines:

> F2: So it just wasn't something that, it didn't become a habit, it didn't become something that I had like quick in my short-term memory how to do, it didn't occur to me to do.

Value was seen in the moments it was in front of them but with all of the other thoughts, planned activities, and observations they were making, it did not make it's way into becoming a habitually checked resource.

Chapter 10

Students

This chapter contains two vignettes about student experiences within the makerspace. These are generalized around two contexts. The first showcases the experiences of the students of ME43. This is informed by interviews with the participant design team members from the pilot study. The second describes students bypassing the UTEM system. This was informed by discussion with the staff, my personal experiences dealing with those bypasses, and an interview with a student caught in the act.

10.1 Taking Senior Capstone Design

The senior capstone design course(ME43) is a requirement for senior mechanical engineers. It is one of the more well-known courses within the major, students having seen previous seniors presenting their projects and those projects displayed throughout the department. It is also one of two mandatory courses were students are required to fabricate their own project for this class of students. Unless they had previously taken a project-based elective or taken the opportunity for fabrication through personal endeavors, extracurricular projects, or through job opportunities, these were the only two courses where they had hands on fabrication experience.

It takes place in the fall semester of their senior year. Their prior required curricular experience with fabrication had been limited to a design and fabrication course their sophomore year which took place in the former machine shop of the mechanical engineering department. There they had learned how to use the tools including the mill and the lathe.

This semester was unique though since it coincided with the inaugural semester of the department's new makerspace. They now had access to new resources and a far greater level of accessibility than was their previous experience:

> WT1: Until this year you weren't allowed to go into [the machine shop] unless you had a specific project or a specific class, so
>
> WT2: Yeah, so not very much access...
>
> WT3: Like I've never gone into there unless we're with our class and we go in, like we did in ME1 we had to go in a few times right? with [prior supervisor], other than that, we didn't go in there at all
>
> —
>
> MT1: But yeah when we took ME1 we were only allowed in the shop if you were taking ME1 or if you're in senior design, and in ME1 you only worked on your one project
>
> MT2: Our one project, part of it had it to be 3D printed and laser cut, and we just like submitted our files to the TA and they printed it for us so it wasn't super hands on in terms of being in the shop or in the maker space

With that new accessibility of a entirely reborn space, they had to deal with new staff and new policies, entering into this space with a clean slate. They couldn't just start using the mills and lathes. There had been no documentation about who had been trained and with the new equipment and policies, there was a staff decision to make a blanket reset of permissions. This required all students to pursue training for any equipment they thought they would need for their senior design projects.

With most students taking full course loads, involved in extracurriculars, having part-time jobs or internships, and other constraints on their time, the pressures of senior year took hold of many students. Time quickly became one of their main concerns, one not alleviated by the training or re-training requirements:

> WT2: Maybe like, going forward that can be something that the freshman classes all do where everyone goes in during class time, cause it's, like I always, I see the emails it's like okay laser cutting at this time it's like well I already have a class then or practice or something else and I can't go.
> WT3: Again with the, the scheduling with when the shop is open, it's like really hard to find time to go to trainings and so it was really cool that we get to do some in class, but nobody finished, and so I don't, it's just there's a really small amount of people trained like nobody is...
> WT2: Still like no one's certified, not to complain about something else, but...

Project selection took place early in the semester, design teams established by the 3rd week of classes. The instructors allowed class time in that third week to meet in the makerspace to give the students a head start on trainings. Some of the students followed through with these trainings but many did not:

> I got shop trained in laser cut training before we even split into groups, and once I realized everybody else had all the other training, it wasn't really necessary.

An economy of time began to form for the students. Once they formed teams, agreements were made on who would be trained on what, distributing expertise which had a time cost to it among the group. This was their attempts to save individuals time while still having coverage of many of the fabrication options for their team:

> Interviewer: Was there any planning on who got trained on what or did you just get trained?
>
> MT12: There was a little forethought put into it that like at least, if at least one of us has it, then we can do what we wanted and then it was usually like if another person was free then they'd do the training together
>
> —
>
> Interviewer: Why did you get trained on the laser as opposed to like 3D printer or something like that?
>
> 3DW2: It just was more valuable to our project.

Value was placed on the trainings based on the time required to gain access and its utility for the project. Students avoided the mill and lathe training due to the several hours they cost to complete and use was limited to under the fabrication supervisor's supervision. The milk tag groups both had originally planned to use steel components for their precision and surface roughness but ended up only using the 3D printers and laser cutter because of the lower time costs for access.

Several students ended up not getting trained on any of the makerspace equipment that required that training. They figured that since the expertise was already covered, they could save themselves the time it would take to finish the trainings:

> MT2 student: I think [other group members] were planning to finish their job training, but just like never did, and then by the time we were prototyping realized they didn't have to, and so they didn't want to like waste time.
>
> —

> 3DW student: I think it was just in essence of time...it was kind of a cost-benefit analysis like what I had time to do.
>
> —
>
> WT student: I think it was just time constraints, we didn't want to take the time to do a training.
>
> —
>
> MT1 student: I took so many classes that I didn't have the time to get certified, so, I was actually not fully certified on anything, but I was able to use obviously all the other tools that you didn't need to be certified for.

In each of the participant teams, at least two members did not finish their training on any of the fabrication resources, limiting their capability in prototyping to hand tools and assembly.

The first half of the semester was spent on idea development for their projects and design of their solution prototypes. As more time was spent working on their project, developing a solution for their client, they spent more time in the makerspace. The students' laid claim onto it as a space of their own, collaborating throughout on their various efforts. They did not just work on their ME43 projects in this environment but used it for other class projects as well as to meet for homework and studying. They became very comfortable in this new resource:

> WT1: I never really spent much time in [the makerspace] besides for [sophomore level machining course], and then this year I was suddenly comfortable coming all the time and just coming in here and taking things out and working on projects.
>
> —
>
> WT2: I think it's definitely improved. The last time I really spent time in [the makerspace] was a little bit for ME1, but even that was only

> just during the labs, and then a little bit of time in Bray for ME18, but that was just using the labview, but I think this semester the senior class basically lived in there. We felt like it was just such a perfect spot for us to all like meet and work.

They shirked old practices of working in dorms and apartments, drawn to the makerspace purpose built for their curricular needs. The students even recognized that to be the case:

> WT2: Just like a space where the group can meet, like freshman year we had a project where my group had to take apart an electric jar opener and we did it in the south common room with like random things we found in our dorm room, so just like a place where you can meet up and work on something just that's a little more appropriate

They would even pass by other computer labs and spaces set up for group work to make their way down the hill to meet in the makerspace. The available tools were the admitted draw, the resources to communicate and work on ideas in several mediums made it a preferred location for many students.

Actual fabrication of their designs started to ramp up as the major deadlines for deliverables approached. The last two weeks before their final presentations was crunch time for the students, their race to have a functioning prototype to display to the department. For many, it was long hours and hard work. That time they couldn't make earlier in the semester due to their many conflicts was found or created in those last three weeks (See Figure 10.1 on page 173 for station use of the participant design teams).

For some teams, this process was more stressful though. According to the data, all of manufacturing of parts was limited to 2 people per team. Larger conflicts occurred when team members could do little more than stand by and wait for parts to be finished, unable to contribute to the manufacturing process since they did not expend the time for training earlier:

> the other people in our group didn't seek out doing [trainings] on their own time, and that actually became a little bit of an issue later on in the, cause like they're, we would say "okay we're gonna go to Bray and like build this assembly and manufacture things," and then there would be people who are like sitting around and can't do anything because they aren't trained.

This simply added to the pressure on those students, some upset because of the uneven workload falling on them and other regretting being unable to help more due to the circumstances their economy of time created.

Final presentations came and went. Students submitted their final reports for the senior capstone design course. They finished up the fall and entered their final semester.

The experience of ME43 for them was enjoyable but stressful. All enjoyed the access they had to the makerspace in comparison to their previous semester. Those who hadn't been trained, even where that became an issue, liked the idea of getting trained but only planned to if they needed to. Time was still a concern for many of the students.

Students interacted with the UTEM system throughout the semester. They held an awareness of it, having interacted with the RFID terminals to access fabrication equipment. It had even found its way into their vernacular with phrases like "Are you RFID certified?" coming up in conversation between students beginning work on an assignment. It created a barrier to access that along with the established policies led students to undertake trainings. Time concerns were exasperated by these requirements though. The nature of the UTEM system limited students who did not spend that time, so team members could not even set them up to do the

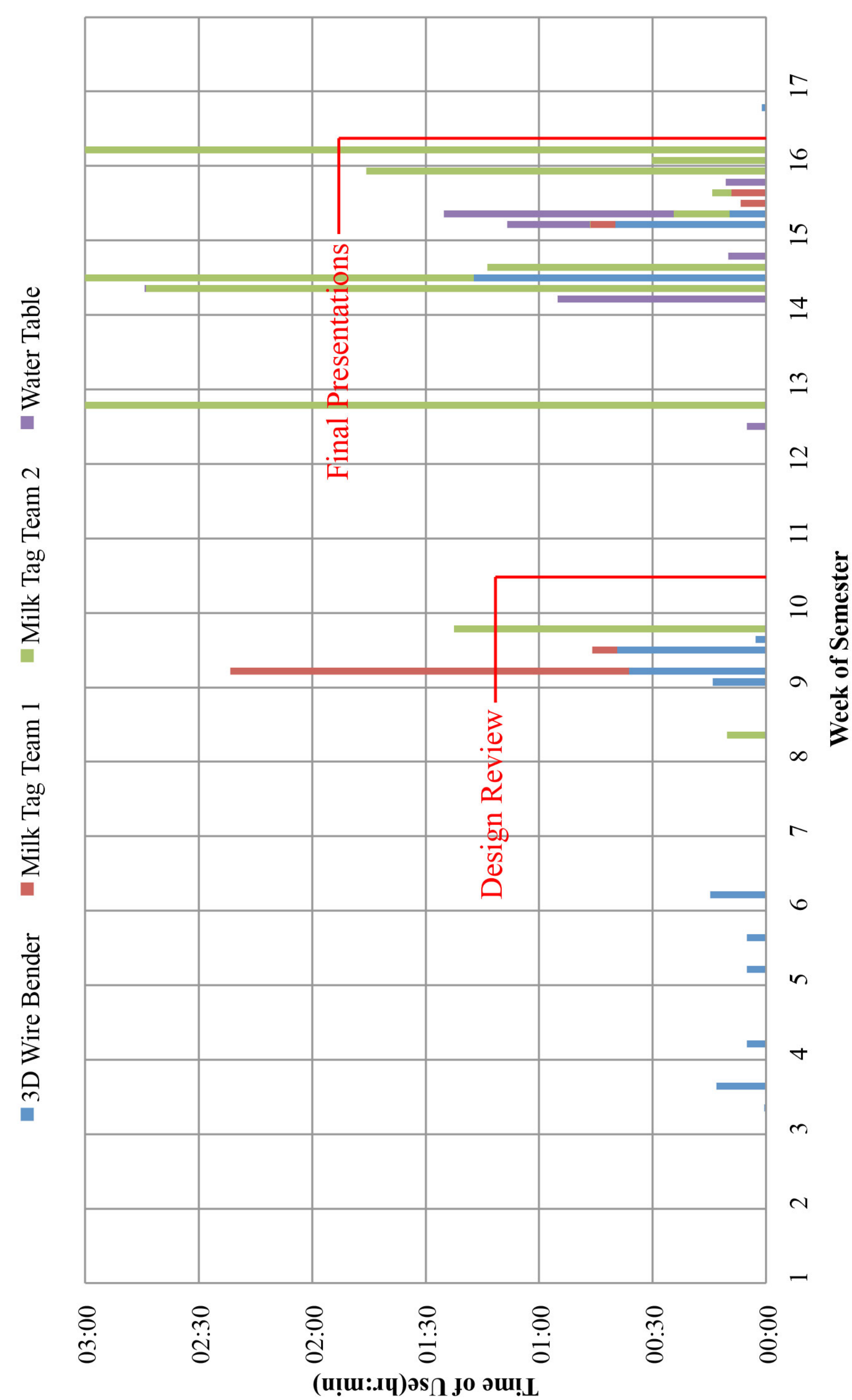


Figure 10.1: Daily Use of Each Design Team

work and get them to help with part fabrication. Earlier in the semester though, those interlock capabilities were tested by unapproved students.

10.2 Bypassing the system

Early during the pilot study, bypassing of the system was an issue of great concern. That mischief went against the values and priorities of the staff who had put in significant effort to provide open-access to the users. The initial design didn't consider certain methods that students could bypass certain interlocks. The computer interlocks could be closed out through a feature of the operating system that allowed closing of applications through a hot-key combination. Someone would close out the application and that enabled every user after them to access the equipment without resorting to using the RFID terminal. Some students weren't even aware they were bypassing the system when using the 3D printers.

This issue was discovered and addressed. Once the mechanism of bypass was discovered, the code was upgraded to account for that method. Students could no longer bypass the interlocks for the 3D printers. The power interlocks on the soldering stations though took longer to find a solution for.

The power interlocks have an outlet on a control circuit, enabling power when permission is granted. The initial setup was a simple connection, plugging the equipment into the RFID terminal and maintaining the connection on the honor system. Students unplugged the soldering irons and reconnecting them into the wall outlets to use them, not an unexpected action. The zip-ties were intended as a temporary until a more permanent solution could be enacted. They were first installed to simply serve as a reminder of the policy requirements, an added step to make the user question their action. These were cut at the start of the first weekend in place so students could bypass the RFID terminal and use the soldering irons.

Eventually, these were replaced with a 16 gauge steel wire, specifically selected for its gauge requiring a more heavy duty tool than was available at the soldering stations. The same day the steel wire cages were installed, a student went to another workstation that had a pair of heavy duty wire cutters tethered to it, cut that tether, and used them to cut the steel wire restraint locking the soldering irons plug to the safety interlocks outlet.

That bypass of the interlock occurred 15 minutes after the staff had gone to lunch. The student who did had an assignment due the next day and needed the soldering station for his project. He didn't know how to get trained on or who to ask about getting approved for the soldering stations. He also remembered having used the soldering stations when the zip-ties had been cut. So he cut the steel wire and used the soldering station.

> Interviewer: So how often have you guys been cutting these things to use them, why don't you just get the training or get permission?
>
> Student: Where, where do you even go about getting the training?
>
> Interviewer: Well, [Staff], the website, anyone
>
> Student: Cause no one's in right now and like, I need the solder for robotics...
>
> Interviewer: Okay, how many times have you come in to use [the soldering stations] and it's already been cut?
>
> Student: A couple times
>
> Interviewer: Couple times? Okay

Others had done this and he was under a time constraint. Staff was not available in the time that he was there. He made a solution without hesitation:

> Interviewer: Okay, so there's no one here, how much hesitation did you have?

> Student: Uh, almost none

This action was not done out of malice but a perceived necessity. This class was put in a unique position of dealing with the transition year for the makerspace, an issue they had some understanding of:

> Student: I mean but like, it should also be less of an issue, theoretically, after our year, if that makes sense... Because we kind of just got like stuck halfway

Staff have noted this issue as well. When working on a course project, students tend to develop a fixation on that.

> Makerspace Coordinator: the way I think about students is that I always try to remind myself that they kind of have tunnel vision when they're working on a project, as that they're only concerned about getting the project done, and they'll do whatever they need to do to get that project done...

That fixation drives them and simply must be considered in designing a learning environment for students as well as any resources within.

Part IV

Implications

I observed many activities within the pilot study that did not speak to focus of the study or simply highlighted shortcomings of the system. Many of these just put a spotlight on future directions for this system and accented potential ways it could be developed or identified different ways in which it could be useful. Several recommendations were made by stakeholders on how to use this system. Data was collected that could serve some stakeholders although they never made use of it. Upgrades can be developed to help those connections between the stakeholders and meaningful data be made. The shear amount of information collected may inform other works and even be of interest to new stakeholder groups. Those implications are presented in this part.

Chapter 11

Discussion

My primary goal in the pilot study was to observe the UTEM system in situ, to see it through the interactions it has with the users in its installed configuration, both direct and indirect. Those observations were used to qualitatively determine if it added value to an academic makerspaces. I believe the assessment shows that, overall, the user level design features of the UTEM system improve stakeholder experiences within this academic makerspace. The system itself is robust enough to function reliably within such a space and provides users with simple and useful interfaces. This pilot study also highlighted the potential of the UTEM system and displayed several implications of its future use, not only in the next technical steps, but also in its benefits and utility for education using these academic makerspaces and their policy/management.

11.1 Technical

Although the UTEM system showed a level of success in its performance, there are clear ways that the technology could be improved, most suggested or inspired by the stakeholders. Some user-level attributes were not used. These are notable since they were also identified as useful by the very stakeholders who never took up their use. One example was the calender view of the usage data. It was successful for the S1 in that she would occasionally examine it but it wasn't used on a regular basis. In an interview with F1, he was introduced to the usage calender view feature and it included an event that started at 4:20AM, clearly a violation of the hours of the makerspace . That event had occurred the night prior and without that information, he would have been unaware that students had spent the entire night in the building.

That single bit of data, a single use seen at a glance on the calendar view interface, gave him insight into how the makerspace was being used and he made note of discussing that use with the rest of the staff. It immediately spoke to his concerns as the faculty manager and he made action on it. He also acknowledged the value in the feature and showed interest in what more it could show him, even ending that portion of the interview with "[This calender view] is a great display, I like this, now I'd like to have access to this."

That instance provided him information towards his stated interest, I assumed that this participant would then make continued use of this feature. He never did so. Similar assumptions were made during the pre-semester interviews with the faculty when they voiced their ideas on how to use the various data. In post-semester interviews, they said that checking the database was not part of their normal routines so it never developed as habit. Now this is not totally the fault of the system's design but also one of how the UTEM system was taken up, specifically it's user interface. This could be improved by better trying to integrate these data into already existing routines.

A feature discussed was daily or weekly emails that present the faculty and staff with data deemed important to their pedagogical or makerspace decisions. For instance, any use event that occurs outside of normal access hours could be compiled in an email and sent to the staff each morning. This feature would necessitate developing more interfaces, a location where stakeholders can sign up for such emails.

It would need to have levels of customization to specify the data they would like to receive. The two participating instructors teaching the same course gave two different pedagogical interests in the data so clearly levels of customization in those auto-emails would be required. Effort would be necessary to determine what level of customization would be necessary and how that data should be presented. Implementation and development of this may help track and define what data these stakeholders are interested in and could be studied by tracking those requests and page views of the data interfaces.

The student participants also recommended features that could be implemented within the current web framework as well. They voiced interest in knowing when equipment was in use. The database already monitors this to inform the computer interlocks when to engage or disengage. Adding a display for this information could be added to the current UTEM system's web interface. A more useful step may be to create an API within the web framework for spaces to use to display that information on their own sites.

Much of the early data had issues of reliability due to how the technology was adopted, or not adopted, by the users. Forgotten RFID tags or cards left on the machine created issues for data integrity by falsely indicating longer use of the equipment and not accounting for user switch over. The earlier bypass attempts had the opposite issues of eliminating tracking during those times. The addition of a new type of terminal would be helpful in understanding actual equipment use. Right now, the UTEM system primarily tracks user interface with equipment station, not the equipment. Incorporating current sensor to track amperage on the equipment power supply could provide information towards the actual use of the equipment. If integrated into the terminals, usage information could have an interfacing and fabricating component to it, providing a greater level of detail to the information, one that could be used to confirm the user level data.

Now that reliability improvements, discovered from issues having occurred during the implementation and addressed, have been integrated into the UTEM system, there is a higher degree of confidence in the data. Students requested knowing when equipment is typically used.

With the reliability now improved from upgrades made in response to issues during implementation, the degree of confidence in the data increased with those improvements. A higher validity and integrity to the data improves the system's ability, with the proper application of various machine learning algorithms, to recognize trends within the equipment usage. Semi-supervised machine learning tasks could be created using this existing data, labeled with the help of staff and faculty, to identify trends of interest to those stakeholders.

The technical capabilities of the system are only limited by cost, time, and creativity. With greater database integrity and as it grows, the potential for gleaming insight from it grows as well. These could lead to information that informs policy and pedagogy. Even more, this type of constant awareness of the data by the UTEM system could automatically identify and provide, in real time, notifications and details of use that interest stakeholders. Given the proper application of machine learning, the UTEM system could be implemented as a simplistic digital teaching assistant, helping students where it can and bringing things to the attention of the staff and faculty when necessary.

11.2 Education

A digital teaching assistant within the UTEM system has some obvious pedagogical uses but there is already that potential, if useful data can make its way to instructors. Both faculty members identified ways in which they could use the data the system provides. They simply did not due to a lack of habit but also a lack of foresight on my part, event triggered emails should have been included along with the button triggered ones. The challenge is in figuring out what events would be of an interest to faculty.

This opens up implications for development potential along side education experts. What does it look like for a student to make good use of this makerspace? Of any makerspace? Sitting down with experienced faculty or experts to assign labels to the data to aide in machine learning identifying students or behavioral trends of interest. Identifying data from these types of environments that means something and could translate would be difficult.

Low hanging fruit would simply be the usage data, being able to at-a-glance examine how students are using the space. Both faculty members noted this to be useful for them. The data from last semester indicated that participant students did not start fabrication until late in the semester, corroborating the instructor's suspicions. Providing them with information on student training statuses would have at least given some warning of students possibly not participating in all aspects of the prototyping process. Total usage could indicate unfair distributions of fabrication on the team. I would need to undertake more direct and in-depth work with faculty to determine what specific data they would like to receive and the frequency with which would be useful though. That type of direct stakeholder involvement development stage will be one of the next steps for this technology.

The UTEM system also has potential for educational research as a data source or even as a focus for research on the pedagogical decision-making around such an educational technology. The pilot study gave insight into how user interacted and engaged with the makerspace and the UTEM system. My primary concern was to the qualification and development of the technology through that study and not for the pursuit of educational theory on how students interact with new technologies or how they react to safety barriers within a makerspaces. If considered a preliminary study, future studies less concerned with the technology and more concerned with the social or cultural phenomena could benefit from the preliminary findings of this study. Future studies more concerned with some of the observed phenomena could build off this work. An example could be an closer examination of how this real-time usage data can inform design course pedagogy or how it effects management decisions in makerspaces. Theory towards the actual learning within academic makerspaces or in using this technology for those purposes could be pursued with this study informing the methodology and the UTEM system providing quantifiable data.

11.3 Policy/Management

It has already been mentioned how the UTEM system captured information that faculty had specifically mentioned would be useful for them. Staff did make extensive use of the UTEM system as a safety measure but also for its data. They actively pursued it though. They made use of the interfaces to query the data and to see what it said. Those who did not though, simply did not access the data. It's not that they saw no benefit in it, they just didn't see enough to pursue or could not identify how the data would help them.

Taking steps to identify the specific information that faculty would like in future interfaces is one next step, to provide automatic reports specific to their needs and desires. Included in that would be the email notifications of these information, giving them timely updates on the goings on within their makerspace. Once enough data accumulates, trends can also begin to form and displays developed for those. Along with that larger data source, other trends can be deduced through machine learning. This would also require collaboration to begin labeling human identified trends or individuals to begin seeking similarities as they occur. Determining what those labels would be though needs further collaboration and research with the makerspace staff.

As with education research, the UTEM system has potential as a data source for organizational research. Researchers interested in organizations like makerspaces or data based policy decisions would have an interest in the data available through the system. This system presents more quantifiable usage information than is typical than in these types of environments. Continuing this study with that focus in mind could create case studies of staff use that could inform implementation of this system in other makerspaces.

Part V

Conclusions

Chapter 12

Conclusion

The IoT usage tracking and equipment management system began development in the summer of 2015. This technology was intended to improve stakeholder relationships with an academic relationship by improving safety and providing greater information and understanding on how the learning environment is being used. Three primary stakeholders, staff, faculty, and students, were identified with archetypes created to inform the design. It resulted in an UTEM system consisting of both physical interfaces for equipment typical to makerspaces and web interfaces for users to interact with the system's information and collected data. The physical interfaces, the RFID terminals, collect data on equipment usage and provide a safety measure through their ability to control access to that equipment. The web interface enables users to view that usage data, input and update user, station, and permissions information.

The UTEM system was initially implemented in the department of mechanical engineering's makerspace in August of 2016. This implementation was limited to seven stations for safety interlock and data collection. A sign in station was installed in the main fabrication room. Computer interlocks were installed on their laser cutter, desktop CNC router, and 2 desktop 3D printers. Their 2 soldering

Table 12.1: The UTEM System Assessment

		Stakeholders		
		Staff	Student	Faculty
User Level Attributes	Automatic equipment safety interlock	✓	✓	+
	A centralized database of system information	✓		o
	Logged usage tracking data and visualizations	✓		o
	help button on each station terminal	o	o	o
	photo button on each station terminal	o	o	o

✓ Met design expectations
- Negatively effected stakeholder
+ No design expectation but saw positive value to attribute
o Did not meet design expectation, neutral effect on stakeholder

stations were outfitted with power interlocks. The pilot study took place during this implementation to examine the performance and any influences of the system on its cultural setting. That study was an ethnographic examination of the makerspaces focusing on the 3 stakeholders and their interactions with the UTEM system and the makerspace overall.

The UTEM system was assessed along the dimensions of the stakeholders and the user level attributes of the system (See table 12.1) . Safety and data acquisition were the two primary drives for developing this system and the most important attributes in determining its success or failure. As a tool for improving safety, the staff perceived the safety interlocks as improving safety within the makerspace and alleviating some of their concerns in that regard. For the students, this meant better access to equipment and the makerspace overall, so even if they did not directly realize it, this attribute had positive impact on their experience. The faculty felt reassured by the safety considerations in a learning environment required in their curriculum.

Data was the other primary drive. This was split into two attributes, the static user inputted information such as user data and equipment permissions and the usage data that is logged by the UTEM system terminals and viewable as a log or calendar by the users. The staff made use of these attributes to organize the information aspects of the makerspaces and to track how equipment has been used. These attributes were not successful in improving the faculty's experience with the makerspace. At worst this feature proved to be neutral for them though. They saw value in these features, even thinking of ways it would benefit their pedagogy. They made no effort to act on those perceived value adding uses.

The final two attributes were not taken up. The help and photo buttons provided functions that all stakeholders saw value in but that did not lead to their use. Even their design, large arcade style buttons with clear labels, was not enough to encourage use.

Overall, the UTEM system had a successful implementation with regard to addressing the original design motivation. In the academic makerspace, it improved safety and accessibility through the safety interlocks enabling, enabling greater access for the students. The centralized database improved the organization of the space for the staff. The usage data provides more awareness of what is going on within the makerspace as well. All of the stakeholders have positive relationships with this academic makerspace and the UTEM system is partially responsible. The future work suggested by the research could further improve that positive influence. The IoT usage tracking and equipment management system was a positive influence within a makerspace.

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Appendix A

UTEM System Documentation

A GitHub repository was set up for this project to serve as the most convenient means to provide this technology as an open-source resource. It contains the following:

- Database
  - Setup of Data Objects and Relational Tables
  - Cleaning scripts
- Django Web Interface
  - Web apps for the UTEM system interfaces
  - Settings - scrubbed of personal information
- RFID Terminals
  - Software
  - Schematic
  - enclosure drawings
  - Pi setup instructions

Version 1.0 Available at the following link –

https://github.com/boconn7782/IoT-makerspace-interlock-system

Appendix B

Interview Protocols

Interview protocols were developed separately for each stakeholder group prior to the start of the research study. These protocols were not formally piloted in a staged interview setting but were reviewed by colleagues experienced in qualitative interviewing before submission for IRB protocols. Updates to the protocol over the course of the semester were discussed with members of the committee. Due to the use pf a semi-structured interviewing style, more concern was given to the subject of the questions rather than the exact phrasing.

B.1 Framing

All interviews began trying to frame interviews as casual conversations. I always preface any interview questions making it clear that the interview is "conversational", that I'm interested in "whatever occurs to you", and that I'll be providing "prompts". I use those phrases in the introduction of every semi-structured interview. Below are two quotes that are typical of how my interviews begin.

> My interviews tend to be kind of more conversational you know, I'll probably throw in comments so whatever occurs to you just, speak it,

> and uh, whatever happens, wherever we go, I'll probably just prompt every now and then to kind of direct conversation.

> Okay so, most of my interviews are pretty conversational, like whatever occurs to you just say, we're just gonna, I've just got some various prompts.

B.2 Re-Framing

Staff and faculty were consistent in staying in a useful frame during interviews. For students though, they would occasionally begin to shift their framing to one where they either could not handle the scope of the discussion or were fearful of the topics being discussed. The indicators of this varied but if I sensed them starting to withdraw from an open and conversational interview frame. The most common issue would be if a student did not have an immediate answer, they would begin to close off. I can not identify the frame they would begin to retreat into but they would begin to indicate a change. They would start repeating filler words, take a long pause, downplay their opinions, or a combination. The main indicator would be an adjustment in their stature to a more closed posture. I would respond with a reassurance and pull myself back but into an open posture, leaning back with my arms open wide. This was to welcome them back into the conversation as it was. I would also provide reassurances such as:

> If you don't have an answer that's fine, don't worry about it.

> And it's okay if nothing comes to mind, don't worry about like, that's all this is about it's like, you know, no answer is data.

Another typical issue would be if I sensed a student was resistant to criticize. When this occurred, I would reassure the student that they can speak freely and I will not share anything they say as part of the research interviews, "You can say anything here, I don't share it with anyone."

B.3 Initial Protocol

Three protocols were developed for times that interviews were expected to take place: interviews before the start of ME43, for those which took place during the semester, and for those that took place after the completion of ME43. The following protocols were used as guidelines and not as a exact script. If questions were answered in conversation or not applicable, they were omitted. Those decisions were made during the interview.

Pre-Semester

Staff

- What are your major responsibilities and concerns in running these makerspaces?
- How have you previously tracked which users have been trained on equipment?
- What means did you have to enforce that restricted use?
- How concerned have you been about safe use of the makerspaces and their equipment?
- How often are you called on to assist students in the space?

Faculty

- Can you describe your experience teaching this course in the past?
- How often do you observe your students outside of course time or in the makerspaces?
- How have you prepared for teaching this course?
- What resources do you expect to use to understand how your students are performing?

- How do you foresee students using the makerspaces as part of their coursework?
- What information and feedback do you use to inform your instruction from class to class?
- What do you think you will do with access to real-time data from the makerspaces?

Students

- Not Applicable - No pre-semester interviews of students

During Semester

Staff

- What difficulties have you noticed in the adoption of this system?
- Has any of the data provided informed your management of the space and equipment? In what way has it?
- Has this made it easier to identify issues in the spaces?
- Do students request help more or less through the system?
- What further data do you think you would need?

Faculty

- What information did you use to inform pedagogical decisions during the course?
- In what ways have you use data from the makerspace in your assessment?
- Has it been useful having access to that data source when planning out weekly lesson plans?
- Did you talk with any students about the data or because of it?
  - How do the students interact with that feedback?
- What data do you wish you had but was not easily available or accessible?
- In what ways could data be organized to have better served your needs?

Students

- How often do you use the makerspaces on Tufts campus?
- Do you use them for personal project or purely for coursework?
- How concerned with getting training for equipment have you been in past years?
- Do your interactions with the system inhibit your work?
- What information do you think would help you as a student or user of the makerspaces?
- Have you made use of the help or snap functions?

Post-Semester

Staff

- How do you think the semester went?
  - As a whole?
  - With regards to the resources in the makerspace?
  - For supporting the classes?
- How reactionary do you feel you were?
  - Did your planning make it easier to react?
- What changes are you preparing for the next semester?
- Did you ever make use of any of the data from the RFID system?
- Did the data affect or trigger any individual interactions?
- What expansions or other uses of the system would you like to implement?

Faculty

- How do you think the semester went?
  - With regards to ME43?
- How much of your pedagogical decisions came from what you either observed in Bray or were hearing about from the staff and students about Bray? Examples?
- Did you ever make use of some of the usage logs or was the data every referenced in your discussions with staff?

- Did this lead to any conversations with students?
- How did they react?

- What about from Slack?
- What information, in general, did you wish you had or collected to help you in either your decision making during the class or in your final assessment?

Students

- How do you think the semester went for ME43?
  - As a whole?
  - For your team?
  - For you individually?
- Were you satisfied with your progress?
- Were you satisfied with accessibility to the makerspace for your purposes?
  - If you were going into ME43 with your knowledge of the makerspace now, would you change your planning or would you push for greater access?
- How many members of your team were trained for using equipment in the makerspaces?
- Now that you no longer have the distributed expertise of your group, do you think youll take on any new trainings or learn how to use any of the other equipment in the makerspace?
- Why did you pick the tools you got trained on?
- What do you think your biggest take away from ME43 was?
- How do you feel about your relationship with the makerspaces resources has changed?