Under the Hood of a Bio-MakerSpace: Automating Lab Operations

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Introduction

Can academic MakerSpaces and open educational laboratories, serving both structured classes as well as general project work, be efficiently staffed, managed, and operated? Traditionally, these spaces are regularly staffed by part-time student employees with regular turn-over. In addition, such lab spaces must quickly switch between different lab courses during the day, as well as open lab use, in a schedule that may vary from day to day. These constant changes may make supply and equipment maintenance incredibly challenging. Access to equipment must be managed for specific users and orders need to be coordinated for student projects. While supply chain and task management software are available for corporations, these options are extremely expensive for small scale lab settings. In this paper, we will present an efficient and incredibly low-cost model for educational laboratory management.

Our laboratory, the George H. Stephenson Foundation Educational Laboratory & Bio-MakerSpace (or alternatively written as "BioMakerSpace"), houses over 50 unique pieces of equipment (e.g. Instron test systems, PCR thermocyclers, a laser cutter, a cell culture hood), including several devices which are maintained at each workstation (e.g. data acquisition devices, spectrophotometers). In addition, the lab has almost 500 different items which need to be inventoried and stocked regularly (e.g. electronic components, disposable test tubes, screws, acrylic and MDF sheets). The lab space hosts over a dozen different classes, and is open for free lab use, both during regular business hours as well as weekends and evenings, serving over 1000 students per year. In many cases, classes need special setups or unique supplies which are not normally available. Some equipment, such as the laser cutter and 3D printers, as well as some expensive supplies such as Arduino Unos, need special access permissions. Moreover, for classes where students have budgets, usually for end of the year projects or for the senior capstone projects, the laboratory and staff must manage orders and distribution. Finally, the laboratory needs to always be maintained and kept clean and organized so all users can comfortably access the space. Customer service and end user satisfaction, both by instructors and students, is necessary. However, with limited staff and high turnover, training and knowledge retention is difficult.

Our solution makes use of generally available software packages which are either free or normally already purchased at the university level, in addition to low cost hardware. In addition, a management system is put in place to help guarantee proper laboratory operation as well as quickly orient new staff. In order to measure usability and user experiences, a survey was administered to student laboratory employees and student end users. Open survey questions were also included and analyzed for common themes to identify future improvements to the system. Student end users who also utilize lab resources in other areas of the School of Engineering compare and contrast their experiences between systems in terms of usability. Lab staff and instructor perspectives will be discussed.

Background

Our Bioengineering, also referred to as Biomedical Engineering, educational laboratory, serves as both a teaching laboratory for regular laboratory courses, while at the same time remains open for general use, as a “MakerSpace.”[1] While some of these classes use traditional procedure-based lab exercises, a majority use project-based models.[2] Due to the breadth of Bioengineering, courses often run back-to-back, and switch between very “wet” setups for fields like molecular biology or tissue engineering, to very “dry” configurations, for such fields as electronics and mechanical engineering. With approximately 30 to 60 students per class, working in groups of 3 to 4, these switchovers can be quite challenging.

In the same manner, since the laboratory is open for all university students, the space must be able to serve all projects, regardless of discipline. Consequently, in addition to providing the supplies, tools, and equipment for the variety of lab modules, everything must be maintained. Supplies must be available for both these independent student projects as well as for the variety of courses held in the lab.

However, since our campus, the University of Pennsylvania, is urban in Philadelphia, space and storage is limited (our lab, serving approximately 1000 students per year, is only 2500 sq. ft.). Consequently, supplies for classes cannot always be hidden away. In addition, since many of the classes are project-based, students need to be able to come into the lab whenever it is open and be able to access the materials needed. Also, certain equipment, such as 3D-printers and the laser cutter are to be restricted for either trained students or for students in specific projects or classes. Finally, for project-based courses, students are normally provided a nominal budget through which they can order supplies not stocked by the laboratory, a process which our laboratory manages.

To allow for the variety of courses and student projects, Penn’s Bio-MakerSpace must be open outside of regular business hours, including weekends. However, to encourage student health, for student safety, and for the proper upkeep of equipment, the laboratory cannot be left unsupervised, and accordingly cannot be open 24-hours a day. Regardless, with the variety of usage, the laboratory must be cleaned and maintained, and supplies managed.

Our Bio-MakerSpace has two full-time staff and hires several part-time student employees. However, the typical turnover for the one full-time staff position is two years, and student employees is one to two years. Staff must be brought up to speed on equipment as well as maintenance procedures incredibly quickly. How does the laboratory maintain its operations?

Staff and Operations Management

Since our educational laboratory encompasses projects and classes which span the breadth of Bioengineering, managing supplies and equipment is incredibly difficult. For example, the lab must maintain stock of various molarities of Hydrochloric acids, serological pipettes, acrylic sheets for laser cutting, and active and passive electronic components. Unlike laboratories which focus only on electrical engineering or mechanical engineering, our breadth makes training employees difficult. Indeed, the logistics of supply management is significantly more complex when adding chemicals and biologics along with traditional electrical and mechanical supplies and equipment.

Adding to this challenge is the rapid turnover of employees, especially student employees. Student employees must be quickly trained on the variety of equipment and on supply chain management procedures. The primary solution presented in this paper is an internal website. This website is akin to a wiki and can be updated easily by students. It is a repository of knowledge related to the lab. Procedures, from autoclaving to package pickup, are described in detail. When employees are presented with a situation for which they may not recall the procedure, the first place to which they go is this internal website. Other examples include maintaining the laser cutter, and typical problems that users encounter and how to help them. This internal site also serves as a file management tool. While many groups now use Google Suites for written materials and spreadsheets, the number of files and file organization can be quite overwhelming. Our internal website provides links to the relevant files.

Our university maintains a subscription to Google's academic software suite which includes tools to make and manage simple websites.[3] This makes managing the site straightforward and efficient. Our Bio-MakerSpace initially tried using a traditional wiki, but the wiki's editor required a significant learning curve which was difficult for our student employees, given the short time in which they would need to be up to speed. The internal website is accessible through our public website (http://belabs.seas.upenn.edu), but is restricted to student employees.

The website includes a list of "start of day" as well as "end of day" tasks, for the respective employees who open and close the lab. These detailed instructions walk the employees through all the steps of the tasks and provide them with links if needed. In addition, scattered throughout the labs are photos of the different lab stations which the employee can use as a reference when organizing the area. Consequently, even on the first evening a student employee opens or closes the lab, the presence of the full-time staff has not been necessary. Moreover, the Bio-MakerSpace always remains clean and organized at the start of each day.

The website also contains a list of tasks for each day for each specific employee. Through the course of the week, each task leads to a deep cleaning of various lab facilities such as microwaves and sinks. It also includes equipment maintenance, such as cleaning the laser cutter lens. Finally, the most extensive part includes checking and restocking consumable supplies, such as pipette tips, screws, and electronic components. In some cases where demand of a specific item is high and restocking would have been a challenge, we maintain a secondary supply not accessible to general lab users from which we can more quickly replenish materials.

Monday	Tuesday	Wednesday	Thursday	Friday
Restock/order stripettes main lab: 2 packs of 10mL and 1 pack of 25 mL [122]; 3 packs each of 10 mL and 25 mL [186/187] Stock in [358]	Refill alcohol bottles (X5), hand soap bottles (X5), and dish soap bottles (X5) next to each sink, regardless of the current level - fill them up	Check/Order gloves:12 boxes of M, 8 boxes each of S, 7 each boxes of L&XL total (1 can be open)	Thoroughly clean scales with 70% Isopropyl	Check supply of calipers [257] - at least 7 - inform Sevile of Patterson if low
Restock/order stripettes in projects room [355/356]: 1 box of 2mL, 5mL, 10mL, 25mL & 50mL (Stock in [358]	Restock/order bleach bottles under each sink [Stock in 353]	Check/order syringe supply [172]: 1 ml, 3 ml, and 60 ml; 1 bin + unopen box of each	Clean labeling/weighing drawers [112 & 170/171]: at least 5 rolls of tape & 5 markers on each side	Wipe down two side tables with cleaning solution (move equipment first - all equipment except sharker-incubator, Instrons, computers, & printer)
Restock/order mol bio area in projects room [207-222]: lots of everything; 2 alumninum foils, 2 sarans, 4 autoclave tapes; fill culture tube drawer with stock on shelf [205] and 96-well plates in [206] - reorder stock when is low	Restock/order 70% isopropyl - make sure there is one under each sink and at least one in the flammable cabinet (6 total) [LOC 226]	Check/order transfer pipettes - 2 boxes [193]; consolidate to one box if possible	Restock/order weighing supplies [112/170]: weighing dishes (both large and small); weigh papers; scoopulas; metal spoonulas; metal scoops; aerosol duster; Stock in [430]	Thoroughly Clean inside of microwaves
Check for mail in BE Office (before 5 pm)	Check supply of banana cables [272] - inform Sevile or Patterson if low	check supply of all batteries [433]- order if low	Check/order parafilm on two sides of room above microwave	Check for mail in BE Office (before 5 pm)
Check/order scalpels (4 FULL boxes) & razor blades (2 boxes) & biopsy punches [218]	Autoclave Pipette Tips and divide up on two sides of lab if necessary. Stock in [204] Order more tips if necessary: > 3 packs per size should be available.	Check for mail in BE Office (before 5 pm)	Wipe down area around all five sinks with cleaning solution	Stock/resupply stationary drawer: 2 scissors, staples in staplers, 2 rulers, some pens and pencils [194/195]
Check/order first aid [357]; Stock in [430]	Organize and Check stock of Mechanical components / small drawers [404]); Restock/reorder if low - but first look for excess above stock	Restock/order cuvettes in main lab [119/166] - each side should have two boxes of 4ml; Drawer 119 should also contain two 1.5mls; Stock should contain 2x of 1.5 mL and 4.5 mL 500 pk boxes; label all boxes with size ("4.5 mL" or "1.5 mL") on whatever side is visible when stored. Stock in [368].	Run eye washes [X3] for 1 minutes	Check supply of Whatmann filter paper [312]- (at least 10) - order if low
Check/order TAE buffer [367] (one open and one unopened box)	Check for mail in BE Office (before 5 pm)	Fill/order 15ml & 50 ml tube drawers [121/166]; stock in [361]; Fill regardless of current level	Check full glass disposal bins and prepare for pick-up if full, and replace; Order if new boxes are low	Ensure there are 4 packs of paper next to the printer [More paper can be found in BE office (by 5 pm)]
Restock electronic equipment in projects room [273-280]: six small breadboards, two large breadboards, ~50-100 protoboards)	Organize and Check stock of electrical components / small drawers [404 & 414]); Restock/reorder if low - first look for excess above stock	Refill wires [265] with stock in 405. Order if low	Check for mail in BE Office (before 5 pm)	after 10 uses of laser cutter, go through maintenance process found in laser cutter manual, except for the filter part. Note cleaning in log.

Figure 1: Segment of the maintenance table with color code for each employee

Rather than waiting until the end of the week, these tasks are distributed and assigned a day and an employee, preventing any employee from being overloaded on any particular day. At the end of each semester, the entire lab staff gather together for a "lessons learned" meeting to discuss what works and what can be improved (these meetings are always followed by lunch!). For example, most recently, a student employee suggested maintaining a secondary stock for adhesives (various glues and glue guns) since adhesives were being used much faster than our regular supply system could handle.

The results of this method are that we can maintain an incredibly clean and organized lab environment where all equipment generally always remains functioning properly, even between its use for non-coursework related projects and lab classes, and supplies are always maintained.

Automating Operations

One of the biggest challenges of having a Bio-MakerSpace (or BioMakerSpace) which is open for both student projects and general student use is access and control, whether determining who should be able to enter the lab, or who has access to specific resources, including borrowing equipment. While the lab is open to all students, it is necessary for us to determine if students have gone through the appropriate training. All classes tied to the lab requires students to go through the training. This information is collected through Canvas and entered into a spreadsheet. Students who enter the lab during extended hours must swipe their university ID card which determines whether or not they are on the list. Since our ID cards use a magnetic stripe, we use a simple magnetic strip card reader which interfaces through USB to a Windows

Surface laptop (since the laptop is very portable). This information is helpful to check lab usage, and to keep an eye on the lab (see below in Figure 2).

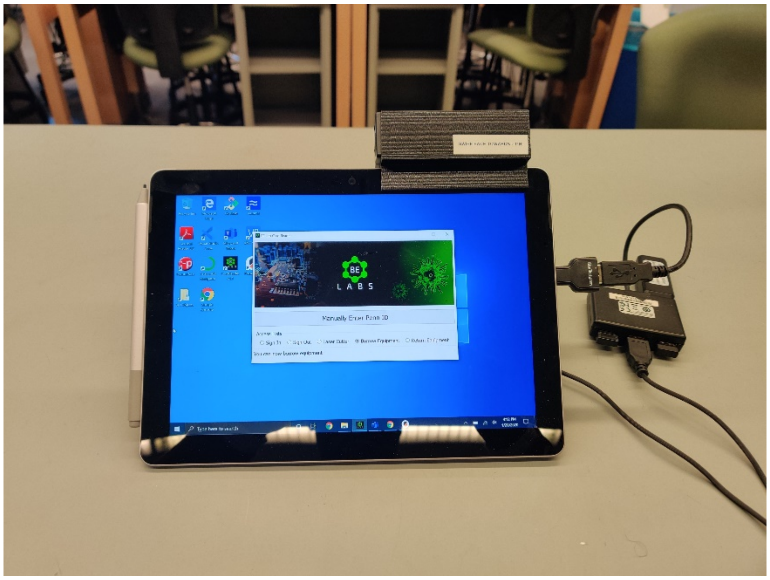

Figure 2: Surface tablet with card reader attached using a 3D printed holder

A custom program was written in Python which reads the student's university ID number (PennCard number) and compares it to the access list. If the student has access, they are allowed into the lab. Alternatively, if the student has not been trained, a training packet is provided for the student to review and sign. In this situation, the student's information is collected, and the student will be able to use the lab freely. The third possibility is that the student is "Blacklisted." This occurs when students do not clean up after themselves or are disruptive. Blacklisted students lose access to various resources and must meet with the lab director to get off the blacklist. Blacklisting also helps to enforce the culture of self-reliance and respect which we try to instill in students. They are expected to get what they need and clean up after themselves.

A similar process is followed for students to use our laser cutter. Once students are trained, they can access the laser cutter, which is confirmed through card swiping. Improper usage can lead to blacklisting as well.

The process for 3D printing usage is more complex. In order to maintain the 3D printers, all printing is done by the lab staff and must be tied to a course for which 3D printing is used. Student data is entered into a spreadsheet using Canvas. Students fill out a Google Form which populates a spreadsheet. A script in the spreadsheet confirms that the student is authorized to 3D print and this is noted; an email is sent to the student employees. The student employee then checks the submission. If the student was not authorized to print, the employee checks with the lab management to confirm print. Otherwise, the employee verifies that the print seems like it is part of a real project and that the print time is within the allotted window. The student employee then indicates the decision on whether or not the print is allowed and marks the spreadsheet. A

Raspberry Pi, running code written in Python, checks for the indicator on the spreadsheet and will then send an email to the student.

The student employee then confers with the 3D print calendar and if a printer is available will begin printing and then place a mark in the spreadsheet. The Pi then emails the student that the print has started and the estimated time it will end. The Pi will also automatically create a calendar event.

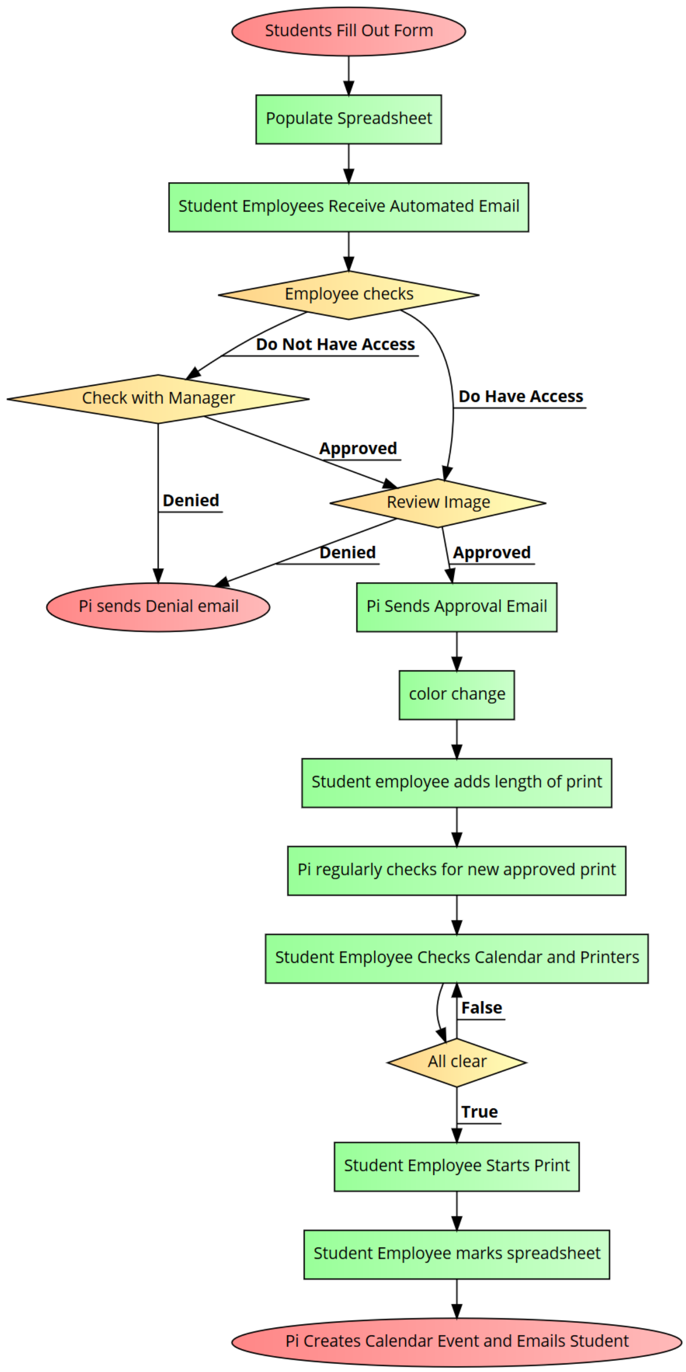

Figure 3: 3D print process

A second challenge is ordering supplies for students. Our classes provide students with a small budget for certain projects which are to be ordered through the lab staff. This involves placing multiple orders, informing the students that their orders have been placed, receiving the orders, and then letting the students know that the order has been received. A similar automation process to 3D printing is used. Students fill out an order form which populates a spreadsheet. An employee receives an email that an order has been requested and then checks the order. If it is appropriate, the information is transferred to an internal order form. When the order is placed (as indicated by the placement of the order date), the Raspberry Pi will send an email to the student with the details of the order.

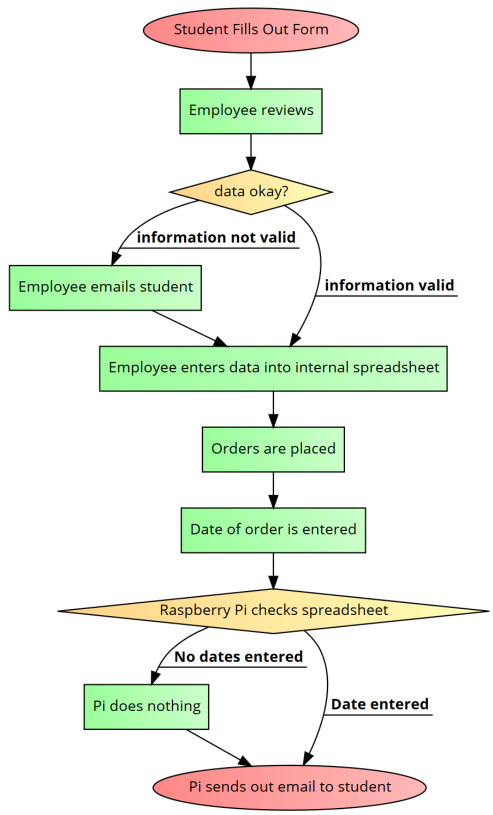

Figure 4: Student order process

When the lab staff receive the order, they mark the order with the requesters name, and indicate the date received on the spreadsheet. The Pi will then send an email to the student indicating the order has been received. Students can then stop by the lab to pick up their order when convenient.

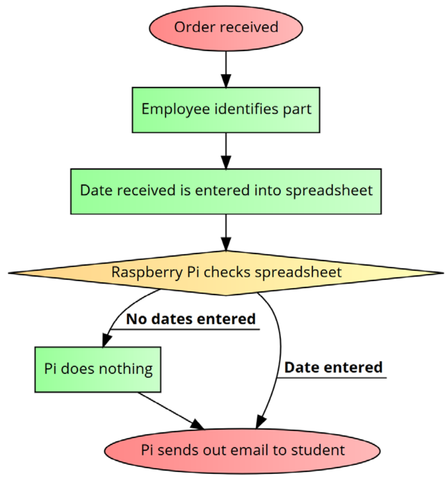

Figure 5: Order received process

The largest cost for this system is the Microsoft Surface PC, which we purchased for approximately $600. The USB card reader and Raspberry Pi are inexpensive, and the software development package, Python, is open-source and free. As mentioned, our university provides the Google suite of software, and consequently this is not an added cost for us.

Results and Discussion

A survey was sent to students who have used Penn's Bio-MakerSpace for courses, students who have used other labs, and student employees. For other labs, ordering systems followed a process of students either emailing a teaching assistant (TA) or instructor, or filling out a Google form. The instructor or TA would then place the order and students were expected to regularly check a location to see if the parts had arrived.

Surveyed students filled a five-point Likert scaled questionnaire with a focus on ordering. Users who were unaware of alternatives were generally favorable of their respective systems, however, as seen in Figure 6, students using our system felt it was easier to use, albeit only slightly more. A Wilcoxon Rank Sum test was used to test the median difference in ease of use between students using our Bioengineering lab (BE students) and students using other labs (non-BE students). The median difference in ease of use between the two groups was statistically significant (5 vs 4, respectively $p = 0.0968$ at $\alpha = 0.1$). We found evidence that our students found their ordering system easier to use compared to students in other educational labs.

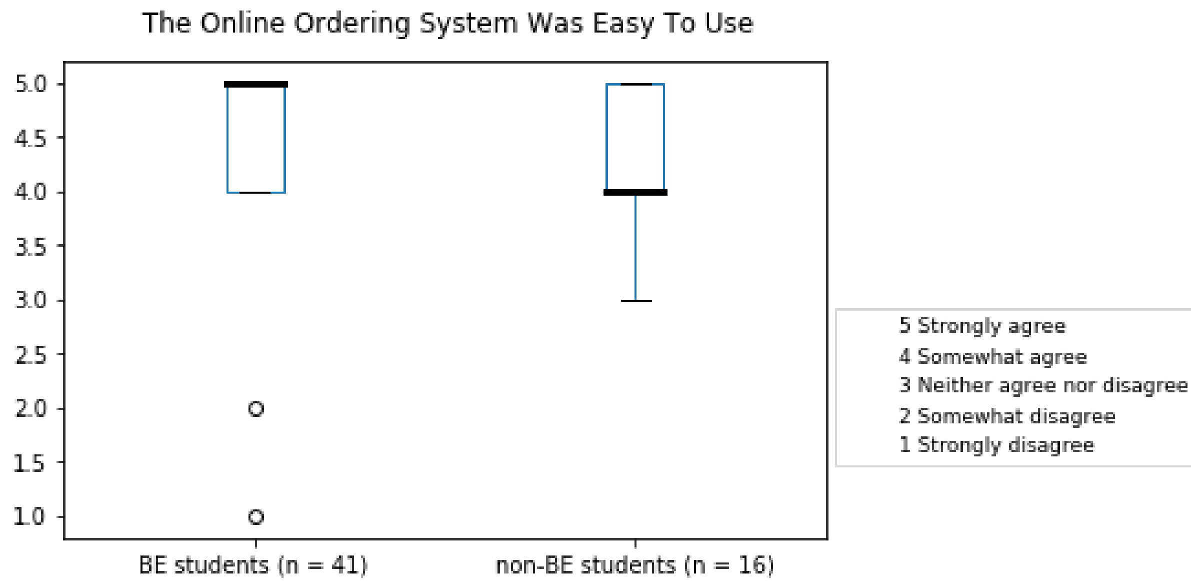

Figure 6: Comparison of ease of use of ordering system

Our automated confirmation system is greatly appreciated and helpful, as seen in Figure 7. A Wilcoxon Rank Sum test was used to test the median difference in knowledge of their order status between student users of our lab (BE students) and student users of other educational labs (non-BE students). The median difference in knowledge of their order status between the two groups was statistically significant (4 vs 2, respectively $p = 0.0095$ at $\alpha = 0.1$). We found evidence that our students had more knowledge about their order status compared to non-BE students.

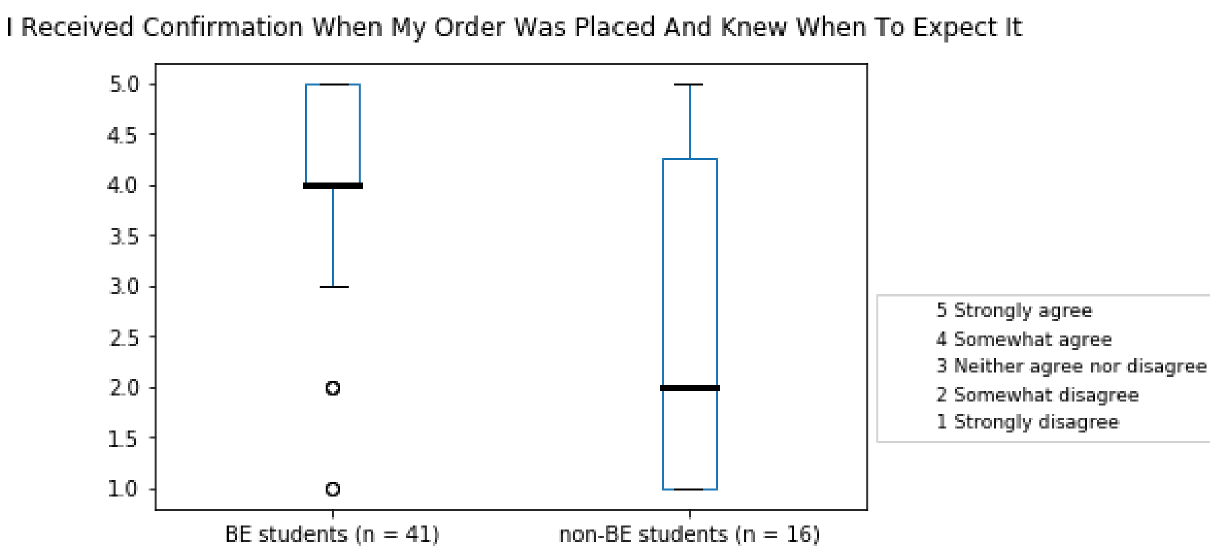

Figure 7: Receiving confirmation of order

Reviewing comments was beneficial. Students who had taken courses using both systems found our lab system to be more ideal: *"This* [our lab's system] *was better than ordering for other project based courses (… where the instructor assigned students to be responsible for other students orders from specific vendors … where some of our orders never arrived). This system in the BE lab was much more straightforward and less stressful."* This comment was representative of all comments by those who took both classes.

The student employees who use our ordering and maintenance system found it to be incredibly easy to use. Speaking to student employees who have worked in other labs, the process of sorting through orders every time students come to pick up their part, or alternatively, to individually email students, was incredibly tedious and difficult. Consequently, and not surprisingly, it suggests that an automated ordering management system is helpful. In the same way, providing detailed instructions for student employees for checking specific inventory each day, provides clarity and ease, making the work less monotonous. In addition, this frees up student employees to be available to work on projects and papers rather than just maintenance tasks.[4, 5] Figures 8 and 9 shows the student employee responses.

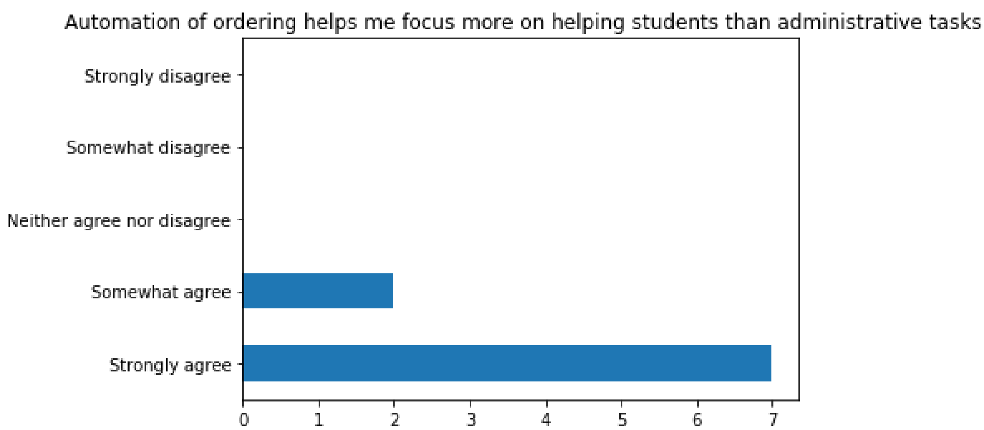

Figure 8: Automation helps with employee performance

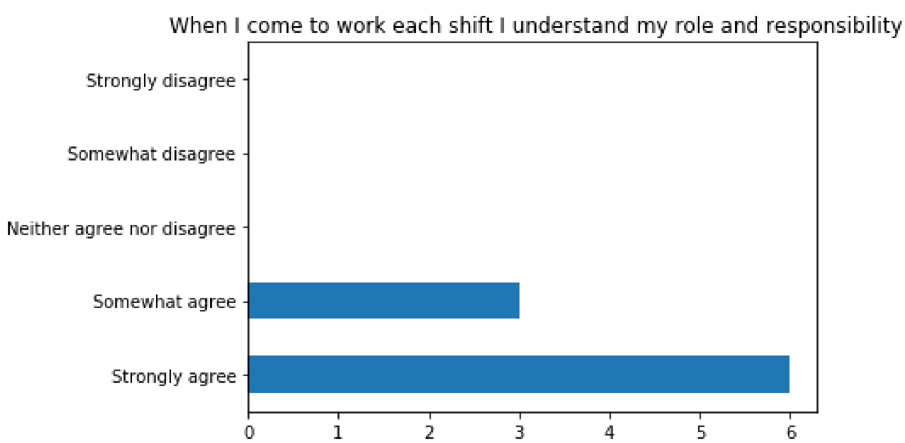

Figure 9: Employees understand their responsibilities during their shifts

Instructor feedback has been positive. Instructors in our department are effectively unaware of the “behind the scene” aspects of the lab. Students seem to place orders and they receive them, supplies are always in the lab when needed, and everything seems organized.

An instructor who teaches in a less automated lab structure found material and supplies disappearing to be an issue. Concerns over maintenance of equipment exist, although this might be a direct result of dealing with larger volumes of students. Finally, the instructors themselves must deal with issues related to student orders (missing materials, orders not going through, orders delayed, etc.), which our centralized and automated ordering system helps alleviate.

An opportunity for us to improve would be to provide tracking numbers for students who place orders. Currently our order form provides suggestions to students on suppliers, and how to determine shipping and delivery time in order to provide students with as much of this information as possible. However, since orders are placed by the lab at regular intervals, several student orders, even to the same supplier, will be lumped together, making separation of tracking information seemingly impossible. Therefore, tying the order, tracking number, and email address of the student would be extremely cumbersome and time consuming. Future solutions will continue to be explored.

Conclusion

Supply chain and operational management of educational laboratories which provide both structured classes as well as open lab time can prove challenging as a result of constant changes and the variety of equipment and supplies used. This is especially the case for Bioengineering which supports work related to biology, chemistry, mechanics and mechanical design, and electronics. For small lab spaces without the resources of larger groups, such as a university library system, dealing with controlled access of space and equipment, equipment maintenance, stocking of supplies, and orders for students can be extremely difficult. Also, using complex systems can be burdensome for student employees with quick turnover. We provide a low cost and customer friendly model for lab operations and staff training.

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