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LEAN APPLICATIONS IN AN ENGINEERING RESEARCH LABORATORY

Abstract: *Learning activities within engineering disciplines take place in both teaching and research laboratories. While Lean principles, which focus on improving process efficiency by eliminating waste (i.e., activities that do not add value), have been used previously across several disciplines to improve the efficiency of learning activities in teaching laboratories, few studies have examined the implementation of Lean practices in engineering research laboratories. This study utilized an action research approach to examine the application of Lean methods in an engineering research laboratory to address operational aspects not previously explored using Lean. The specific issues addressed include reducing both inefficiencies in staff onboarding and the occurrence of material stock outs. Lean's "respect for people" principle ensured those who do the work (lab staff) were directly involved, and action research's cyclical, iterative approach ensured learning resulting from action in one phase of the investigation was used as the input to the next phase.*

Keywords: *Lean, Process Improvement, Higher Education, Research Laboratory, Staff Onboarding, Inventory Stock Outs*

1. Introduction

Excellence in research and teaching is required to fulfill the goals of higher education institutions (HEIs), which include developing new knowledge and educating students (UNESCO, 1998). Lean methods, which focus on improving process efficiency by eliminating waste (i.e., activities that do not add value) (Liker, 2021), have been both taught within and used to significantly enhance HEIs. For example, Lean practices were used to reduce transactional library service time (Kress, 2008), enhance the student recruitment process (Buster-Williams, 2009), and improve outcomes in academic programs (Al-Shargabi, 2019; Chibaira, 2015; Emiliani, 2004, 2005, 2015). Additional prior research focused on applying Lean tools in teaching laboratories across disciplines to improve efficiency of learning activities (Deranek, Kramer, & Siegel, 2021; Marcelino, Lima, & Gaspar, 2023; Sremcev, Lazarevic, Krainovic, Mandic, & Medojevic, 2018).

Learning activities within engineering disciplines in particular have a unique way of developing cognitive and situated skills that require manipulating materials and working collaboratively (Feisel & Rosa, 2005; Johri & Olds, 2011). In addition to teaching laboratories, this type of learning also takes place in research laboratories (Park, Choe, Schallert, & Forbis, 2017). Yet, few studies have examined the implementation of Lean practices in

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engineering research labs. Prior studies have demonstrated the use of Lean methods in a materials engineering lab to reduce sample processing time (Gramajo, Kovach, & Carden, 2014) and in industrial engineering labs to organize materials for optimal resource usage and safety (Jiménez, Romero, Domínguez, & del Mar Espinosa, 2015). However, other operational aspects of engineering research labs discussed in prior research, including lack of standard operating procedures and a surplus or deficit of supplies (Dagdeviren, Durak, & Sadat, 2020), remain unexplored using Lean.

To fill this gap in the literature, this study utilized an action research approach to examine the application of Lean methods to address inefficiencies in staff onboarding and material stock outs within an engineering research lab. Through this approach, researchers worked side-by-side with staff in the Architected Intelligent Matter (A.I.M.) lab at the University of Houston to facilitate operational change. Lean's "respect for people" principle ensured those who do the work (lab staff) were directly involved (Liker, 2021), and action research's cyclical, iterative approach ensured learning resulting from action in one phase of the investigation was used as the input to the next phase (Coughlan & Coghlan, 2002, 2016). While some may suggest the solutions implemented were obvious, it is important to note that the details identified through this investigation contributed to the successful adoption of process improvements that lead to positive changes in performance outcomes for this lab.

The A.I.M. lab designs novel materials and demonstrates their characteristics through digital fabrication and precision experiments. It is managed by a full-time faculty member and is staffed by research assistants (students) working on a diverse range of 3D printing-related research projects. This lab tends to hire one or two new researcher assistants per semester, which are often international students. It consists of four small individual lab spaces with more than 20 pieces of equipment and works on four to five research projects at a time. More specifically, it has four 3D printers and produces 30-60 print jobs per semester. Unfortunately, excessive onboarding time and/or shortages of 3D printing materials caused delays to research projects conducted in the lab; hence, the goal of this study was to identify the issues causing these delays and develop solutions to address the issues identified. In addition to achieving positive changes in performance outcomes for this lab, demonstrating how Lean methods were applied to address these problems provides useful case examples from which other research lab management and staff can learn to improve their operations.

2. Materials and Methods

The materials used in this study consisted mainly of information obtained through detailed observation of the staff onboarding and 3D printing material use and reorder processes in the A.I.M. lab, as well as interviews and brainstorming sessions held with the lab's management and staff.

Following the Education Lean Improvement Model (Waterbury, 2008; Waterbury & Holm, 2011) and with the direct involvement of the lab management and staff, the staff onboarding and 3D printing material use and reorder processes were observed and mapped, performance metrics were identified, and data were collected to quantify current performance. Then, ideas for how to smooth the flow of work were identified through adaptations of onboarding approaches used in various (Baker & DiPiro, 2019; Kumar & Pandey, 2017; Ross, Huang, & Jones, 2014; Trost, 2021) and inventory auditing/tracking methods applied in other laboratory settings (Dennert, Friedrich, & Kumar, 2021; Marcelino et al., 2023). Finally, changes were implemented within these processes, and performance data were collected and compared to prior measures to determine the level of improvement in process performance that was achieved.

2.1. Improving Staff Onboarding Process

The literature describes two key objectives of staff onboarding that contribute to employee satisfaction and overall job performance. These objectives include structuring the onboarding process to 1) develop a long-term relationship between the organization and the employee and 2) set up new employees for early success and increased task efficiency (Baker & DiPiro, 2019).

To learn about the current staff onboarding process, initially unstructured interviews were held with the lab manager and staff about the specific steps in the process, their chronological order, and the person/ department responsible for each task. To map the current process at a high level, a suppliers, inputs, process, outputs, and customers (SIPOC) diagram was created, as shown in Figure 1. This process begins when new lab staff are hired. Before joining the lab team, they complete various pre-arrival activities such as applying for a student ID, communicating a laptop preference, getting a Social Security Number (international students only), etc. Their first day few days at the lab involves orientation in which the lab manager introduces them to the lab facilities and team and provides them with access to the lab's online platforms (i.e., Slack, Google Drive). Next, they receive additional role-specific training from other lab staff regarding how to operate the 3D printers (including obtaining access to and reviewing manuals and tutorials) and how to place a purchase order for needed materials. The inputs for this process include the lab manager, research assistants, tools and software, and forms, and the suppliers are the UH community and the A.I.M. lab. The outputs generated by this process are onboarded staff and completed forms, and the customer is the A.I.M. lab.

Suppliers	Inputs	Process	Outputs	Customers
UH community A.I.M. lab	Lab manager Research assistants Tools and software Forms	1. Get hired. 2. Complete pre-arrival activities. 3. Attend lab orientation. 4. Participate in role-specific training.	Onboarded staff Completed forms	A.I.M. lab

Figure 1. High-level overview of the A.I.M. lab's staff onboarding process

Next, data were collected about the lab's current onboarding process cycle time through interviews with five current research assistants working in the lab, two of which were recently onboarded. The questions asked during the interviews were about the orientation and training steps of the process, and more specifically, the time from when they were hired until they began work on their first research project in the lab. Based on these data, a baseline measurement was defined for the time that it took research assistants to complete the onboarding process. The orientation and training steps alone took an average of approximately 12.5 days to complete. Hence, some work in the lab was delayed nearly two weeks while new research assistants were onboarded.

A brainstorming session with the lab manager and staff (five research assistants) was held to identify potential causes for why the onboarding process takes so long. As shown in Table 1, these causes were prioritized using nominal group technique in which causes were ranked by the lab manager and staff based on their perceived impact of each cause on excessive cycle time, where a score of "3" denoted the cause with the highest impact. Individual rankings were summed across rows to determine the total score for each cause. "No standard process" and "undefined roles" had the highest scores; hence, these became the focus of the improvement efforts moving forward.

Relevant literature was then reviewed to generate ideas for how to standardize the onboarding process. Prior discussions in the literature suggested dividing the onboarding process into time-based phases and grouping tasks by role (Kumar & Pandey, 2017; Trost, 2021). Those working in the lab suggested organizing tasks into four phases: 1) prior to first day, 2) first day, 3) first week, and 4) first month. They felt that by dividing the process into phases, staff would have a better understanding of not only what needed to be done but also when it should be done.

Table 1. Potential cause rankings for excessive staff onborading cycle time

Potential Cause	Lab Mgr.	Staff					Total
		A	B	C	D	E	
No standard process	3	3	3	2	2	2	15
Undefined roles	2	1	2	3	3	1	12
Poor time manage-ment	1	2	1	1	1	3	9

Additional unstructured interviews with the lab manager and and staff (five research assistants) provided details about the tasks that should be included in each phase of the onboarding process. This group also provided links to specific resources to support various tasks (Baker & DiPiro, 2019). They felt that providing a list of specific tasks would help ensure that the process is performed the same way every time a new research assistant joins the lab, thus establsihng a standard operating procedure for onboarding within the lab.

Throughout this study, successive drafts of the improved process were shared with the labe manager and research assistants. Then, revisions were made based on their feedback to ensure all the necessary details regarding the onboarding process were included in the appropriate phase of the process and for the appropriate role. The final map depicting the improved onboarding process is shown in Figure 2 in the form of a cross-functional flowchart/swim-lane diagram. As shown in the initial section, the "prior to first day" phase starts when a new student receives their university admission document and is hired by the lab. The student then reviews the information necessary and arranges for their visa and plans their travel. At the same time, the lab manager decides to hire the student, completes their hiring paperwork, and sends them the onboarding process map and an invitation to join the lab's Slack channel. Next, the student looks for and secures a place to live. When the department administrative personnel contacts the student and provides instructions to complete required forms and a background check, the student then completes these tasks, and the department administrative personnel processes the completed forms. Next, the student establishes their start date and schedules a meeting during their first week with the lab manager. Finally, they obtain their student ID (CougarCard).

As shown in the middle section of Figure 2, a student's "first day at the lab" phase starts by going to the college and meeting with staff to set up their monthly pay, and then checking in with the Graduate Admissions Director. Directly following that, they meet with the lab manager and provide their contact information. The lab manager then introduces the student to the lab team and their assigned lab colleague (an internal resource the new student can request help from at any time) (Ross et al., 2014). The lab manager also gives the student their educational plan/timeline and their laptop. While the assigned lab colleague introduces the student to the lab facilities and equipment, the lab manager adds the student to the lab's user workstations and invites the student to the lab’s network drive, Google Drive, and wiki. Finally, the lab colleague invites the student to the lab’s shared calendar, and the student accepts all invitations.

As shown in the final section of Figure 2, during their “first week at the lab” phase, the student gets a local cell phone, Social Security Number, opens a local bank account, and completes a request for lab keys. They also spend time reviewing the lab’s website and the many manuals and information stored in the lab’s Google Drive for the different types of equipment.

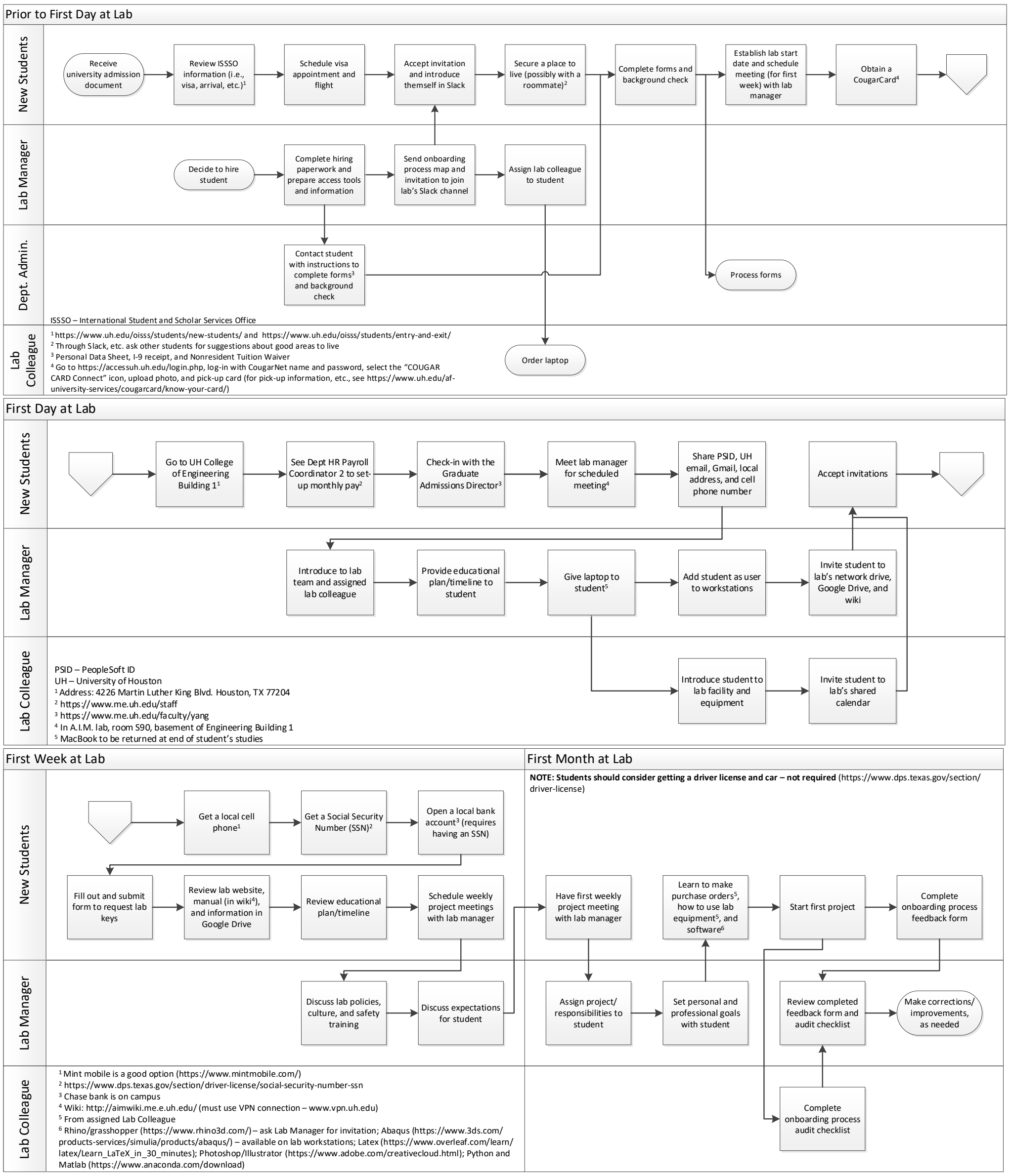

Figure 2. A.I.M. lab’s improved staff onboarding process

In addition, the student spends time reviewing the educational plan/timeline for their studies. The lab manager takes time during the student's first week to discuss the lab's policies, culture, and safety training, as well as their expectations for the student's education and lab work.

Within the "first month" phase, which is also shown in the final section of Figure 2, students will have their first weekly project meeting with the lab manager. During these meetings the lab manager assigns a project and/or other responsibilities to the student and works with them to set their personal and professional goals. The student's job during their first month is to learn as much as possible about making purchase orders, how to use the lab equipment, and about the software used in the lab. During this time, the student starts work on their first project and completes the feedback form, which contains questions concerning satisfaction and areas in need of improvement, as shown in Table 2.

Table 2. Staff onboarding process feedback form

Question	**Response**				
The onboarding process…	Strongly Agree		Neutral		Strongly Disagree
…map was useful.	5	4	3	2	1
…went smoothly.	5	4	3	2	1
What aspect of the onboarding process should the lab…					
…start doing?	…stop doing?			…continue doing?	
Additional comments?					

Finally, as shown in Table 3, an audit checklist was created to verify whether key aspects of the improved onboarding process were completed within the designated phases. As illustrated in the bottom right of Figure 2, the assigned lab colleague, with input from the student, completes this checklist within the student's first month working in the lab and then provides it to the lab manager for review. The lab manager then uses this information and that collected through the feedback form to take action to further improve the process, as needed.

Table 3. Staff onboarding process audit checklist

Task	**Phase**	**Yes**	**No**
Added to Slack channel?	Prior to first day		
Monthly pay set-up?	First day		
Educational plan/timeline shared?			
Added to user workstations?			
Added to network drive?			
Added to Google Drive?			
Added to wiki?			
Added to shared calendar?			
First project meeting held?	First month		

2.2. Reducing Material Stock Outs

Previous studies acknowledge the inherent challenges of managing inventory in a shared laboratory setting. These challenges include the difficulty of accurately monitoring usage and stock levels of shared materials, the lack of efficiency in ordering and restocking supplies, and the increased potential for inventory loss or waste (Befekadu, Cheneke, Kebebe, & Gudeta, 2020). In addition, inventory controll can be challenging when there is no designated individual within the organization responsible for managing inventory or when the person responsible lacks sufficient authority to effectively carry out the task. This lack of clear ownership and/or authority can lead to inefficiencies and challenges in maintaining accurate stock levels and efficient inventory management

(Zomerdijk & de Vries, 2003). Prior reserach as also discussed the need to make inventory management systems user-friendly in terms of both their design and implementation, because by implementing a system that is easy for users to navigate, users are motivated to participate actively in managing inventory. This results in enhanced data accuracy and improved overall efficiency (Hansen et al., 2023).

To learn about the current 3D printing material use and reorder process, initially unstructured interviews were held with the lab manager and staff (only the graduate reserach assistants working in the lab are invovled in this process) about the specific steps in the process, their chronological order, and the person/department responsible for each task. The information obtained from these interviews was mapped using a cross-functional flowchart/swim-lane diagram, as shown in the first three rows of Figure 3.

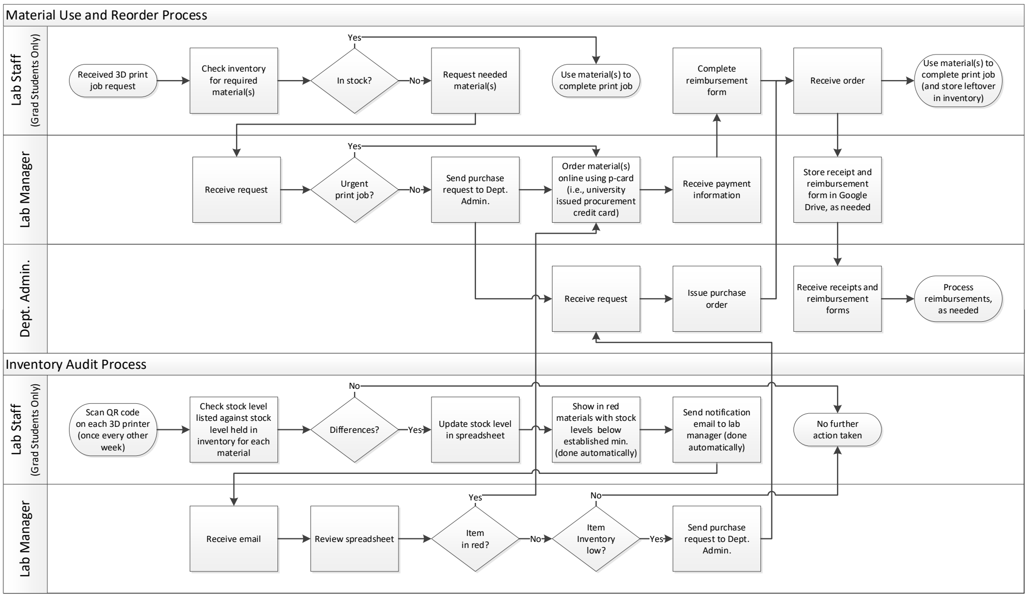

Figure 3. A.I.M. lab's printing material use, reorder, and inventory audit process

First, lab staff receive a request for a 3D print job. Then, they check the lab's inventory and determine if the material(s) required is in stock. When it is in stock, lab staff complete the print job. However, when required material(s) is out of stock, lab staff send a request to the lab manager. If the print job is not urgent, the lab manager forwards the material(s) request to the department administrative personnel who then issues a purchase order. Unfortunately, this path often takes a significant amount of time for the lab to receive an order. Therefore, when print jobs are urgent, the lab manager orders the material(s) online using a p-card (i.e., university issued procurement credit card). Subsequently, the lab manager seeks reimbursement by providing the payment information to the lab staff who complete the reimbursement form and collect the receipt after the order is received. Regardless of the method used to place an order, once an order is received in the lab the material(s) is used to complete the print job, and any leftover material(s) is stored in inventory. Finally, the lab manager stores the completed reimbursement form and receipt in the lab's Google Drive and sends them to the department administrative personnel who processes the reimbursement.

To help prevent delays in completion of 3D print jobs due to material stock outs, each material has an established minimum quantity that should be kept in the lab's inventory. Unfortunately, stock outs still occur. To quantify the occurrence of material stock levels below established minimums, which represent a potential for a stock out to occur, data regarding this metric were collected every other week for three months. These data indicated the percentage of materials with stock below the established minimum levels averaged 15.5%; hence, a goal was set to reduce this metric to an average of 11% or less.

A brainstorming session with lab staff (three graduate reserach assistants) was held to identify potential causes for 3D printing material stock levels being below the established minimums. As shown in Table 4, these causes were prioritized using nominal group technique in which causes were ranked by the lab staff based on their perceived impact on causing materials stock levels to be below the established minimums, where a score of "4" denoted the cause with the highest impact. Individual rankings were summed across rows to determine the total score for each cause. “No inventory tracking spreadsheet” and “no procedure for auditing inventory levels” had the highest scores; hence, these became the focus of the improvement efforts moving forward.

Table 4. Potential cause rankings of materials stock levels below the minimums

Potential Cause	**Staff**			**Total**
	A	**B**	**C**	
No inventory tracking spreadsheet	4	4	1	9
No procedure for auditing inventory levels	2	3	4	9
No reminders to check inventory levels	3	1	3	7
Limited staff for 3D printing job tasks	1	2	2	5

Next, relevant literature was reviewed to generate ideas for how to create a process for periodically auditing and tracking the lab's 3D printing material stock levels that went beyond simply periodically checking and recording stock levels in a spreadsheet. Two prior studies provided examples of electronic inventory auditing/tracking systems that utilized custom spreadsheets and databases (Dennert et al., 2021; Marcelino et al., 2023). These examples inspired the A.I.M. lab to create a custom process to audit material stock levels for each of the lab's four 3D printers that could be integrated with the current material use and reorder process. However, given that the lab had no budget to support this work, the lab management and staff brainstormed ideas that could be implemented easily with little to no cost.

The last two rows of Figure 3 (shown previously) illustrate the new inventory auditing process adopted in the lab. This process starts with lab staff, once every other week, scanning the QR code posted on each 3D printer, which is linked to a spreadsheet stored in the lab's Google Drive. This spreadsheet lists the materials used for each specific printer with the established minimum stock level and the amount of current stock for each material. Lab staff then check the actual amount of stock for each material available in the lab's inventory. If it matches that listed in the spreadsheet, no further action is taken. However, if there is a difference, lab staff update the available stock amount listed in the spreadsheet. If this amount is less than the established minimum stock level, the material is automatically listed in red. Once the spreadsheet is updated, an email is automatically sent to the lab manager that prompts a review of the updated inventory spreadsheet. Materials listed in red are then ordered via p-card by the lab manager (as described previously). For materials not listed in red but that do have low stock levels, the lab manager sends a purchase request to the department administrative personnel who issues a purchase order (as described previously).

Finally, after lab staff were trained on the new inventory audit process, it was put into use within the lab. Subsequently, through the receipt of emails automatically generated each time the inventory spreadsheet for a 3D printer is updated, the lab manager can easily verify that the new inventory audit process is being used as intended. Hence, not receiving these emails once every other week would cause the lab manager to provide staff with feedback to remind them to complete their inventory audits.

3. Results and Discussion

3.1. Improving Staff Onboarding Process

Data were collected about the improved onboarding process cycle time for one new student who joined the lab after the improved process was implemented and this was compared with the prior measurements. The onboarding cycle time in terms of the orientation (first day activities) and training steps (first week activities) was reduced by 60% (from an average of approximately 12.5 days to 5 days).

While the efficiency of the lab's onboarding process increased somewhat, the larger achievement resulting from the implementation of the improved onboarding process is that all required onboarding tasks are clearly defined, when each task should occur is specified, and each task is assigned to the appropriate role within the lab. This ensures everyone involved in the onboarding process knows what they need to do and the timeframe in which it is expected to be completed. In turn, the establishment of a standard operating procedure for staff onboarding provided the foundation needed to audit the process, hold those involved accountable for their assigned tasks, and provide them with feedback to improve their performance, as needed.

3.2. Reducing Material Stock Outs

Data were recorded in the material inventory spreadsheet over two and half months as part of the new inventory audit process implemented in the lab. These data indicated the percentage of materials with stock levels below the established minimums averaged 10.7%, which is a 4.8% reduction compared to the prior measure of the same metric taken before the new inventory audit process was implemented in the lab.

Different from the approach used to improve the lab's staff onboarding process (i.e., defining it in much greater detail), the existing process for using and reordering 3D printing materials was sufficient for its intended purpose. Instead, to address the issue of material stock outs, an entirely new process for periodically auditing the lab's inventory had to be created. The development of this new process also faced significant cost constraints, and, therefore, it leveraged ideas for what could be done using only existing/free resources.

4. Conclusion

This study contributes to the literature by demonstrating the practical application of Lean methods in an engineering research lab setting with implications for higher education institutions seeking to enhance efficiency and effectiveness in their research labs. Following the Education Lean Improvement Model (Waterbury, 2008; Waterbury & Holm, 2011) and utilizing an action research approach (Coughlan & Coghlan, 2002, 2016) in which researchers worked alongside lab management and staff to facilitate operational change, this study demonstrated how to apply Lean practices in an engineering research lab. In addition, it addressed aspects of an engineering reserach lab's operations not previously explored in the literature, including the lack of standard operating procedures and a deficit of supplies (Dagdeviren et al., 2020).

Specifically, this study helped the A.I.M. lab at the University of Houston improve its operational efficiency by onboarding staff more thoroughly and reducing delays in research projects due to 3D printer material stock outs. By standardizing the onboarding process and defining roles, this lab was able to reduce its average onboarding time. The implementation of a feedback form and an audit checklist further ensured the effectiveness of the improved process. In addition, the creation of a new process for periodically auditing the lab's inventory led to meaningful reduction in materials with stock levels below the established minimums. This was achieved by leveraging existing resources and implementing a system that was easy for users to navigate. Given that this study illustrated in detail the process improvement tools used in the two case examples presented, it can serve as a model for others working in research labs seeking to improve their operations.

Finally, because this study was conducted in only one engineering research lab at a public university, the specific results achieved through the solutions implemented may not be generalizable to other lab or university settings. Instead, it is recommended that others adapt the Lean tools and methods discussed in this research to fit the needs for improvement within their own research lab's operations. Future research could explore the application of Lean methods in other research settings and for additional operational aspects within research labs.

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