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Research Resiliency through Lean Labs

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Academic research groups, especially the ones directed by new junior faculty are under pressure to produce high-quality work timely while constrained by limited budget, resources, and lab space. A well-organized lab is crucial for a wide range of reasons, from keeping costs low, to protecting the health and safety of users. The focus herein is on developing lab-level systems that create a lean and productive space in the context of academic cleanrooms. The efforts made at implementing the 5S organizational methodology to improve cleanroom functions, including regulatory compliance, organization, and resource stewardship, is described. The quantifiable result is that chemical consumption spending is reduced by 41%, between 2018 and 2019, whereas materials consumption spending is reduced by 52%. Meanwhile, there is a 116% increase in the number of fabricated devices, showing greater output using less resources. This management system also proved itself to be beneficial during emergency situations. The recent COVID-19 pandemic is one such instance that showcased the ability to systematically ramp-down operations within 15 min, taking a huge burden away from the research group, and thus allowing to focus on what is most important during this time of crisis: the health and safety of the group and community.

1. Introduction

The term "lean production" was coined by John Krafcik at the MIT Sloan School of Management in his article "*Triumph of the Lean Production System*".[1] It was inspired by the Toyota Production System (TPS), which is considered to be a leader in the automotive manufacturing industry largely due to Toyota's seamless integration of lean principles in its daily operations.[2] Despite having originated in a manufacturing setting, lean principles can be adopted to fit in virtually any working environment.

Lean principles have been introduced in analytical labs, with the goal of eliminating the inefficiencies that take many forms in a lab space.[3] These inefficiencies include: lack of standard operating procedures, surplus or deficit of supplies, ineffective layout of space, and too much time spent on upkeep, all resulting in wasted or idle time by users.[4] The overall goal is to identify these issues before they happen, resulting in higher-quality work by lab users in a shorter period of time.[3] We have applied these same lean principles to our research lab structure at the Conformable Decoder's cleanroom facility, called "YellowBox" through a partnership with MIT Environment, Health and Safety (EHS), to achieve this goal.[5]

Although lean principles take on many different forms, our research group has chosen to focus on using the 5S methodology. 5S is a visually intuitive system that uses five guiding practices to organize a work space for efficiency and effectiveness: Sort, Set in Order, Shine, Standardize, and Sustain.[2] The implementation of this organizational methodology has helped us identify inefficiencies and provided improved operational performance, resulting in: 1) A safer lab space, 2) Faster experimental turn-around times, 3) Decreased raw material consumption, 4) Reduced cost, and 5) Improved quality of end results.

2. Safety

In our academic cleanroom facility, the 5S methodology has had a positive impact on applicable regulatory compliance and best practices. A major feature of 5S is that it is "primarily visual in nature".[2] The method "uses intuitive color-mapping to show function and placement, with the added benefit of reducing the amount of brain-drain associated with planning and executing a specific task".[2] In essence, there is no ambiguity as to where anything in the space belongs, whether it be a pair of scissors or a piece of scientific equipment or portable piece of furniture in the means of egress (**Figure 1**). New users entering the cleanroom will find its layout to be intuitive and easy to navigate. This feature and the associated safety implications were especially highlighted during our biannual Level II regulatory compliance inspections, conducted by MIT EHS. Safety professionals, who were unfamiliar with our lab layout, upon first-time entry were able to carry out compliance inspections with ease. To quote one member of MIT's EHS office; "With the application of 5S principles, the Dagdeviren Group has demonstrated a clear and

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substantial benefit to the overall health and safety of lab personnel and to their environmental impact. We hope that other labs will take note and employ the same principles".

Here, two facets of this methodology especially lends themselves useful to safety. On one hand, during their inspection, EHS officers require minimal time establishing the structure of the lab and where items are located. As a result, they are able to identify potential safety hazards or items of interest within seconds. This is due to the visually structured appearance of the lab, in which fewer mental calculations are required when visually scanning the entire floor space (Figure 1). In contrast, the very nature of 5S methodology complies with a multitude of the items from the inspection checklist. In fact, MIT's EHS department has indicated that our methodology is directly associated with 23 questions on its inspection checklist and indirectly related to many more.[6] Indeed, our lab has had no "findings" since the 5S method has been implemented, indicating high levels of regulatory compliance. For instance, the means of egress in the cleanroom is highlighted by our 5S vinyl floor tape, which indicates to users the proper placement of chairs and equipment on the facility floor space, while more importantly clearing the floor space of clutter that may block the means of egress (Figure 1). Again, this is just one way in which a lean lab principle reduces waste (in the form of wasted time), and allows users to instead focus on their work.

In addition, our methodology has an impact on safety in less obvious ways. In terms of housekeeping, it is a well-known tenet among EHS professionals that there is a direct correlation between housekeeping and accidents and injuries. A lab that is neat, orderly, and clean is less likely to have an accident. Our lab has had zero accidents, zero injuries, and zero near misses since it began applying lean principles in 2018.

3. Just-in-Time Ordering

Another example of regulatory compliance stems from the application of Just-In-Time (JIT) ordering, which is another industrial lean practice that can complement 5S. JIT ordering is defined as an "inventory management system with the objective of having just enough inventory readily available to meet current demand but avoiding excess".[6] In our lab, we use JIT ordering to complement 5S based on the concept of each inventory item's (e.g., chemical bottle) physical footprint on our shelf/floor space. This means that 5S vinyl tape marks the inventory item's physical footprint on the shelf space. Once that inventory item has been removed, we are visually left with an empty space highlighted by tape—a visual cue to order more. In our academic cleanroom, this system helps to eliminate inefficiency and encourage safe practices in a few different ways.[7] First, we are able to reduce the amount of chemicals that are wasted as a result of expiration. We only order new chemicals when we know they will be necessary for an upcoming project, and take careful note of expiration dates in our digital inventory system. This way, we do not run into the problem of "stocking up" on chemicals that could potentially be used, only to find ourselves having to dispose of them when they expire as a result of poor planning.

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Second, this system reduces the overall quantity of hazardous materials present in the lab at any given moment. The benefit can be easily demonstrated in, say, the event of a fire in the lab. Less flammable solvent available in the lab decreases the chemical loading on our floor and our building, which directly impacts the potential severity of the fire.

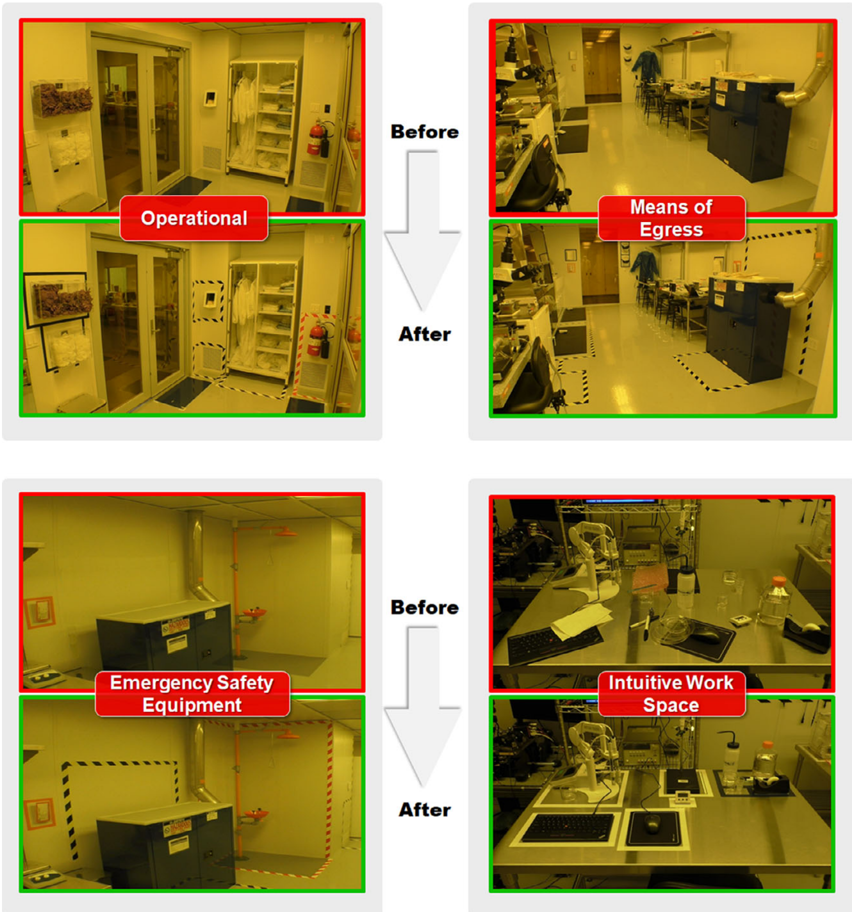

Figure 1. Comparison of the before-and-after images of our cleanroom lab facility with the 5S methodology. The before images (highlighted in red) show the lab space prior to the introduction of the 5S methodology. The after images (highlighted in green) show how 5S intuitively organizes the space, while highlighting lab safety equipment in the cleanroom space, such as the safety shower and chemical cabinet.

Third, ordering lead-time, a very critical component of the inventory management discipline, can be coordinated much more seamlessly under the 5S and JIT ordering practice. In the context of supply chain and inventory management, order lead time can be defined as the time from customer order received to customer order delivered.[8] In a less structured setting, it can often be the case that resources (i.e., chemicals, supplies) become fully consumed before or during the experiment. Implications to this may include unplanned research downtime, lower productivity, and a last-minute struggle to expedite orders and replenish inventory. By establishing a par-level system, based on known or measured user consumption, we can set the min/max inventory quantity of an item. By combining this system with knowledge of customer lead times for inventory ordering, the result is that, upon visual inspection of depleted inventory levels (i.e., the 5S visual cues mentioned earlier), we can seamlessly and intuitively coordinate lead-time and expected deliveries, without jeopardizing spending budget, research progress, or safety.

Finally, we eliminate wasted space in our cleanroom because JIT is also a system based on visual cues. Similar to 5S, there are physical 5S vinyl tape markers in both our stainless steel and plastic wet benches that denote individual spaces allocated for materials such as chemicals. It is not until a chemical has been fully depleted, and its bottle has been removed from its space indicating a need for replenishment, that we order more. Thus, the 5S system lends itself to making JIT ordering very efficient in the context of an academic cleanroom facility.

4. Decreased Raw Material Consumption

In lab environments, inefficiency often takes shape in the form of wasted raw material. This is problematic in both an environmental and economic sense. We compared the amount of raw materials used between 2018 and 2019 under the 5S methodology at our lab, and found that the system helped contribute to an overall decrease in waste and consumption across multiple categories. We saw a decrease in total expenditure on chemicals consumed, from \$3,461.92 in 2018, to \$2,016.63 in 2019 (**Figure 2**a). We also measured the total amount of chemicals consumed in liters and found that there was a slight decrease over time from 72.83 L in 2018 to 63.7 L in 2019 (Figure 2b). Finally, we measured the cost of miscellaneous materials (i.e., accessories, raw materials) used in the

Figure 2. Comparison of 2018 and 2019 in terms of the cost of consumed chemicals, amount of consumed chemicals, and cost of consumed materials. a) Comparison of the cost of chemicals consumed in the cleanroom between 2018 and 2019. Chemicals include: isopropanol (IPA), acetone, AZ 726 metal-ion-free (MIF), AZ 400K, SlyGard, 495 polymethyl methacrylate acrylic (PMMA), gold etchant, chromium etchant, buffered oxide etchant, PI-2545 nonphotodefinable, wet etch, Ecoflex 00-30, and remover PG. This shows that there was a reduction in overall spending on chemicals between 2018 and 2019. b) Comparison of the amount of chemicals consumed measured in liters in the cleanroom between 2018 and 2019. Chemicals include: IPA, acetone, AZ 726 MIF, AZ 400K, SlyGard, PMMA, gold etchant, chromium etchant, buffered oxide etchant, PI-2545 nonphotodefinable, wet etch, Ecoflex 00-30, and remover PG. This shows that there was a reduction in overall chemical consumption between 2018 and 2019. c) Comparison of the cost of materials consumed in the cleanroom between 2018 and 2019. Materials include: nitrile gloves, bouffants, beard covers, shoe covers, trionic gloves, BetaWipes, Petri dishes, floor mats, spec wipes, and aluminum foil. This shows that there was a reduction in overall spending on lab supplies between 2018 and 2019.

cleanroom, and saw a decrease in total expenditure on those items, from $2,016.56 in 2018 to, $960.00 in 2019 (Figure 2c).

In addition to the reduction in raw chemicals used, we have also seen a reduction in our hazardous waste stream. In 2018, 420 gallons of liquid waste were collected, versus 295 gallons in 2019. This reduction can likely be attributed to better efficiency in the context of our group becoming more acclimated to the 5S methodology. As in most labs, after our users complete their experiments in our cleanroom's wet bench, the chemicals are poured either down the chemical sink or into separate waste stream containers. Our goal is to minimize our footprint in the context of chemical waste generation. In an inefficient lab, however, many challenges to this may arise. For instance, cluttered work spaces may prevent users from locating Petri dishes or bowls of the appropriate size (i.e., smaller size) for their wet bench experiment, leading to excessive amounts of the chemical being poured into an oversized bowl, which generates more waste than necessary. As another example, poor communication tools inside the lab may also lead to higher waste generation in the form of missed opportunities to save and reuse batches for another round of processing. To elaborate, in academic laboratories chemical solutions may be utilized more than once, such as the reuse of photoresist developer solutions to develop multiple devices by multiple users. This is in contrast to high-volume manufacturing facilities where, due to potential yield and reliability concerns, such cost-saving practices may not be considered because of strict process-control measures. With these points in mind, we have uniquely adopted a concept from the lean manufacturing environment into our lean academic cleanroom lab—the Work-in-Progress (WIP) form—to facilitate better communication regarding ongoing research activities with other users. In our version of the WIP form, the forms themselves uniquely adhere to the 5S intuitive color coding system (i.e., they are highlighted in a highly visible orange color). In the context of waste generation, these WIP forms inform users of the dates and times of previous chemical usage, thus empowering the next user to make an informed decision as to whether or not they have the ability to reuse those chemicals safely.

5. Improved Quality and Quantity of End Results

As stated previously, lean laboratory principles focus on delivering results in the most efficient way in terms of cost, speed, or both, with the added goal of reducing our lab's physical footprint to maximize our floorspace. We found that through the 5S methodology, our lab's levels of output improved in a number of different categories from 2018 to 2019. We observed an increase in the amount of working devices that were produced in our lab. In 2018, we produced 24 fabricated devices on record, and in 2019 that number had more than doubled to 52 fabricated devices. These increases are indicative of streamlined processes and improved productivity in the cleanroom.

In addition, there have been other considerations that further highlight the improvement in productivity of our cleanroom. For example, in 2018, we had nine group members utilizing the cleanroom for various projects compared to seven group members in 2019. Despite this decrease in personnel, we still saw increases in the number of fabricated devices, showing greater results using less labor. Finally, the amount of time spent on cleanroom maintenance decreased dramatically between 2018 and 2019, going from an average of 60 min to an average of 15 min. Given that our working conditions remained the same from 2018 to 2019, these improvements in efficiency and output can be attributed to the improvement in adaptation of the 5S principles in our working space by our cleanroom facility users.

By defining our measures of success as working devices and cleanroom maintenance time, we are able to put the implementation of the 5S system into perspective and ask the important question: Is the methodology actually achieving what it sets out to do? We found the answer to be a resounding "yes". 5S played a major role in streamlining our efforts to work efficiently by reducing waste and other factors that could potentially weigh us down, and instead increase productivity and quality of work in the cleanroom.

6. Ramp-Down/Ramp-Up Time

Jay J. Bavel, an associate professor of psychology and neural sciences at NYU, recently published an article in which he reflects on the painful realities that he and his lab members had to face in mid-March when they were forced to ramp down.[9] He described canceled travel plans, lost networking opportunities, projects being stalled, an underlying anxiety about the lab's future—in other words, experiences to which all academic researchers can relate to right now, as academic labs around the entire country have been forced to shut down due to the COVID-19 pandemic. However, even during these times of uncertainty, Bavel describes a silver lining that our group, Conformable Decoders,[10] has also taken to heart: "We turned the conversation to ways we could learn something from the current pandemic and, quite possibly, make a positive impact on public health".[9] This line resonated with us because we have chosen to use this situation as an opportunity to reflect on aspects of our group that we are proud of, and that have shown resilience during this difficult time. As a result, our eyes have been opened as to just how key the 5S system is to our group's culture, and how it can benefit other labs when they reopen.

When lean principles are thoroughly ingrained into a lab's culture, it is easy to overlook or take for granted their day-to-day benefits. Indeed, when these systems become second nature, sometimes it takes an extreme external force, such as the COVID-19 pandemic, to really highlight the value. As a result of this unprecedented force, we found out that our group was capable of shutting down all cleanroom-related operations within about 15 min of being told that the MIT Media Lab would be moving toward a remote working environment. This streamlined shutdown was only possible because of the nature of our cleanroom set-up. Similar to what we see with our Level II safety checks, the 5S system lent itself extremely well to an emergency ramp-down scenario because it provided automatic regulatory compliance in areas such as communications, proper chemical and glassware storage, secured physical hazards (i.e., sharps), cleared means of egress and more. Using visual cues, it only took a few minutes to identify the necessary actions that needed to be taken during this unique scenario. Furthermore, when we do finally get to return to our cleanroom, we anticipate the same seamless and expedient process in terms of ramping back up. In the face of adversity and uncertainty, having a lean laboratory took a huge burden off our research group's shoulders, and allowed us to focus on what was most important: the health and safety of our group and our community.

7. Conclusion

We have seen lean laboratory principles help eliminate raw-material consumption and waste generation, increase efficiency, and decrease costs in our academic cleanroom, all while contributing to measurable improvements in our research output. We believe this model is not just suitable to our cleanroom facility, YellowBox—the process and the framework can be applied to a variety of different types of research and development laboratories. The general principles discussed in this article, such as using 5S for JIT ordering or adherence to regulatory compliance, are general enough to have applications in laboratories beyond our own. Benefits of this system will vary from lab to lab, with some seeing great value in the more obvious perks (i.e., lower costs, greater output), and others drawn in by the more subtle ones (e.g., seamless ramp-down strategy in the event of an emergency). It is also worthy to note that our contributions to published peer-reviewed journals increased during the course of 2018–2019 as an attributed productivity measure due to our management. We are proud of the success we have achieved in our first couple of years; but, we do not want our story to stop there. We believe that our methodology and ideology align closely with the goals set out by MIT EHS. Thus, we will continue to work together and identify new collaboration opportunities with other labs across the MIT campus and beyond. We believe our collaboration will be a starting point for junior faculty members to begin thinking about how to maintain their lab spaces; so that they can become lean, safe, and efficient, assuring the longevity of their research endeavors. Regardless of where each lab finds the most value, there is no denying that these lean lab principles can provide numerous distinct benefits.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

lean labs, research management, research resiliency, safety, 5S

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[1] J. F. Krafcik, *MIT Sloan Management Review*, Vol. *30*, Cambridge, MA **1988**, p. 41.
[2] C. Dagdeviren, Managing a Lab, **2018**, https://medium.com/mit-media-lab/managing-a-lab-6a1206c8c2d1 (accessed: March 2020).
[3] D. Lake, Pharmaceutical Online, **2012**, https://www.pharmaceuticalonline.com/doc/applying-lean-principles-in-the-analytical-0001 (accessed: March 2020).
[4] '5S' Lean Labs— MIT Media Lab, Conformable Decoders, EH&S, **2019**, https://www.youtube.com/watch?v=kEwkOxxN6KQ (accessed: March 2020).
[5] C. Dagdeviren, Medium, **2019**, https://www.medium.com/mit-media-lab/teaching-at-the-media-lab-fa3000c9129f (accessed: March 2020).
[6] MIT Environmental Health and Safety, Inspections: Level I and Level II, https://www.ehs.mit.edu/.lab-research-program/inspections-level-i-and-level-ii/ (accessed: March 2020).
[7] 'Pros and Cons of Just-In-Time Ordering.', **2016**, https://www.cleanlink.com/news/article/Pros-and-Cons-of-Just-In-Time-Ordering—19446, (accessed: March 2020).
[8] R. Joonas, Lead Time Terminology in Manufacturing, **2012**, https://www.leadtimes.org/, (accessed: March 2020).
[9] J. J. Bavel, Science, American Association for the Advancement of Science, 2020, (accessed: March 2020).
[10] C. Dagdeviren, MIT Media Lab, **2017**, https://medium.com/mit-media-lab/launching-a-lab-7b02413072ad (accessed: March 2020).