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Designing for the Future: Sensor and Gauge Assembly Work Cell Design

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by

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Abstract

Effective workstation designs are critical to the overall performance of a manufacturing department and efficient layouts are necessary. The purpose of this thesis project is to design a work cell for a local Baton Rouge manufacturing plant, BBP, with a goal to improve its spatial efficiency and flexibility to perform additional assemblies without sacrificing throughput. This project included process observations and analysis of operators in their initial workstations. The operators' verbal feedback and perspective were heavily taken into consideration when designing the new layout. The results show that based on the highly variable nature of their work, a linear series of individual u-shaped workstations is the optimal work cell layout for this facility.

Introduction

The mark of a successful facility design is one that understands that a facility is a dynamic entity and that the design is only as successful as its adaptability and ability to become suitable for new use (Tompkins et al., 2010). Over the past 30 years, BBP's business functions have evolved, while the facility layout has remained relatively stagnant. The company's original emphasis as a primarily sales focused organization led to the construction of a facility principally comprised of office space; however, BBP has recently shifted corporate priorities towards a greater emphasis on the manufacturing arm. Moreover, the COVID-19 pandemic and its radical effect on how work is performed has transformed the nature of in-office work at the company, with many administrative tasks having moved out of the shared office environment. This shift has brought further visibility to BBP's underutilization of their office space.

With increased customer demands for manufactured products on one side and an outdated production area constrained by the post-COVID reality, BBP is placed in a unique situation: to re-purpose or re-build. Despite being burdened with an underutilized office area, BBP's current intention is to start from scratch to design and build an entirely new facility; however, creative problem solving could be the cure to their current infrastructure constraints. Redesigning work cells to perform optimally and efficiently is the necessary first step in determining whether they can repurpose their current facility or should rebuild with an improved layout design. With that in mind, this project has two objectives. The primary objective is to reduce the footprint of the sensor and gauge assembly work cell. As a second objective, this project will serve as a case study for the company to reassess if a total re-build is truly the best or only option.

The work cell redesign from this thesis project resulted in a 51% reduction of the sensor and gauge assembly workstation footprint by incorporating the implementation of a circular product flow. In addition to the benefits of lower space requirements, the new design is flexible and nimble to accommodate BBP's various and evolving assembly needs: one operator independently assembling sensors, multiple operators working in a line to batch assemble sensors, and one operator working on a large sensor.

Background & Literature Review

An organization's work environment is crucial to its success due to the environment's direct impact on productivity, quality, and ultimately customer satisfaction. Poorly designed environment can lead to poor quality products, tardy deliveries, reworks and errors, and a resulting high cost. Additionally, poor design can lead to operator dissatisfaction, fatigue, and injuries. Due to the significant impact facilities have on companies, it is no wonder the US

Census found that US businesses invested over a thirty billion dollars on structures from 2005-2010, with 95% being spent on new facilities (Tompkins et al., 2010, p. 9). Moreover, between 1955 and 2010, “approximately 8% of the gross national product (GNP) had been spent annually on new facilities in the United States”, with the manufacturing industry representing 40% of that 8% (Tompkins et al., 2010, p. 10).

These statistics highlight the reality that both construction and renovation is costly and ties up human and working capital. Businesses spend significant money, time, and energy resources creating facilities with the goal of improving operations. Consequently, if businesses spend a significant proportion of the available resources and working capital, it is crucial to the company’s success that it is done thoughtfully so that the anticipated benefits materialize.

To this end, this thesis incorporated numerous techniques to analyze the optimal layout to provide the maximum benefits to BBP. The methodology primarily incorporated motion studies, ergonomics, and the implementation of lean principles to redesign the workstation. All relevant industrial engineering principles and industry standard approaches worked in concert business strategy incorporating lean principles.

Facility Planning

Successful organizations prioritize customer satisfaction at every phase, especially facility planning. Once considered a science with strictly delineated, limited, and static layouts being the industry standard, modern facility planning is now viewed as more of an artful strategy that can determine an organization’s ability to achieve supply chain excellence and thus enjoy success in the global marketplace (Tompkins et al., 2010). Because the financial and human resource costs associated with organization’s infrastructure is significant, this task has taken on increased significance. Facilities must be carefully and thoughtfully designed to help an organization achieve supply chain excellence. Some (Tompkins et al., 2010).

Lean Manufacturing

Optimizing overall performance is the objective of any company and since “one of the most effective methods for increasing productivity and reducing cost is to reduce or eliminate all activities that are unnecessary or wasteful”, organizations in a variety of industries utilize Lean principles (Tompkins et al., 2010). Lean can be defined as a “relentless pursuit of the perfect process through waste elimination” and is derived from the ‘just-in-time’ production system by Ohno Taiichi at the Toyota Production System (TPS) (Ohno, T. and Setsuo, M., 1988). Although these principles began in manufacturing, they have evolved into a flexible set of principles which are broadly applicable across most industries and universally applied in numerous business settings today.

Lean manufacturing principles categorize activities in two ways: ‘value-added’ or ‘non-value added’ and are from the perspective of the customer (Realyvasquez-Vargas et al., 2020). An activity that is ‘value-added’ is something the customer is willing to pay additional money for because it transforms raw material to meet customer requirements. On the other hand, ‘non-value added’ activities are activities that take up time, resources, materials, and space, but do not actively contribute to the transformation of the product or service. Lean terminology considers non-value-added activities as ‘waste’ and seeks to reduce as much, if not all, ‘non-value-added’ tasks, or waste, from every step of the process possible (Ohno, 1988).

While seeking to eliminate waste is a worthy mission and crucial to optimize output value, it is difficult to do without carefully analyzing and then specifying the type of waste and each step that contributes to this waste so that a root cause, and thus a true solution can be obtained. Research done by Patidar et al., (2017) further denotes waste as “driving waste”, which influences other wastes, versus “dependent waste”, which is influenced by other wastes, to prioritize waste reduction areas to those most significant to the operations.

Ohno and Setsuo (1988) categorize waste into seven types: transportation, inventory, motion, waiting, overproduction, over processing, and defects and describes them in the following way:

- **Transportation** waste is material movement that are not required to perform processing like moving parts between process departments. In a work cell, transportation waste is seen in activities such as operators moving materials or equipment from different locations in the work area.
- **Inventory** waste is any materials on hand that are in excess of the current customer demand and includes raw materials and work in process. In a work cell, inventory waste manifests as a surplus of raw materials or partially assembled parts or products.
- **Motion** waste is movement waste caused by people or machines and includes people searching for items, gathering materials, or moving between or within a workstation. Motion waste within a work cell is particularly vexing because it not only wastes time, but operator energy. This waste is caused by unnecessary operator motion like searching for tools and equipment in a different area of the work cell.
- **Waiting** waste is defined as any idle time that occurs when a component in the system is not ready for the subsequent step in the process and includes waiting for a machine to be available, waiting for parts to arrive, etc. In a work cell, this can occur if there are bottlenecks in the system.
- **Overproduction** is waste associated with producing more products than the customer demand and can be referred to as the “just in case” thinking where more product than necessary is produced “just in case” it is needed. This is referred to as the “ultimate waste”

and can be seen in work cells that produce a surplus of products in preparation for orders that have not been actualized.

- **Over processing** is waste caused by additional effort that does not add value from a customer's perspective. Work cell overprocessing includes activities such as paperwork, rework, and unnecessary tests and procedures.
- **Defects** waste is waste due to erroneous work that cannot be salvaged and thus not sold and includes materials lost to rework, chemical spills, and products that do not pass quality control. In a work cell, defects can occur when the environment effects the operator's ability to perform their job, like poor lighting effecting precision work.

Due to the nature and scope of this thesis project, waste due to motion and transportation are the primary focuses for this redesign.

Ergonomics

Ergonomics is the purposeful consideration of humans in and interacting with their work environment including the physical space, the tools used to perform the work, and the physical and mental strain on the human body to perform said work (Pulat, 1997). The primary objective is to create an effective environment that enables the task at hand to be performed by any available human resource. It is important for every work area and each task to be accessible and universally applicable to employees of various heights, physical strengths, and mental abilities. Each area and task must be designed to accommodate employees ranging across the entire employable age spectrum. Ensuring that tasks are not limited to a narrow population ensures numerous benefits to the business including ease of staffing and the ability to flex and exchange employees as business needs dictate. Conversely, a lack of consideration to ergonomics can be quite costly. Unintentional costs incurred can include less production output due to ineffective human/material relationships. Most poor ergonomic design can expect to result in some or all the following negative effects: increased lost time due to worker fatigue, higher rate of worker injury resulting in higher medical and worker's compensation claims and costs, higher material costs due to wasted material that result from increased worker mistakes, and lower-quality work because of a higher defect rate (Pulat, 1997). The types of ergonomics problems include anthropometric, cognitive, musculoskeletal, cardiovascular, and psychomotor.

While psychomotor problems relate to the problems that strain the psychomotor system due to job requirements or human capabilities, cognitive problems relate to the information processing requirements and if the person is overloaded or underloaded (Freivalds, 2013). Noise pollution can cause problems to workers in both areas, acting as a "performance moderating factor" (Molesworth et al., 2015). For instance, in a recent study testing noise's effect on memory and psychomotor performance, participants were exposed to simulated incabin aircraft noise at 75 dBA and tested their recognition memory, working memory, and reaction time (Molesworth et al., 2015). Participants' memory was also tested without noise but with a blood alcohol concentration (BAC) of 0.5 or 0.10 (Molesworth et al., 2015). These noise levels are comparable to noise experienced often in workplaces across the transport, construction, and manufacturing industries (Atmaca et al., 2005; Neitzel et al., 1999). The results found that noise exposure and alcohol degraded recognition memory performance similarly and there was a positive relationship between the use of noise attenuating headphones in reducing the effect of noise on performance (Molesworth et al., 2015). This research highlights the importance of proper consideration to noise mitigation during workstation design to ensure operators are not negatively impacted by noise (Freivalds, 2013).

Anthropometric problems relate to the interactions between human dimensions and the geometry of the functional space (Freivalds, 2013). Poor anthropometric consideration when designing the workspace can negatively impact workers exponentially (Realyvasquez-Vargas et al., 2020). For example, lack of consideration for the proper table height for an operator to perform a given task starts as an anthropometric issue but could transform into a musculoskeletal problem if repetitive poor posture is performed due to standing at an incorrectly sized table (Kamat et al., 2017; Gomez-Galan et al., 2018).

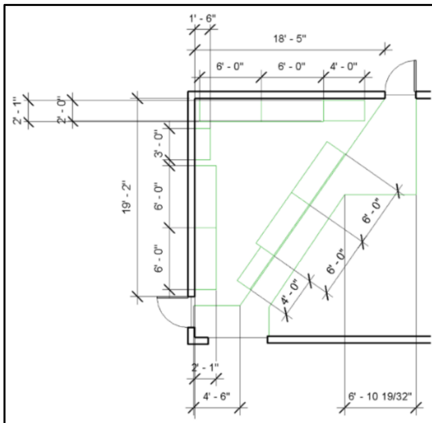
Musculoskeletal problems relate to the muscular and skeletal system and singular/repetitive trauma that could be endured (Freivalds, 2013). Pain and discomfort because of sustained neck positions is an example of a musculoskeletal problem caused by poor workstation design and is the most frequent reason for increased levels of sick leave in populations of workers with manual precision tasks (Adriens et al. 2002; Bepko and Mansalis, 2016; Graf et al. 2021). Research measuring the craniovertebral angle (or forward head angle) which is done by taking two lateral photos of a subject without a back support. The decrease in values of forward head angle is associated with greater incidence of neck pain, meaning the angle is significantly smaller in subjects with neck pain (Weon et al., 2010). Recent research has been conducted to determine the efficacy of the implementation of camera systems to elevate neck pain in workstations like BBP where manual work is performed often. The Graf et al. (2021) study found that there was a significantly larger forward head angle in both sitting and standing positions with the use of the camera. Not only did this research suggest camera systems can improve operator posture and reduce neck pain, but the study also confirmed that there was no loss of productivity with the use of the camera system (Graf et al., 2021).

Cardiovascular problems relate to the potential stress to the circulatory system (Freivalds, 2013). Although carrying heavy loads and performing aerobic activity are commonly referred to as causes for cardiovascular disorders, exposure to prolonged standing has also been found to cause cardiovascular disorders (Smith et al., 2018). A common solution to this problem is the recommendation of sit-stand desks, or desks that can adjust so that the worker can perform their job either seated or standing (Viggiani et al., 2020). Research suggests that the introduction of short sitting times in the workstation throughout the day leads to better "work engagement" (Jindo et al. 2020).

Methodology

Site Background and Objectives

This project was performed for BBP, a regional distributor of industrial instrumentation in Baton Rouge, Louisiana. As customer demands continue to grow, BBP is in search of an efficient modular workstation design that is easily replicable to implement as needed in any enhanced or new facility. BBP's Baton Rouge facility currently experiences most of their annual sales volume in their sensor and gauge product line. This product line appears to be enjoying sales growth in the marketplace; consequently, any improvements to the manufacturing capability and results of these products would significantly impact BBP's operations, customer satisfaction, and bottom line. The objective of this project is to develop a new workstation design for their sensor and gauge assembly process that is at least a 50% reduction from their current layout without sacrificing current throughput.



Initial Work Cell Layout

Product Category	Quantity
Gauge	767
Plate	16
RTD	727
Thermocouple	673
Thermometer	331
Thermowell	871
Transmitter	52
Other	259
Grand Total	**3,696**

BBP Throughout (6 months)

Figure 1 - Initial Site Documentation

BBP's initial work cell layout and throughput is shown in Figure 1. The area of the initial work cell layout, or $Area_{original}$, was determined to be 229.17 ft^2. With an objective of a 50% area reduction and using Equation 1, the recommended design's an area cannot surpass 114.59 ft^2. BBP's sensor throughput over the past six months was a total of 3,696 products. The recommended design must maintain or, ideally, improve upon these production levels.

Equation 1 - Area Reduction Calculation

$$\% \ Reduction = \frac{Area_{original} - Area_{final}}{Area_{original}}$$

Initial Layout Data Collection and Analysis

An understanding of current operations was first developed by measuring the current layout and spending several weeks observing operators assembling products and performing candid field interviews with operators throughout the day on their experience in the current layout.

Due to the variable nature of their assembly process, a work sampling study was performed to document the type of activity an operator was performing at a given point in time as well as their corresponding instantaneous position in the work cell. Additionally, a spaghetti diagram was created to document operator movement during the assembly process. The analysis of this data is shown below in Figure 2.

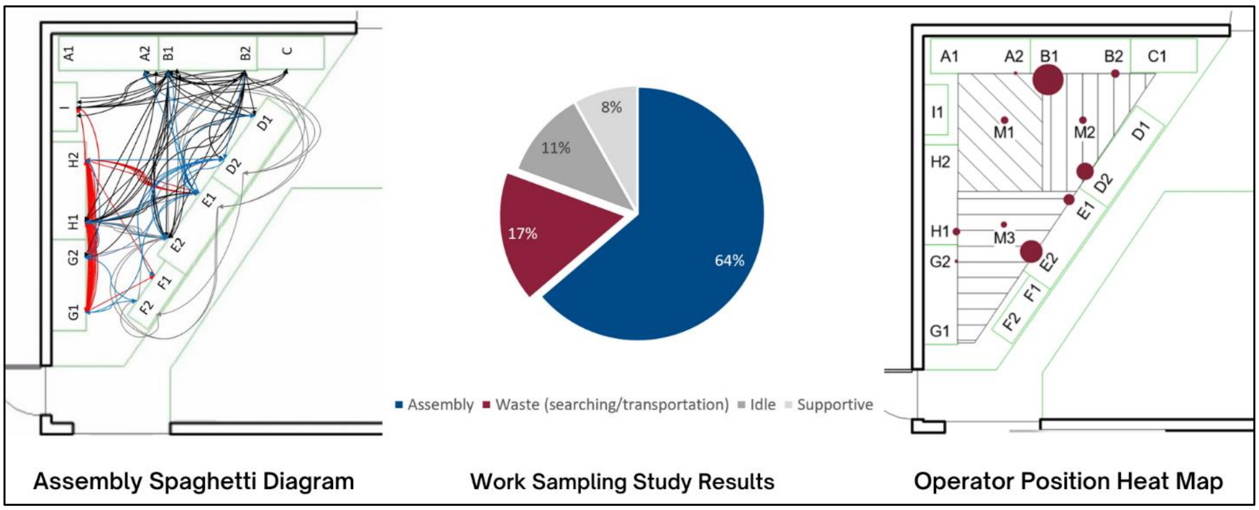


Figure 2 - Initial Layout Data Collection Results

The z-score calculation shown below in Equation 2 was performed to determine the confidence level of our work sampling results where N equals the number of observations, A equals the desired accuracy and p equals the percent of time spent on an element. Using the calculated z-score and a z-table, the work sampling's confidence level was then found. This confidence level was used to determine the likelihood that the true values of the work sampling results fell within the desired accuracy.

Equation 2 – Z-score Calculation

$$z = \sqrt{\frac{N * A^2}{(1-p)p}}$$

The spaghetti diagram observation was performed while four operators were working to assemble a single, large order. Each operator had a specific step in the overall process and each operator's movements are denoted with a different color.

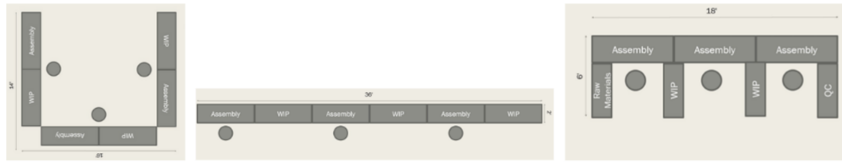
The observation process meaningfully brought visibility to the excessive amount of movement operators were performing during an assembly and the corresponding waste that can be attributed to this movement and transportation of materials. Operators would often travel back and forth between areas of the work cell searching for tools or transporting work in progress to the next location. Some areas of the work cell that may have allowed for operators to assemble with less movement were unusable because they held partially assembled products, or it was unorganized and cluttered with trash and/or tools not in use.

The work sampling study was performed over a two-week period with a total of 196 data points and observed three different operators. Random observation times were produced with the use of Excel and at these times, it was noted whether the operator was completing an assembly, idle, conducting supportive activities (engraving/glycerin filling), or searching/transporting (waste). The results of the work sampling study found that 64% of time was spent on assembly, 17% time spent was waste, 11% of time was spent idle, and 8% of time was spent performing supportive activities. Performing the z-score calculation resulted in a z-score of 2.56 which corresponds to a 99.48% confidence level with 5% error. This indicates that there is a 99.48% probability that the reality of each reported value fall within +/- 5%, meaning that the confidence interval for time lost to waste is [12%, 22%].

Using the instantaneous position data collected during the work sampling study, an operator position heat map was created to understand the location frequency of operators throughout the work cell. While the spaghetti diagram showed a large amount of movement in the work cell, the operator position heat map emphasizes that assemblies primarily take place in one location and do not inherently require significant operator movement.

Alternative Layout Assessment

Based on the initial analysis, three potential layouts, U shape, Line, and Spine, were created and compared against each other to determine the most effective option. Each work cell layout accommodates three workers. The most important metric to meet for the new work cell layout was the 50% footprint reduction. However, based on the initial layout observation results and industry best practices in ergonomics, a series of additional criteria was added for the comparison analysis. I was responsible for coming up with the alternative designs and performing the comparison assessment between each of the three alternatives. I then was responsible for presenting the results of the assessment to the group so that the recommended design could be identified and presented to BBP. A summary of the comparison assessment is shown in Figure 3.



OBJECTIVE	U SHAPE	LINE	SPINE
50% Footprint Reduction Met	✗ 2.36% REDUCTION	✗ 29.4% REDUCTION	✓ 52.9% REDUCTION
Minimize travel distance among workstations	✓	✗	✗
Optimize material flow within work cell for assembly-line style operations	✓	✓	✓
Material handling capability improvement	✗	✗	✓
Pneumatic tooling access	✗	✓	✓
Can accommodate larger assemblies	✗	✓	✓

Figure 3 - Alternative Layout Comparison

The first alternative modeled is the U Shape work cell layout which is formed with six tables, aligned in three sets of two in a U shape. The total area of this work cell is 224 ft^2 where each operator has one work-in-progress table and one assembly table. The advantages of this work cell layout are that it minimizes the travel distance between the other operator's workstations and optimizes the material flow within the work cell for assembly-line style operations because workers can easily pass along their work-in-progress to the next operator's table for the next step of the required assembly. However, there are also disadvantages to this layout. The most significant disadvantage is that there is only a 2.36% footprint reduction and thus the 50% footprint reduction objective is not met. Additionally, this layout is not as flexible as desired. The U shape limits material handling capability, does not provide access to pneumatic tooling for all workstations, and cannot accommodate larger assemblies.

The second alternative modeled is the Line work cell layout which is formed with six tables in a single line. This layout is the classic 'assembly line' layout. The total area of the work cell is 180 $ft^2$where each operator has one work-in-progress and one assembly table. The advantages of this work cell layout are that it can accommodate larger assemblies up to 12 ft, each workstation can have access to pneumatic tooling, and it optimizes the material flow within the work cell for assembly-line style operations because workers can easily pass along their work-in-progress to the next operator's table for additional assembly. Although there is a higher footprint reduction with the Line layout than the U shape, because it is only a 21.46% reduction, it also does not meet the 50% footprint reduction objective as set by BBP. Additional disadvantages to this layout are that it limits material handling capability, and it does not minimize the travel distance among workstations since it is in one long line.

The final alternative modeled is the Spine work cell layout which is formed with three tables against the wall in a straight line and four smaller, shelved rolling tables placed perpendicular to the tables to create a linear series of individual u-shaped workstations. This spine layout enjoys several advantages over the U shape and Line layouts. The total area of the work cell is 108 ft^2 which is a 52.9% footprint reduction, meeting the 50% footprint reduction objective. Another advantage is the flexibility to quickly reset for different types of assemblies depending on the current day's needs. The Spine layout also accommodates various categories and sizes of product assemblies. This configuration enables the operators to utilize the space in different ways depending on the assembly type. For independent assemblies, each operator has a rolling table to their right for raw materials on top and adequate space to assemble on the table against the wall. For batch assemblies, work-in-progress can be passed to the left and placed on the next operator's rolling table in readiness to then be assembled on the table by the following operator. Finally, for large assemblies of up to 18 ft, the rolling tables can slide out to create an aisle parallel to the line of assembly tables. Moreover, this layout provides access to pneumatic tooling for all workstations as well as optimizes the material flow within the work cell for assembly-line style operations. The only disadvantage of the Spine layout is that it does not minimize the operators' travel distance among the workstations, thus not reducing the potential for motion or transportation waste.

Layout Recommendation Decision

Based on this comparison analysis, the Spine work cell layout was determined to be the best option for BBP's planned workspace redesign because it met several of the requested criteria for a successful outcome. The Spine layout is the only layout which met the required minimum 50% footprint reduction objective. The Spine layout is also advantageous to BBP's expected growth projections because it is replicable based projected increasing production needs and provides footprint flexibility to adapt to an acceptable layout for every type of assembly the operators currently perform.

A key desired outcome of a workspace redesign included improving time required for a successful assembly of the components sold and serviced by BBP operators and reducing wasted operator time. An expected time savings approximation with the implementation of the recommended design was performed by analyzing the initial work sampling results and isolating the search and transportation activities that occurred outside of the operator's given workstation to determine how much waste would be eliminated with more defined workstations like the recommended design. Through this study, it was determined that those isolated activities made up an estimated 45% of the overall time lost to waste, or 8% of the aggregate assembly time.

Operators assemble sensors and gauges Monday through Friday between 11:00 and 14:00 with a 30-minute break for lunch which equates to 2.5 assembly hours per day or 12.5 hours per standard work week. Referencing the work sampling study that found 17% of aggregate assembly time wasted, this means that 0.425 hours (about 26 minutes) are lost to waste per day per operator, or 111.01 hours annually per operator if assemblies occur 261 days out of the year. Assuming an annual shop rate of $20 per hour, this equates to $2,220.20 per operator in labor costs spent on non-value-added activities. The recommended layout's 8% reduction in time lost to waste means BBP will save an estimate 51 hours annually per operator. These 51 hours of expected time savings can be reallocated to fit BBP's needs. Assuming average operator assembly time to be 10 minutes per product, the expected time savings would result in an estimated 306 additional assemblies annually.

In addition to quantitative analytics informing this decision, operator feedback was also taken into consideration. Earning the buy-in of the staff on the production floor is a crucial component to any successful improvement project. Operator buy-in can and often is the 'make or break' factor in determining if a redesign initiative is a success or failure. As noted in Ikuma et al. (2011), "process ownership" was found to be highly effective for achieving worker buy-in and increasing the chances implementation success. Over the course of the project, based on the operators' involvement in the project's ground floor of data collection and interviews, BBP staff felt emboldened to begin independently taking steps to adjusting their sensor and gauge assembly work cell. These iterative improvements produced a similar layout to the layout we ultimately recommended. While their adjusted layout addressed some issues, it did not meet the 50% reduction and did not significantly reduce operator movement. While these mid-project adjustments caused complexity in obtaining accurate data collection and interviews over the lifecycle of this project, the operator enthusiasm was a welcome factor. These adjustments, spear headed by the operators themselves, showcased that the operator buy-in necessary to successfully complete any improvement project was present.

Implemented Layout Data Collection & Analysis

Management accepted the recommended layout and implemented it in late Fall 2021. The implemented layout, seen in Figure 4, while not an exact replica of the recommendation, had a total work cell area of 112 ft^2 which is a 51.13% footprint reduction, meeting the 50% footprint reduction. Additionally, the previously identified benefits of the recommended layout were still achieved with the implemented layout. The primary difference between the implemented layout and our recommended layout is the position and use of the rolling carts. The recommended design had the rolling carts against the table, creating three individual stalls, each 40 inches wide. Due to the resource location constraints in the current facility like outlet location and peg wall location, BBP had to set tables farther apart than the recommended design and thus put the rolling carts in between those tables. This resulted in each operator having a full 6 ft long table of assembly space as well as two rolling carts per station instead of one. There was no cost of implementation because all tables and rolling carts were also used in the initial layout.

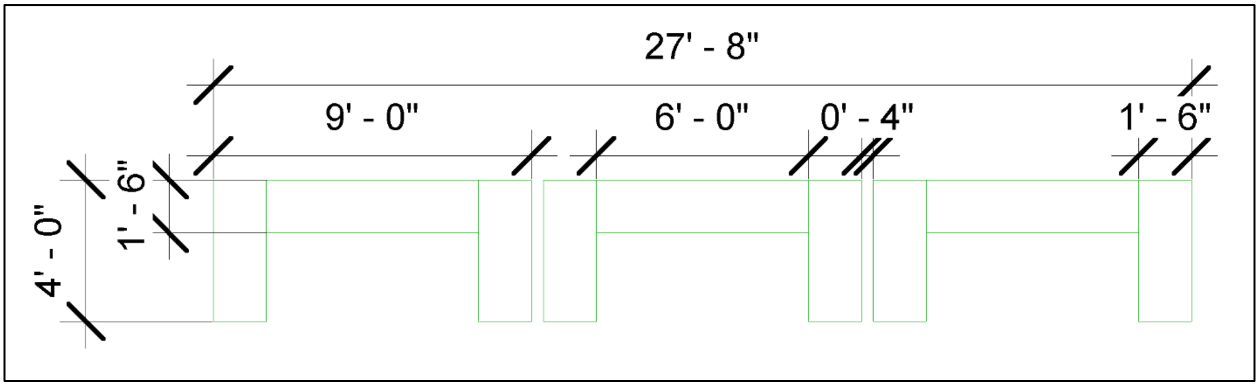


Figure 4 - Implemented Layout Documentation

Results

Three operators were observed over a two-week period to collect 296 data points. Random observation times were produced with the use of Excel and at these times, it was noted whether the operator was completing an assembly, idle, conducting supportive activities (engraving/glycerin filling), or searching/transporting (waste).The results of the work sampling study, seen in Figure 5 performed while observing the implemented layout found that 57.77% of time was spent on assembly, 10.14% time spent was waste, 10.14% of time was spent idle, and 21.96% of time was spent performing supportive activities.

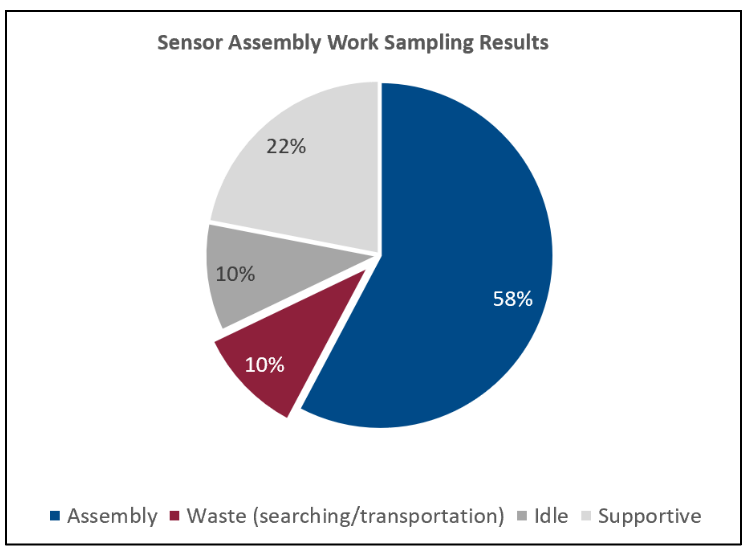


Figure 5 - Implemented Layout Work Sampling Results

A total of 296 data points were collected, and the z-score calculation resulted in a z-score of 2.85, corresponding to a confidence level of 99.78% with 5% error. This indicates that there is a 99.78% probability that the reality of each reported value fall within +/- 5%, meaning that the confidence interval for time lost to waste for the implemented layout is [5.14%, 15.14%]. indicates the implemented layout contributed to a 40.35% reduction in time lost to waste. This equates to approximately 0.171 hours (about 10.3 minutes) saved per day per operator, or 44.76 hours saved annually per operator. This waste reduction saves approximately $895.20 annually per operator in labor costs spent on non-value-added activities. Additionally, if operator assembly time is assumed to be 10 minutes per product, the calculated time savings of the implemented design results in an estimated 268 additional assemblies annually per operator. BBP could use the saved 44.76 hours to cross train operators to assist in other product departments such as the valve department or have available staff if they develop an entirely new product or business line that requires operator time. Conversely, BBP could choose to reduce staff headcount if reducing Human Resource costs are a mandate in the future.

Discussion

The purpose of this project was to determine a better work cell layout to support BBP's efforts in meeting a growing customer demand as well as investigate if a facility re-build is a necessary venture for the company. The results indicate that a linear series of individual u-shaped workstations is the best work cell layout for the nature of BBP's work.

Process observations and motion studies were performed in the beginning and end of the project to capture operator activity and compare the impact that the introduction of lean principles and ergonomics had on the system. Overall, the team observed a drastic decrease in operator motion due to searching for materials as all materials were stored and kept at their individual workstations. Material transportation waste was also significantly reduced due to the incorporation of the rolling carts at each station.

One limitation to our data is the operator turnover that occurred between our initial data collection and final data collection of the implemented layout. Between these periods of time, all except one operator were moved to different roles and new operators were brought on for assemblies. While collecting data to capture the operators interacting in the implemented layout, it was clear during observations that the new operators were assembling slower than the previous operators; however, the team does not believe it was due to a layout issue, but instead a symptom of the high operator turnover that occurred between data collection periods. In addition, BBP's management decided to change the assembly process which may have further skewed data. Despite these limitations, our data still showed a 40.35% reduction in time waste. However, more data would need to be collected to confirm that the implemented layout does not negatively affect assembly time and overall throughput.

From an ergonomics perspective, many areas of the workstation were already using anthropometric best practices like appropriate table height and depth, adequate foot clearance, and reasonable maximum arm reach, given the size of the operators. Moreover, each operator had access to foam mats they could stand to make standing for long durations more comfortable, aiding in the prevention of potential musculoskeletal problems. However, in the future, additional recommendations to improve workstation ergonomics could be made. Recent research has supported a correlation between increased productivity and safety because of implementing Lean and emphasizing ergonomic best practices (Ikuma et al. 2011). BBP's operators spend a considerable amount of their assembly time in sustained forward neck positions performing manual work which can lead to harmful biomechanical effects in the future like disc herniations (Bunch, 2016). The harm in sustained forward neck positions primarily occurs when workers are in the field "reaching and looking straight or upward while leaning the trunk forward" (Bunch, 2016). Given this, further observations and analysis are recommended to determine if the use of novel cameras at each workstation would improve performance and prevent spinal injuries, like the study discussed in the background of this thesis done by Graf et al (2021). Additionally, incorporating adjustable sit-stand tables could be beneficial since BBP operators remain on their feet for most of the day which could lead to cardiovascular disorders (Smith et al., 2018).

Conclusion

Due to a fundamental change in BBP's nature of work, physical space was a constraint and a new facility felt necessary. This project illustrates the impact dynamically designed and spatially efficient entities can have in transforming a facility's potential production capacity. To that end, the potential production increase caused by the sensor and gauge assembly work cell redesign serves as a case study in the advocation of repurposing he current facility instead of starting from scratch. By utilizing work sampling and motion analysis techniques, the sensor and gauge assembly work cell footprint was reduced by 51% and there was a 40.35% reduction in time lost to non-value-added activities.

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