# Improving Changeover Efficiency in Opticap® XL Encapsulation Process

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**Abstract**

This project studied MilliporeSigma's changeover efficiency within the Opticap® XL encapsulation process to alleviate throughput issues associated with increasing demand. Our team conducted time and observational studies, together with stakeholder interviews, to identify and prioritize improvement areas. We developed a production schedule optimization tool, Single Minute Exchange of Dies analysis for changeover tasks, and conditions to streamline melt-check procedures. We recommend our deliverables be implemented to improve changeover efficiency, and estimate that 230 minutes can be saved in changeover time over two days.

**Acknowledgements**

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- David Plourde, Operations Manager
- Scott McGillivray, Opticap® XL Schedule Planner
- Opticap® XL Production Lead
- Material Handler Lead
- Quality Engineers

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## Authorship

This report was written equally by Serhan Delareyna, Emily Doherty, Samantha Kwan, and Nicolas Riart. Sections of the report were initially drafted by an individual, however each section was revised and edited in a combined group effort to comprise the final report. The mathematical formulation of the optimization model was devised by Professor Andrew Trapp and implemented in Excel and VBA as a team. A majority of coding for the model was completed by Serhan Delareyna.

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# 1 Introduction

Within the United States, the life sciences industry is one of the country's largest markets encompassing biotechnology, medical technology, and pharmaceuticals (*Global - Pharmaceuticals, Biotechnology & Life Sciences*, 2012). Because this industry is steadily growing and directly affects consumers, the Food and Drug Administration (FDA) oversees it and mandates specific regulations. In addition to FDA regulations, economic and time factors are considered when manufacturing and distributing health care products. Due to these regulations, manufacturing can be disrupted and production times may be adversely affected. Bio-manufacturing companies use extensive resources to properly prepare and install filter elements, sterilize the production area and filter elements, and maintain the facility (Rios, 2003). This consideration, in addition to the Affordable Care Act, which provides better health security by expanding coverage, lowering healthcare costs, and enhancing the quality of care (Affordable Care Act), has led to the need for innovation in the industry.

Life sciences companies have adopted single-use equipment into their manufacturing process to help reduce the burden caused by FDA regulations during manufacturing. Significant benefits to single-use equipment are the reduction in cross-contaminations, as well as faster, more flexible product changeover (Eibl & Eibl, 2010). Additionally, disposable equipment has improved process safety, environmentally-friendly cleaning and sterilization, and reduced time, cost, and facility footprint (Eibl & Eibl, 2010). Furthermore, because single-use systems are made from plastic, disposing in an environmentally-friendly manner can help alleviate any detrimental impact to the environment (Olawuyi, 2013).

MilliporeSigma is a leading manufacturer of single-use filters for the life sciences and beverage industries. These products are essential to MilliporeSigma's customer base as their customers utilize these filters to separate "suspended particles from the fluid through a porous material in which the fluid can pass while the suspended particles are retained" ("Filtration," 2009). This process is otherwise known as filtration. MilliporeSigma's Opticap® XL products, one of MilliporeSigma's top-selling filtration products, currently run at a very high level of capacity utilization. Despite pending capacity upgrades planned for the second half of 2015, utilization is anticipated to be above desired levels in 2016. Reduction in changeover time will directly enhance asset availability and delay or even avoid future capital investment. We believe that through simplified tooling and process optimization, changeovers and the need for technical staff to accomplish them can be reduced.

The goal of this project is to reduce changeover frequency and complexity in the Opticap® XL encapsulation process. The scope includes production scheduling and operational procedures. In order to achieve the goals, our team set the following objectives:

1. Identify areas of improvement
2. Evaluate and prioritize the areas of improvement
3. Develop and potentially implement three improvement strategies

Our first area of improvement focused on the optimization of MilliporeSigma's production schedule in which the team delivered an optimization model to improve the sequence of lots in the production schedule. Next we analyzed the standardization of changeover tasks in which we delivered a standardized sequence of changeover tasks through Gantt charts and standard operating procedures. Finally, we looked at redesigning the melt check procedures and produced a set of procedures to be reviewed by the quality team at MilliporeSigma. We believe the implementation of our deliverables will substantially improve the changeover frequency and complexity in the Opticap® XL production lines at MilliporeSigma.

In continuation of this report, Chapter 2 presents background research concerning the context of our project. Chapter 3 provides information on the methods that we utilized to achieve our objectives. Chapter 4 presents the results and analysis of our methods that describe our deliverables. Chapter 5 describes our conclusions, impact of our deliverables in reducing the changeover time, and recommendations based on our findings. Lastly, Chapter 6 contains our overall reflections on our work with MilliporeSigma and suggestions for future research.

# 2 Background

The background chapter begins with MilliporeSigma's company overview and its role in the bioscience industry with the production of filters. The following sections discuss the Opticap® XL filter, its manufacturing process, and changeover procedure. In addition, this chapter provides research on past projects related to MilliporeSigma's Opticap® XL changeover procedure, lean manufacturing, and modeling tools.

## 2.1 EMD Millipore

EMD Millipore, founded in 1954, is a billion-dollar company operating in the life sciences industry. Acquired in 2010 by Merck KGaA, Darmstadt, Germany, EMD Millipore became Merck KGaA's, Darmstadt, Germany, life science tools division and produces over 60,000 different products. However, on September 22, 2014, Merck KGaA, Darmstadt, Germany and Sigma Aldrich publicly announced their acquisition agreement ("Sigma-Aldrich Shareholders Approve Merger With Merck," 2014), which neared closing on November 10, 2015 ("Sigma-Aldrich and Merck KGaA, Darmstadt, Germany, Obtain EC Antitrust Approval and Work Toward Closing Planned Acquisition," 2015). With the acquisition of Sigma Aldrich, Merck KGaA, Darmstadt, Germany has rebranded EMD Millipore as MilliporeSigma. Merck KGaA, Darmstadt, Germanyand MilliporeSigma products are known worldwide for their quality and performance in the life science industry. MilliporeSigma acts as a supplier to scientists, engineers, and researchers, ensuring that all facets of the life science industry have access to their products ("Our History," 2015).

MilliporeSigma is divided into three business sectors (Figure 1): Bioscience, Lab Solutions, and Process Solutions. The Bioscience division focuses on delivering products to the academic and pharmaceutical environments. MilliporeSigma Lab Solutions' goal is to ensure that all products are cost effective and uphold their quality standards. The Lab Solutions' products, water purification systems, and microbiology testing solutions are used in laboratories among various industries. Finally, the Process Solutions' products are used by drug manufacturing companies ("The Merck Group: Business Sectors and Businesses," 2015). With these three subdivisions, MilliporeSigma is able to help customers succeed in research, development, and production.

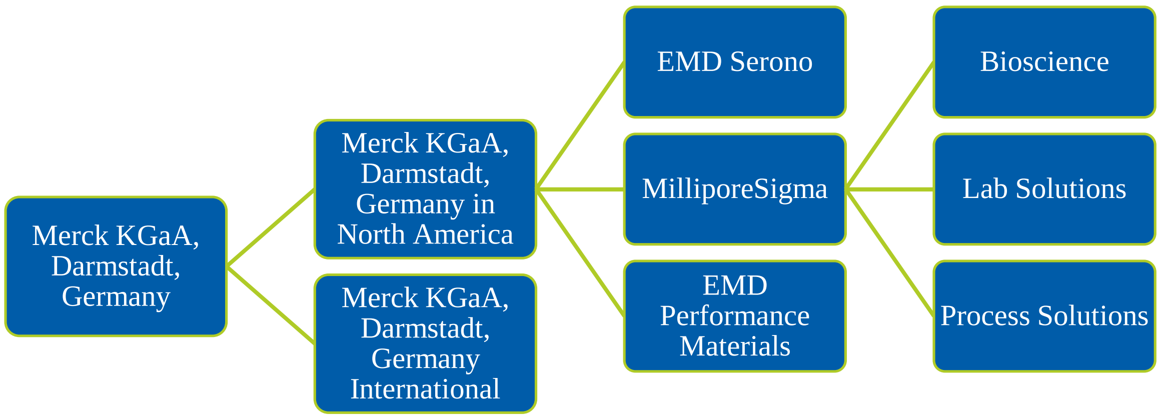


*Figure 1 Merck KGaA's, Darmstadt, Germany Organizational Structure*

Merck KGaA, Darmstadt, Germany and MilliporeSigma's goal is to "deliver entrepreneurial success through innovation" ("Mission Statement," 2015). Worldwide, MilliporeSigma has 28 manufacturing sites and 10,000 employees in 66 countries ("Our History," 2015). Their headquarters are located in Billerica, Massachusetts and the distribution center is in Taunton, Massachusetts. The Jaffrey, New Hampshire site is considered a Manufacturing Center of Excellence by MilliporeSigma, has more than 800 employees, and is where our project took place (Hocter, 2015).

MilliporeSigma is an industry leader that includes competitors Pall Corporation and General Electric Healthcare in the production of disposable or single-use filters (Hocter, 2015). These capsule filters save customers time and money that is usually lost while assembling, cleaning, and validating stainless steel housings. Every disposable filter produced by MilliporeSigma must pass an integrity test to ensure the filters meet quality standards ("Opticap® XL and XLT Disposable Capsule Filters with Milligard Media - Dairy," 2015).

The two disposable filter types produced by MilliporeSigma are Tangential Flow Filtration (TFF) and Normal Flow Filtration (NFF) filters. The differences between TFF and NFF are related to how the solution travels and what the filter collects. In TFF (Figure 2), the solution travels by the surface of the membrane filter where the difference in pressure pushes components through the membrane pores. The remainder of the solution continues to flow through the filtration process (General Electric Biosciences, 2014).

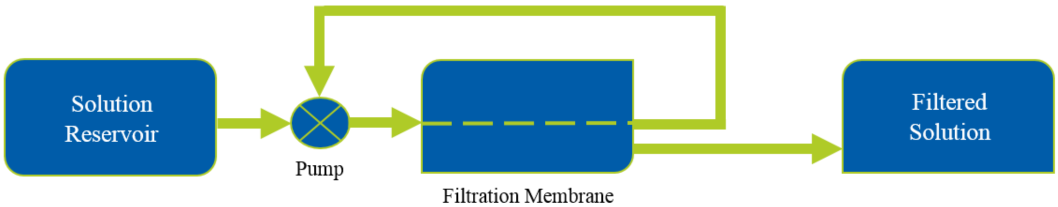


*Figure 2 Tangential Flow Filtration Diagram*

On the other hand, during NFF (Figure 3) the solution travels perpendicular to the filter. The membrane in this filtration retains all components that do not pass through the pores due to the size of the components. Over time, the flow is reduced due to the residual build up in the membranes and requires the NFF to be replaced (General Electric Biosciences, 2014). The following sections will discuss the Opticap® XL's primary applications, manufacturing process, and MilliporeSigma's current state of production.

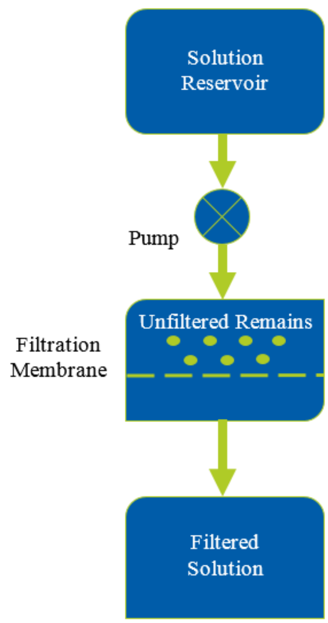


*Figure 3 Normal Flow Filtration*

## 2.2 Opticap® XL

Opticap® XL is a NFF disposable capsule used in primary pharmaceutical applications such as cell culture media, final aseptic fill of small volume parenteral, large volume parenteral, plasma proteins, and serum. Table 1 provides a description of the pharmaceutical applications for Opticap® XL.

| Pharmaceutical Applications | Description |
|---|---|
| Cell Culture Media | Removes particles and colloidal contaminants without impeding the flow of vital constituents |
| Buffer Filtration | Provides a means of rendering buffer solutions sterile by creating a microbial barrier capable of trapping common bacterial contaminants |
| Final Aseptic Fill of Small Volume Parenteral | Increases the service life of downstream sterilizing filters to remove colloidal and particulate contaminants |
| Large Volume Parenteral | Increases the service life of downstream sterilizing filters to remove colloidal and particulate contaminants |
| Plasma Proteins – Human Albumin | Removes colloids, aggregated and non-product proteins, lipids and particles before downstream purification without holding back fractions of interest. |
| Serum | Removes colloids, aggregated and non-product proteins, lipids and particles from serum before final sterilizing filtration without holding back fractions of interest. |

*Table 1 Pharmaceutical Applications for Opticap® XL*
*("Opticap® XL and XLT Disposable Capsule Filters with Milligard Media - Beer Processing," n.d.)*

The disposable feature of the Opticap® XL reduces time and exposure associated with assembly, cleaning, and validation in comparison to stainless steel capsule filters. The Opticap® XL is reliable in sterility and cleanliness; in effect it eliminates cross-contamination. MilliporeSigma produces the Opticap® XL in compliance with ISO 9000 Quality Systems Standard and is extensively tested for quality assurance throughout production ("Opticap® XL and XLT Disposable Capsule Filters with Milligard Media - Beverage Processing," 2015). MilliporeSigma produces multiple types of Opticap® XL which differ in cartridge size, fitting combinations, capsule housings, and membranes ("Opticap® XL and XLT Disposable Capsule Filters with Milligard Media - Beverage Processing," 2015). Additionally the product can differ in sterilization grades which include autoclavable, gamma irradiated, and gamma compatible.

### 2.3 Encapsulation Process in MilliporeSigma's Jaffrey Plant

Encapsulation is one of the final processes for MilliporeSigma's Opticap® XL products prior to becoming a final product. Encapsulation is the covering of a device to protect it from the surrounding environment ("Potting & Encapsulation," 2015). The encapsulation process is one of the main functions of MilliporeSigma's Jaffrey Plant (Figure 4, ("Jaffrey, NH Maps," 2015)), and is the main focus of this project.


*Figure 4 Project Site Location*

MilliporeSigma's Jaffrey Plant dedicates three production lines for the encapsulation process of Opticap® XL products, XL1, XL2, and XL4. The production lines operate five days a week, three shifts per day, with an optional weekend shift depending on the need for production.

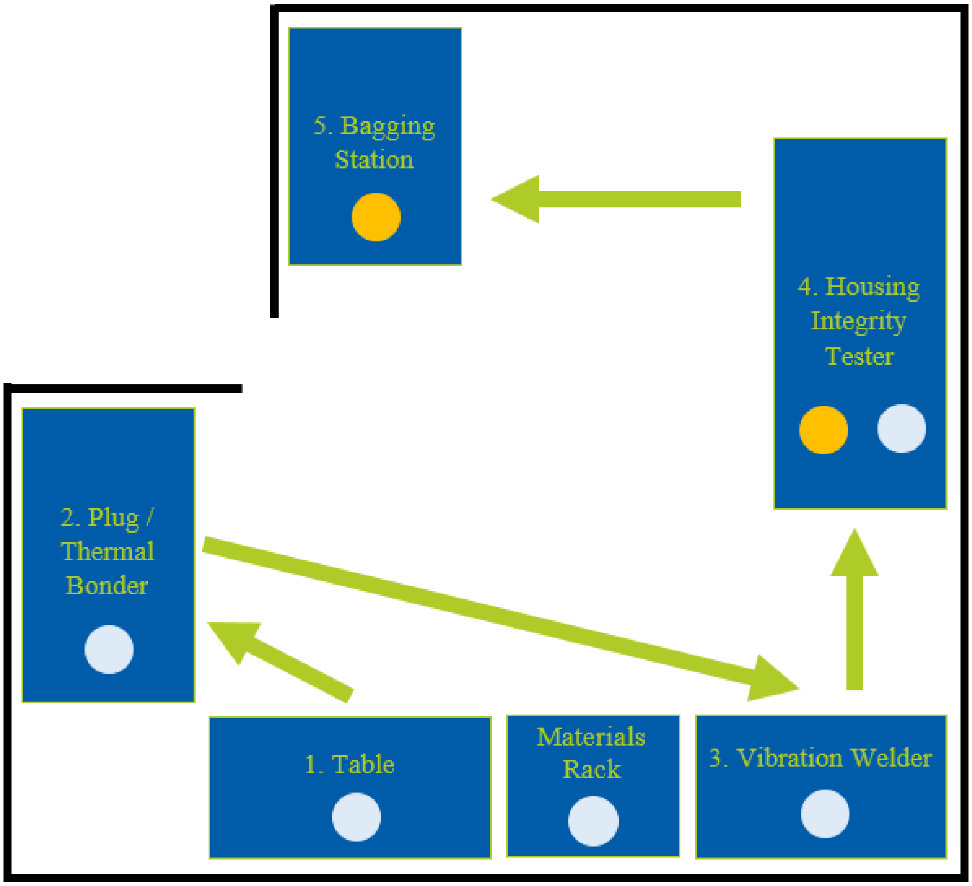


*Figure 5 Facility Layout of Production Line XL1*

Production lines XL1 (Figure 5) and XL2 (Appendix A: Production Lines Facility Layouts) are similar in characteristics, as both lines include one bonder machine, one welder machine, one tester machine, and one bagger machine. Production line XL4 (Appendix A: Production Lines Facility Layouts), however, has two bonder machines, one welder machine, two tester machines, and one bagger machine. Since the cycle time of the welder is half of the other machines, this production line is added by MilliporeSigma to balance cycle times and improve efficiency. This allows MilliporeSigma to run a higher volume of filters in the XL4 production line. The scope of our project starts from the transportation of the materials from the warehouse to the encapsulation process, and the packaging process that follows the encapsulation (Hocter, 2015).

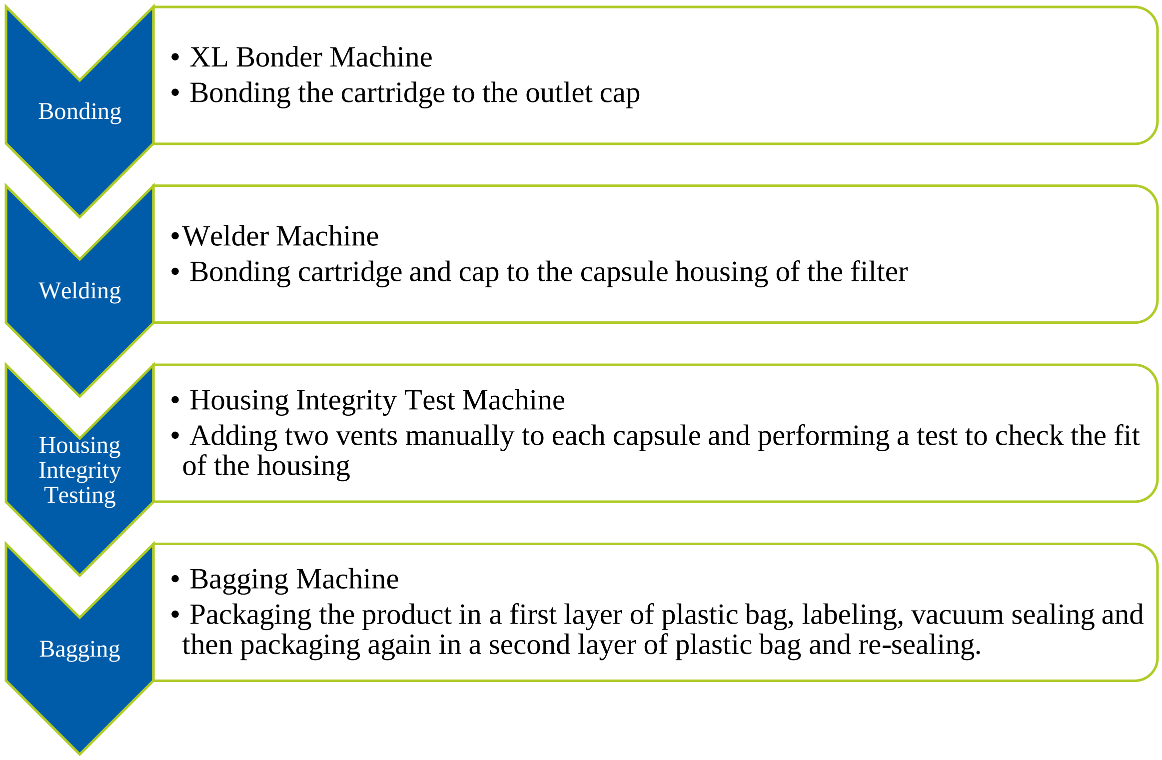


*Figure 6 Encapsulation Process at MilliporeSigma*

The operators of the encapsulation production lines mentioned earlier complete four major steps, which are illustrated in the process chart in Figure 6. After these four steps are completed, all final products are packaged and become ready for storage or delivery (Hocter, 2015).

Four operators currently run the XL1 and XL2 production lines, two on each respectively. One operator is responsible for placing the cartridge and its respective cap into the bonder and then placing it into the welder. After the welding process, the operator picks up the product and places it into the housing integrity test area. Then the second operator packages the product using the bagging machine. These lines are mostly used for production of lots with smaller sizes. Since three, five, and ten inch cartridge size filters have less demand, they tend to have smaller lot sizes, and therefore filters with those cartridge sizes are produced in cells XL1 and XL2. Unlike the other cells, the XL4 production line requires three operators due to the additional throughput the extra machine creates. The first operator is responsible for placing the filters into the bonder machine, a second operator is responsible for the welder and the housing integrity test, and the third operator is responsible for the bagging process. This line is most often utilized to produce two and four inch cartridge sized products, because it can handle the larger demand and lot sizes for these filters (Jaffrey Facility Observations, 9/10/2015).

The bonders have an average machine cycle time of one minute and the welder has an average cycle time of thirty seconds. These cycle times are standard and do not include the manual work done by the operators of inserting a piece in the machine and removing it. The housing integrity test also has a cycle time of one minute.

The processes mentioned above are for a line that is assumed to be running and for a single type of product. However, in a typical day there are a variety of Opticap® XL products going through the same line, requiring changeovers. Changeovers are performed in between the production of different batches and requires significant time to ensure production for the next batch to be performed correctly.

## 2.4 Changeover Time

Changeover time, also known as setup time, is an essential concept in every production process that features changing materials, dyes, and machine recalibration (etc.). After the production of a product is completed, a sequence of changeover activities is performed on a machine prior to starting the production of another batch. During these activities, the machine stands idle. Hence, reducing changeover time is necessary to increase productivity of a machine, especially in production lines with small batch or lot sizes that lead to a large number of changeovers (Singh & Khanduja, 2010).

As plants are unable to dedicate a production line to a single product type, changeovers are inevitable for flexible production. Changeovers require basic work such as paperwork, cleaning, and tooling modifications that need to be performed depending on the product type and its production system constraints. However, non-value added activities that increase the duration of changeover times are performed in actual practice.

## 2.5 Time Studies

A variety of methods may be used to further understand a process's complexities and find possible ways for improvement. A time study is a method that encompasses both objectives. A time study is a "systematic observation, analysis, and measurement of the separate steps in the performance of a specific job for the purpose of establishing a standard time for each performance, improving procedures, and increasing productivity" ("Time and Motion Study," 2015). It can highlight possible areas to improve based on the time the process takes, as well as record improvements. Conducting time studies includes several steps. The first is the preparation process that includes knowing the purpose for the time study, understanding the process being measured, measuring its components in a representative time period, and gathering a good sample size for reliable results ("Preparing to Measure Process Work with a Time Study," 2015). The second step involves choosing a process and the respective operator to observe. Next the researcher would devise a data collection sheet. Lastly, the researcher observes the process and collect times from the start to finish. Using time studies, observers can compare the baseline data to the data resulting from the improved solutions ("Industrial Engineering and the Engineering Digest," 1915).

### 2.6 Current State: Changeover Process in XL1, XL2, and XL4 Production Lines

Specifically for the Opticap® XL products, changeovers are performed by the operator and involve several steps, including changing parts to fit a specific capsule or cartridge size. These steps are dictated by standard operating procedures (SOPs), which specify tasks to execute in order to complete the changeover process. However, the SOPs do not include the order in which to complete the tasks. The changeover tasks include operations both before and after running a lot.

Before running a specific lot of filters, the first step is to check the work order information. During this process the operator counts the number of cartridges and also checks if the cartridges' lot number matches with the number on the batch record, and the correct number of labels have been provided. This allows operators to plan what changeover is needed in order to start production. Each machine in the encapsulation process has specific SOPs.

For bonding, the bonder machine secures the parts in place with the help of inserts and cartridge spacers. This step is completed by attaching the cartridge to the cap. These parts are interchangeable based on the specific cartridge size. During the changeover, the inserts, located in the upper nest, are used for two and four inch cartridges, while three, five, and ten inch cartridges do not need the upper nest inserts. The lower nest of the machine, however, does not need any adjustments. For all the cartridge sizes except the ten-inch, the changeover process requires operators to switch out spacers based on the specific cartridge size ("Opticap® XL Cartridge Bonder - SOP," n.d.). After the bonder is set up for the next batch, the operator uses scrap parts to perform the bubble and burst tests, which confirm the strength and integrity of the parts, respectively ("Opticap® Bubble and Burst Tester (Melt Sample) - SOP," n.d.).

The changeover process for the welder, however, involves the change of the top plate and bottom nests. Because the welder is bonding the element created by the bonder to a housing capsule, each nest requires a specific fixture plate based on capsule size. There are three pairs of fixture plates, one for two and four inch, three and five inch, and ten inch capsules. The plates are changed using a torque wrench set at a designated value. The setting of the wrench must be checked for accuracy in between each shift and lot ("Opticap® XL Housing Weld - SOP," n.d.).

For the housing integrity tester, the machine's air pressure setting and fixtures are changed based on the capsule's size. Because each product is of different sizes, the amount of air that needs to go through the product to test for integrity directly increases as size increases.

The cartridge counting, mentioned previously, can be done while the testing occurs, or if there is a mechanic failure and production stops. There is no standard procedure established for when it will be done. The testing process is performed again if the machine test fails and usable parts from the batch are needed to perform another test. Once machines pass the quality test, operators must complete the corresponding paperwork. The operator must transcribe the serial number of the lot, his or her signature, and the date for each individual product in the lot; this process allows MilliporeSigma to trace their products back to the specific lot and date in case defects are reported.

After the paperwork is complete, the operators run the lot for the encapsulation process. When the lot is complete, the changeover tasks that happen upon the completion of a lot are performed. These tasks include replacing the missing parts, filling out the line closing paperwork, sending samples for quality assurance, and cleaning the workstation before the next work order. Operators sanitize the entire workstation (machines, bins, tables) with provided disinfectant wipes. After sanitation is complete, the cycle starts from the beginning with checking the accuracy of the next lot (Hocter, 2015).

## 2.7 Previous Project Work at MilliporeSigma

In 2013, a team of Worcester Polytechnic Institute (WPI) industrial engineering students analyzed MilliporeSigma's facility to improve the workflow and output of the Opticap® XL filter encapsulation process (Chevis, Ortiz, & Vallenilla, 2014). The team's objectives were to: "(1) gain an in-depth understanding of the Opticap® XL encapsulation lines, (2) comprehend the current state of production scheduling of the Opticap® XL encapsulation lines, (3) collect data on the current state of the changeover process through time studies, (4) build a discrete-event simulation (DES) model of the current process, (5) determine the impact of dedicating lines to product characteristics by conducting scenarios analysis in the DES model, (6) analyze the results from the different scenarios and provide recommendations regarding line dedication" (Chevis et al., 2014).

By working towards these objectives the team was able to understand the current state of the facility and develop an accurate representation of the environment using simulation. The team used their simulation model to test different scenarios of line dedication to find the most beneficial solution for MilliporeSigma. Through simulation, the team found that by dedicating production lines by filter size, the total changeover time and cycle time improved significantly (Chevis et al., 2014). The team recommended that production lines should be dedicated by filter size, specifically having 2" and 4", 3" and 5", and 10" filters produced on production lines XL4, XL1, XL2 respectively (Chevis et al., 2014).

After the completion of the 2013 project, MilliporeSigma took the team's findings under consideration. Currently, MilliporeSigma is dedicating the production lines by filter size which has improved the current state of the facility. However as demand increases by 20-30% per year for biopharmaceutical products, MilliporeSigma still faces the challenge to keep up with demand. Because lot sizes can range from tens to hundreds of units, the frequency of changeovers can be high and rather unpredictable (Hocter, 2015). Since the Jaffrey plant is 24-hour facility and management needs to deal with problems related to production, the WPI team assumed the role of helping MilliporeSigma in devising methods to further reduce the changeover time in Opticap® XL production line. In the next section we will discuss the lean methods we researched to reduce the changeover time.

### 2.8 Lean Manufacturing

Our team researched lean manufacturing tools that can help reduce the complexity in the Opticap® XL changeover process, as lean manufacturing's goal is to eliminate waste from processes (Womack & Jones, 2010). Waste is everything in the process that does not add value to the customer ("What is Lean?," 2015). Amongst the established lean manufacturing tools, our team pre-selected tools that may be more applicable for our purposes. Table 2 below describes the lean manufacturing tools and presents potential applications for the Opticap® XL changeover process.

| Lean Manufacturing Tools | | Description | Potential Application |
|---|---|---|---|
| **1** | 5s | Organizes the work area by following five progressive steps: Sort, Set in Order, Shine, Standardize, and Sustain | Improve the organization of the production line work area (Gomes, Lopes, & de Carvalho, 2013) |
| **2** | Bottleneck Analysis | Improves the process performance by identifying the step(s) of the process that delays the throughput | Find the changeover bottleneck and focus on it to improve its performance (Vorne Industries Inc, 2013) |
| **3** | Just in Time | Pulls the parts instead of pushing throughout the production process | Reduce the level of inventory and improve flow of materials (Voehl, Harrington, Mignosa, & Charron, 2014) |
| **4** | Muda (Waste) | Identifies the waste in the process | Eliminate Muda and reduce the duration of the changeover process (Voehl et al., 2014) |
| **5** | Poka Yoke | Error-proofs design into the production process | Correct common defects in the process (Vinod, Devadasan, Sunil, & Thilak, 2015) |
| **6** | Root Cause Analysis | Resolves the root problem instead of treating early symptoms | Eliminate a common defect that adds waste to the changeover process (Vorne Industries Inc, 2013) |
| **7** | Single Minute Exchange of Die | Reduces changeover time by converting processes performed while machines are idle to when machines are running | Reduce the changeover time by modifying the changeover procedures (Voehl et al., 2014) |
| **8** | Six Big Losses | Provides a framework of most common causes of waste: breakdowns, set up, small stops, reduced speed, startup rejects, production rejects | Organize the identified wastes by creating a framework of the six big losses (Vorne Industries Inc, 2013) |
| **9** | Standard Work | Documents steps of a procedure to standardize best practices | Document the identified best practices to ensure a well-done changeover process (Vorne Industries Inc, 2013) |

*Table 2 Lean Manufacturing Tools*

***Singe Minute Exchange of Dies***

Among the pre-selected lean manufacturing tools we considered implementing to fulfill our project's objectives, we further investigated tool ID 7, Single Minute Exchange of Dies (SMED), since it is directly related to changeover processes. SMED is a system for reducing equipment changeover times (Vorne Industries Inc, 2013). This system divides the changeover process into each of its elements, sub-processes, and analyzes these elements in detail to see if they can be eliminated, moved, simplified, and/or streamlined.

To analyze the changeover processes, the first step is to categorize processes as internal or external activities. Internal activities can only be performed while the machine is shut down, whereas external activities can be performed without shutting down the machine. The activities that are categorized as external should be performed while the machine is running to prevent any unnecessary machine downtime. Since the external activities can be performed while the machine is running, the next step is to review the remaining internal activities and question how they can be converted to external activities. The third step is to review all the remaining internal activities to streamline and simplify. At this step, the changeover activities are simplified, sequenced, and distributed to the workers in the way that maximizes efficiency. Once this step is complete, the final step is to create standard operating procedures to sustain the new reduced changeover time and start the cycle again periodically to seek continuous improvement opportunities. While Lean Manufacturing tools can help improve processes, oftentimes problems are too complex and need to be modeled to represent reality. The next section will discuss why mathematical modeling is an important tool and how it can be utilized to optimize processes.

## 2.9 Modeling Tools & Optimization

Understanding and analyzing a given real-world scenario can be difficult, as physically conducting a study is costly and time consuming (Chevis et al., 2014). To accurately portray a situation, models can be used to mathematically represent reality. Through modeling, one can test, modify, and predict the effects of a variety of different scenarios without having to physically alter the environment. Another benefit includes the ability to learn from these scenarios. For example, if the results of a model show negative consequences, then the researcher could identify areas to modify in order to obtain the desired output. However, models are limited by their inability to perfectly portray all aspects of the problem, and by the input information due to the different levels of complexity each problem entails. A model's complexity increases as a practitioner attempts to represent every aspect of the real world problem. Because it is often impossible to display every aspect of the problem, simplified models of the same situation are made using assumptions and approximations (Sarker & Newton, 2007). Although models create opportunities for companies to continuously improve and test new practices, models often have inherent limitations, and the results should be carefully analyzed.

One way models are utilized is through optimization, "an act, process or methodology of making something as fully perfect, functional or effective as possible" ("Optimization," 2015). An optimization model consists of three main components: decision variables, an objective function, and constraints. Decision variables are the aspects of the problem that are changed to result in different types of outcomes for the model. The numbers of units to produce at a specific manufacturing center or which location would be best to build a warehouse are examples of decision variables. Decision variables are essential as the values assigned to these variables provide an optimal solution for the given problem (Sarker & Newton, 2007). The objective function of a model drives the solution of a problem by providing a goal or objective to be reached. The objective function looks to either minimize or maximize some metric related to the problem. In manufacturing problems, objective functions are commonly trying to maximize profits, minimize costs, or minimize makespan. Additionally, constraints represent the limitations or restrictions stated in the problem. Constraints are necessary to accurately represent a given scenario. The hours in a workday or the number of available workers during a shift would be examples of constraints. By combining variables, an objective function, and constraints, a realistic representation of a real-world scenario can be created.

Through optimization an optimal solution can be reached given that the associated model accurately represents the problem. It can be utilized in a wide variety of disciplines such as engineering, mathematics, economics, and administration. Additionally optimization can be applied to forecasting, budgeting, process control, and production scheduling. In the context of MilliporeSigma, an optimization problem may seek to minimize the number of the changeover activities performed by choosing an improved sequence of materials, as indicated by the decision variables, therefore reducing the complexity of the changeover process.

Optimization problems can range in size based on the number of decision variables and constraints in the model. Optimization also varies in complexity with respect to the types of equations, variables, and whether uncertainty is included. Some classic optimization problems include the traveling salesman problem, vehicle routing, knapsack, facility location and layout, and production planning and scheduling. Each type of optimization problem has specific attributes. For example in a travelling salesman problem, the model's objective is to find the minimal length tour that passes through all locations and returns to the origin.

### *Scheduling*

Scheduling is a domain that has seen many benefits from optimization. With scheduling, planners focus on the number of resources available and the tasks that need to be completed. Resources differ based on the problem, however they can be machines, production lines, personnel, or tools. Tasks can also differ from operations in a process to stages in a project. Machine scheduling can optimize one or several different criteria (Pinedo, 2012). Because scheduling is dynamic, it incorporates external information such as utilization of the manufacturing center, material inventory, and number of customer orders (Framinan, Leisten, & Garcia, 2014). As situations arise where production must stop or be delayed, rescheduling or rearrangement of the original schedule to adapt to changes occurs.

Through scheduling, companies are able to have detailed information on not only what is in production, but also provide information on what material needs to be restocked, when customers should expect their order, and predict future orders. Although scheduling helps determine what should be produced when, it is not exact. As information is revealed closer to the actual date of production, for example in terms of material required, schedules may change and become more detailed. Thus schedules are only as detailed as the information provided. Some objectives for scheduling problems include minimizing the total schedule duration, total weighted flow time, number of tardy jobs, or weighted earliness and tardiness. Because of the wide range of criteria scheduling models can address, there are a variety of scheduling problems. Some of the problems include job shop, flow shop, single machine, and identical machines in parallel (Pinedo, 2012).

### *Traveling Salesman Problem*

Another kind of optimization problem is the traveling salesman problem, which aims to find the shortest route or tour for a travelling salesman to visit all the cities on a list and return back to the starting point (Applegate, Bixby, & Chvatal, 2011). The distance in which these problems try to minimize depends on the order of the route. Traveling Salesman Problems (TSP) are “typically hard combinatorial optimization problems” (Gutin & Punnen, 2002) which can be difficult to solve due to their intractability. Despite these difficulties, TSPs are popular because they can be easily understood. A travelling salesman problem consists of a graph that includes locations to be visited, as well as inter-distances between locations. (Gutin & Punnen, 2002).

The variations in TSPs consist of either quadratic or linear permutation representation. Quadratic permutation representation consists of sequencing problems, while linear permutation representation focuses on cyclic or binary linear programming (Gutin & Punnen, 2002). TSPs can be applied to a variety of disciplines such as computer science, operations research, genetics, and electronics. Some surprising applications where Traveling Salesman Problems can be found include machine scheduling, cellular manufacturing, VLSI chip design, and frequency assignment problems. The formulation of these problems, however, can differ from a traditional Traveling Salesman Problem. Some Traveling Salesman Problems seek to maximize the total cost or distance of the tour, while other incorporate multiple salesmen.

A reason why Traveling Salesman Problems are difficult to solve is due to the number of constraints needed to accurately represent the problem in the model. Constraints limit the model from performing specific evaluations. For example in a TSP a constraint is to have the salesman visit each location once and ensure that the salesman does not return to a location previously visited. Problems that can arise in a TSP are subtours, which are addressed by subtour elimination constraints. Subtour elimination constraints add additional limitations within the model to ensure subtours do not exist. A common subtour elimination constraint is a Miller Tucker-Zemlin (MTZ) constraint. MTZ constraints allow flexibility in the assignment of a set location (Gutin & Punnen, 2002). However, MTZ constraints also “produce a weak linear programming relaxation” (Sherali & Driscoll, 2002).

## 3 Methodology

The goal of our project was to reduce changeover frequency and complexity in the Opticap® XL encapsulation process. Our team achieved this goal by completing the following objectives:

1. Identify the areas of improvement in the changeover procedure
2. Evaluate and prioritize areas of improvement
3. Develop and potentially implement three improvement strategies

Our team learned about the changeover procedure by visiting the MilliporeSigma Jaffrey, New Hampshire facility on a weekly basis from September 2015 to December 2015. We were introduced to the project and supervised by our project liaison, Justin Hocter who is the Production Manager responsible for overseeing the Opticap® XL as well as other products. During our weekly visits our team collected information from observations, data collection, and initial interviews with the operators and production leads. Next, we analyzed our findings to identify the areas of improvement in the changeover process to then evaluate and prioritize our improvement strategies. Finally, our team targeted three areas of improvement that resulted in a strategy to reduce changeover frequency and complexity for the Opticap® XL encapsulation process. Figure 7 presents the methodology road map.

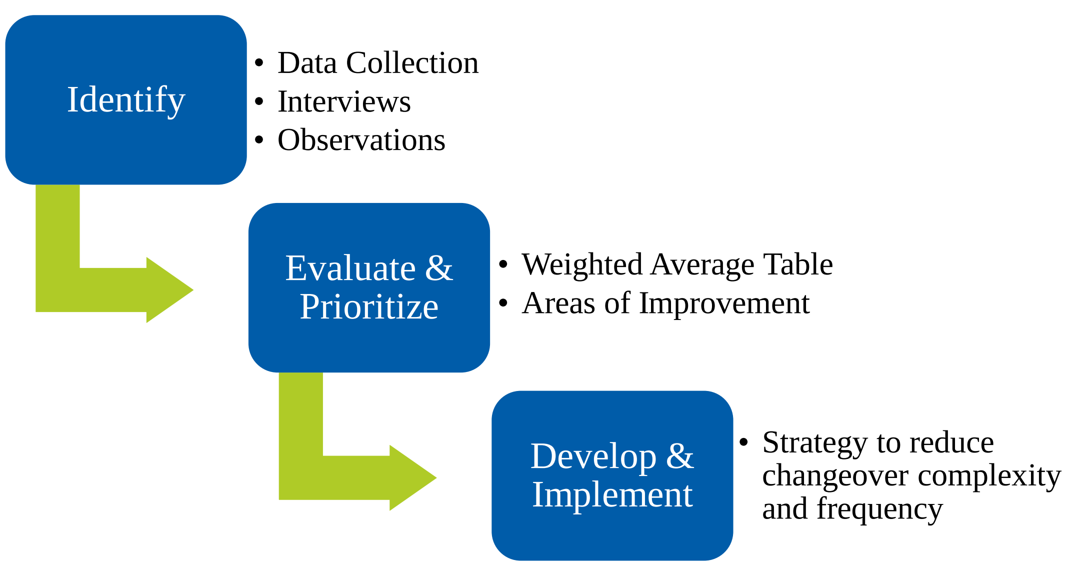


*Figure 7 Methodology Road Map*

## 3.1 Identify Areas of Improvement

In order to develop strategies to reduce changeover complexity, our team observed the encapsulation and changeover processes to learn MilliporeSigma's operations and how the Opticap® XL products are produced. During our observations, our intent was to learn about the bottlenecks in the process. The team gained an understanding of the encapsulation process for Opticap® XL products by visiting the Jaffrey plant, observing production lines, and interviewing the operators and other stakeholders in the process.

***Site visits and observations***

During our site visits, our team sought to observe the production lines and learn information about all of the processes that directly or indirectly affect the changeover process. We took notes and documented how the operators in the production lines performed the processes. Through our observations, we hoped to gain an unbiased opinion on what the bottlenecks were in the system. We also used the initial observations to identify stakeholders in the process that we could interview to gain further insight on the areas that need improvement.

***Interviews***

The main purpose of the interviews was to understand the operators' perspective on the tasks they perform that directly or indirectly affect the changeover process. Our team interviewed operators on the XL production lines to understand the encapsulation and changeover processes. We also interviewed the production lead, the material handler, and production planner. Through these interviews, we sought to learn about the overall process at MilliporeSigma and gain insight into where we might make the most impact.

In order to understand their processes, we interviewed the operators that perform the changeover tasks in the production lines. We asked questions (Appendix B: Operators Interview Questions) about the tasks that they perform, what they perceived to be the biggest difficulties during the changeover process, and the step that takes the most time. We also interviewed the production lead of the shift that we were observing. The production lead has the duty of supervising the cells and creating the daily schedules for the production lines. With this interview we sought to understand how lots are presented to associates and identify the possible areas of improvement with regards to scheduling that would simplify the tooling during the changeover process. Because we wanted to encompass additional perspectives on the most difficult changeover task, we acquired the supervisor's opinion and observations of any variations between shifts and operators. This information would indicate whether MilliporeSigma's processes should be more standardized. The full list of interview questions with the production lead can be found in Appendix C: Production Lead Interview Questions.

To identify whether altering the way the materials are delivered could have an effect on the changeover time, we interviewed the Material Handler. As counting material is included in the changeover time, we asked the Material Handler's perspective on the efficiency of using alternative delivery methods for cartridges, caps, and housings such as bins with designated space for each unit. Because counting is a non-value added activity, we looked into identifying any areas of improvement with material handling that would have an indirect effect of minimizing or eliminating the need for counting during a changeover process. The full set of interview questions can be found in (Appendix D: Material Handler Interview Questions).

We also had an informational interview with the Production Planner, who prepares the lots to be completed and presents them to the Production Lead. During this interview we sought to understand the Production Planner's methodology of preparing daily lots for production and whether changeover complexity is taken into account. We wanted to identify if improving communication between the planner and lead would have a significant impact in the changeover process.

Through the site visits, observations and interviews, we were able to understand the encapsulation and changeover process at MilliporeSigma. From this, we identified and analyzed the areas for improvement and determined the difficulties the employees have during these processes.

### 3.2 Evaluate & Prioritize Areas of Improvement

Through site visits, observational studies, and interviews, we identified twelve areas of improvement, which we evaluated and prioritized. We evaluated these improvement areas by thoroughly understanding the intricacies of each, how each would affect the changeover process, and what the improvement would entail. Through this evaluation, we classified the twelve improvement areas into three categories: production scheduling, operational procedures, and presentation of materials. Once each improvement area was categorized, we prioritized all of them in order to narrow our focus on the areas with highest impact.

We strategically prioritized the areas using simple multi-attribute ranking technique (SMART). SMART is an analysis technique used to help decision makers make a provisional decision through an eight stage process (Goodwin & Wright, 2009). First, we identified the decision maker and the different alternatives or areas of improvements. Next, we derived three attributes in which to compare each improvement area. The alternatives and attributes were arranged into a table. A sample table (Table 3) depicts a generic table for which our SMART analysis was performed.

| **Alternatives** | **Attribute 1** | **Attribute 2** | **Attribute 3** |
|---|---|---|---|
| | | | |

*Table 3 SMART Sample*

We documented our relative scores for each area of improvement given the attribute in the table. The scores were based on a one-to-five scale with one being poor and five being very good for each criterion. Next we assigned weights to each attribute using a one-to-three scale with one being the least important and three being the most important. The weights assigned for the attributes represent how much the specific attribute affects our decision.

Given our scores and assigned weights, we performed a weighted sum. Through a weighted sum we were able to reflect the importance of each attribute on its respective score by multiplying the two values. After each weight score was derived, the scores for each attribute per alternative were summed to create an overall score. The overall scores were then ordered from highest to lowest in the table. This ordering provided our list of areas of improvements that we should prioritize first.

After our prioritization, we presented all twelve ideas to our liaison, Mr. Hocter. We asked Mr. Hocter to perform his own analysis to determine which improvement areas were of higher priority for MilliporeSigma. In an open discussion, we compared the results of both analyses to find commonalities and the most important ideas. Through the evaluation and prioritization of the areas of improvements, we determined three main ideas to concentrate on to reduce the changeover frequency and complexity. From these ideas, we developed improvement strategies to potentially implement within MilliporeSigma's Opticap® XL production lines.

## 3.3 Develop Improvement Strategy

After we evaluated and analyzed our areas of improvement, our team worked on developing the improvement strategies. The following three improvement strategies were developed and presented to MilliporeSigma for potential implementation; optimization of production schedule, standardization of changeover process, and redesign of melt check procedures. This section further describes how each improvement strategy was developed.

### 3.3.1 Optimization of Production Schedule

Our team first identified scheduling lots as an area of improvement from our initial meeting with the Opticap® XL Production Planner, Scott McGillivray on October 5, 2015. After our project team and MilliporeSigma liaisons agreed upon exploring this area of improvement, we requested work order data to further investigate potential improvements. Mr. Hocter provided our team with the work order details from January 2014 to December 2015 in a Microsoft Excel spreadsheet file. Next, our team analyzed the data to better understand the components that together make up a work order and used the standard operating procedures as an aid to ensure we were analyzing the correct components throughout our analysis. We used Microsoft Excel to analyze the data that included the lot code with the Excel MID function that returns the characters from the middle of a text string, given a starting position and length. This allowed us an efficient way to break down the individual work orders by material type, cartridge size, inlet and outlets.

Our team then arranged a second meeting with Mr. Hocter and Mr. McGillivray to clarify uncertainties. We asked about potential constraints related to the number of days a work order is visible to the planner. From our background research found in Section 2.9, we identified that a Traveling Salesman Problem model would be the right framework. Knowing this information, our team followed optimization-modeling procedures of defining variables, setting constraints, and developing an objective function before framing the model in Microsoft Excel. Lastly, our team implemented the model in Microsoft Excel using VBA and OpenSolver to deliver a user-friendly tool for MilliporeSigma to run for any given number of work orders to schedule a production plan that minimizes the amount of changeover time.

### 3.3.2 Standardization of Changeover Tasks

For our team to successfully achieve the goal of standardizing the processes involved in the changeover process, we interviewed operators, conducted time studies, implemented the Single Minute Exchange of Dies (SMED) methodology, and compiled a list of best practices for the operators throughout the changeover process. First, we interviewed the operators that perform the changeover tasks in the production lines to identify similarities and differences in the practices in which changeovers were performed. Next we compared the similarities and differences to identify best practices to perform changeovers more effectively. Second, we conducted time studies during our site visits at MilliporeSigma to gain a quantitative understanding of bottlenecks in the encapsulation and changeover process. During these time studies, we recorded the process time for each step in the process as well as the steps during the changeover process. Our data collection sheets can be found in Appendix E: Data Collection Sheet. These time studies gave us a quantitative answer to what the bottleneck was and an understanding of the variability between operators. We conducted time studies on different lines to determine whether there was variability between the production lines and operators.

Next, we used the SMED turnover chart to better organize the changeover tasks and to reduce the changeover times. The completed turnover chart can be found in Appendix F: Task Turnover Chart. We identified the changeover tasks and determined if they were completed while the machines were running (external) or while the machines were not in production (internal). We used the data from our time studies to fill in this chart with the appropriate time for each task. Finally, we discussed with operators which tasks could be completed externally instead of internally. This information helped us complete the standardized changeover process and understand if there were any best practices that the team could recommend for the changeover process.

Finally, the team created a list of best practices to standardize the changeover processes. The team studied the SOPs and used the results of the SMED turnover chart, the interviews, and time studies to ensure all tasks were listed and the recommendations were feasible.

### 3.3.3 Redesign of Melt Check Procedures

To understand the importance of melt checks and understand the areas of improvement, the team interviewed operators and quality engineers, created and implemented a data tracking document, and developed a new procedure for determining the frequency of melt checks.

The team interviewed the operators on the production line to understand how and when the melt checks were completed. We analyzed this information and determined the melt check was a bottleneck in the changeover process. Through our discussions with the operators and Mr. Hocter, we brainstormed a list of possible scenarios in which melt checks would be completed, found in Appendix G: Melt Check Scenarios. We presented this material to the Quality Engineers. In this meeting, we received their feedback and determined more data is necessary before the Quality Engineers could ensure that reducing the number of melt checks would not decrease the quality of the products.

From this information, the team created a data collection form to be filled out by the operators to understand how often the melt checks fail. This form was put in the production process for two weeks and the operators recorded their data on the sheet provided by the team. A sample of a completed data collection log can found in Appendix H: Melt Check Data Collection Sheet. Next, the team analyzed the results of the data collection sheet in order to present findings to the quality engineers.

Upon the completion of data analysis, the team presented the collected information to the Quality Engineers for review. The team discussed the results and determined a feasible schedule for performing melt checks to reduce the changeover time.

## 4 Results & Analysis

This chapter discusses our findings and the respective analysis from our methodologies. From those practices we identified areas of improvement to then evaluate and prioritize these areas. Next, with the MilliporeSigma liaisons we discussed and decided the improvement areas our team would focus for the project. An analysis was performed which resulted in the development of improvement strategies. As a result, these improvement strategies formulated our changeover reduction strategy that effectively reduced the complexity from MilliporeSigma's Opticap® XL changeover process (Figure 8).

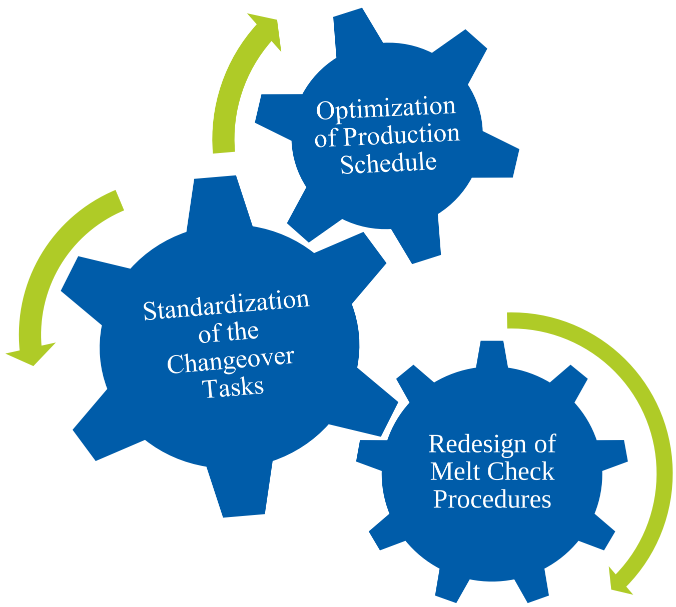


*Figure 8 Our Areas of Improvements*

### 4.1 Areas of Improvement

This section presents the identified areas of improvement based on the results of our observations and interviews of the Opticap® XL encapsulation process. We begin the section by presenting the findings from our observations of the XL1, XL2, and XL4 production lines at the MilliporeSigma's Jaffrey, New Hampshire site. Furthermore we present the initial results from our interviews with the Production Lead, Line Operators, Material Handler Lead, and Production Planner.

### 4.1.1 Observations

In our first two visits we observed the Opticap® XL encapsulation process to understand all of the activities involved in production. During these observations we analyzed the three production lines dedicated to produce the Opticap® XL. The production lines follow strict sanitary measures to ensure a hygienic quality in the Opticap® XL, in addition to regulated procedures and documentation involved in the production process. As previously discussed, XL1 and XL2 have two operators working on the lines and share the same throughput capacity. On the other hand, XL4 has a higher throughput capacity because there are two bonder machines, hence there are three operators working on this line. We observed that materials were prepared and grouped by work orders in a Kanban room, located next to the production lines, before the material handler delivered them to the production lines. From our initial observations we scheduled interviews to learn more about the production scheduling, the preparation and presentation of materials, and operational procedures related to the changeover procedures.

### 4.1.2 Interviews

The interviews gave us a deeper understanding of the Opticap® XL encapsulation and changeover process from the stakeholder's point of view. It gave us insightful information on operational procedures, preparation and production scheduling, and the presentation of materials that allowed us to formulate our areas of improvement.

Through our interviews with operators, our team learned that there were variations on how tasks were performed based on production line and operators. For example, some operators stated that they counted material while performing the melt checks, whereas other operators mentioned completing paperwork. With this information, we identified an order of the tasks that would minimize the overall changeover time. In addition to variations in performance, operators highlighted that performing melt checks, counting the material, and completing paperwork were the most time consuming tasks during the changeover process. When asked about the significance behind the melt checks and paperwork, operators were not clear on why they needed to be completed. Performing long changeovers without a deep understanding of the purpose of the paperwork was also a demotivating factor for the operators in the production line. From these interviews, we found that there was a misconnection between the managers and the operators that can be improved.

In our interview with the Production Lead, we learned the intricacies of the role and the part the production lead played in the production of the Opticap® XL products. We found that once work orders were released by the Production Planner two days in advance, the Production Lead created a daily schedule. While devising the schedule, the Production Lead assigned the work orders to specific production lines and took into consideration filter size to minimize the changeover time. The Production Lead also confirmed there was a variation in how changeover tasks were performed. Because of the scheduling information we received, this encouraged us to interview both the Material Handler and Production Planner.

During our interview with the Material Handler, we learned more about how the materials were stored and delivered to the production lines. The Material Handler showed us the warehouse in which the material was stored in bins on various racks. The warehouse had visual aids including hanging labels from the ceiling indicating the material type and outlines on the floor indicating where racks should be placed. These visual systems helped Material Handlers within the department locate material and ensure the area was organized. We then learned that parts for specific work orders were delivered to the production floor in bins and queued in the Kanban room. The material is packaged in a plastic bag within the bin that required operators to cut the bags in order to count the number of parts.

This framed our next question of whether there would be a trade-off between reducing the counting time for the operator versus adding counting time for the material handler. The Material Handler's perspective on the alternative delivery methods was that it would increase the time for them to move the products to the production lines because of the need to arrange the materials in a certain way in the bins rather than quickly grabbing and delivering. Additionally we found another disconnect in communication between the Material Handlers, Production Lead, and Line Operators causing scheduling problems, machine downtime, and labor inefficiency. For example, Material Handlers were not notified immediately by a warning system when the production schedule had changed, and they were only able to see the change when they checked the shared Excel file. This often created excess inventory in the Kanban room as materials would be brought to the encapsulation area and enter a holding pattern.

From the interview with the Production Planner, we found that the changeover complexity was not taken into account when preparing the daily orders. For example, it was not among the duties of the Production Planner to assign two batches of the same product in the same day because it would reduce the changeover complexity. Instead, the only factors that were taken into consideration were material availability and the deadline of the order. We identified that this is an area of significant improvement as reducing changeover complexity will result potential additional production time due to the saved changeover time. For example, by assigning same size and material type filters back to back, MilliporeSigma could gain five minutes of tooling per changeover, which generates time for three-five more units to be produced.

### 4.2 Evaluation & Prioritization

The evaluation of the twelve areas of improvements broadened our understanding of each idea and allowed us to properly assess the feasibility, impact, and easiness of each. Through our evaluation, we categorized the twelve areas of improvements into one of three categories: production scheduling, operational procedures, and presentation of materials Table 4.

| | |
|---|---|
| **Production Scheduling** | Planner send schedule earlier |
| | Combine work orders |
| | Melt checks performed after specific number of units |
| **Presentation of Materials** | Smaller number of materials in bins |
| | Color code bins by cartridge size |
| | Improve communication |
| | On-site label maker |
| **Operational Procedures** | Sequence processes in changeover |
| | Perform tasks in parallel |
| | Simplify documentation |
| | Universal tooling |
| | Send production plan earlier |

*Table 4 Categorized Areas of Improvement*

After the categorization of the ideas, we prioritized them using SMART described in Section 3.2. To perform our SMART analysis we listed all twelve areas of improvements as the alternatives. Because we considered several improvement possibilities, we prioritized them focusing on the feasibility and impact of the idea in reducing changeover time, as well as, its easiness in terms of implementation. For the attributes we assigned feasibility, impact, and easiness a weight of two, three, and one respectively. With these attribute weights, we scored each improvement area taking into consideration how feasible the idea would be considered by

MilliporeSigma, how much of an impact the idea's solution would have if implemented, and the easiness of implementing a solution. The scores were then calculated into weight sums and the areas of improvements with the top four highest overall weighted scores (Table 5) were considered.

| **Attributes:** | Feasibility | Impact | Easiness |
|---|---|---|---|
| **Weights:** | 2 | 3 | 1 |

| **Order** | **Areas of Improvement** | **Feasibility** | **Impact** | **Easiness** | **Overall Score** |
|---|---|---|---|---|---|
| **1** | Melt checks performed after specific number of units | 4 | 5 | 3 | 26 |
| **2** | On-site label maker | 3 | 5 | 3 | 24 |
| **2** | Send production plan earlier | 5 | 4 | 2 | 24 |
| **4** | Sequence processes in changeover | 4 | 4 | 3 | 23 |
| **5** | Combine work orders | 3 | 4 | 4 | 22 |
| **5** | Perform tasks in parallel | 5 | 3 | 3 | 22 |
| **5** | Simplify documentation | 3 | 4 | 4 | 22 |

*Table 5 Our Team's SMART Analysis Results*

The same process was performed with Mr. Hocter to gain his perspective on the twelve areas of improvements. Through the presentation of the improvement areas without our results, our liaison conducted his SMART analysis (Table 6).

| **Attributes:** | Feasibility | Impact | Easiness |
|---|---|---|---|
| **Weights:** | 1 | 3 | 2 |

| **Order** | **Areas of Improvement** | **Feasibility** | **Impact** | **Easiness** | **Overall Score** |
|---|---|---|---|---|---|
| **1** | Sequence processes in changeover | 4 | 4 | 4 | 24 |
| **2** | Perform tasks in parallel | 4 | 4 | 3 | 22 |
| **2** | Simplify documentation | 4 | 4 | 3 | 22 |
| **4** | Combine work orders | 3 | 4 | 3 | 21 |
| **5** | Create integrated system | 3 | 4 | 3 | 21 |
| **5** | Melt checks performed after specific number of units | 2 | 4 | 3 | 20 |
| **5** | Improve communication | 4 | 3 | 3 | 19 |

*Table 6 Mr. Hocter's SMART Analysis Results*

With these results, we conducted an open dialogue to come to a common consensus on which of the areas of improvements our projects should focus on. Our team and Mr. Hocter discussed the reasoning behind our scoring of each idea and sought each other's opinions. Through the discussion, we collectively redefined some of the areas of improvements to reflect how we would address solving the specific improvement area. In conclusion the discussion resulted in three main improvement areas to focus on to reduce changeover frequency and complexity.

1. Optimization of production schedule (Scheduling communication plan)
2. Standardization of the changeover tasks (Sequence processes in changeover)
3. Redesign of melt check procedures (Melt checks performed after certain number of units)

With these findings, we further researched each area to determine improvement strategies.

### 4.3 Improvement Strategy Deliverables

Our team created three improvement strategy deliverables that would each reduce certain parts of the changeover time. Each strategy can be implemented individually, however our team calculated the impact to be largest when all three implemented together. We created a production schedule optimization tool to optimize the production schedule, reorganized the allocation of tasks through Gantt charts, and redesigned melt check procedures to eliminate any unnecessary checks while ensuring quality. The following sections will discuss these three improvement strategies in detail.

#### 4.3.1 Optimization of Production Schedule

To understand how production scheduling can influence the changeover time, our team analyzed and decoded the Opticap® XL catalog numbers. We found that an Opticap® XL catalog number contains the characteristics pertaining to the lot. Table 7 below provides a description of an Opticap® XL catalog number.

<table>
<tr><td>Character</td><td>1st & 2nd</td><td>3rd & 4th</td><td colspan="2">5th</td><td colspan="2">6th & 7th</td><td>8th</td><td>9th</td><td colspan="2">10th</td></tr>
<tr><td>Character Meaning</td><td>Product Type</td><td>Cartridge Membrane</td><td colspan="2">Material Type</td><td colspan="2">Cartridge Size (Inches)</td><td>Inlet Type</td><td>Outlet Type</td><td colspan="2">Quantity per Package</td></tr>
<tr><td rowspan="6">Options</td><td rowspan="6">Opticap®</td><td rowspan="6">-</td><td rowspan="2">A</td><td rowspan="2">Autoclavable</td><td>01</td><td>1 in.</td><td rowspan="6">F<br>H<br>N<br>T</td><td rowspan="6">F<br>H<br>N<br>T</td><td rowspan="2">1</td><td rowspan="2">1/pack</td></tr>
<tr><td>02</td><td>2 in.</td></tr>
<tr><td rowspan="2">G</td><td rowspan="2">Gamma Compatible</td><td>03</td><td>3 in.</td><td rowspan="2">2</td><td rowspan="2">2/pack</td></tr>
<tr><td>04</td><td>4 in.</td></tr>
<tr><td rowspan="2">S</td><td rowspan="2">Gamma Sterilized</td><td>05</td><td>5 in.</td><td rowspan="2">3</td><td rowspan="2">3/pack</td></tr>
<tr><td>10</td><td>10 in.</td></tr>
</table>

*Table 7 Code to Catalog Number Characteristics*

From our interview with Mr. Hocter, we learned that changes in the following characteristics affect the changeover time between lots: cartridge size, material type, inlet type, and outlet type. The above mentioned characteristics specifically influence tooling changes in the bonder, welder, and the housing integrity tester. Therefore, having changes between the above mentioned characteristics increases the length of changeovers. Furthermore, Mr. Hocter informed us that each characteristic change impacted the changeover length differently. Table 8 below indicates how much tooling time changing each characteristic add to changeover length.

| **Characteristic** | Material Type | Cartridge Size | Inlet Type | Outlet Type |
|---|---|---|---|---|
| **Weight (Minutes)** | 3 | 5 | 2 | 2 |

*Table 8 Product Characteristics' Weight (Minutes)*

An example of the influence cartridge size, material type, inlet type, and outlet type can have on changeovers between lots can be seen in the table below.

| Catalog Number | Product | Membrane | Material Type | Size | Inlet | Outlet |
|---|---|---|---|---|---|---|
| | KV | EP | S | 03 | T | T |
| | KH | GE | A | 05 | T | H |
| Changeover Value | - | - | 3 | 5 | 0 | 2 |

*Table 9 Example Characteristic Influence*

In Table 9, we observed that there was a material type change from "S" to "A", which added three minutes of tooling. Additionally, there was a size change from "03" to "05", which added five minutes of tooling. Furthermore, there was an outlet change from "T" to "H", which added two minutes of tooling. In total this change would add ten minutes of tooling time.

To illustrate the effects of the product characteristics during changeover, we selected a random two day production schedule from December 9, 2015 and December 10, 2015 to use as a case study. In the two day production schedule we evaluated, there were 15 lots produced in XL1, six lots produced in XL2, and six lots produced in XL4. Sequencing of the lots for each production line is shown in the tables below.

| XL1 Production Schedule | | | |
|---|---|---|---|
| **Catalog Number** | **Number of Units** | **Issues Date** | **Start Date** |
| KHGEG10TT1 | [redacted] | 12/9/2015 | Wednesday |
| KN50A10TT1 | [redacted] | 12/9/2015 | Wednesday |
| KVVLA10TT1 | [redacted] | 12/9/2015 | Wednesday |
| KW19A10HH1 | [redacted] | 12/9/2015 | Wednesday |
| KGEPS10HH1 | [redacted] | 12/9/2015 | Wednesday |
| KVGBA05FF1 | [redacted] | 12/9/2015 | Wednesday |
| KGEPA05TT1 | [redacted] | 12/9/2015 | Wednesday |
| KHGEA05TT1 | [redacted] | 12/9/2015 | Wednesday |
| KN03A10TT1 | [redacted] | 12/10/2015 | Thursday |
| KR01A10TT1 | [redacted] | 12/10/2015 | Thursday |
| KGEPA10HH1 | [redacted] | 12/10/2015 | Thursday |
| KVVLG10HH1 | [redacted] | 12/10/2015 | Thursday |
| KTGRA10FF1 | [redacted] | 12/10/2015 | Thursday |
| KVGLA10FF1 | [redacted] | 12/10/2015 | Thursday |
| KW19A04TT3 | [redacted] | 12/10/2015 | Thursday |

*Table 10 XL1 Production Schedule*

| XL2 Production Schedule | | | |
|---|---|---|---|
| **Catalog Number** | **Number of Units** | **Issues Date** | **Start Date** |
| KVEPS03TT3 | [redacted] | 12/9/2015 | Wednesday |
| KHGEA05TH1 | [redacted] | 12/9/2015 | Wednesday |
| KHGEG05HH1 | [redacted] | 12/10/2015 | Thursday |
| KGEPS10TT1 | [redacted] | 12/10/2015 | Thursday |
| KVGLS10TH1 | [redacted] | 12/10/2015 | Thursday |
| KW19A04NN3 | [redacted] | 12/10/2015 | Thursday |

*Table 11 XL2 Production Schedule*

| XL4 Production Schedule | | | |
|---|---|---|---|
| **Catalog Number** | **Number of Units** | **Issues Date** | **Start Date** |
| KW19A04HH3 | [redacted] | 12/9/2015 | Wednesday |
| KVVLA04HH3 | [redacted] | 12/9/2015 | Wednesday |
| KVGLG04FF3 | [redacted] | 12/9/2015 | Wednesday |
| KTGRA04TT3 | [redacted] | 12/10/2015 | Thursday |
| KTGRA04TT3 | [redacted] | 12/11/2015 | Thursday |
| KVVLA02TT3 | [redacted] | 12/10/2015 | Thursday |

*Table 12 XL4 Production Schedule*

By using the weight values (Table 8) and characteristic influence values (Table 9), we were able to calculate the total changeover tooling time based on the schedules provided. We found that tooling time with the current schedule totaled to 114 minutes, where XL1, XL2, and XL4 scored 54 minutes, 49 minutes, and 19 minutes respectively.

Professor Andrew Trapp developed the algebraic formulation of the optimization model that simultaneously represents the assignment of lots to production lines and the sequencing of the assigned lots on each of the lines. The sequencing is quite similar to the sequencing in a traveling Salesman Problem as the goal of the TSP is to minimize the distance, or time, for a salesman to travel from its starting point to all its corresponding point destinations.

In the developed production scheduling optimization model, the salesman can be interpreted as the production line, the starting point would be the first lot, the distance would be the tooling time that would take to change from one lot to another, and the remaining points would be the lots that have been assigned to the particular line.

For the purpose of this project, we used past production schedule data to create the initial design of our model and understand all of the constraints that we would need to consider.

Additionally, we assumed that the input data for the model must contain at least three different cartridge sizes and the throughput is one minute. The sets, parameters, variables, constraints and objective function that constitute the production scheduling optimization model are described below.

***Sets:***

L is the set of lots to be scheduled, indexed by "i" and "j"

K is a set of production lines, indexed by "k"

***Parameters:***

$c_i$ is the cartridge size of lot "i"

$d_{ij}$ is the changeover value from lot "i" to lot "j"

$p_i$ is the processing times for lot "i"

$a^k$ is the capacity of production line "k"

$n$ is the number of lots being optimized

$l^k$ is the anchor lot for line "k"

*Conditions for $l^k$:*

$l^3$ is the non 10 inch lot with the largest $p_i$

$l^2$ is the lot with the largest $p_i$ that is not $l^3$

$l^1$ is the lot with the largest $p_i$ that is not $l^3$ and not $l^2$

***Variables:***

$x_{ij}^k$ is equal to 1 if there is transition from lot "i" to lot "j" on production line "k", otherwise, it is equal to 0

$y_i^k$ is equal to 1 if there is an assignment for lots "i" to production lines "k", otherwise, it is equal to 0

$y_j^k$ is equal to 1 if there is an assignment for lots "j" to production lines "k", otherwise, it is equal to 0

$u_i^k$ is the MTZ subtour constraint value for lot "i" in production line "k"

$u_j^k$ is the MTZ subtour constraint value for lot "j" in production line "k"

***Constraints:***

(1) $\sum_{i \in L} \sum_{k \in K} x_{ij}^k = 1 \; \forall \, j \in L$

(2) $\sum_{j \in L} \sum_{k \in K} x_{ij}^k = 1 \; \forall \, i \in L$

(3) $x_{ij}^k \leq y_i^k \; \forall \, i \in L, j \in L, k \in K$

(4) $x_{ij}^k \leq y_j^k \; \forall \, i \in L, j \in L, k \in K$

(5) $\sum_{k \in K} y_i^k = 1 \; \forall \, i \in L$

$y_i^3 = 1 \; for \; l^3$

$y_i^2 = 1 \; for \; l^2$

$y_i^1 = 1 \; for \; l^1$

(6) $(\mathrm{n}-1) * x_{ij}^k + u_i - u_j + (\mathrm{n}-3) * x_{ji}^k \leq (n-2) \; \forall \, k \in K, i \in L, j \in L: i \neq j, i \neq l^k, j \neq l^k$

(7) $\sum_{i \in L} p_i * y_{ik} \leq a^k \; \forall \, k \in K$

(8) $u_i^k \leq n * y_i^k \; \forall \, i \in L, k \in K$

(9) $y_i^3 = 0 \; \forall \, i: c_i = 10$

(10) $x_{ij}^k = 0, \forall \, k \in K, i \in L, j \in L: i = j$

(11) $q \geq \sum_{i \in L} \sum_{j \in L} d_{ij} * x_{ij}^k + \sum_{i \in L} p_i * y_{ik} \; \forall \, k \in K$

***Objective Function:***

$$Min \; q$$

The algebraic formulation, takes MilliporeSigma’s current operations into consideration. Specifically, constraint set (1) ensures that exactly one lot precedes lot “j”, whereas constraint set (2) ensures that exactly one lot comes after lot “i”. Constraints (3) and (4) ensure that a lot first needs to be assigned to a production line before being scheduled in that line. Constraint (5) ensures that one lot is only assigned to one line and it also anchors certain lots to each production line. Constraint sets (6) and (8) ensure that there are no subtours between lots and each lot is visited at least once before returning to a previously visited lot. Constraint set (7) ensures that the number of units produced cannot exceed the capacity of the machines. Currently XL1 capacity is 500 units per day, XL2 capacity is 500 units per day, and XL4 capacity is 1,000 units per day. Constraint set (9) ensures that that ten-inch cartridges cannot be produced on production line XL4, as this production line does not have a plug bonder. Constraint set (10) ensures that there are no transitions from one lot to itself. Constraint set (11) ensures that the total of process and changeover times in each production line is less than the specified value q, which is the value that the objective function seeks to minimize. This serves the purpose of minimizing the maximum value of the value of the total process plus changeover times for all production lines.

Because the number of lots produced could vary on a daily basis, it was necessary to code the optimization model with Visual Basic for Applications (VBA) in Microsoft Excel to design a flexible and dynamic framework. The full VBA code for the model we constructed can be found in Appendix I: VBA Code for the Production Schedule Optimization Tool. We selected OpenSolver to solve the model because it has the capacity to handle the quantity of the constraints and variables for a two-to-three day production schedule. Finally, we designed the optimization model interface (Figure 9) to be user-friendly for the MilliporeSigma production team.

*Figure 9 Production Schedule Optimization Tool Interface*

The interface allows MilliporeSigma's production team to input the catalog number, the number of units in each lot, and the capacity for each production line. The interface also allows MilliporeSigma's production team to edit the weight values for the characteristics and the run time allowed for the optimization model. The ability to edit the above mentioned features adds flexibility to the model to run various production lot sets and modify the production line capacity or the weight value if they change. Generally, the longer the model runs the closer to global optimal the solution will be. However, since this particular optimization model can run for several hours, we added a time limit field to set a maximum run time for MilliporeSigma's production team to select, when there is a trade-off between a faster solution and a better solution. Our team encouraged MilliporeSigma to run the model for at least thirty minutes to allow the model to allow the solver to search for a solution that is high-quality, if not the global optimal solution.

To test the production schedule optimization tool, we ran the 27 lots from December 9, 2015 and December 10, 2015. We ran the model for thirty minutes and the lots were sequenced and assigned to production lines (Figure 10).

| XL1 Schedule | | XL2 Schedule | | XL4 Schedule | |
|---|---|---|---|---|---|
| 17 | KHGEA05TH1 | 25 | KTGRA04TT3 | 27 | KVVLA02TT3 |
| 13 | KTGRA10FF1 | 1 | KHGEG10TT1 | 15 | KW19A04TT3 |
| 14 | KVGLA10FF1 | 12 | KVVLG10HH1 | 26 | KTGRA04TT3 |
| 5 | KGEPS10HH1 | 20 | KVGLS10TH1 | 22 | KW19A04HH3 |
| 11 | KGEPA10HH1 | 19 | KGEPS10TT1 | 21 | KW19A04NN3 |
| 4 | KW19A10HH1 | 16 | KVEPS03TT3 | 23 | KVVLA04HH3 |
| 9 | KN03A10TT1 | | | 24 | KVGLG04FF3 |
| 10 | KR01A10TT1 | | | 18 | KHGEG05HH1 |
| 3 | KVVLA10TT1 | | | 6 | KVGBA05FF1 |
| 2 | KN50A10TT1 | | | 8 | KHGEA05TT1 |
| | | | | 7 | KGEPA05TT1 |

*Figure 10 Production Schedule Optimization Tool Output Data*

Using the production schedule optimization tool, the total tooling time decreased from 114 minutes to 92 minutes, where XL1, XL2, and XL4 scored 23 minutes, 25 minutes, 44 minutes respectively. The respective scores actually quite balanced, given that XL4 has twice as much capacity as the other lines. The bar graph (Figure 11) compared the tooling times from the manual schedule MilliporeSigma created and the sequence that the scheduling optimization tool created to minimize total tooling time.

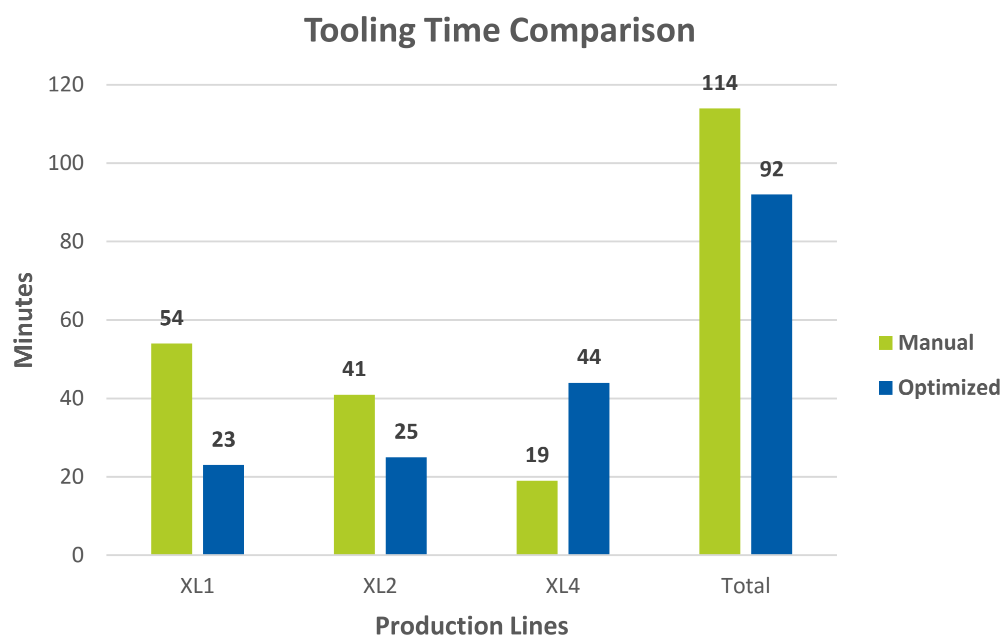


*Figure 11 Tooling Time Comparison*

The production schedule optimization tool can significantly reduce the changeover time by sequencing lots in a way that minimizes tooling changes. In addition to this feature, the production schedule optimization tool also creates a balance across the production lines XL1, XL2, and XL4 according to the constraints described in the algebraic model. MilliporeSigma can follow the instructions (Appendix J: Production Schedule Optimization Tool User Instructions) to use the production schedule optimization tool and edit according to their necessities.

### 4.3.2 Standardization of Changeover Tasks

Through our interviews and time studies, we concluded that it was essential to sequence and standardize the changeover tasks. Through our methodologies described in Section 3.3.2, we were able to complete the turnover chart. A sample of the turnover chart can be seen in Table 13 and the full turnover chart can be found in Appendix F: Task Turnover Chart.

| Task ID | Task Name | Task Description | Task Time (seconds) | Task Class |
|---|---|---|---|---|
| **1** | Clean and organize work area | Sweep the area, remove the leftover caps and housings from the previous batch | 30 | Internal |
| **2** | Finalize paperwork | Finish any leftover paperwork from the previous batch | 287 | Internal |
| **3** | Prepare quality assurance sample | Prepare and package the sample that will Internal be sent to the quality assurance department for testing | 148 | Internal |
| **4** | Walk to the rack | Walk to the rack area to get the housings & caps for the upcoming batch | 25 | Internal |

*Table 13 Sample Turnover Chart*

In addition to classifying tasks in the turnover chart as internal or external, we used the turnover chart to devise a Gantt chart of all the changeover tasks with its associated operator (See Excel Document "Gantt Charts for Changeover Tasks": "Current Procedures"). As shown in the Gantt chart, the current changeover process takes approximately 24:30 minutes. We found that operator two (shown in orange) ends ten minutes earlier than operator one (shown in blue) and stands idle during the remainder of changeover. We also found that operator one, who runs the bonder machine, completes the majority of the tasks. Based on these findings, our team evaluated the possibility of moving the melt check earlier in the changeover process and assigning operator two with more responsibilities. This new sequence of the changeover tasks reduced the overall changeover time by 1:45 minutes. The SOP for performing this changeover can be found in Appendix K: SOP Proposal 1.

Using SMED practices, we evaluated each task to see if time could be saved in the changeover process by changing the task from internal to external. During the encapsulation process, it currently takes the operators one minute to prepare the next part, which is the cycle time for the bonder as described in our background chapter. The preparation process can be completed in 30 seconds, leaving 30 seconds to complete changeover tasks. From our turnover chart, some tasks take less than 30 seconds and could be completed during the time the operator is idle. These tasks include counting the cartridges, counting the labels, and putting the housings and caps in their designated bins. The Gantt chart for Proposal 2 can be found in the attached Excel document "Gantt Charts for Changeover Tasks": "Proposal 2". By making these tasks external, MilliporeSigma can reduce their changeover time by 3:15 minutes. This would require moving to a two-bin system in which the second work order would be brought to the production area when the number of remaining parts in the previous lot reaches a certain quantity level. Additionally, visual systems can be implemented to ensure the work orders remain separated. For example, during the last six parts, the operator running the bonder would walk to the rack, grab the housings, caps, and the cartridges, and count the parts. The SOP for Proposal 2 can be found in Appendix L: SOP Proposal 2.

Finally, Proposal 3 is similar to Proposal 2 but the quality assurance task is converted to external. The SOP can be found in Appendix M: SOP Proposal 3 and the full Gantt chart for Proposal 3 can be found in Excel document "Gantt Charts for Changeover Tasks": "Proposal 2".

### 4.3.3 Redesign Melt Check Procedures

Through our interviews with the Quality Engineers, our data collection, and our data analysis, we found that the melt check procedures should be redesigned. In our initial interview with the Quality Engineers, we discussed the possibility of changing the frequency of melt checks. We identified that melt checks were not being performed during the production of lots with up to 600 units, which gave us reason to believe that machine calibration could handle 600 units. We also identified that the machine calibration was adversely affected when there was a temperature change in the bonder. The conditions that required a temperature change in the machine were when there was a material type change or filter size change in between lots. Therefore, performing melt checks was not necessary in between small-sized lots when there was no change in material type or the filter size. We proposed different conditions under which a melt check would need to be performed to the quality engineers. We suggested that a melt check would be required (1) if the material type or size was changed between work orders; (2) if the material type or size were not changed, then a melt check would be completed once per shift. With this new procedure, lots could be ordered by the same material type and size to decrease the number of changeovers.

The new procedure also required making changes to the paperwork. In the old procedure, since melt checks would be performed in every lot, the melt check paperwork would simply be attached to the paperwork for the lot being produced. The new procedure created the need for alternative methods to associate melt checks with the paperwork for the lot, since one melt check could be associated with more than one lot. To address this need, our team proposed adding a row in documentation for the melt check identification number as well as a box containing the conditions to check off to illustrate that the conditions have been met. We also suggested two methods that can be used to attach melt-check paperwork to the corresponding lots. These methods, and more information about the melt check scenarios, can be found in Appendix G: Melt Check Scenarios.

We presented our proposal to the Quality Engineers in a meeting that explained the reasoning behind the proposal, as well as the conditions that melt checks need to be performed. The Quality Engineers were in favor of our proposed solution, however, they needed more data with regard to how often the melt checks failed. If most of the melt checks passed in the first attempt, it would validate that the machines were calibrated correctly and melt checks are not necessary after every lot.

To provide more information to the Quality Engineers, we devised a data collection sheet (Appendix E: Data Collection Sheet) to collect information on the number of times a melt check failed in between lots. This data was collected for five days across each shift and production line. Over the course of five days, the data collection yielded 57 data points. From this data we analyzed the results to present back to the quality department.

Our data analysis yielded that melt checks only failed when there was a shift change or a change in cartridge size. There were no failed checks between lots with similar traits. These results supported our proposal, and strengthened the idea that certain melt checks did not add any value to ensure quality production. We stressed the importance of controlling the process strategically rather than applying melt checks without a specific reason for every single batch, and transferred the information about our proposal and our findings from the data collection to the Quality Engineers to evaluate and start the change management procedure if they agree that the new procedure would result in better process control for the Opticap® XL production lines.

## 5 Recommendations & Conclusions

The goal of our project was to reduce changeover times of Opticap® XL production lines by improving changeover efficiency and reducing changeover complexity. Initially the changeover process took approximately 24:30 minutes, and it could reach up to 30 minutes for various different types of changeovers. Our team identified and proposed three different improvement strategies, each of which focused on reducing the length of different portions of the changeover process. These were the optimization of production schedule, the standardization of the changeover processes, and the redesign of melt check procedures. Based on the impact of each of the three areas of improvement, our team proposed the following recommendations to MilliporeSigma.

***Production Schedule Optimization Tool***

The production schedule optimization tool focused on reducing tooling time from the changeover by grouping lots with similar characteristics and assigning them to appropriate production lines. By implementing the optimization model, for a two-day case study, our team saved approximately 22 minutes in changeover tooling time.

We recommended that MilliporeSigma implement this optimization model with the Production Planner. The planner would receive the orders and input the orders for the two-day period they were scheduling. This implementation would require a brief training on how to use the model and how the VBA code could be modified if necessary. Once the training is completed, the optimization model can be implemented and used to make the production schedule. This tool can reduce changeover time by over 2,500 minutes in one year.

***Standardization of the Changeover Processes***

Standardization of the changeover processes focused on reorganizing tasks in the changeover process and eliminating any activity that can happen while the machine is running from the changeover. Our team proposed three different scenarios for MilliporeSigma that could be used to standardize the changeover processes. The first was reallocating changeover tasks, the second was changing tasks from internal to external, and the third was to include the quality assurance sample to an external task to the second proposal. The first scenario saves one minute and 25 seconds. The second scenario saves three minutes and 15 seconds. Finally, the third scenario saves five minutes and 30 seconds.

Our team recommended that MilliporeSigma implement the first scenario of reallocating tasks to evenly distribute them between the operators. This scenario requires that MilliporeSigma have a training session with their operators to review the new SOPs and ensure that all operators understand the new assignment of tasks. While the second and third scenarios save the company more time on changeovers and increase their revenue, they require further analysis into how the tasks can efficiently be changed from internal to external. By implementing the first scenario, MilliporeSigma can save over 4,500 minutes annually.

### *Melt Check Procedures*

The melt check procedures focused on reevaluating the conditions in which melt checks are performed. Our team realized that melt checks were performed before every single lot, which can vary in quantity from 1-600 units. Therefore melt checks were not consistent. We developed a set of melt check procedures and recommended MilliporeSigma to present these procedures to the quality engineers to ensure that they meet quality standards. By eliminating the melt checks in situations where the cartridge size, material type, and operator do not change, MilliporeSigma can save nine minutes and fifteen seconds per changeover.

Implementing the new melt check procedures will require extensive change management procedures, however the quality team understands the value of the change. From our data collection we are certain that by implementing the procedures MilliporeSigma can still maintain their high quality standards while increasing production efficiency.

### *Impact*

While each area of improvement has its own impact for MilliporeSigma, the greatest impact comes from implementing all three areas of improvement. By using the optimization tool, the schedule will have like sizes and materials run in sequential lots. Additionally, by sequencing lots of similar sizes and material types, the melt check procedures become more beneficial. The team conducted a cost analysis of the total benefit to MilliporeSigma, given if each area of improvement was implemented including the time saved during the changeover process. Table

14 shows the worst case, average case, and best case scenarios for each implementation scenario, based on the same two-day set of production data from December 2015.

| Strategy | Worst Case | Average Case | Best Case |
|---|---|---|---|
| **Production Schedule Optimization Tool** | 22 minutes<br>[redacted] | 22 minutes<br>[redacted] | 22 minutes<br>[redacted] |
| **Standardization of Changeover Tasks** | **Proposal 1**<br>36 minutes<br>[redacted] | **Proposal 2**<br>84 minutes<br>[redacted] | **Proposal 3**<br>143 minutes<br>[redacted] |
| **Redesign of Melt Check Procedures** | - | - | 74 minutes<br>[redacted] |
| **Approximate Revenue Increase in 2 days:** | [redacted] | [redacted] | [redacted] |

*Total Number of Changeovers: 26*

*Table 14 Impact Summary*

As can be seen in Table 14, a best case scenario can result in approximately 230 minutes saved for MilliporeSigma in two days, which can significantly reduce the changeover time in MilliporeSigma's operations. Even though there is great potential impact, our recommendations also require a well-planned implementation phase, during which the proposals could be adapted and improved. Due to time constraints, our team was able to focus on only three improvement strategies, and we were not able to implement all of our ideas. The next section will discuss our reflections on the project, as well as more features and problems we realized that still needs to be addressed to continuously improve the changeover efficiency.

## 6 Reflections

Throughout our project, we came across challenges that we overcame through our organization and communication. The two main challenges we faced were in the data collection process and modeling our optimization model. In this section, we provide a brief explanation of those challenges for teams that can potentially continue our project.

### *Data Collection*

Our team collected data on the machine process times, the changeover process times, and the preparation time for parts. The data was collected during the first production shift (7:00 am - 9:00 am) due to our class schedules and availability. Our data may be skewed considering we only collected time studies during the first shift, however we felt that it gave an accurate representation of the average process times, changeover process times, and preparation time for parts. If we had more time and more availability, we would collect more time studies during second and third shifts and we would conduct time studies on more operators to understand if there is a significant difference in time between the shifts.

Collecting data on the changeover process times was also an obstacle for our team. Changeovers are not planned events and it was difficult for our team to observe changeovers at the times we conducted observations. We collected most of our data from observing a few changeovers and interviewing operators. With more time, it would be beneficial to observe more changeovers during different production shifts to account for variability and ensure all time studies are accurate.

### *Modeling*

Through the modeling process in our project, we learned that coding should be started earlier because unexpected difficulties arise and learning a new coding language takes practice. While our team started as early as possible, if we had started earlier in our project we could have added additional features to improve our model. During our research in learning the VBA coding conventions, we found that our model was very specific and there was limited research on a problem similar to ours. While our model had characteristics of other models, we found it beneficial to not rely on these models. For future projects, we recommend using other models as guidance, but to build your own model because every problem is different. A specific feature we wanted to add to the model was the ability for the planner to assign certain lots to certain production lines when necessary. A limitation of the model was that it needed at least three different cartridge sizes to be scheduled for the model to run without errors. Although generally MilliporeSigma has at least three sizes to schedule the model will give errors in a case where only 10 inch sized products are being scheduled. With more time, these limitations of the model can be eliminated and the model can be made user-friendlier with added features.

***Team Organization***

While our team faced challenges throughout our project, we were able to overcome them through our high work level, communication and organization. We kept an organized list of tasks needed to complete our project and divided up the work evenly to ensure that all work was completed in a timely manner. Our recommendation to groups completing their project is to maintain open lines of communication with your group at all times and ensure that your team is organized and every member of the team is clearly communicated about the team’s goals.

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### Appendix A: Production Lines Facility Layouts

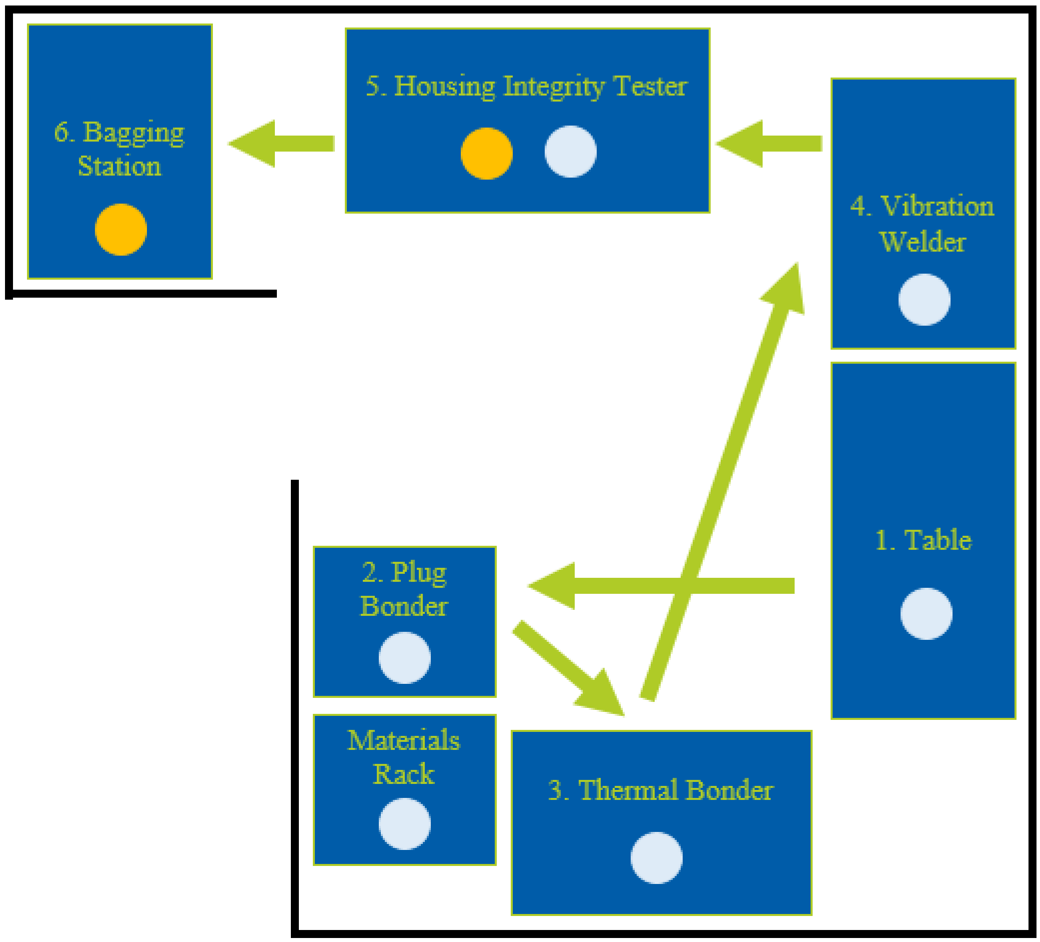


*Figure 12 Facility Layout of Production XL2*

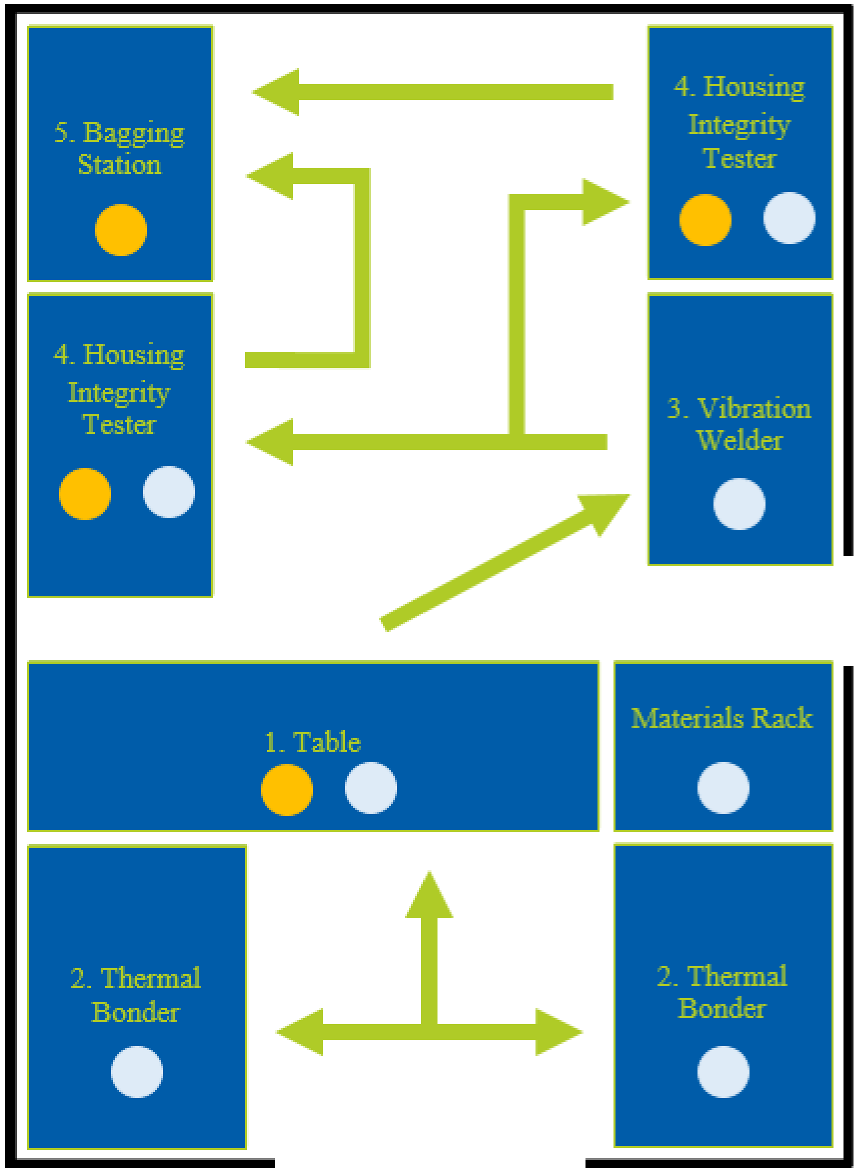


*Figure 13 Facility Layout of Production Line XL4*

**Appendix B: Operators Interview Questions**

1. What are your responsibilities during a changeover process?
2. What is the biggest difficulty during the changeover process?
3. What step takes the most time during this changeover process (approximately how long)?
4. What are problems you encounter during the changeover process?
5. Have you received formal training for this changeover process?
6. How do you determine who fills out the necessary paperwork for the changeover?
7. How do you determine who cleans the machines during the changeover?
8. Do you perform the machine setup or does the mechanic on shift for the changeover? If so, how is this completed?

**Appendix C: Production Lead Interview Questions**

1. How are changeovers planned or scheduled?
    a. Are there standard operating procedures for changeovers?
2. How are work orders communicated throughout all parties involved (packaging, operators, material handlers, warehouse, etc.)?

. How are work orders planned (in which order are they produced)?

3. When you assign a work order, can you estimate how long it is going to take depending on the product type and the batch size?
    a. If yes, does this help with scheduling?
    b. If no, would it help with scheduling batches if you had a method of estimating this?
4. Do operators on all shifts complete tasks in parallel?
5. What is the bottleneck in the changeover process?
    a. Do you think improving the tooling could decrease the changeover time?
    b. We heard through talking with the operators that the heat bonder has the largest variability in changeover time. What do you see as the problem with this?
    c. What are the common malfunctions that require a mechanic during a changeover process?
6. Do you see much of a difference in productivity between shifts and product lines?
7. What are the company's, FDA, ISO regulations with regards to the changeover process?
8. Could the presentation of materials be altered?

. Example: could the housings be delivered in bins instead of bags

**Appendix D: Material Handler Interview Questions**

1. Describe the process of receiving materials, sorting materials and transferring materials to the production lines.
    a. What procedure takes the most time?
    b. Which batch is most difficult to deliver (small batches, large, etc.)?
    c. Do you count all the parts once they arrive?
    d. Do you count all the parts prior to delivery to the production line?
2. We've seen that the pieces are delivered in bags. Why are they delivered in bags?
3. How are operators given materials when they run out during a batch?
4. How are you informed that there is a new work order?
    a. How do you schedule this and when do you bring the new material out to the production lines?
    b. How far in advance are you communicated that the lines will need a new batch of materials?
5. How do you manage the storage of materials at the workstations, in the Kanban room and at the warehouse?
6. What are your ergonomic standards for transporting goods?
7. How many material handlers are there per shift?
    a. Do they rotate among different areas or are they designated to a specific line?
8. Have you tried delivering materials in bins?
9. What is the availability of bin sizes and the number of total bins available?
    a. Do the bins have to be ESD?
    b. Does the color or look of the bin matter?

## Appendix E: Data Collection Sheet

| | Product 1 | Product 2 | Product 3 | Product 4 | Product 5 | Product 6 |
|---|---|---|---|---|---|---|
| **Production Time** | | | | | | |
| Line | | | | | | |
| Shift | | | | | | |
| Lot Size | | | | | | |
| **Assembly** | | | | | | |
| Previous Assembly No | | | | | | |
| Material type | | | | | | |
| Current Assembly No | | | | | | |
| **Cycle Times** | | | | | | |
| XL Thermal Bonder Duration | | | | | | |
| XL Vibration Welder Duration | | | | | | |
| XL Housing Integrity Test Duration | | | | | | |
| XL Bagging Duration | | | | | | |
| **Cell Operators** | | | | | | |
| Cell Operator 1 | | | | | | |
| Cell Operator 2 | | | | | | |
| Cell Operator 3 | | | | | | |
| **Changeover Process** | | | | | | |
| Clean Up Duration | | | | | | |
| Filter Counting Duration | | | | | | |
| Pre-Paperwork Completion Duration | | | | | | |
| Tooling Duration | | | | | | |
| Melt Test Duration | | | | | | |
| Melt Test # times performed | | | | | | |
| Bond Integrity Test Duration | | | | | | |
| Integrity Test # times performed | | | | | | |
| Strength Test Duration | | | | | | |
| Strength Test # times performed | | | | | | |
| Post-Paperwork Completion Duration | | | | | | |

**Appendix F: Task Turnover Chart**

| Task ID | Task Name | Task Description | Task Time (seconds) | Task Class |
|---|---|---|---|---|
| **1** | Clean and organize work area | Sweep the area, remove the leftover caps and housings from the previous batch | [redacted] | Internal |
| **2** | Finalize paperwork | Finish any leftover paperwork from the previous batch | [redacted] | Internal |
| **3** | Prepare quality assurance sample | Prepare and package the sample that will Internal be sent to the quality assurance department for testing | [redacted] | Internal |
| **4** | Walk to the rack | Walk to the rack area to get the housings and caps for the upcoming batch | [redacted] | Internal |
| **5** | Grab housings and caps | Grab the packages for the housings and caps and remove them from packages | [redacted] | Internal |
| **6** | Set housings and caps in bins | Empty the packages in respective bins and place the bins in the appropriate areas to use while batch run | [redacted] | Internal |
| **7** | Count cartridges and verify lot number | Confirm the number of cartridges presented in the bins and check that the lot number is correct | [redacted] | Internal |
| **8** | Complete corresponding paperwork to Task 7 | Sign the paperwork to confirm the number, and write the lot number to the corresponding area in the paperwork | [redacted] | Internal |
| **9** | Revise labels | Check the first label's number and the last label's number to make sure the amount of labels are correct | [redacted] | Internal |
| **10** | Complete corresponding paperwork to Task 9 | Stick a sample label in the corresponding area of the paperwork and sign the paperwork | [redacted] | Internal |

| | | | | |
|---|---|---|---|---|
| **11** | Set up housing integrity test | Change the clamps and the pressure settings of the Housing Integrity Tester according to the next batch | [redacted] | Internal |
| **12** | Complete corresponding paperwork to Task 11 | Complete the Housing Integrity Test paperwork | [redacted] | Internal |
| **13** | Select bonder recipe | Select the correct recipe for the upcoming batch among the provided options in the bonder screen | [redacted] | Internal |
| **14** | Perform melt checks in the bonder | Perform the 3 melt-check operations on the bonder machine consequently | [redacted] | Internal |
| **15** | Complete corresponding paperwork to Task 14 | Complete the encapsulation set up sheet by writing the values from each melt-check test to the corresponding area | [redacted] | Internal |
| **16** | Walk to bubble and burst | Walk to the bubble and burst test machine, which is located outside the work station close to the Kanban room | [redacted] | Internal |
| **17** | Perform the bubble and burst tests | perform the bubble and burst tests on the part that came out of the melt check to test the strength and integrity of the bond sample | [redacted] | Internal |
| **18** | Complete corresponding paperwork to Task 17 | Complete the encapsulation set up sheet by writing the values from bubble and burst tests to the corresponding area | [redacted] | Internal |
| **29** | Perform weld changeover tasks | Change the value on the weld screen | [redacted] | Internal |
| **20** | Test - run two parts | Run the first two parts of the batch through all of the encapsulation operation | [redacted] | Internal |
| **21** | Verify approval to initiate batch production | Operator finds indicated person to verify and sign the quality checks of the two test-runs in order to start batch production | [redacted] | Internal |

## Appendix G: Melt Check Scenarios

We propose that MilliporeSigma take in consideration the following conditions for melt check procedures to reduce the complexity of the changeover process, as well as, increase quality within larger lot sizes.

**Condition 1: Transition between Material Types**

Perform a melt check when there is a change in material type given that the cartridge sizes of the previous and current lot remains the same.

**Condition 2: Transition between Cartridge Sizes**

Perform a melt check if there is a change in cartridge size given that the material type of the previous and current lot remain the same.

*If the line has been running on the same type of product (cartridge size and material type), the Production Lead schedules one melt check during the shift to ensure there has not been any calibration problems after a shift change.*

**Condition 3: Large Batch Sizes**

Perform a melt check during the production of a large batch size to ensure calibration has not changed. For example, in a 600 piece lot perform a melt check half way through production.

To implement our proposed melt check procedure suggest using one melt check documentation to be used across multiple work orders and redesigning the required paperwork to include a melt check identification number and proposed melt check conditions.

**Melt Check Identification**

We propose adding a unique identifier to each melt check performed. This identification number can be used to help streamline the process as well can be tracked easily.

**Melt Check Paperwork**

To incorporate the different scenarios within the documentation of the work orders, we propose adding a row for the melt check identification number.

**Work Order Paperwork Redesign**

With the current paperwork, we propose adding a row in documentation for the melt check identification number as well as a box containing the conditions to check off to illustrate that the conditions have been met.

**Methods to Incorporate Proposed Procedure**

Operators would be responsible for checking the conditions and inputting the melt check identification number onto the corresponding paperwork. To associate all the information the following are proposed methods.

**Method 1: Photocopy Melt Check Paperwork**

To ensure the melt check paperwork is included in the batch record, a photocopy of the original melt check paperwork can be made. This photocopy would be immediately attached by the operator to the rest of the work order documentation

**Method 2: Melt Check Paperwork Attached After**

After the completion of the melt check, it would be scanned and saved to the server. To associate the melt check documentation, it can be later pulled from saved documents, copied, and attached to the entire batch record before the lot is released.

## Appendix H: Melt Check Data Collection Sheet

OPERATOR: [redacted]
PREVIOUS CAT / LOT NUMBER:
CURRENT CAT / LOT NUMBER:

PRODUCTION LINE: XL2
DATE: 20Nov15

| Melt Check Process | First Test Result | First Test (PASS / FAIL) | Second Test Result (if needed) | Second Test (PASS / FAIL) | Third (or More) Test Result (if needed) | Third (or More) Test (PASS / FAIL) |
|---|---|---|---|---|---|---|
| Melt Depth Endcap Top Heater (inch) | 0.046 | Pass | | | | |
| Melt Depth Endcap Bottom Heater (inch) | 0.046 | Fail | 0.046 | Fail | 0.038 | Pass |
| Final Bond Depth (inch) | 0.075 | Pass | | | | |
| Cartridge Bond Integrity Bubble Test (no bubbles @ 30 psi) | No bubbles | Pass | | | | |
| Cartridge Strength Burst Test (≥ 350 psi) | 501 | Pass | | | | |

**Appendix I: VBA Code for the Production Schedule Optimization Tool**

```
Sub FindLastRow()

  'Turn on screen updating after performing tasks
    Application.ScreenUpdating = False


  'Determine the index of the last row (procedure)
    Dim LastRow As Integer
     LastRow = 2
    While Not Cells(LastRow, 1).Value = Empty
     LastRow = LastRow + 1
    Wend

    Dim NumLots As Integer
    NumLots = LastRow - 2

  'Make all the sheets visible
    For Each sh In Sheets
        sh.Visible = True
    Next sh

  'This code deletes any worksheet in the workbook named "New_Model"
    Dim WS As Worksheet
    For Each WS In Worksheets
     If WS.Name = "New_Model" Then
        Application.DisplayAlerts = False
         Sheets("New_Model").Delete
        Application.DisplayAlerts = True
     End If
    Next

    'Add new optimization model sheet
    Sheets.Add.Name = "New_Model"

    'Read the data and create error message if there are not at least 3 different sizes in the
data
    Sheets("New_Model").Cells(1, 7).Formula = "=SUM(IF(FREQUENCY(Data!" &
Range(Cells(2, 5), Cells(2 + (NumLots - 1), 5)).Address & ",Data!" & Range(Cells(2, 5),
Cells(2 + (NumLots - 1), 5)).Address & ")>0,1))"

    If (Sheets("New_Model").Cells(1, 7).Value < 3) Then
      MsgBox ("Please schedule at least three sizes.")
      Sheets("New_Model").Visible = xlSheetHidden
      Sheets("Data").Visible = xlSheetHidden
```

```
    Sheets("Optimized_Schedule").Visible = xlSheetHidden
    End
  End If

  If NumLots > 40 Then
    MsgBox ("Attention: scheduling too many lots at one time can cause significant
delays. It is recommended to schedule no more than 40 lots at one time.")
    Sheets("New_Model").Visible = xlSheetHidden
    Sheets("Data").Visible = xlSheetHidden
    Sheets("Optimized_Schedule").Visible = xlSheetHidden
    End
  End If

  'Write to new sheet
  Sheets("New_Model").Cells(4, 1).Value = Sheets("Original Data Input").Cells(3,
8).Value
  Sheets("New_Model").Cells(4, 2).Value = Sheets("Original Data Input").Cells(3,
9).Value
  Sheets("New_Model").Cells(4, 3).Value = Sheets("Original Data Input").Cells(3,
10).Value
  Sheets("New_Model").Cells(4, 4).Value = Sheets("Original Data Input").Cells(3,
11).Value

  Dim RollingValue As Integer

 'Create the dij variables for lots

  For c = 2 To (NumLots + 1)
    For r = 7 To (NumLots + 6)


      RollingValue = 0

      'Compares the filter sizes between the two lots

      If (Sheets("Data").Cells(r - 5, 5).Value <> Sheets("Data").Cells(c, 5).Value) Then
        RollingValue = RollingValue + Sheets("New_Model").Cells(4, 1).Value
      'Range("r-5 + c-2),5").AutoFill Destination:=Range(("r-5 + c-2),5") & ("NumLots
+ 6, 5")), Type:=xlFillDefault
      End If

      'Compares the material type between the two lots

      If (Sheets("Data").Cells(r - 5, 4).Value <> Sheets("Data").Cells(c, 4).Value) Then
        RollingValue = RollingValue + Sheets("New_Model").Cells(4, 2).Value
      End If
```

```
        'Compares the inlet between the two lots

         If (Sheets("Data").Cells(r - 5, 6).Value <> Sheets("Data").Cells(c, 6).Value) Then
           RollingValue = RollingValue + Sheets("New_Model").Cells(4, 3).Value
         End If

        'Compare the outlet between the two lots

         If (Sheets("Data").Cells(r - 5, 7).Value <> Sheets("Data").Cells(c, 7).Value) Then
           RollingValue = RollingValue + Sheets("New_Model").Cells(4, 4).Value
         End If

        Sheets("New_Model").Cells(r, c).Value = RollingValue

    Next r
  Next c


 'Create the process time variables by pulling data from other sheets
  'shift is the number of cells we skip to build the next part of our model

  shift = 3

  For r = 7 To (NumLots + 6)
      Sheets("New_Model").Cells(r, 2 + NumLots - 1 + shift).Value = Sheets("Original
Data Input").Cells(r - 5, 4).Value * Sheets("Data").Cells(r - 5, 8).Value

  Next r

  Sheets("New_Model").Cells(5, 2 + (NumLots - 1) + shift).Formula = "=SUM(" &
Range(Cells(7, 2 + (NumLots - 1) + shift), Cells(7 + (NumLots - 1), 2 + (NumLots - 1) +
shift)).Address & ")"
  Sheets("New_Model").Cells(4, 27).Formula = "=SUM('Original Data Input'!" &
Range(Cells(6, 10), Cells(8, 10)).Address & ")"
  If Sheets("New_Model").Cells(5, 2 + (NumLots - 1) + shift).Value >
Sheets("New_Model").Cells(4, 27).Value Then
    MsgBox ("A solution to this model does not exist; try adding additional line capacity,
or reducing the number of lots to be scheduled.")
    Sheets("New_Model").Visible = xlSheetHidden
    Sheets("Data").Visible = xlSheetHidden
    Sheets("Optimized_Schedule").Visible = xlSheetHidden
    End
  End If

  'Create xij variables for k = 1
```

```
For r = 7 + (NumLots - 1) + shift To 7 + (NumLots - 1) + shift + (NumLots - 1)
   For c = 2 To 2 + (NumLots - 1)
      Sheets("New_Model").Cells(r, c).Value = 0
   Next c
Next r

'Create xij variables for k = 2

For r = 7 + (2 * (NumLots - 1)) + (2 * shift) To 7 + (3 * (NumLots - 1)) + (2 * shift)
   For c = 2 To 2 + (NumLots - 1)
      Sheets("New_Model").Cells(r, c).Value = 0
   Next c
Next r

'Create xij variables for k = 3
For r = 7 + (3 * (NumLots - 1)) + (3 * shift) To 7 + (4 * (NumLots - 1)) + (3 * shift)
   For c = 2 To 2 + (NumLots - 1)
      Sheets("New_Model").Cells(r, c).Value = 0
   Next c
Next r

'Create yik variables for k = 1
For r = 7 + (NumLots - 1) + shift To 7 + (NumLots - 1) + shift + (NumLots - 1)
   Sheets("New_Model").Cells(r, 2 + (NumLots - 1) + shift).Value = 0
Next r

'Create yik variables for k = 2
For r = 7 + (2 * (NumLots - 1)) + (2 * shift) To 7 + (3 * (NumLots - 1)) + (2 * shift)
   Sheets("New_Model").Cells(r, 2 + (NumLots - 1) + shift).Value = 0
Next r

'Create yik variables for k = 3
For r = 7 + (3 * (NumLots - 1)) + (3 * shift) To 7 + (4 * (NumLots - 1)) + (3 * shift)
   Sheets("New_Model").Cells(r, 2 + (NumLots - 1) + shift).Value = 0
Next r

'Create uik variables for k= 1
For r = 7 + (NumLots - 1) + shift To 7 + (NumLots - 1) + shift + (NumLots - 1)
   Sheets("New_Model").Cells(r, 2 + (NumLots - 1) + 2 * shift).Value = 0
Next r

'Create uik variables for k = 2
For r = 7 + (2 * (NumLots - 1)) + (2 * shift) To 7 + (3 * (NumLots - 1)) + (2 * shift)
   Sheets("New_Model").Cells(r, 2 + (NumLots - 1) + 2 * shift).Value = 0
Next r
```

```
    'Create uik variables for k = 3
    For r = 7 + (3 * (NumLots - 1)) + (3 * shift) To 7 + (4 * (NumLots - 1)) + (3 * shift)
        Sheets("New_Model").Cells(r, 2 + (NumLots - 1) + 2 * shift).Value = 0
    Next r

   'Create variables for start and ending cells for objective function to use in the range
function later on

    DistIndexStartCell = Sheets("New_Model").Cells(7, 2).Address
    DistIndexEndCell = Sheets("New_Model").Cells(7 + (NumLots - 1), 2 + (NumLots -
1)).Address

    K1xIndexStartCell = Sheets("New_Model").Cells(7 + (NumLots - 1) + shift,
2).Address
    K1xIndexEndCell = Sheets("New_Model").Cells(7 + (NumLots - 1) + shift +
(NumLots - 1), 2 + (NumLots - 1)).Address

    K2xIndexStartCell = Sheets("New_Model").Cells(7 + (2 * (NumLots - 1)) + (2 *
shift), 2).Address
    K2xIndexEndCell = Sheets("New_Model").Cells(7 + (3 * (NumLots - 1)) + (2 * shift),
2 + (NumLots - 1)).Address

    K3xIndexStartCell = Sheets("New_Model").Cells(7 + (3 * (NumLots - 1)) + (3 *
shift), 2).Address
    K3xIndexEndCell = Sheets("New_Model").Cells(7 + (4 * (NumLots - 1)) + (3 * shift),
2 + (NumLots - 1)).Address

    ProcessIndexStartCell = Sheets("New_Model").Cells(7, 2 + NumLots - 1 +
shift).Address
    ProcessIndexEndCell = Sheets("New_Model").Cells(7 + NumLots - 1, 2 + NumLots -
1 + shift).Address

    Yi1IndexStartCell = Sheets("New_Model").Cells(7 + (NumLots - 1) + shift, 2 +
(NumLots - 1) + shift).Address
    Yi1IndexEndCell = Sheets("New_Model").Cells(7 + (NumLots - 1) + shift +
(NumLots - 1), 2 + (NumLots - 1) + shift).Address

    Yi2IndexStartCell = Sheets("New_Model").Cells(7 + (2 * (NumLots - 1)) + (2 * shift),
2 + (NumLots - 1) + shift).Address
    Yi2IndexEndCell = Sheets("New_Model").Cells(7 + (3 * (NumLots - 1)) + (2 * shift),
2 + (NumLots - 1) + shift).Address

    Yi3IndexStartCell = Sheets("New_Model").Cells(7 + (3 * (NumLots - 1)) + (3 * shift),
2 + (NumLots - 1) + shift).Address
    Yi3IndexEndCell = Sheets("New_Model").Cells(7 + (4 * (NumLots - 1)) + (3 * shift),
2 + (NumLots - 1) + shift).Address
```

```
    Ui1IndexStartCell = Sheets("New_Model").Cells(7 + (NumLots - 1) + shift, 2 +
(NumLots - 1) + 2 * shift).Address
    Ui1IndexEndCell = Sheets("New_Model").Cells(7 + (NumLots - 1) + shift +
(NumLots - 1), 2 + (NumLots - 1) + 2 * shift).Address

    Ui2IndexStartCell = Sheets("New_Model").Cells(7 + (2 * (NumLots - 1)) + (2 * shift),
2 + (NumLots - 1) + 2 * shift).Address
    Ui2IndexEndCell = Sheets("New_Model").Cells(7 + (3 * (NumLots - 1)) + (2 * shift),
2 + (NumLots - 1) + 2 * shift).Address

    Ui3IndexStartCell = Sheets("New_Model").Cells(7 + (3 * (NumLots - 1)) + (3 * shift),
2 + (NumLots - 1) + 2 * shift).Address
    Ui3IndexEndCell = Sheets("New_Model").Cells(7 + (4 * (NumLots - 1)) + (3 * shift),
2 + (NumLots - 1) + 2 * shift).Address



    'Begin creating the optimization model
    SolverReset

    'Set Solver Options
   'SolverOptions MaxTime:=3600, Iterations:=10000, Precision:=0.00001,
AssumeLinear:=True, IntTolerance:=0, AssumeNonNeg:=True
    If Not Sheets("Original Data Input").Cells(12, 10).Value = Empty Then
        SolverOptions Precision:=0.00001, AssumeLinear:=True, IntTolerance:=0,
AssumeNonNeg:=True, MaxTime:=Sheets("Original Data Input").Cells(12, 10).Value
    Else
        SolverOptions Precision:=0.00001, AssumeLinear:=True, IntTolerance:=0,
AssumeNonNeg:=True, MaxTime:=36000
    End If

    'set the objective cell
    SolverOK SetCell:=Range(Cells(1, 10), Cells(1, 10)), MaxMinVal:=2,
ByChange:=Union(Range(K1xIndexStartCell, K1xIndexEndCell),
Range(K2xIndexStartCell, K2xIndexEndCell), Range(K3xIndexStartCell,
K3xIndexEndCell), Range(Yi1IndexStartCell, Yi1IndexEndCell),
Range(Yi2IndexStartCell, Yi2IndexEndCell), Range(Yi3IndexStartCell,
Yi3IndexEndCell), Range(Ui1IndexStartCell, Ui1IndexEndCell),
Range(Ui2IndexStartCell, Ui2IndexEndCell), Range(Ui3IndexStartCell,
Ui3IndexEndCell), Range(Cells(1, 10), Cells(1, 10)))


    'Constraint: xij <= yik for all i for k = 1
    For r = 7 + (NumLots - 1) + shift To 7 + (NumLots - 1) + shift + (NumLots - 1)
        For c = 2 To 2 + (NumLots - 1)
```

```
        SolverAdd cellRef:=Range(Cells(r, c), Cells(r, c)).Address, relation:=1,
formulatext:=Range(Cells(r, 2 + (NumLots - 1) + shift), Cells(r, 2 + (NumLots - 1) +
shift)).Address
      Next c
   Next r

   'Constraint: xij <= yik for all i for k = 2
   For r = 7 + 2 * (NumLots - 1) + 2 * shift To 7 + 3 * (NumLots - 1) + 2 * shift
      For c = 2 To 2 + (NumLots - 1)
        SolverAdd cellRef:=Range(Cells(r, c), Cells(r, c)).Address, relation:=1,
formulatext:=Range(Cells(r, 2 + (NumLots - 1) + shift), Cells(r, 2 + (NumLots - 1) +
shift)).Address
      Next c
   Next r

    'Constraint: xij <= yik for all i for k = 3
   For r = 7 + 3 * (NumLots - 1) + 3 * shift To 7 + 4 * (NumLots - 1) + 3 * shift
      For c = 2 To 2 + (NumLots - 1)
        SolverAdd cellRef:=Range(Cells(r, c), Cells(r, c)).Address, relation:=1,
formulatext:=Range(Cells(r, 2 + (NumLots - 1) + shift), Cells(r, 2 + (NumLots - 1) +
shift)).Address
      Next c
   Next r

   'Constraint: xij <= yjk for all i for k = 1
   y = 7 + (NumLots - 1) + shift
   For c = 2 To 2 + (NumLots - 1)
   i = 0
      For r = 7 + (NumLots - 1) + shift To 7 + (NumLots - 1) + shift + (NumLots - 1)
        SolverAdd cellRef:=Range(Cells((r - i), c), Cells((r - i), c)).Address, relation:=1,
formulatext:=Range(Cells(y, 2 + (NumLots - 1) + shift), Cells(y, 2 + (NumLots - 1) +
shift)).Address
      Next r
   y = y + 1
   i = i + 1
   Next c

   'Constraint: xij <= yjk for all i for k = 2
   y = 7 + 2 * (NumLots - 1) + 2 * shift
   For c = 2 To 2 + (NumLots - 1)
   i = 0
      For r = 7 + 2 * (NumLots - 1) + 2 * shift To 7 + 3 * (NumLots - 1) + 2 * shift
        SolverAdd cellRef:=Range(Cells((r - i), c), Cells((r - i), c)).Address, relation:=1,
formulatext:=Range(Cells(y, 2 + (NumLots - 1) + shift), Cells(y, 2 + (NumLots - 1) +
shift)).Address
      Next r
```

```
    y = y + 1
    i = i + 1
    Next c

    'Constraint: xij <= yjk for all i for k = 3
    y = 7 + 3 * (NumLots - 1) + 3 * shift
    For c = 2 To 2 + (NumLots - 1)
    i = 0
        For r = 7 + 3 * (NumLots - 1) + 3 * shift To 7 + 4 * (NumLots - 1) + 3 * shift
            SolverAdd cellRef:=Range(Cells((r - i), c), Cells((r - i), c)).Address, relation:=1,
formulatext:=Range(Cells(y, 2 + (NumLots - 1) + shift), Cells(y, 2 + (NumLots - 1) +
shift)).Address
        Next r
    y = y + 1
    i = i + 1
    Next c

    ' Constraint: sum of xij rows for all of the ks equal to 1
    For r = 7 + (NumLots - 1) + shift To 7 + 2 * (NumLots - 1) + shift
        Sheets("New_Model").Cells(r + (2 * (NumLots - 1)) + (2 * shift), 2 + (NumLots - 1)
+ 3 * shift).Formula = "=SUM(" & Range(Cells(r, 2), Cells(r, 2 + (NumLots -
1))).Address(False, False) & ") +SUM(" & Range(Cells(r + (NumLots - 1) + shift, 2),
Cells(r + (NumLots - 1) + shift, 2 + (NumLots - 1))).Address(False, False) & ") +SUM("
& Range(Cells(r + (2 * (NumLots - 1)) + 2 * shift, 2), Cells(r + (2 * (NumLots - 1)) + 2 *
shift, 2 + (NumLots - 1))).Address(False, False) & ") "
    Next r
    SolverAdd cellRef:=Range(Cells(7 + 3 * (NumLots - 1) + 3 * shift, 2 + (NumLots - 1)
+ 3 * shift), Cells(7 + 4 * (NumLots - 1) + 3 * shift, 2 + (NumLots - 1) + 3 *
shift)).Address, relation:=2, formulatext:=1

    ' Constraint: sum of xij columns for all of the ks equal to 1
    For c = 2 To 2 + (NumLots - 1)
        Sheets("New_Model").Cells(7 + (4 * (NumLots - 1)) + (4 * shift), c).Formula =
"=SUM(" & Range(Cells(7 + (NumLots - 1) + shift, c), Cells(7 + 2 * (NumLots - 1) +
shift, c)).Address(False, False) & ") +SUM(" & Range(Cells(7 + 2 * (NumLots - 1) + 2 *
shift, c), Cells(7 + 3 * (NumLots - 1) + 2 * shift, c)).Address(False, False) & ") +SUM("
& Range(Cells(7 + 3 * (NumLots - 1) + 3 * shift, c), Cells(7 + 4 * (NumLots - 1) + 3 *
shift, c)).Address(False, False) & ") "
    Next c
    SolverAdd cellRef:=Range(Cells(7 + 4 * (NumLots - 1) + 4 * shift, 2), Cells(7 + 4 *
(NumLots - 1) + 4 * shift, 2 + (NumLots - 1))).Address, relation:=2, formulatext:=1

    ' Constraint: sum of yik values for all of the ks equal to 1
    For r = 7 + (NumLots - 1) + shift To 7 + 2 * (NumLots - 1) + shift
        Sheets("New_Model").Cells(r, 2 + (NumLots - 1) + 3 * shift).Formula = "=SUM("
& Range(Cells(r, 2 + (NumLots - 1) + shift), Cells(r, 2 + (NumLots - 1) +
```

```
shift)).Address(False, False) & ") +SUM(" & Range(Cells(r + (NumLots - 1) + shift, 2 +
(NumLots - 1) + shift), Cells(r + (NumLots - 1) + shift, 2 + (NumLots - 1) +
shift)).Address(False, False) & ") +SUM(" & Range(Cells(r + 2 * (NumLots - 1) + 2 *
shift, 2 + (NumLots - 1) + shift), Cells(r + 2 * (NumLots - 1) + 2 * shift, 2 + (NumLots -
1) + shift)).Address(False, False) & ") "
   Next r
   SolverAdd cellRef:=Range(Cells(7 + (NumLots - 1) + shift, 2 + (NumLots - 1) + 3 *
shift), Cells(7 + 2 * (NumLots - 1) + shift, 2 + (NumLots - 1) + 3 * shift)).Address,
relation:=2, formulatext:=1

   'Assign the largest non 10 inch lot to Production Line 4 (3rd Production Line)
   LongestTime = 0
   LineFourAnchorIndex = -1
   For r = 7 To 7 + (NumLots - 1)
      If Sheets("Data").Cells(r - 5, 5) <> 10 Then
         If LongestTime < Sheets("New_Model").Cells(r, 2 + (NumLots - 1) + shift).Value
Then
            LongestTime = Sheets("New_Model").Cells(r, 2 + (NumLots - 1) + shift).Value
            LineFourAnchorIndex = r - 6
            LineOneSize = Sheets("Data").Cells(r - 5, 5)
         End If
      End If
   Next r

   'Add constraint that forces the y value for the lot we assigned to Production Line 4 to
be 1
   SolverAdd cellRef:=Range(Cells(7 + 3 * (NumLots - 1) + 3 * shift +
(LineFourAnchorIndex - 1), 2 + (NumLots - 1) + shift), Cells(7 + 3 * (NumLots - 1) + 3
* shift + (LineFourAnchorIndex - 1), 2 + (NumLots - 1) + shift)).Address, relation:=2,
formulatext:=1

   'Assign the largest lot that is not the size of the lot assigned to Production Line 4 to
Production Line 2 (2nd Production Line)
   LineTwoSize = -1
   LongestTime = 0
   LineTwoAnchorIndex = -1
   For r = 7 To 7 + (NumLots - 1)
      If Sheets("Data").Cells(r - 5, 5) <> LineOneSize Then
         If LongestTime < Sheets("New_Model").Cells(r, 2 + (NumLots - 1) + shift).Value
Then
            LongestTime = Sheets("New_Model").Cells(r, 2 + (NumLots - 1) + shift).Value
            LineTwoAnchorIndex = r - 6
            LineTwoSize = Sheets("Data").Cells(r - 5, 5)
         End If
      End If
   Next r
```

```
    'Add constraint that forces the y value for the lot we assigned to Production Line 2 to
be 1
    SolverAdd cellRef:=Range(Cells(7 + 2 * (NumLots - 1) + 2 * shift +
(LineTwoAnchorIndex - 1), 2 + (NumLots - 1) + shift), Cells(7 + 2 * (NumLots - 1) + 2 *
shift + (LineTwoAnchorIndex - 1), 2 + (NumLots - 1) + shift)).Address, relation:=2,
formulatext:=1

    'Assign the largest lot that is not the size of Line 4 and not the size of Line 2 to
Production Line 1 (2nd Production Line)
    LongestTime = 0
    LineOneAnchorIndex = -1
    For r = 7 To 7 + (NumLots - 1)
        If Sheets("Data").Cells(r - 5, 5) <> LineOneSize And Sheets("Data").Cells(r - 5, 5)
<> LineTwoSize Then
            If LongestTime < Sheets("New_Model").Cells(r, 2 + (NumLots - 1) + shift).Value
Then
                LongestTime = Sheets("New_Model").Cells(r, 2 + (NumLots - 1) + shift).Value
                LineOneAnchorIndex = r - 6
            End If
        End If
    Next r

    'Add constraint that forces the y value for the lot we assigned to Production Line 2 to
be 1
    SolverAdd cellRef:=Range(Cells(7 + (NumLots - 1) + shift + (LineOneAnchorIndex -
1), 2 + (NumLots - 1) + shift), Cells(7 + (NumLots - 1) + shift + (LineOneAnchorIndex -
1), 2 + (NumLots - 1) + shift)).Address, relation:=2, formulatext:=1



    'Create the ujs for k=1
    x = 7 + (NumLots - 1) + shift
    For c = 2 To 2 + (NumLots - 1)
        Sheets("New_Model").Cells(7 + 2 * (NumLots - 1) + shift + 1, c).Formula = "=" &
Sheets("New_Model").Cells(x, 2 + (NumLots - 1) + 2 * shift).Address(False, False)
        x = x + 1
    Next c


    'Create the matrix formula for k = 1
    Sheets("New_Model").Cells(1, 4).Value = NumLots
    For c = 2 To 2 + (NumLots - 1)
        For r = 7 + (NumLots - 1) + shift To 7 + 2 * (NumLots - 1) + shift
            Sheets("New_Model").Cells(r, c + (NumLots - 1) + 4 * shift).Formula = "=" &
Cells(r, c).Address(False, False) & "*" & (NumLots - 1) & "+" & Cells(r, 2 + (NumLots -
```

```
1) + 2 * shift).Address(False, False) & "-" & Cells(7 + 2 * (NumLots - 1) + shift + 1, c).Address(False, False) & "+" & (NumLots - 3) & "*" & Cells(c + 5 + (NumLots - 1) + shift, r - (NumLots - 1) - shift - 5).Address(False, False)
      Next r
   Next c

   'Add the u constraints for k = 1
   For r = 7 + (NumLots - 1) + shift To 7 + 2 * (NumLots - 1) + shift
      For c = 2 + (NumLots - 1) + 4 * shift To 2 + 2 * (NumLots - 1) + 4 * shift
         If (c - (NumLots + (4 * shift))) <> (r - ((NumLots - 1) + 7 + shift - 1)) And ((c - (NumLots + (4 * shift))) <> LineOneAnchorIndex) And ((r - (NumLots + 7 + shift - 2)) <> LineOneAnchorIndex) Then
            SolverAdd cellRef:=Range(Cells(r, c), Cells(r, c)).Address, relation:=1, formulatext:=(NumLots - 2)
         End If
      Next c
   Next r

      'Create the ujs for k=2
   x = 7 + 2 * (NumLots - 1) + 2 * shift
   For c = 2 To 2 + (NumLots - 1)
      Sheets("New_Model").Cells(7 + 3 * (NumLots - 1) + (2 * shift) + 1, c).Formula = "=" & Sheets("New_Model").Cells(x, 2 + (NumLots - 1) + 2 * shift).Address(False, False)
      x = x + 1
   Next c


   'Create the matrix formula for k = 2
   For c = 2 To 2 + (NumLots - 1)
      For r = 7 + 2 * (NumLots - 1) + 2 * shift To 7 + 3 * (NumLots - 1) + 2 * shift
         Sheets("New_Model").Cells(r, c + (NumLots - 1) + 4 * shift).Formula = "=" & Cells(r, c).Address(False, False) & "*" & (NumLots - 1) & "+" & Cells(r, 2 + (NumLots - 1) + 2 * shift).Address(False, False) & "-" & Cells(7 + 3 * (NumLots - 1) + (2 * shift) + 1, c).Address(False, False) & "+" & (NumLots - 3) & "*" & Cells(c + 5 + 2 * (NumLots - 1) + 2 * shift, r - 2 * (NumLots - 1) - 2 * shift - 5).Address(False, False)
      Next r
   Next c

   'Add the u constraints for k= 2
   For r = 7 + 2 * (NumLots - 1) + 2 * shift To 7 + 3 * (NumLots - 1) + 2 * shift
      For c = 2 + (NumLots - 1) + 4 * shift To 2 + 2 * (NumLots - 1) + 4 * shift
         If (c - (NumLots + (4 * shift))) <> (r - (2 * (NumLots - 1) + 7 + 2 * shift - 1)) And _
          ((c - (NumLots + (4 * shift))) <> LineTwoAnchorIndex) And _
         ((r - (2 * (NumLots - 1) + 7 + 2 * shift - 1)) <> LineTwoAnchorIndex) Then
```

```
            SolverAdd cellRef:=Range(Cells(r, c), Cells(r, c)).Address, relation:=1,
formulatext:=(NumLots - 2)
          End If
      Next c
   Next r

       'Create the ujs for k=3
   x = 7 + 3 * (NumLots - 1) + 3 * shift
   For c = 2 To 2 + (NumLots - 1)
      Sheets("New_Model").Cells(7 + 4 * (NumLots - 1) + (3 * shift) + 1, c).Formula =
"=" & Sheets("New_Model").Cells(x, 2 + (NumLots - 1) + 2 * shift).Address(False,
False)
      x = x + 1
   Next c

   'Create the matrix formula for k = 3   fix this
   For c = 2 To 2 + (NumLots - 1)
      For r = 7 + 3 * (NumLots - 1) + 3 * shift To 7 + 4 * (NumLots - 1) + 3 * shift
         Sheets("New_Model").Cells(r, c + (NumLots - 1) + 4 * shift).Formula = "=" &
Cells(r, c).Address(False, False) & "*" & (NumLots - 1) & "+" & Cells(r, 2 + (NumLots -
1) + 2 * shift).Address(False, False) & "-" & Cells(7 + 4 * (NumLots - 1) + (3 * shift) +
1, c).Address(False, False) & "+" & (NumLots - 3) & "*" & Cells(c + 5 + 3 * (NumLots -
1) + 3 * shift, r - 3 * (NumLots - 1) - 3 * shift - 5).Address(False, False)

      Next r
   Next c

   'Add the u constraints for k = 3
    For r = 7 + 3 * (NumLots - 1) + 3 * shift To 7 + 4 * (NumLots - 1) + 3 * shift
      For c = 2 + (NumLots - 1) + 4 * shift To 2 + 2 * (NumLots - 1) + 4 * shift
         If (c - (NumLots + (4 * shift))) <> (r - (3 * (NumLots - 1) + 7 + 3 * shift - 1)) And
_
          ((c - (NumLots + (4 * shift))) <> LineFourAnchorIndex) And _
         ((r - (3 * (NumLots - 1) + 7 + 3 * shift - 1)) <> LineFourAnchorIndex) Then
            SolverAdd cellRef:=Range(Cells(r, c), Cells(r, c)).Address, relation:=1,
formulatext:=(NumLots - 2)
         End If
      Next c
   Next r

   'Add constraints that ensure machines are not going over capacity
   Sheets("New_Model").Cells(1, 26).Formula = "=SumProduct(" &
Range(ProcessIndexStartCell, ProcessIndexEndCell).Address(False, False) & "," &
Range(Yi1IndexStartCell, Yi1IndexEndCell).Address(False, False) & ")"
```

```
    Sheets("New_Model").Cells(2, 26).Formula = "=SumProduct(" &
Range(ProcessIndexStartCell, ProcessIndexEndCell).Address(False, False) & "," &
Range(Yi2IndexStartCell, Yi2IndexEndCell).Address(False, False) & ")"
    Sheets("New_Model").Cells(3, 26).Formula = "=SumProduct(" &
Range(ProcessIndexStartCell, ProcessIndexEndCell).Address(False, False) & "," &
Range(Yi3IndexStartCell, Yi3IndexEndCell).Address(False, False) & ")"

    'Write Line max capacities on the model

    Sheets("New_Model").Cells(1, 27).Value = Sheets("Original Data Input").Cells(6,
10).Value
    Sheets("New_Model").Cells(2, 27).Value = Sheets("Original Data Input").Cells(7,
10).Value
    Sheets("New_Model").Cells(3, 27).Value = Sheets("Original Data Input").Cells(8,
10).Value

    SolverAdd cellRef:=Range(Cells(1, 26), Cells(1, 26)).Address, relation:=1,
formulatext:=Cells(1, 27).Address
    SolverAdd cellRef:=Range(Cells(2, 26), Cells(2, 26)).Address, relation:=1,
formulatext:=Cells(2, 27).Address
    SolverAdd cellRef:=Range(Cells(3, 26), Cells(3, 26)).Address, relation:=1,
formulatext:=Cells(3, 27).Address

    'add binary constraints for xij, and yik
    SolverAdd cellRef:=Range(K1xIndexStartCell, K1xIndexEndCell).Address,
relation:=5
    SolverAdd cellRef:=Range(K2xIndexStartCell, K2xIndexEndCell).Address,
relation:=5
    SolverAdd cellRef:=Range(K3xIndexStartCell, K3xIndexEndCell).Address,
relation:=5
    SolverAdd cellRef:=Range(Yi1IndexStartCell, Yi1IndexEndCell).Address, relation:=5
    SolverAdd cellRef:=Range(Yi2IndexStartCell, Yi2IndexEndCell).Address, relation:=5
    SolverAdd cellRef:=Range(Yi3IndexStartCell, Yi3IndexEndCell).Address, relation:=5

    SolverAdd cellRef:=Range(Ui1IndexStartCell, Ui1IndexEndCell).Address,
relation:=3, formulatext:=0
    SolverAdd cellRef:=Range(Ui2IndexStartCell, Ui2IndexEndCell).Address,
relation:=3, formulatext:=0
    SolverAdd cellRef:=Range(Ui3IndexStartCell, Ui3IndexEndCell).Address,
relation:=3, formulatext:=0


    'Add the ui<= n*yik constraint for k = 1
    For r = 7 + (NumLots - 1) + shift To 7 + 2 * (NumLots - 1) + shift
        Sheets("New_Model").Cells(r, 2 + (NumLots - 1) + shift + 1).Formula = "=" &
NumLots & "*" & Cells(r, 2 + (NumLots - 1) + shift).Address(False, False)
```

```
    Next r

    SolverAdd cellRef:=Range(Ui1IndexStartCell, Ui1IndexEndCell).Address,
relation:=1, formulatext:=Range(Cells(7 + (NumLots - 1) + shift, 2 + (NumLots - 1) +
shift + 1), Cells(7 + 2 * (NumLots - 1) + shift, 2 + (NumLots - 1) + shift + 1))

    'Add the ui<= n*yik constraint for k = 2
    For r = 7 + 2 * (NumLots - 1) + 2 * shift To 7 + 3 * (NumLots - 1) + 2 * shift
    Sheets("New_Model").Cells(r, 2 + (NumLots - 1) + shift + 1).Formula = "=" &
NumLots & "*" & Cells(r, 2 + (NumLots - 1) + shift).Address(False, False)
    Next r

    SolverAdd cellRef:=Range(Ui2IndexStartCell, Ui2IndexEndCell).Address,
relation:=1, formulatext:=Range(Cells(7 + 2 * (NumLots - 1) + 2 * shift, 2 + (NumLots -
1) + shift + 1), Cells(7 + 3 * (NumLots - 1) + 2 * shift, 2 + (NumLots - 1) + shift + 1))

    'Add the ui<= n*yik constraint for k = 3
    For r = 7 + 3 * (NumLots - 1) + 3 * shift To 7 + 4 * (NumLots - 1) + 3 * shift
        Sheets("New_Model").Cells(r, 2 + (NumLots - 1) + shift + 1).Formula = "=" &
NumLots & "*" & Cells(r, 2 + (NumLots - 1) + shift).Address(False, False)
    Next r

    SolverAdd cellRef:=Range(Ui3IndexStartCell, Ui3IndexEndCell).Address,
relation:=1, formulatext:=Range(Cells(7 + 3 * (NumLots - 1) + 3 * shift, 2 + (NumLots -
1) + shift + 1), Cells(7 + 4 * (NumLots - 1) + 3 * shift, 2 + (NumLots - 1) + shift + 1))

    '10 inch lots cant go to line 4 constraint
    For r = 2 To 2 + (NumLots - 1)
        If Sheets("Data").Cells(r, 5) = 10 Then
            SolverAdd cellRef:=Range(Cells(6 + 3 * (NumLots - 1) + (3 * shift) + (r - 1), 2 +
(NumLots - 1) + shift), Cells(6 + 3 * (NumLots - 1) + (3 * shift) + (r - 1), 2 + (NumLots -
1) + shift)).Address, relation:=2, formulatext:=0
        End If
    Next r

   ' make the diagonal xij varibles 0 for k = 1
   col = 2
    For r = 7 + (NumLots - 1) + shift To 7 + 2 * (NumLots - 1) + shift
        SolverAdd cellRef:=Range(Cells(r, col), Cells(r, col)).Address, relation:=2,
formulatext:=0
        col = col + 1
    Next r

    ' make the diagonal xij varibles 0 for k = 2
    col = 2
    For r = 7 + 2 * (NumLots - 1) + 2 * shift To 7 + 3 * (NumLots - 1) + 2 * shift
```

```
        SolverAdd cellRef:=Range(Cells(r, col), Cells(r, col)).Address, relation:=2,
formulatext:=0
        col = col + 1
    Next r

      ' make the diagonal xij varibles 0 for k = 3
    col = 2
    For r = 7 + 3 * (NumLots - 1) + 3 * shift To 7 + 4 * (NumLots - 1) + 3 * shift
        SolverAdd cellRef:=Range(Cells(r, col), Cells(r, col)).Address, relation:=2,
formulatext:=0
        col = col + 1
    Next r

    'add the constraint that changeover times + process times for line 1 <= q

    Sheets("New_Model").Cells(1, 12).Formula = "=SumProduct(" &
Range(DistIndexStartCell, DistIndexEndCell).Address(False, False) & "," &
Range(K1xIndexStartCell, K1xIndexEndCell).Address(False, False) & ") +SumProduct("
& Range(ProcessIndexStartCell, ProcessIndexEndCell).Address(False, False) & "," &
Range(Yi1IndexStartCell, Yi1IndexEndCell).Address(False, False) & ")"
    Sheets("New_Model").Cells(2, 12).Formula = "=SumProduct(" &
Range(DistIndexStartCell, DistIndexEndCell).Address(False, False) & "," &
Range(K2xIndexStartCell, K2xIndexEndCell).Address(False, False) & ") +SumProduct("
& Range(ProcessIndexStartCell, ProcessIndexEndCell).Address(False, False) & "," &
Range(Yi2IndexStartCell, Yi2IndexEndCell).Address(False, False) & ")"
    Sheets("New_Model").Cells(3, 12).Formula = "=0.5 * (SumProduct(" &
Range(DistIndexStartCell, DistIndexEndCell).Address(False, False) & "," &
Range(K3xIndexStartCell, K3xIndexEndCell).Address(False, False) & ") +SumProduct("
& Range(ProcessIndexStartCell, ProcessIndexEndCell).Address(False, False) & "," &
Range(Yi3IndexStartCell, Yi3IndexEndCell).Address(False, False) & "))"

    SolverAdd cellRef:=Range(Cells(1, 12), Cells(1, 12)).Address, relation:=1,
formulatext:=Range(Cells(1, 10), Cells(1, 10)).Address
    SolverAdd cellRef:=Range(Cells(2, 12), Cells(2, 12)).Address, relation:=1,
formulatext:=Range(Cells(1, 10), Cells(1, 10)).Address
    SolverAdd cellRef:=Range(Cells(3, 12), Cells(3, 12)).Address, relation:=1,
formulatext:=Range(Cells(1, 10), Cells(1, 10)).Address

    Sheets("New_Model").Cells(1, 1).Value = "passF"
    Sheets("New_Model").Cells(1, 2).Value = 1000
    Sheets("New_Model").Cells(2, 1).Value = "preprocess"
    Sheets("New_Model").Cells(2, 2).Value = "on"

    SetSolverParameters "CBC", Range("A1:B2"), Sheets("New_Model")

    Dim ReturnValue As OpenSolverResult
```

```
    ReturnValue = RunOpenSolver(False, True)

    'create the match function for line 1
    IndexValue = 1
    For r = 7 + (NumLots - 1) + shift To 7 + 2 * (NumLots - 1) + shift
        Sheets("New_Model").Cells(r, 2 + 2 * (NumLots - 1) + 5 * shift).Formula = "=" &
IndexValue
        IndexValue = IndexValue + 1
    Next r

    For r = 7 + (NumLots - 1) + shift To 7 + 2 * (NumLots - 1) + shift
        Sheets("New_Model").Cells(r, 2 + 2 * (NumLots - 1) + 5 * shift + 1).Formula =
"=Match(1," & Range(Cells(r, 2), Cells(r, 2 + (NumLots - 1))).Address(False, False) &
",0)"
    Next r

    'create the match function for line 2
    IndexValue = 1
    For r = 7 + 2 * (NumLots - 1) + 2 * shift To 7 + 3 * (NumLots - 1) + 2 * shift
        Sheets("New_Model").Cells(r, 2 + 2 * (NumLots - 1) + 5 * shift).Formula = "=" &
IndexValue
    IndexValue = IndexValue + 1
    Next r

    For r = 7 + 2 * (NumLots - 1) + 2 * shift To 7 + 3 * (NumLots - 1) + 2 * shift
        Sheets("New_Model").Cells(r, 2 + 2 * (NumLots - 1) + 5 * shift + 1).Formula =
"=Match(1," & Range(Cells(r, 2), Cells(r, 2 + (NumLots - 1))).Address(False, False) &
",0)"
    Next r

    'create the match function for line 3
    IndexValue = 1
    For r = 7 + 3 * (NumLots - 1) + 3 * shift To 7 + 4 * (NumLots - 1) + 3 * shift
        Sheets("New_Model").Cells(r, 2 + 2 * (NumLots - 1) + 5 * shift).Formula = "=" &
IndexValue
    IndexValue = IndexValue + 1
    Next r

    For r = 7 + 3 * (NumLots - 1) + 3 * shift To 7 + 4 * (NumLots - 1) + 3 * shift
        Sheets("New_Model").Cells(r, 2 + 2 * (NumLots - 1) + 5 * shift + 1).Formula =
"=Match(1," & Range(Cells(r, 2), Cells(r, 2 + (NumLots - 1))).Address(False, False) &
",0)"
    Next r

    Dim wa As Worksheet
    For Each wa In Worksheets
```

```
    If wa.Name = "Optimized_Schedule" Then
      Application.DisplayAlerts = False
      Sheets("Optimized_Schedule").Delete
      Application.DisplayAlerts = True
    End If
  Next

  Sheets.Add.Name = "Optimized_Schedule"
  Sheets("Optimized_Schedule").Cells(2, 2) = LineOneAnchorIndex
  Sheets("Optimized_Schedule").Cells(2, 5) = LineTwoAnchorIndex
  Sheets("Optimized_Schedule").Cells(2, 8) = LineFourAnchorIndex

  'Count the number of lots assigned to production line 1
  Yi1Count = 0
  For r = 7 + (NumLots - 1) + shift To 7 + 2 * (NumLots - 1) + shift
    If Sheets("New_Model").Cells(r, 2 + (NumLots - 1) + shift).Value = 1 Then
      Yi1Count = Yi1Count + 1
    End If
  Next r

  'Perform the lookup function only the amount of times equal to the count
  For r = 3 To 3 + (Yi1Count - 2)
    Sheets("Optimized_Schedule").Cells(r, 2).Formula = "=VLOOKUP(" & Cells(r - 1,
2).Address(False, False) & ",New_Model!" & Range(Cells(7 + (NumLots - 1) + shift, 2 +
2 * (NumLots - 1) + 5 * shift), Cells(7 + 2 * (NumLots - 1) + shift, 2 + 2 * (NumLots - 1)
+ 5 * shift + 1)).Address(True, True) & ",2)"
  Next r

  'Find the catalog number from the original data input that corresponds to index value
  For r = 2 To 2 + (Yi1Count - 1)
    Sheets("Optimized_Schedule").Cells(r, 3).Value = Sheets("Original Data
Input").Cells(Sheets("Optimized_Schedule").Cells(r, 2).Value + 1, 2)
  Next r

  'Count the number of lots assigned to production line 2
  Yi2Count = 0
  For r = 7 + 2 * (NumLots - 1) + 2 * shift To 7 + 3 * (NumLots - 1) + 2 * shift
    If Sheets("New_Model").Cells(r, 2 + (NumLots - 1) + shift).Value = 1 Then
      Yi2Count = Yi2Count + 1
    End If
  Next r

  'Perform the lookup function only the amount of times equal to the count for line 2
  For r = 3 To 3 + (Yi2Count - 2)
    Sheets("Optimized_Schedule").Cells(r, 5).Formula = "=VLOOKUP(" & Cells(r - 1,
5).Address(False, False) & ",New_Model!" & Range(Cells(7 + 2 * (NumLots - 1) + 2 *
```

```
shift, 2 + 2 * (NumLots - 1) + 5 * shift), Cells(7 + 3 * (NumLots - 1) + 2 * shift, 2 + 2 *
(NumLots - 1) + 5 * shift + 1)).Address(True, True) & ",2)"
    Next r

    'Find the catalog number from the original data input that corresponds to index value
    For r = 2 To 2 + (Yi2Count - 1)
        Sheets("Optimized_Schedule").Cells(r, 6).Value = Sheets("Original Data
Input").Cells(Sheets("Optimized_Schedule").Cells(r, 5).Value + 1, 2)
    Next r

    'Count the number of lots assigned to production line 3
    Yi3Count = 0
    For r = 7 + 3 * (NumLots - 1) + 3 * shift To 7 + 4 * (NumLots - 1) + 3 * shift
        If Sheets("New_Model").Cells(r, 2 + (NumLots - 1) + shift).Value = 1 Then
            Yi3Count = Yi3Count + 1
        End If
    Next r

    'Perform the lookup function only the amount of times equal to the count
    For r = 3 To 3 + (Yi3Count - 2)
        Sheets("Optimized_Schedule").Cells(r, 8).Formula = "=VLOOKUP(" & Cells(r - 1,
8).Address(False, False) & ",New_Model!" & Range(Cells(7 + 3 * (NumLots - 1) + 3 *
shift, 2 + 2 * (NumLots - 1) + 5 * shift), Cells(7 + 4 * (NumLots - 1) + 3 * shift, 2 + 2 *
(NumLots - 1) + 5 * shift + 1)).Address(True, True) & ",2)"
    Next r

    'Find the catalog number from the original data input that corresponds to index value
    For r = 2 To 2 + (Yi3Count - 1)
        Sheets("Optimized_Schedule").Cells(r, 9).Value = Sheets("Original Data
Input").Cells(Sheets("Optimized_Schedule").Cells(r, 8).Value + 1, 2)
    Next r

    Sheets("Optimized_Schedule").Cells(1, 2).Value = "XL1 Schedule"
    Sheets("Optimized_Schedule").Cells(1, 5).Value = "XL2 Schedule"
    Sheets("Optimized_Schedule").Cells(1, 8).Value = "XL4 Schedule"

    'Write optimized value in the Optimized Schedule Sheet
    'The writing would not give the right value as it added the cost of the changeover from
the last lot back to the first lot
    'Therefore as of now it is commented out, in the future this code can be used to write
optimized value in the sheet

    'Sheets("New_Model").Cells(1, 15).Formula = "=SumProduct(" &
Range(DistIndexStartCell, DistIndexEndCell).Address(False, False) & "," &
Range(K1xIndexStartCell, K1xIndexEndCell).Address(False, False) & ") +SumProduct("
& Range(DistIndexStartCell, DistIndexEndCell).Address(False, False) & "," &
```

```
Range(K2xIndexStartCell, K2xIndexEndCell).Address(False, False) & ") +SumProduct("
& Range(DistIndexStartCell, DistIndexEndCell).Address(False, False) & "," &
Range(K3xIndexStartCell, K3xIndexEndCell).Address(False, False) & ")"
   'Sheets("Optimized_Schedule").Cells(1, 20).Value = Sheets("New_Model").Cells(1,
15).Value

   Sheets("New_Model").Visible = xlSheetHidden
   Sheets("Data").Visible = xlSheetHidden

   'Turn on screen updating after performing tasks
   Application.ScreenUpdating = True

End Sub
```

## Appendix J: Production Schedule Optimization Tool User Instructions

Please apply the following instructions to optimize the schedule:

1. Open the "Original Data Input" tab, and select the data in columns A through D, starting from row 2
2. Select all of the data from row 2 to where the data ends, and press delete to clear the data
3. Starting from row 2 column A, input the appropriate catalog numbers, quantity started and ID number

   **Note:**

   - To test the model, start with scheduling smaller number of lots for 1-2 days (about 20-26 lots)
   - Slowly scale up the model as you see appropriate. Currently the model can only schedule up to 40 lots
4. Date Started column is not essential for the model to run, therefore it is optional
5. Make sure that ID number is in column A, Item number is in column B and Quantity Started is in column D

   **Note:**

   - Quantity started is the amount of boxes, not the amount of filter units. For example for a 2 inch lot quantity started can be 2, this would mean 2*3 = 6 units are being produced, since 2 inch filters are usually 3 units per box.
6. Make sure that among the data inputted there are at least 3 different size lots to ensure the model works properly

   **Note**:

   - It is possible to improve the code to eliminate this requirement
7. Make changes to the "conversion of changeover tasks" region if necessary. The values are how long it would add to changeover to make each change
8. Input the maximum capacity for each line so that scheduling do not cause a machine to go over capacity

   **Note**:

- Machine capacities have to be filled for the model to work, they cannot be left blank

9. Fill out the maximum time limit permitted for the model (it will output either the best overall schedule, or the best found schedule thus far)
10. Click "Optimize Schedule" and wait for the model to run. Depending on the time limit set, this can take hours, please give ample time to the model to run

    **Note:**

    - You can hit the Esc key to escape the solution at any time. The more time given, the closer to optimal the solution found will be.

11. Analyze the results and use it to create schedules. The model shows an optimized schedule, but changes can still be made, it is just a tool to advise.

**Appendix K: SOP Proposal 1**

| Steps | Task ID | Step Description |
|---|---|---|
| 1 | 1 | Once the final unit of a work order leaves the Bonder, Operator 1 cleans and organizes the workstation. During this process the Operator 1 discards scrap materials and organizes the area corresponding to the Table and Bonder. Operator 2 will clean their workstation upon the completion of their final product. |
| 2 | 2 | Operator 1 prepares Quality Assurance sample from the previous work order by bagging the units and complete corresponding forms. Next, he/she delivers the sample to the quality testing rack located at the center of the production floor next to the Production Lead's desk. |
| 3 | 3,1 | Next, Operator 1 finalizes and organizes the paperwork corresponding to the previous work order and then hands the paperwork folder to Operator 2. Operator 2 then completes the paperwork for their workstation and passes the paperwork folder to the packaging department. |
| 4 | 4,5,6 | Once the paperwork is completed, Operator 1 will walk to the Materials Rack, grab the housing and cap bags, and set the housings and caps in the bins on the Table. Then, he/she disposes the bags in the trash can. |
| 5 | 15,16, 17 | Operator 1 selects the Bonder recipe for the upcoming work order. Then, the Melt Check is performed according to MilliporeSigma's Bonder SOP and the paperwork is completed. |
| 6 | 12,13 | Operator 2 sets up the housing integrity test according to MilliporeSigma's Housing Integrity Test SOP and completes corresponding paperwork. |
| 7 | 7,8,9 | Once the Housing Integrity Test is set up, Operator 2 walks to the Materials Rack and grab the cartridges. The cartridges are brought to the Table beside the Bonder and are counted for accountability purposes. The corresponding paperwork is then completed by Operator 2. |
| 8 | 10,11 | Next, Operator 2 ensures that all labels are accounted for and attaches a sample label to the paperwork. |
| 9 | 21 | Operator 2 then completes the changeover procedure for the Welder. This is described in MilliporeSigma's Welder SOP. |
| 10 | 18,19, 20 | After Operator 1 finishes the Bonder melt check, he/she walks to the Bubble and Burst machine to perform the Bubble and Burst Tests according to MilliporeSigma's Bubble and Burst Test SOP. Next, Operator 1 completes the corresponding paperwork to the Bubble and Burst Tests. |

**Appendix L: SOP Proposal 2**

| Steps | Task ID | Step Description |
|---|---|---|
| 1 | 4, 5, 6 | With nine units remaining in the work order, Operator 1 will prepare sufficient material between the Bonder and Welder to allocate one minute of queue time. During the one minute of queue time, Operator 1 will walk to the materials rack, grab the housing and cap bags, and set the housings and caps in the bins on the table. Then, he/she disposes the bags in the trash can. |
| 2 | 7 | With at least seven remaining units, Operator 1 will prepare sufficient material between the Bonder and Welder to allocate fifteen seconds queue time. Then, Operator 1 then walks to the rack and grabs the cartridges. |
| 3 | 8 | With at least six remaining units, Operator 1 will allocate thirty seconds to count the cartridges for accountability purposes. |
| 4 | 9 | With at least five remaining units, Operator 1 allocates thirty seconds to complete the corresponding paperwork to Task 8. |
| 5 | 10 | With at least four remaining units, Operator 1 will set aside fifteen seconds between wait time for the Bonder and Welder to ensure all labels are accounted for. |
| 6 | 11 | With at least three remaining units, Operator 1 will set aside thirty seconds between wait time for the Bonder and Welder to complete the paperwork associated with label accountability. |
| 7 | 1 | With at least two remaining units, Operator 1 cleans and organizes his/her workstation. During this process the Operator discards scrap materials and organizes the area corresponding to the Table and Bonder. Operator 2 will clean their workstation upon the completion of their final product. |
| 8 | 2 | Operator 1 prepares Quality Assurance sample from the previous work order by bagging the units and complete corresponding forms. Next, he/she delivers the sample to the quality testing rack located at the center of the production floor next to the production lead's desk. |
| 9 | 3 | Next, operator 1 finalizes and organizes the paperwork corresponding to the previous work order and then hands the paperwork folder to Operator 2. Operator 2 then completes the paperwork for their workstation and passes the paperwork folder to the packaging department. |
| 10 | 15, 16 | Operator 1 selects the Bonder recipe for the upcoming work order. Then, the melt check is performed according to MilliporeSigma's Bonder SOP and the paperwork is completed. |
| 11 | 12, 13 | Operator 2 sets up the Housing Integrity Test according to MilliporeSigma's Housing Integrity Test SOP and completes corresponding paperwork. |
| 12 | 21 | Operator 2 then completes the changeover procedure for the Welder. This procedure is described in MilliporeSigma's Welder SOP. |
| 13 | 18, 19, 20 | After Operator 1 finishes the Bonder melt check, he/she walks to the Bubble and Burst machine to perform the Bubble and Burst Tests according to MilliporeSigma's Bubble and Burst Test SOP. Next, Operator 1 completes the corresponding paperwork to the Bubble and Burst Tests. |

**Appendix M: SOP Proposal 3**

| Steps | Task ID | Step Description |
|---|---|---|
| 1 | 4, 5, 6 | With at least thirteen units remaining in the work order, Operator 1 will prepare sufficient material between the Bonder and Welder to allocate one minute of queue time. During the one minute of queue time, Operator 1 will walk to the materials rack, grab the housing and cap bags, and set the housings and caps in the bins on the table. Then, he/she disposes the bags in the trash can. |
| 2 | 7 | With at least eleven remaining units, Operator 1 will prepare sufficient material between the Bonder and Welder to allocate fifteen seconds queue time. Then, Operator 1 then walks to the rack and grabs the cartridges. |
| 3 | 8 | With at least ten remaining units, Operator 1 will allocate thirty seconds to count the cartridges for accountability purposes. |
| 4 | 9 | With at least nine remaining units, Operator 1 allocates thirty seconds to complete the corresponding paperwork to Task 8. |
| 5 | 10 | With at least eight remaining units, Operator 1 will set aside fifteen seconds between wait time for the Bonder and Welder to ensure all labels are accounted for. |
| 6 | 11 | With at least seven remaining units, Operator 1 will set aside thirty seconds between wait time for the Bonder and Welder to complete the paperwork associated with label accountability. |
| 7 | 2 | With at least six remaining units, Operator 1 prepares Quality Assurance sample from the previous work order by bagging the units and complete corresponding forms. Next, he/she delivers the sample to the quality testing rack located at the center of the production floor next to the production lead's desk. |
| 8 | 1 | With at least two remaining units Operator 1 cleans and organizes his/her workstation. During this process the Operator discards scrap materials and organizes the area corresponding to the Table and Bonder. Operator 2 will clean their workstation upon the completion of their final product. |
| 9 | 3 | Next, operator 1 finalizes and organizes the paperwork corresponding to the previous work order and then hands the paperwork folder to Operator 2. Operator 2 then completes the paperwork for their workstation and passes the paperwork folder to the packaging department. |
| 10 | 15, 16 | Operator 1 selects the Bonder recipe for the upcoming work order. Then, the melt check is performed according to MilliporeSigma's Bonder SOP and the paperwork is completed. |
| 11 | 12, 13 | Operator 2 sets up the Housing Integrity Test according to MilliporeSigma's Housing Integrity Test SOP and completes corresponding paperwork. |
| 12 | 21 | Operator 2 then completes the changeover procedure for the Welder. This procedure is described in MilliporeSigma's Welder SOP. |
| 13 | 18, 19, 20 | After Operator 1 finishes the Bonder melt check, he/she walks to the |

| | | |
|---|---|---|
| | | Bubble and Burst machine to perform the Bubble and Burst Tests according to MilliporeSigma's Bubble and Burst Test SOP. Next, Operator 1 completes the corresponding paperwork to the Bubble and Burst Tests. |