Throughput Time Reduction at Saint-Gobain Abrasives

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Authorship

This project was completed equally in all aspects by all five members of the team. Team members include: Allison Holmes, Katherine LaPierre, Celeste Nicoletti, Ashley White, and Chelsea White.

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Abstract

Saint-Gobain North America is a global leader in building materials and abrasives. After acquiring Norton Company, a legacy manufacturing plant based in Worcester, in 1990, they were able to expand their market to a variety of grinding, cutting, blending, finishing, and polishing solutions. Today, Saint-Gobain continues to manufacture a wide variety of products. The Worcester campus manufactures ceramics, plastics, abrasives, and superabrasives. One particular product they manufacture are large resin superabrasive grinding wheels. The process, however, is not as efficient as it could be. Identifying opportunities for waste reduction is essential in creating a sustainable and successful process.

The overall objective of this project is to help Saint Gobain's Worcester plant to reduce the throughput time for their large resin superabrasive grinding wheels by utilizing industrial engineering principles, lean manufacturing techniques, axiomatic design, and computer simulation models. The proposal included a series of changes that the plant could make in order to operate more efficiently while reducing bottlenecks and increasing the likelihood of shipping customer orders on time. A financial analysis of the potential increase in sales revenue based on process improvements was provided, as well as a cash flow analysis for capital investment opportunities.

A review of the state of the art revealed examples of waste in the current system. Observations and data collection showed that customer orders are frequently late, the wheels travel a significant distance throughout the facility, and there is a long queue time between steps of the process. These delays and waste cause an increase of non-value added time in the process. Addressing these issues will allow a potential decrease in throughput time for the large resin superabrasive grinding wheels.

The approach was to decompose the overarching problem of an unacceptably long throughput time by analyzing scheduling, transportation, and wait time.

Methods used include the creation of a current and future state value stream map, Arena® simulation models, a spaghetti diagram with calculated travel distances, as well as an axiomatic design decomposition and financial analysis of the impact of the team's proposed recommendations.

The provided data that and the data that the team collected shows a high variance in overall process times. These results raise concerns regarding the repeatability of the throughput time, especially considering that all wheels are custom made. The manufacturing process varies for each order.

The analysis of our collected data and models lead the team to three findings that in order to reduce the throughput time and maintain improvements, Saint-Gobain should consider revising their production scheduling methods, baking wheels more often, and stocking commonly used preform molds.

Chapter 1: Introduction

1.1 Introduction to Saint-Gobain

Saint-Gobain, a French manufacturing company, is a global leader in sustainable habitat, and the world's largest building materials company (Saint-Gobain in North America, 2014). Originally known as the Royal Manufactory of Mirror Glass, Saint-Gobain's roots date as far back as 1665 (Norton Saint-Gobain, 2014). Over 350 years later, they now design, manufacture, and distribute building and high-performance materials. The company also provides innovative solutions to the challenges of growth, energy efficiency, and environmental protection (Norton Saint-Gobain, 2014).

In 1990, an effort to expand their market led Saint-Gobain to acquire Norton, a legacy plant that has been manufacturing abrasives for over 130 years. The Norton Company began as a tiny start-up in Worcester, Massachusetts in 1858, owned by cousins Frederick Hancock and Frank B. Norton (Saint-Gobain, 2014). They began their business making grinding wheels. As they rapidly expanded, the products they made were diversified to include industrial products and other abrasives. By the 1980's, the Norton Company consisted of four successful divisions (abrasives, high-performance ceramics, high-performance plastics, and healthcare products), which is what attracted Saint-Gobain to the company. The 10-billion-dollar acquisition was a major turning point in Saint-Gobain's history, allowing the company to double its presence in America, as well as to enter the abrasives market.

Norton, both at the time of their acquisition in the 1990s and today, is a world leader in abrasives. Norton offers the widest selection of grinding, cutting, blending, finishing, and polishing solutions for many different markets, materials and applications, as well as offering the most advanced and affordable technology (About Norton, 2014). Norton products are commonly used for construction purposes, in the iron, steel, and paper industries, and in high tech industries for automobiles, aeronautics, and electronics. Saint-Gobain has locations across the United States and Canada, with 8 facilities and over 2,200 employees (About Norton, 2014). Although Norton has changed its name to Saint-Gobain

Abrasives, the company continues to be a household name in abrasives. The headquarters for the abrasives unit remains at the Norton legacy plant in Worcester.

Today, Norton Saint-Gobain manufactures many products, including light construction equipment, non-abrasive products, and abrasive products. This project is focused on their superabrasive products, in particular the large resin grinding wheels, which was one of the original products of The Norton Company.

1.2 Problem Statement

The lead-time for the large resin grinding wheels in the super abrasive department at Saint-Gobain's Worcester plant is longer than desired. Saint-Gobain is a world leader in the grinding wheel industry, and the Worcester location is a job shop manufacturing facility. The majority of the orders are for single products or small made-to-order batches for customers. Due to the nature of the business, there are inefficiencies when scheduling production. It is difficult to make a uniform schedule, since each product takes a different amount of time to manufacture. The resulting production schedules often causes bottlenecks throughout the process. These bottlenecks are rate-limiting steps in the process. A more descriptive summary of bottlenecks can be found in Appendix A. Saint-Gobain strives to reduce the bottlenecks in order to decrease overall lead-time. Using several lean tools, the team will identify opportunities for process improvement to aid in reducing overall lead-time. These opportunities will become suggestions for Saint-Gobain as they move forward in designing a more efficient grinding wheel production process.

1.3 Project Goals and Objectives

The goal of the project is to reduce the total lead-time for the large resin superabrasive grinding wheels by identifying opportunities for process improvement. Through the utilization of lean manufacturing techniques, the team could analyze and improve the overall flow of the process. This subsequently aided in the reduction of bottlenecks in the system. A current state value stream map gives visualization of how the process currently runs. A future state value stream map will help Saint-Gobain identify areas for continued improvement and opportunities to relieve bottlenecks. In addition to both value stream maps, the team also simulated the production system using the simulation software Arena®. This software helps to replicate what is happening in the shop, and allows adjustments to be made to simulate different scenarios such as process distribution times, process flow steps, and likely outcomes. From here, it was easier to identify changes that would create an optimal production system. Finally, the team used a spaghetti diagram to demonstrate where the wheels travel throughout the plant. By completing these initiatives, the team identified process improvements to the overall process.

1.4 Scope and Deliverables

Saint-Gobain manufactures several different varieties of grinding wheels; however, the focus of this MQP was on the large DC-30 superabrasive grinding wheels and how to reduce its throughput time. The project analyzed sources of waste within the manufacturing process, identified bottlenecks, and provided future recommendations for Saint-Gobain to pursue in order the improve the process. The deliverables used to identify waste and bottlenecks included:

- Both a current and future state value stream map created in Microsoft Visio
- A hierarchical decomposition of the functional requirements and design parameters of the manufacturing process using Acclaro® software
- An Arena® simulation that models the production process
- A spaghetti diagram of the manufacturing floor shows likely outcomes with travel distances of the large resin wheels
- A financial analysis of the impact of our proposed recommendations

1.5 Project Timeline

The timeframe for completing this MQP spanned from the beginning of A-term 2017 to the end of B-term 2017 (August 24th through December 15th). A Gantt chart broke down the project into a series of goals and tasks. Each phase of the project was outlined as follows:

- Phase 1 (late August - mid September): Team familiarization with Saint-Gobain's history and current manufacturing process; background research on superabrasives and Lean manufacturing; introduction writing
- Phase 2 (mid to late September): Worked on the floor to collect data for determining lead times and bottlenecks; first drafts of current state & ideal state value stream maps; axiomatic design decomposition; and preliminary Arena® simulation
- Phase 3 (late September to mid-October): Interviews with operators and management; final draft of axiomatic design decomposition;
- Phase 4 (late October to mid-November): Final drafts of current state & ideal state value stream maps and Arena® simulation; financial analysis; mid-project presentation for sponsor
- Phase 5 (mid-November to mid-December): Finalized recommendations; completed final paper and presentation for sponsor

Due to the two term nature of this MQP, the team planned to gather the majority of the data required for the project during A-term in order to allow B-term to be focused on creating the final drafts of the deliverables and paper.

Chapter 2: Background

2.1 Superabrasive Grinding Wheels

Abrasives are essential to many manufacturing processes today. They aid in the cutting, grinding, and polishing operations of materials. In order to make uniform and dependable cuts, abrasive grains must be of a controlled size, free of impurities, and uniformly distributed (Norton Company, 1951). Abrasives are used to cut material that is softer than the material doing the cutting (Norton Company, 1951).

This project focuses on superabrasives. Superabrasives are manufactured either using diamond or cubic boron nitride (CBN) (Krar, 1995, p. 21). Superabrasives have certain properties that cause them to stand out amongst regular abrasives. Their hardness is much greater than that of other abrasives. Diamond is the hardest material with a hardness range of 7,000 -10,000 on the Knoop hardness scale, while CBN has a hardness of about 4,700. (Krar, 1995, p. 21). Diamonds also have a greater abrasion resistance, thus allowing them to wear much more slowly, subsequently reducing the frequency of replacement. Superabrasives have a greater compressive strength, which is the maximum amount of stress an abrasive can undergo before breaking (Linke, 2016). For example, the superabrasive diamond has 19 times the compressive strength of silicon carbide, a regular abrasive (Krar, 1995, p. 21). Lastly, the thermal conductivity of superabrasives surpass that of conventional abrasives (Krar, 1995, p. 21). These superabrasives are able to grind the hardest industrial materials, thus increasing productivity and quality while reducing manufacturing costs.

Grinding wheels are used in grinding machines to grind various types of material. The types of industries Saint-Gobain’s superabrasive grinding wheels are used to manufacture include:

- Automobile engines
- Transmission and bearing components
- High-hardness cutting tools for machining and oil and gas exploration
- Semiconductor chips and other electronic devices
- Automotive and architectural glass processing (Saint-Gobain Abrasives, 2017)

In these industries, superabrasive materials are used to cut especially resistant substances such as glass, stone, ceramics, and cemented carbides (Lewis, 1951, p. 14).

2.2 Grinding Wheels Process

The wheels that were the focus of this project are DC-30 Grinding Wheels. DC-30 is the name of the bonding agent used in the wheel (Molding ATL, Personal Communication, November 15, 2017). These wheels can be between 10" and 30" diameters, and their weights can vary depending on their size. The superabrasive grinding wheel travels through multiple processes during manufacturing. All DC-30 wheels go through similar steps during manufacturing. One difference in these steps is with the 30" diameter wheels due to the size restrictions of some of the machines. Additionally, wheels that require both parent and child parts will go through additional steps, which a single wheel does not have to go through. A parent-child wheel has multiple wheels that will eventually be cemented together as one for final assembly. In order to understand the process fully, the team physically walked the operations of the DC-30 grinding wheels from start to finish. The process for a parent-child wheel is as followed:

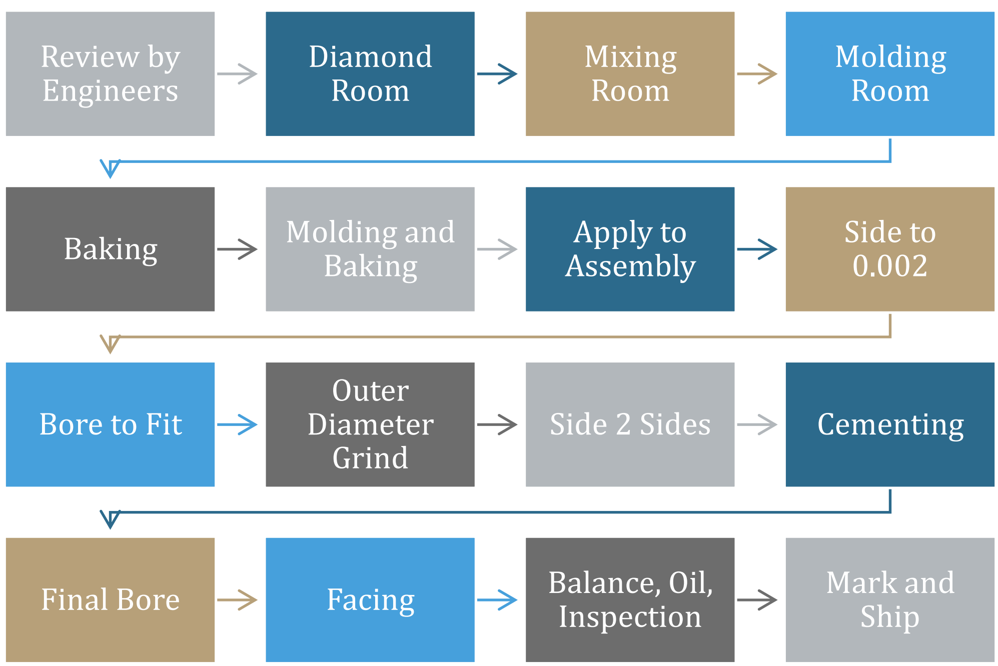


Figure 1. Process of Large Resin Grinding Wheels.

A full description of the manufacturing process can found in the Appendix B.

2.3 Lean Tools

Lean manufacturing is a systematic approach that aims to eliminate waste, create flow, and increase the speed of a process while continuously improving quality, cost, and the speed of delivery for customers (Plenert, 2012, p. 6). Originally based on a Japanese concept most commonly known as the Toyota Production System or Total Quality Management, lean strives to eliminate anything that is not required for the delivery of a valuable product to a customer, which is also known as eliminating non-value added time (Feld, 2001, p. 12).

The first step in lean process improvement requires that value be defined from the customer's perspective; the value should not be defined from the industry's perspective (Plenert, 2012, p. 148). Anything that the customer would not deem valuable is considered waste. Several methods are used to analyze where waste exists in a production system and how to remove it. Some of these methods include value stream mapping, spaghetti diagrams, 5S, Six Sigma, fishbone diagrams, and the seven wastes in manufacturing (Feld, 2001, p. 85).

2.3.1 The Seven Wastes

Taiichi Ohno, who proposed these wastes while analyzing the Toyota Production System (Jackson, 2012), originally developed the idea of the Seven Wastes in manufacturing. Since Ohno, the seven wastes have become a crucial element of the lean improvement process. The seven wastes allow for two things: they help decompose a process and assist in identifying where deficiencies lie, and they help differentiate between value added and nonvalue added time. Ohno's wastes are as follows (Plenert, 2012, p. 176)

1. **Unnecessary transportation:** information, people, or materials that are unnecessarily transported, handled, or stored
2. **Excess inventory:** materials, products, or information that is waiting to be processed; holding or ordering unnecessary inventory; storage of resources not directly needed to satisfy current customer demand
3. **Unnecessary movement by employees:** excess movement or repeated activities; handling steps that should be automated; poor layout

4. **Waiting:** time delays; idle time in the process; delays caused by shortages, downtime, or redundancy
5. **Overproduction**: processing more or more quickly than meets customer demand; producing product for which there is no customer demand
6. **Over-processing:** unneeded or redundant processing; adding more value to a product than a customer wants or is willing to pay for
7. **Defects**: rework and correction or errors; scrap

2.3.2 Value Stream Mapping

Value Stream Mapping (VSM) is another process mapping and waste identification tool that is used to identify lean improvement opportunities by focusing on finding non-value added processes in a system (Bradley, 2014, p. 28). In a manufacturing setting, the value stream generally spans the time from which the order is received to the time when the product is delivered and payment is received from the customer. Value stream mapping allows everyone involved in a process (i.e. management, the workforce, suppliers, customers, etc.) to participate and differentiate between value and waste, and create a plan of action for waste elimination. Value stream maps are drawn as pictures of the entire process. There are standard value stream mapping symbols used to present a logical representation of the process (Nash & Poling, 2008). These standard icons are seen in Figure 2.

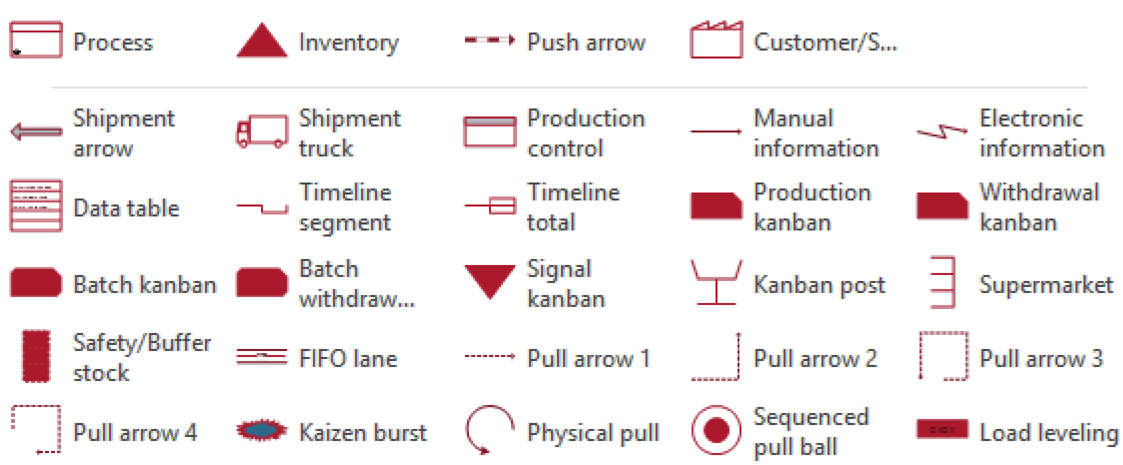


Figure 2. Standard Value Stream Map Icons.

There are certain guidelines to follow when making a value stream map. Implementation of a value stream map involves the following steps (Mignosa, Voehl, Charron, & Harrington, 2016):

1. Identify the process to be evaluated
2. Construct a flowchart of the current process (current state) to identify
    a. Steps
    b. Delays
    c. Information flows require:
        i. Raw materials
        ii. Design flow
        iii. Handling
3. Evaluate the current state value stream map flow to eliminate waste
4. Identify areas of improvement in the current state value stream map
5. Construct a future state value stream map
6. Implement plans to move toward the future state process flow

The current state value stream map is based on how the process works currently, while the future state value stream map combines the current state with ideas and lean tools to produce an idea for how the process could function in the future. The purpose of developing a future state value stream map is to identify realistic goals to focus improvements on. The future state is not the ideal process, rather an achievable one given the company's available resources.

2.3.3 Axiomatic Design

Axiomatic Design is a problem solving technique developed by Nam Suh, an engineering professor at MIT, in the 1990's. The goal of axiomatic design is to reduce the complexity of a problem by being able to make right design decisions at all levels (Suh, 1990). This matrix-based approach analyzes the customer needs (CNs) by breaking them down into functional requirements (FRs), design parameters (DPs), and process variables (PVs) (Borgianni & Dominik, 2015). Axiomatic design is a beneficial problem solving tool because it identifies and defines the FRs and the constraints before progressing towards a solution. The purpose of using axiomatic design for this project was to help break down the problem statement to better understand the factors contributing to the long lead-time for the large resin grinding wheels.

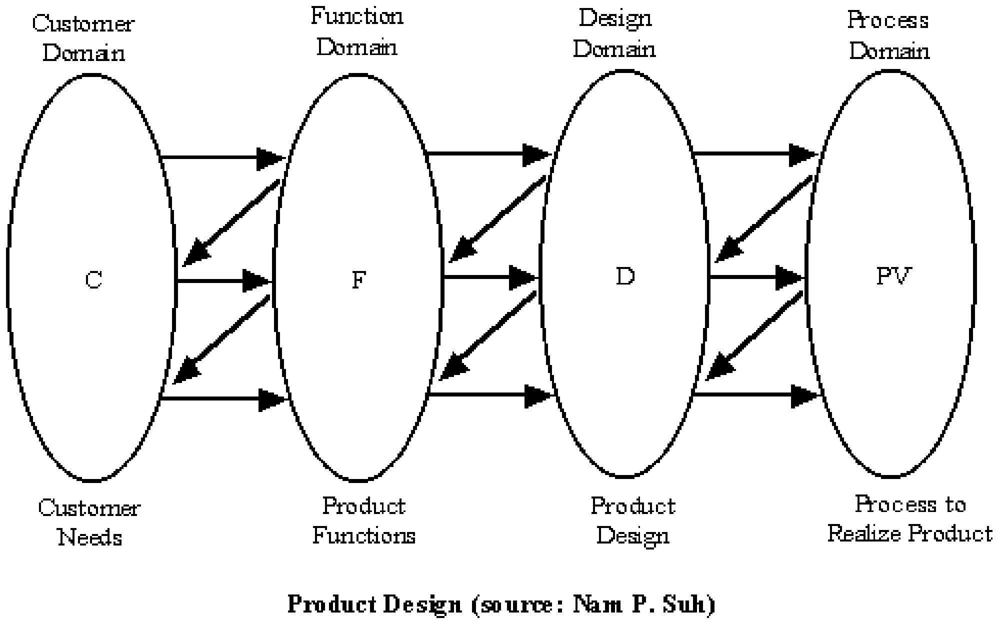


Figure 3. Axiomatic Design Domains. Source: (Sohlenius, 1998).

When using axiomatic design to solve a problem the first step is to determine the customer needs. From here, the functional requirements are identified. The FRs are the minimum set of independent requirements that the design must satisfy (El-Haik, 2005, p. 24). Once the FRs are mapped, the design parameters are identified.

There are two design axioms that must be followed:

- Axiom 1: The Independence Axiom
- Axiom 2: The Information Axiom

The Independence Axiom states that FRs must be independent from one another (El-Haik, 2005, p. 45). When a design satisfies the Independence Axiom, it is a stable design since the DP controls a specific FR without affecting other FRs (Suh, 1990).

The Information Axiom is used to minimize the information content of the design in order to make it as straightforward as possible. Suh stated, “Among all designs that satisfy the Independence Axiom, the one that possesses the least amount of information is the best” (Suh, 1990).

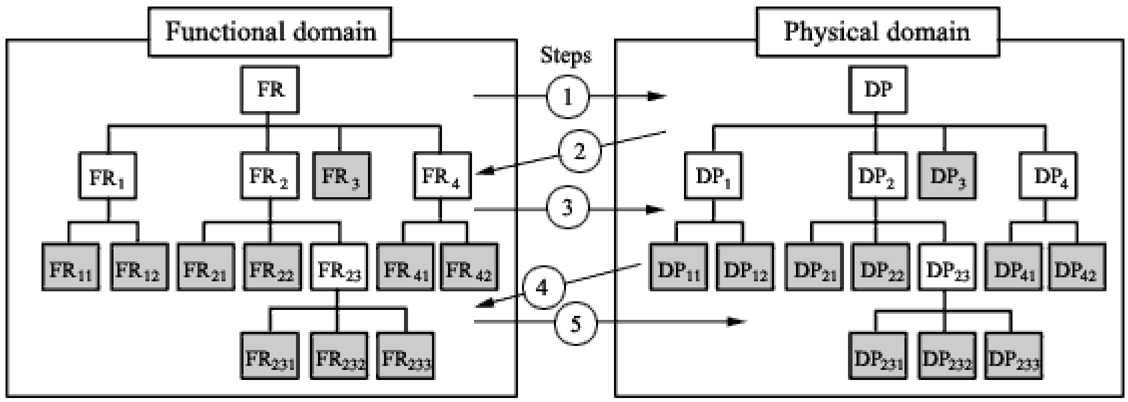


Figure 4. Functions Requirements & Design Parameters. Source: (Suh & Do, 2000).

Chapter 3: Methodology

3.1 Design of Methods

In order to achieve the overall project goal of providing suggestions to reduce the throughput time for the large resin grinding wheels at Saint-Gobain Abrasives, the team designed a methodology as a sequential systematic process, with each step building off data from the previous. Each step is done before the preceding step. For each method the team used, the purpose was also identified to ensure that all of the methods were useful in achieving the project goal. There is one overall purpose for each method. See Figure 5 for a breakdown of each method and its corresponding purpose.

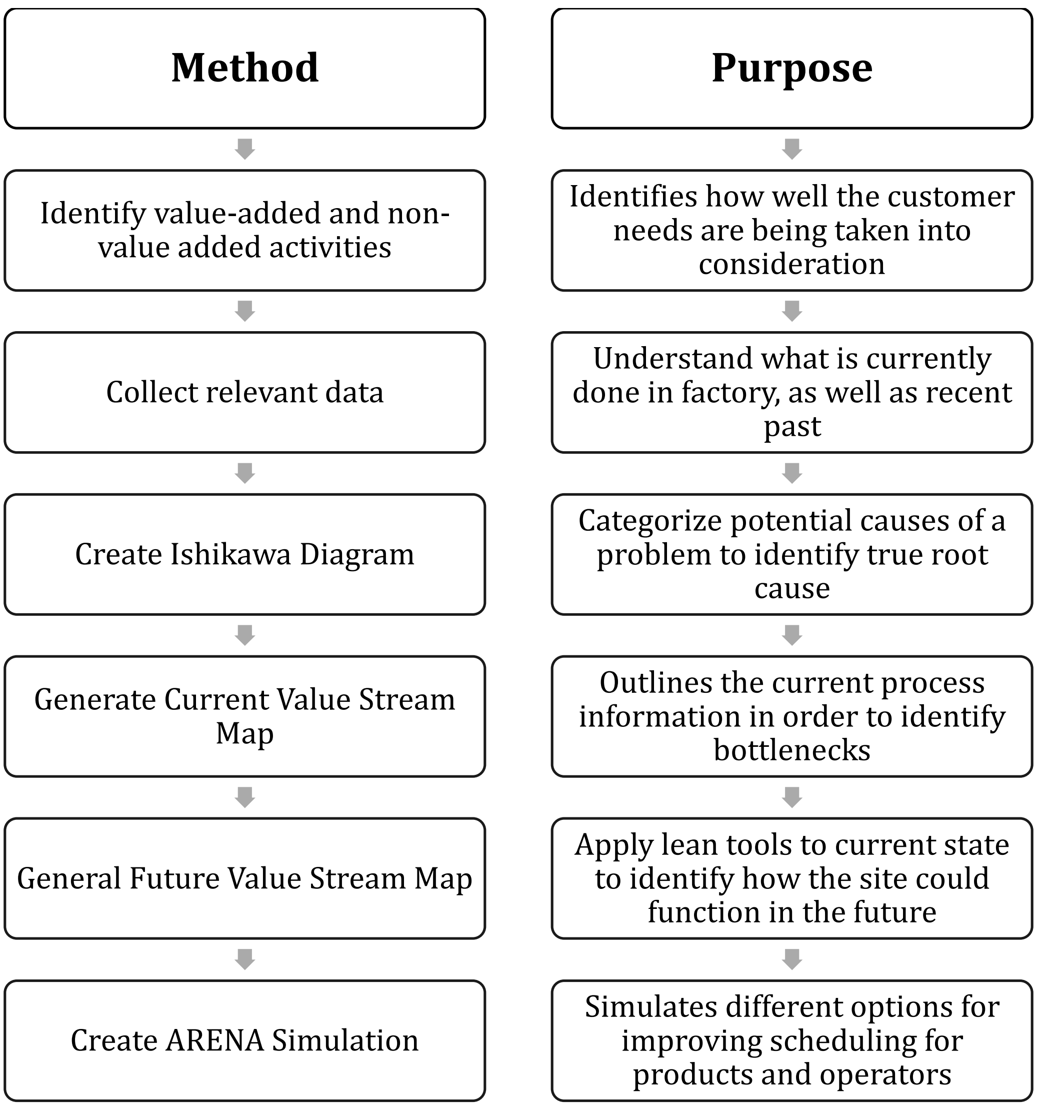


Figure 5. Flow Chart of Methods.

3.2 Problem Decomposition

To analyze the current state of the large resin grinding wheel production process, the team utilized axiomatic design in order to decompose the process into functional requirements to identify the customer needs. The team identified the top-level functional requirement, FR_0, as a need to reduce the throughput time for the large resin grinding wheels. From there, the Seven Wastes of Lean manufacturing, commonly known by the acronym "TIMWOOD", further broke down the problem. The team chose to adapt the acronym to "TIMPWOD" slightly. This is the acronym used by the production management team at Saint-Gobain. It focuses on the following:

- **Transportation:** reducing the distance each wheel is traveling. Depending on the type of wheel ordered, it may have to go through a nonlinear process and cycle back to a station it has already visited.
- **Inventory:** each wheel is made-to-order and lead time can be long, so there is constantly a sizeable amount of WIP in the system which could be minimized
- **Motion:** reducing unnecessary motion of employees, which includes repetitive motions, as well as movement to and from the workstation due to distractions, or placement of materials.
- **Personnel Utilization:** improving the utilization of employees during each shift to ensure that each employee is using time as efficiently as possible. This will help identify whether or not additional employees need to be hired, or if more shifts should be added to the schedule.
- **Waiting:** reduce waiting due to machine downtime, machine shortages, and setup/shift changes. Several steps in the process cause long waits and increase non-valued added time and due to the timing of shifts, some steps of the process take longer than necessary.
- **Overprocessing:** some wheels go through a step more than once, which leads to an increase in lead-time and overall transportation of the wheel.
- **Defects:** reducing the amount of defective wheels that are produced by identifying if these issues are usually caused by a certain machine or step in the process.

The team chose to focus on personnel utilization in place of overproduction because of the job shop nature of Saint-Gobain's manufacturing for this line of grinding wheels. On the other hand, personnel utilization is important because of the low number of employees and shifts, which may create bottlenecks in certain departments. The team could then identify which parts of the process may need more operators or additional shifts added.

After identifying the upper level functional requirements, most of the top level FRs were broken down further, with their children requirements describing actions that would also need to be taken in order to fulfil the parent FR, and ultimately, the team's FR_0. Using Acclaro® software, the team input the decomposition in order to generate the design matrix.

FR_0: Reduce the throughput time for the large resin superabrasive grinding wheels using IE and OM principles

FR_1: Reduce TRANSPORTATION waste caused by nonlinear processes

- $FR_{1.1}$: Reduce the amount of touches for each wheel

FR_2: Reduce excess INVENTORY in the system

- $FR_{2.1}$: Identify opportunities to reduce the amount of raw materials and WIP in the system

FR_3: Reduce unnecessary MOTION due to interruptions

- $FR_{3.1}$: Identify sources of employee distraction

FR_4: Improve PERSONNEL UTILIZATION of employees

- $FR_{4.1}$: Identify if the number of employees should be increased

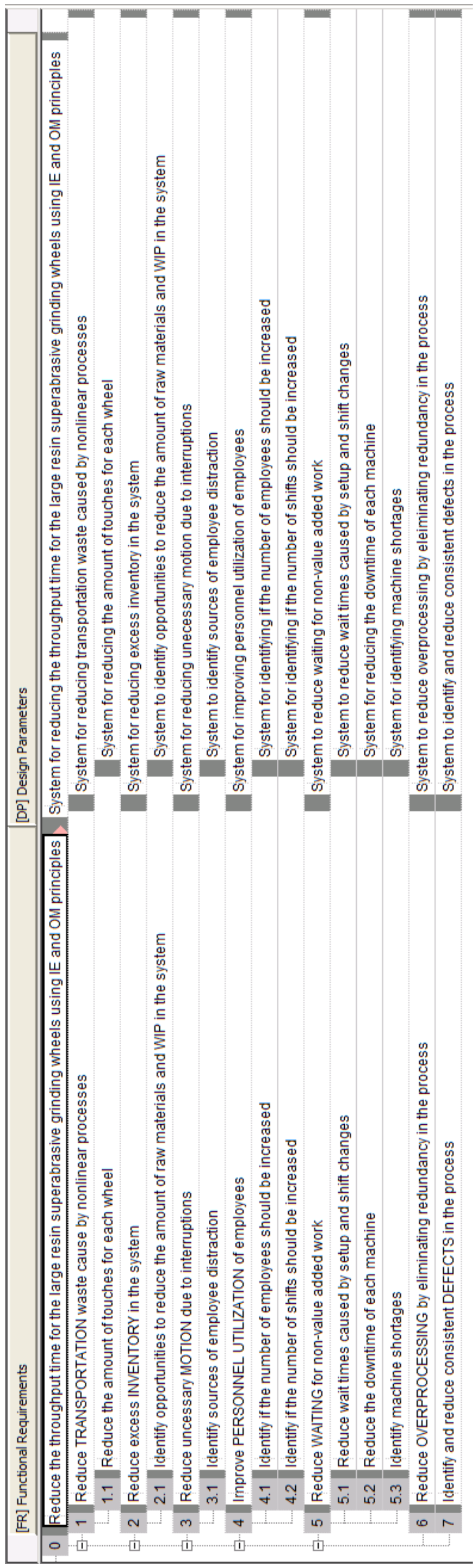
FR_5: Reduce WAITING for non-value added work

- $FR_{5.1}$: Reduce wait times caused by setup and shift changes
- $FR_{5.2}$: Reduce the downtime of each machine
- $FR_{5.3}$: Identify machine shortages

FR_6: Reduce OVERPROCESSING by eliminating redundancy in the process

FR_7: Identify and reduce consistent DEFECTS in the process

Figure 6. Axiomatic Design.



	[FR] Functional Requirements	[DP] Design Parameters
0	Reduce the throughput time for the large resin superabrasive grinding wheels using IE and OM principles	System for reducing the throughput time for the large resin superabrasive grinding wheels using IE and OM principles
1	Reduce TRANSPORTATION waste cause by nonlinear processes	System for reducing transportation waste caused by nonlinear processes
1.1	Reduce the amount of touches for each wheel	System for reducing the amount of touches for each wheel
2	Reduce excess INVENTORY in the system	System for reducing excess inventory in the system
2.1	Identify opportunities to reduce the amount of raw materials and WIP in the system	System to identify opportunities to reduce the amount of raw materials and WIP in the system
3	Reduce uncessary MOTION due to interruptions	System for reducing unecessary motion due to interruptions
3.1	Identify sources of employee distraction	System to identify sources of employee distraction
4	Improve PERSONNEL UTILIZATION of employees	System for improving personnel utilization of employees
4.1	Identify if the number of employees should be increased	System for identifying if the number of employees should be increased
4.2	Identify if the number of shifts should be increased	System for identifying if the number of shifts should be increased
5	Reduce WAITING for non-value added work	System to reduce waiting for non-value added work
5.1	Reduce wait times caused by setup and shift changes	System to reduce wait times caused by setup and shift changes
5.2	Reduce the downtime of each machine	System for reducing the downtime of each machine
5.3	Identify machine shortages	System for identifying machine shortages
6	Reduce OVERPROCESSING by eliminating redundancy in the process	System to reduce overprocessing by eleiminating redundancy in the process
7	Identify and reduce consistent DEFECTS in the process	System to identify and reduce consistent defects in the process

Figure 7. Axiomatic Design Functional Requirements and Design Parameters.

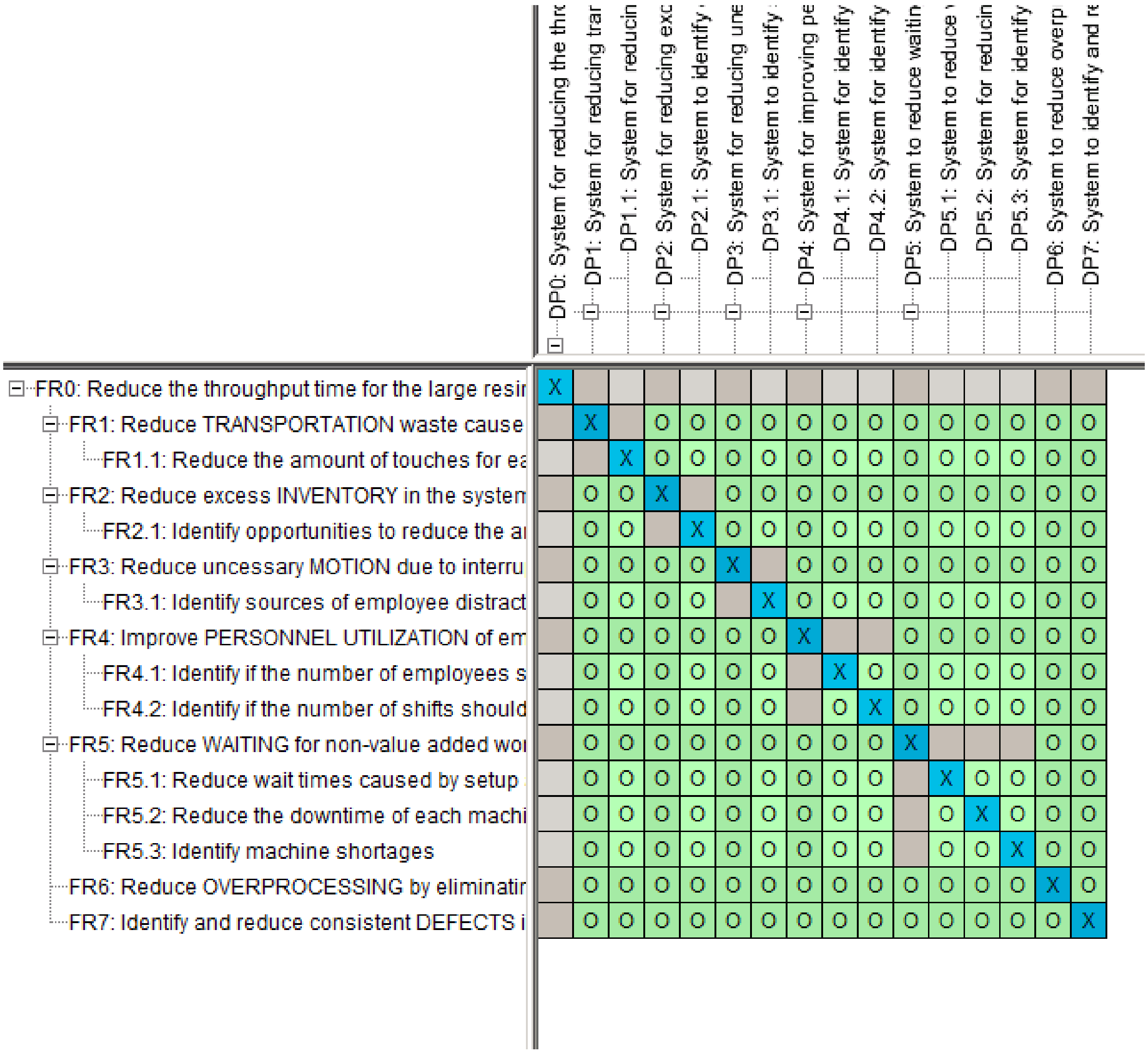


Figure 8. Axiomatic Design Matrix.

As shown in the design matrix for this decomposition, there is no coupling of functional requirements and design parameters, which is ideal. This eliminated the need for the team to identify ways to decouple FRs and DPs for specific processes in order to maintain the Independence Axiom. It is crucial to maintain this axiom because each design parameter should only influence its related functional requirement. This allowed the team to work on each design parameter independently, without concern that the design would affect other requirements, and vice versa.

By decomposing the problem statement using axiomatic design, the team was able to easily proceed to the analysis portion of the project after data collection because the goals of the project were clearly defined. By having the project focus clearly communicated from the beginning, the team was able to avoid changing the scope throughout the duration of the project. While axiomatic design does not directly solve the problem statement, it allows the user avoid unnecessary iterations in the design of solutions.

3.3 Root Cause Analysis

Root cause analysis is a set of tools and methods that is used to evaluate significant events to help identify the root causes of potential problems (Vanden Heuvel, Lorenzo, Montgomery, Hanson & Rooney, 2005). There are different methods that can be used to perform a single case bore analysis or evaluate any undesirable event. Before identifying the root cause of an event, the problem must be defined and data must be collected (Ammerman, 1998, p. 79). There are many different approaches for collecting data, such as reviewing records, conducting interviews, and observing the actual scene of the event (Andersen & Fagerhaug, 2006, p. 31). After identifying the problem and collecting the data, the event can be analyzed. There are four different kinds of analysis: task analysis, change analysis, control barrier analysis, and event and causal factor charting (Ammerman, 1998, p. 81). The team implemented task analysis.

Task analysis is a method of "dividing or breaking down a task into its steps or subtasks by identifying the sequence of actions, instructions, conditions, tools, and materials associated with the performance of a particular task" (Ammerman, 1998, p. 86). The goal of task analysis is to figure out what is supposed to be happening in a system. When determining the root cause of the problem, there must be different kinds of data that is collected. A common way to collect data is through interviewing key stakeholders. Understanding what information the user is seeking is critical. In the case of Saint-Gobain, the goal of the interviews was to identify opportunities for improvement and recommendations to reduce the lead-time based on the observations of the employees.

The team also created an Ishikawa diagram, or fishbone diagram, to help identify the root cause of the problem. A fishbone diagram is a visual tool that helps categorize the potential causes of the problem (Law, 2016). Working back from the initial problem, the team identified four main categories that potential causes could fall in, which include people, environment, process, and equipment. These categories were broken down further to identify the potential problems and the causes within these categories.

When determining the root cause, it is important to remember, "Data plus analysis equals information" (Ammerman, 1998, p. 86). There are many benefits to solving a problem using root cause analysis. One benefit is that a root cause analysis is that it is used to determine presumptive causes of the performance problem. It is also used to eliminate apparent and presumptive causes that data does not support (Ammerman, 1998, p. 88). A root cause analysis determines what actions need to be corrected. By looking at these causes, it is easier to identify all the corrective actions that are required when preventing the problem from reoccurring.

3.3.1 Interviews

Each stage in the grinding wheel manufacturing process plays a crucial role in completing a wheel on time. To get a complete picture of the current opportunities for improvement at Saint-Gobain, the team interviewed members of management and operators. The goal was to attempt to draw parallels between the responses from each group, as we expected each to have different perspectives. First, the team conducted interviews with operators because they are the closest to the process. In order to get a complete view of what works well and what does not on the manufacturing floor, the interviewed employees all worked on different aspects of the process. These employees all had several ideas regarding potential improvement opportunities. The team used a basic questionnaire for the operators and it was modified based on their responses. The full questionnaire for the operators is in Appendix C.

These employees are the experts in their respective departments and could offer insightful information regarding improvement opportunities. A different set of questions was created for each of these interviewees. These questions were beneficial in understanding the role of the management employee and changes that the employee envisions for Saint-Gobain. These questions, as well as the responses from the managers can be found in Appendix D.

These interview sessions with both operators and managers helped to identify the positive and negative aspects of the process. It also helped the team understand what improvement efforts were made in the past and whether or not they were successful. The collected responses helped the team identify potential areas to focus their efforts for process improvement.

Chapter 4: Results and Discussion

4.1 Observations and Constraints

Observing both the steps of the manufacturing process as well as the operators working on the production were essential to further understanding the problem statement and helping develop feasible recommendations for improvement. The team made observations from the first step of the process in the diamond room through to the final step in finishing. Based on the observations, it was clear that the process is slow moving and there is not a lot of opportunity for automation since each of the parts are different dimensions (Capital Purchasing Engineer, Personal Communication, October 4, 2017).

After the observations were complete, the team identified scheduling, molding, and baking as the main rate limiting steps. Some of the orders the team observed on the floor appeared to be behind schedule, indicating that the production schedule may not be optimal given the number of resources and operators.

The part goes through two different molding processes. The preform mold must be completed before the diamond mold starts. On average, the preform molding takes 3 days, but starts on average 2 days after the initial order is placed, leaving those previous days wasted. Once the preform is molded, the part must bake, which causes a delay for the second molding process. This becomes a common bottleneck. The elongated queue time for the molding process is based on an influx of parts to the system when the initial baking of the preform is complete. Parts are supposed to be done in a first-in first-out (FIFO) order. Due to the influx, there is no specified order, so some parts sit longer, causing them to get further behind schedule. Based on the data that was provided, it was clear that the queue time for the molding operation is significantly higher than the other operations (Production Engineer, Personal Communication, October 25, 2017). Another constraint with the system is that the scheduler assumes infinite capacity, although in reality, only a certain number of wheels can be molded per day based on the size and time that molding takes. There are only eight presses to mold the preforms and wheels, making them a limited resource.

The last major constraint that was identified was in Baking. Baking takes between 16 and 37 hours on average, although the parts sit in the oven for approximately 48 hours (Production Scheduling, Personal Communication, November 8, 2017). Therefore, there are between 11-32 unused hours in the baking process where the wheels are just sitting, depending on the cycle. Additionally, the wheels that bake for 16 hours sit for the same amount of time as the wheels that bake for 37 hours because the operator that unloads the wheels comes every day and a half after baking starts (Molding ATL, Personal Communication, November 15, 2017). This is a scheduled person so currently there is no option to make this more frequent. The wheels are usually cooled and unloaded at 3am. Another issue with the baking station is that the operators generally wait to start the baking until an oven is filled. Since each oven can hold approximately 20 large resin wheels, there are many wheels that are ready to be baked, but the wheels sit and wait until a full batch can be made (Molding ATL, Personal Communication, November 15, 2017). Once the baking of these large batches of wheels is complete, the wheels flood the queue for other processes, causing a longer throughput time.

4.2 Interview Responses

By analyzing and breaking down the interview responses from employees, the team was able to identify key takeaways from the interviews. These takeaways were broken into five categories of the highest repeated responses. The categories were:

- Scheduling problems
- Management
- Plant employees
- Physical space in the plant
- Capital investment

When designing the interview questions for the management, it was important to tailor the questions to each person's respective expertise. Interviewing someone from each of the categories was important to understand if the operator's needs matched the needs and goals of the company and management. The team interviewed six employees from management: the capital-purchasing engineer, manufacturing manager (staffing), quality manager, production scheduling manager, materials manager, and finance controller. Each management employee was asked a standard set of questions. From there, another set of questions was created to extract the information that was pertinent to each of the employees. These questions helped the team understand the root cause for the opportunity to reduce the lead-time.

Through the interviews, the team was able to identify the following opportunities for improvement:

- Adjust when the wheel is scheduled to begin production
- Operator accountability for FIFO

In an interview with the Manufacturing Manager, the team learned that Saint-Gobain typically promises their customers 20 working days to produce the order (Manufacturing Manager, Personal Communication, October 5, 2017). Each part currently has a scheduled for a lead-time of 16 days. The scheduling system that Saint-Gobain uses creates the timeline for the production of a wheel beginning at the required date of completion and works backwards to determine the projected start date (Manufacturing Manager, Personal Communication, October 5, 2017). However, the way the dates end up being spaced out leaves approximately 4 days unaccounted for at the beginning of the process because it calculates it as a late-start date instead of early-start. These extra days are unused, which in turn contributes to the late production. The manufacturing manager believes that having the orders mixed the day after the order is printed could make a significant impact on reducing throughput time.

The interviews conducted also showed that there is a disconnect between what management plans and what the operators do in terms of the order in which the parts are worked on. Through an interview with Production Scheduling Manager, the team learned that management intends for the manufacturing to work on FIFO (Production Scheduling, Personal Communication, October 5, 2017). In an interview with a Laser Marker employee, we learned that he tries to work by FIFO dates, but often times he gets products out of order because machine operators will prioritize parts that are easier to finish (Laser

Marker, Personal Communication, September 13, 2017). The parts that are easier to complete move along quickly, which leaves the parts that are more difficult to produce get behind schedule and need to rush to be finished.

4.3 Fishbone Diagram

The fishbone diagram tool was used to breakdown and categorize the potential causes of the long throughput time. The team identified four main categories influencing the root cause; environment, equipment, process, and people. The people and the process categories played significant roles in the potential root cause. Currently, the employee resources are spread thin throughout the factory. Employees do not have one standard process that they work on; rather the employees flex throughout the facility depending on where there is a need. This means that the employees could be working on a different part of the process each day depending on the production needs. Employees are shared resources between large and small wheels, and there is no standard written schedule. The amount of work in the system currently requires a frequent need for overtime. These factors, as well as the nature of the workforce, plays a role in the employee morale. This also can influence the throughput time based on injuries and the pace that the employee works.

Another category that significantly influences the throughput time is the process. This process has shared resources, so the machines are shared between multiple parts. Since no machines are dedicated solely to the large resin grinding wheels, these parts enter long queues. There is no FIFO system that is utilized currently, so parts can sit in the queue far past their scheduled date. The nonlinear process also plays a role in the increased throughput time. Since parts have to loop back through multiple steps of the process, the distance traveled increases, and the amount of parts that are in certain queues. Looking at a combination of the process and the people, the team identified that there is a lack of operator accountability for logging the process. This is important because if the process times are accurately recorded, it is hard for the management staff to understand the nature of the process. The data that the management is looking at is reliant on whether or not the operators are following each step of their job at certain times.

The other two categories of the fishbone diagram are also significant. The environment is a fixed commodity and cannot be altered. Since the size of the factory cannot be changed, any suggestions that are created based on the root cause analysis has to take this into account. The equipment is also a major component in the cause of the lengthened throughput time. Equipment in some areas of the production process are out of date and inefficient to today's standards. Although there is not a lot of open space to bring in new machines, it could be useful to update these machines in order to account for out of date equipment. Each of the categories make up the potential causes for a lengthened throughput time. By identifying these causes, the team could move forward in identifying potential solutions and recommendations to reduce the throughput time for the large wheels. The full fishbone diagram is in Figure 9.

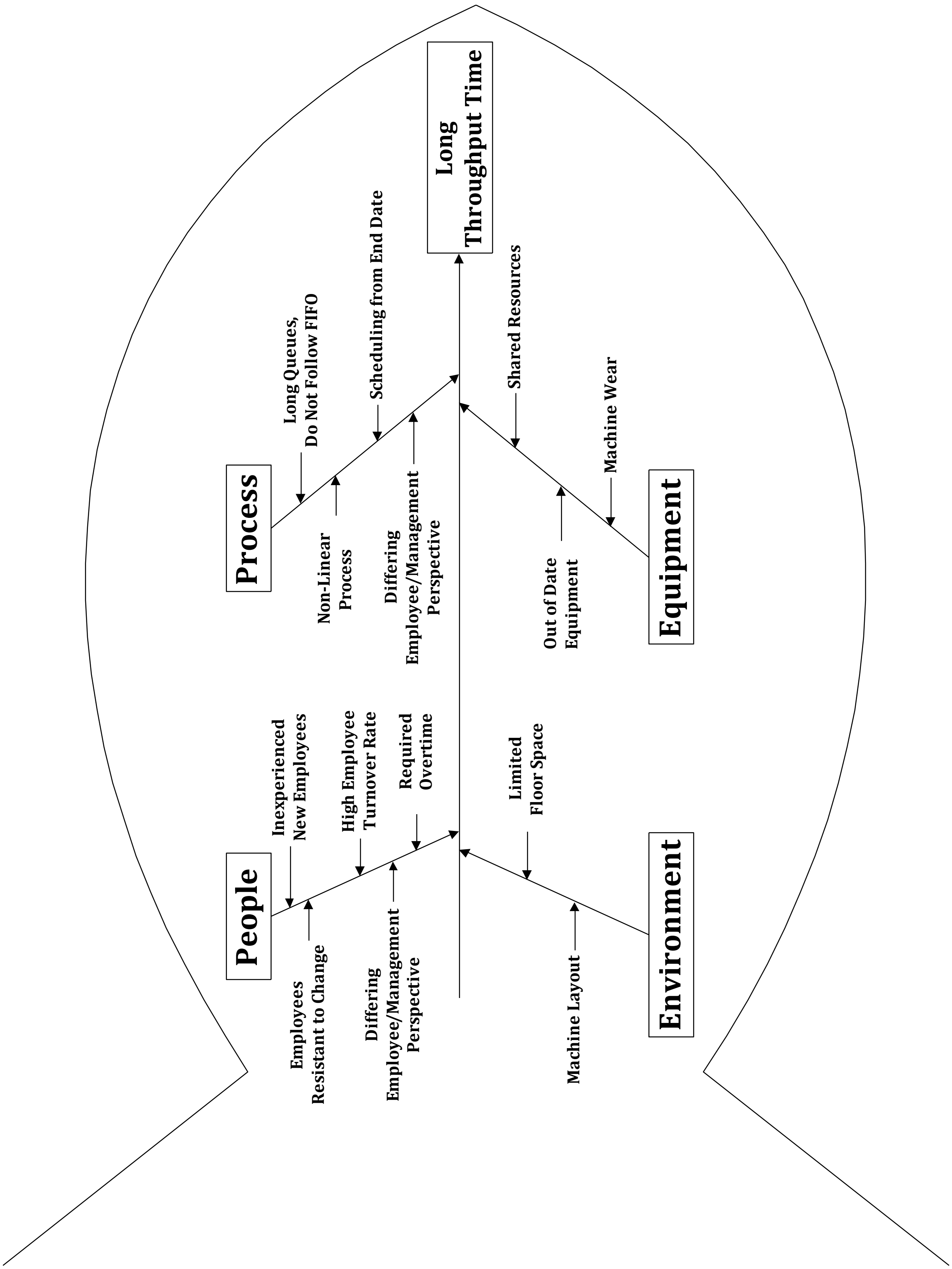


Figure 9. Fishbone Diagram.

4.4 Discussion of Production Data

Based on the data collected and the data provided by various resources at Saint-Gobain, the team was able to develop a better understanding of what was happening in the process. The production data, which includes the late start log, routing sheet dates, and travel distances, was analyzed and used to create the value stream maps and the Arena® models (Rockwell Automation, 2017).

4.4.1 Late Start Log in the Diamond Room

Looking at the start of the process helps to identify if the process is beginning on time. If the process is not starting on time, it is more likely that the final product will miss its production deadline. The diamond room is where the production of the superabrasive grinding wheels begins. Since it is the first step in the production process, it was important to understand how often and why the orders were late to the diamond room. The team lead in the diamond room keeps track of late orders in a paper log (Diamond Room ATL September 15, 2017, Personal Interview). They allowed the team to use the recent collected data in order to deduce the most common cause for the delayed starts. The collected information includes:

- Scheduled receive date
- Actual receive date
- Reason for being late (See Figure 10 below)

From mid-August through mid-September, there were 193 late orders. These late orders are not all DC-30 wheels, and the late log does not specify which order types were late. Of those 193 orders, 147 orders were released late because the engineers did not review wheel specifications on time. This is the cause of 76% of the late shop orders. On average, wheels are 3 days late to the diamond room.

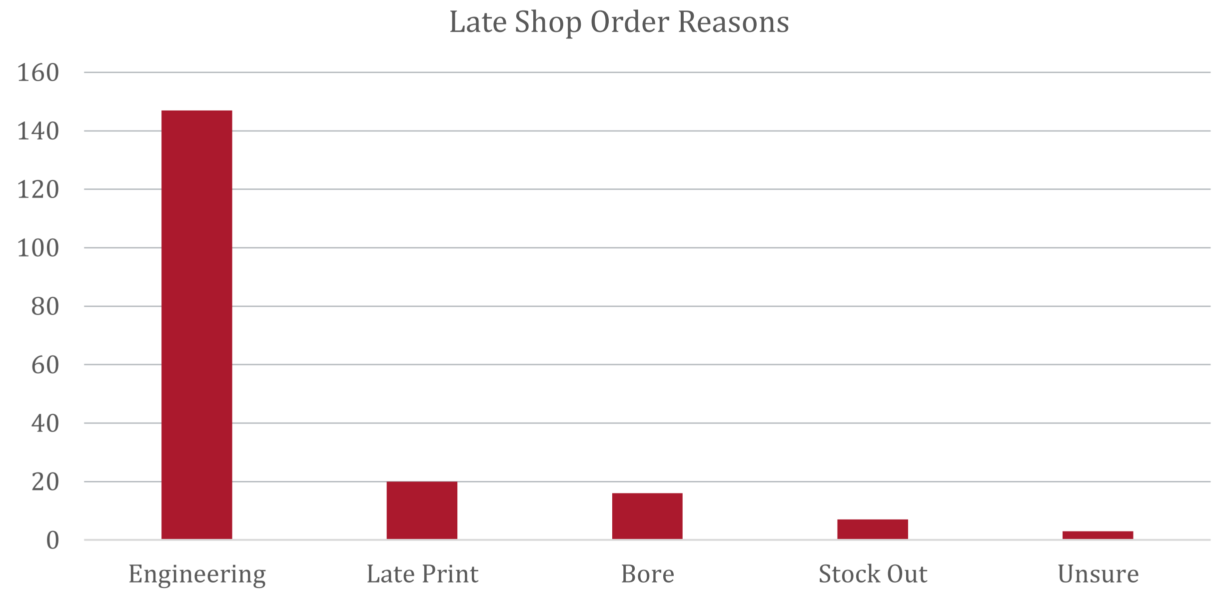


Figure 10. Reasons for Orders Arriving Late to the Diamond Room.

4.4.2 Routing Sheet Historical Data

Another great opportunity for data collection was the routing sheets. The team was provided historical data on the large resin grinding wheels from the past year (Plant Manager, October 11, 2017, Email Correspondence). The majority of these data points came in the first and second quarter of 2017. These excel sheets had data about start dates, run times, and finishing dates. Coupled with this data was data that the team collected from tracking sheets on the manufacturing floor. The data was collected on multiple days in the morning, throughout the month of September (Finishing ATL, September 27, 2017, Personal Interview). Information collected from the tracking sheets included:

- Product number
- Wheel size
- Finish date (the day the wheel is expected to be completed)
- Promise date (the latest date the wheel can be completed before the customer may rescind the order)
- Operation description along with that operations scheduled start date and actual start date

Both types of data were analyzed and averaged to best understand the order and of the average amount late per operation. Figure 11 below shows the average amount of days that each operation was late in the large resin grinding wheel-manufacturing process. The data collected compared the scheduled start dates to the actual start dates on tracking sheets that were provided to the team, as well as tracking sheets from the production floor. While these dates are cumulative, the chart still shows that the process ends roughly 8 days behind schedule, on average. The chart also shows that the process begins, on average, two days behind schedule.

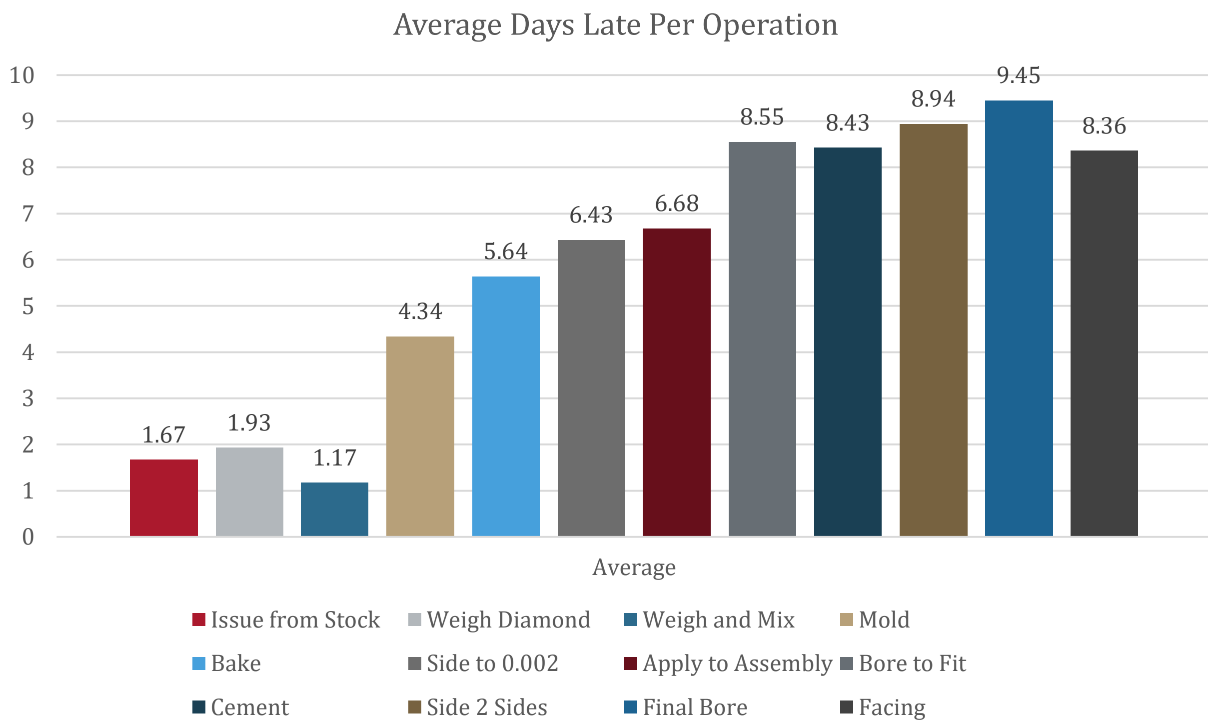


Figure 11. Average Days Late Per Operation.

Using tracking sheets, as well as production data logged in the manufacturing software ShopVue, helped the team better understand production time and queue time. Operators log the start and end times for each step of the process, which can then be used to generate process times and queue times between steps. The graph below illustrates that the wheels generally spend significantly more time in the queue than in the cycle, indicating that it is mostly wait time contributing to the long lead-time, not the speed of the processes themselves.

While Figure 12 displays the total production time for twelve recent orders, Figure 13 below breaks down the production time for each step of the process as an average using data from these orders.

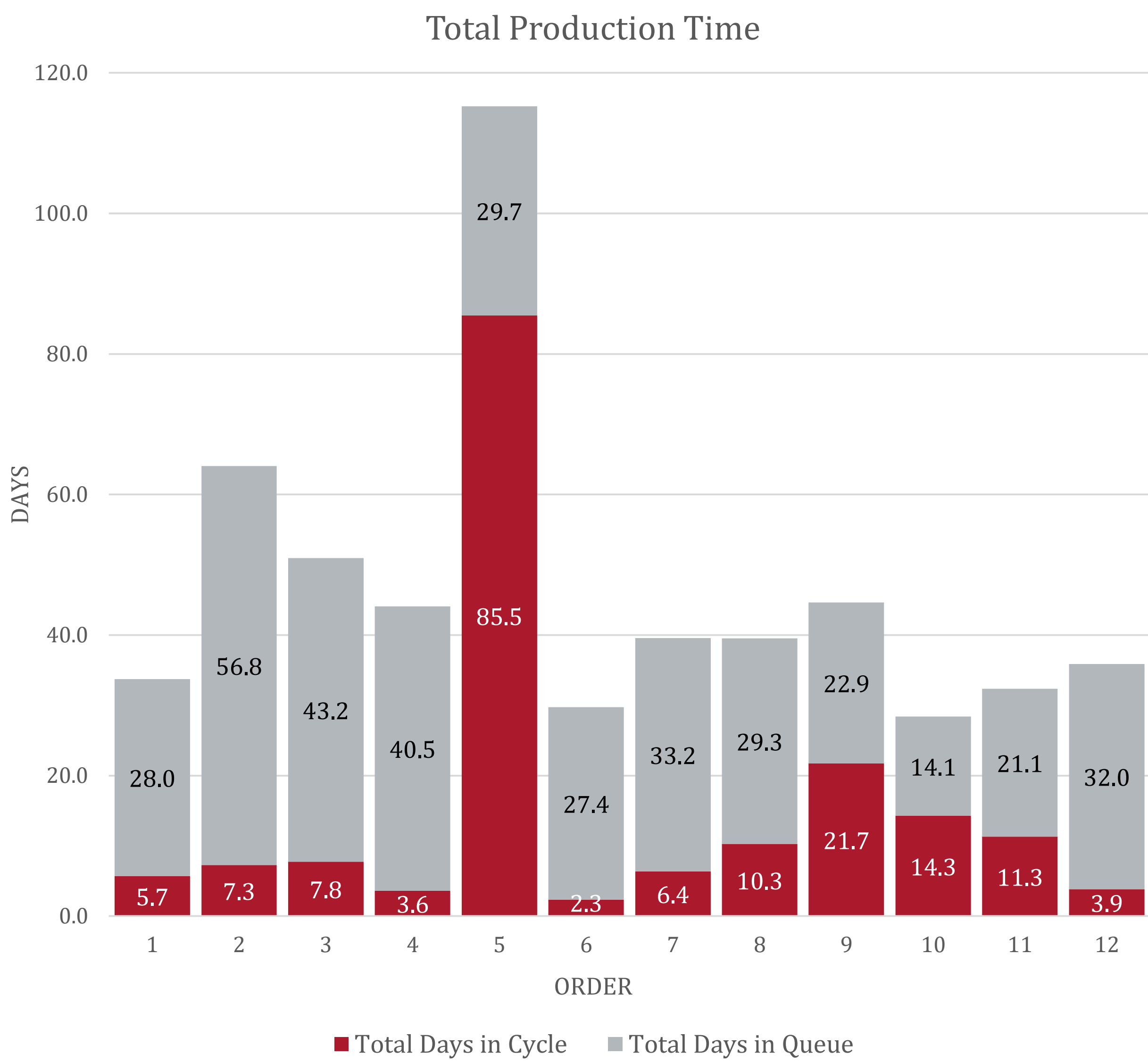


Figure 12. Total Production Time in Days.

As shown in Figure 12, queue times make up a majority of the production time for eleven of these twelve orders.

Figure 13. Average Production Time by Operations in Hours

It is important to note that the data used in Figures 12 and 13 is based off of only twelve orders that have been received and processed in the past several months (July 2017 through September 2017), and this small sample size may not be representative of the entire population. In addition, it should be noted that both of these graphs represents parent-child orders, so these charts will be representative of the steps in these processes. It is also important to note that this data was collected by Saint-Gobain and provided to the team, and the employee who compiled the information informed us that log times are not always accurate (Production Engineer, Personal Communication, October 25, 2017). Operators sometimes do not log their work right at the beginning or end of the task, or do not log their work at all, causing some times to be zero hours. The blank section of the graphs show this. As both process and queue times are calculated based off these logged start and end times, any inaccuracies in employee logging would cause the data to be skewed. For the purpose of these graphs, statistically significant outliers were not removed.

4.4.3 Distance Between Operations

To gain a better understanding of how and where the wheels are transported throughout the process, the team observed operators as they transported the wheel from one operation to the next. A measuring wheel was then then used to track the distance as the wheel moves through the process. The two colored lines seen below represent two separate parts of the process. The blue lines represents the steps that the preform mold goes through before it actually begins. The red lines are the standard steps for the wheel. Operations 1 and 2 are done in parallel with the blue lines. These two operations come together and become one process at red point 3. This is seen below in Figure 14. Between operations 1, 2 and 3 of the red lines, the diamond mix is transported by hand, but once it becomes a molded part it is exclusively moved by cart until it is packed at the final step. Based on these numbers, the team observed that the majority of the long distances was by traveling between repeated processes. The preform mold and the diamond mold each go between molding and baking twice which accounts for 1,225 feet of the total distance of the parts traveled, which is nearly 50% of the total distance traveled between both preform and diamond molds. (Molding ATL, Personal Communication, September 20, 2017). A table of the distances between operations is found in Appendix E. Since the process is not linear and many machines are shared resources, the part has to travel through the final assembly process loop twice. By making this a linear process, it would significantly reduce the amount of time a part travels.

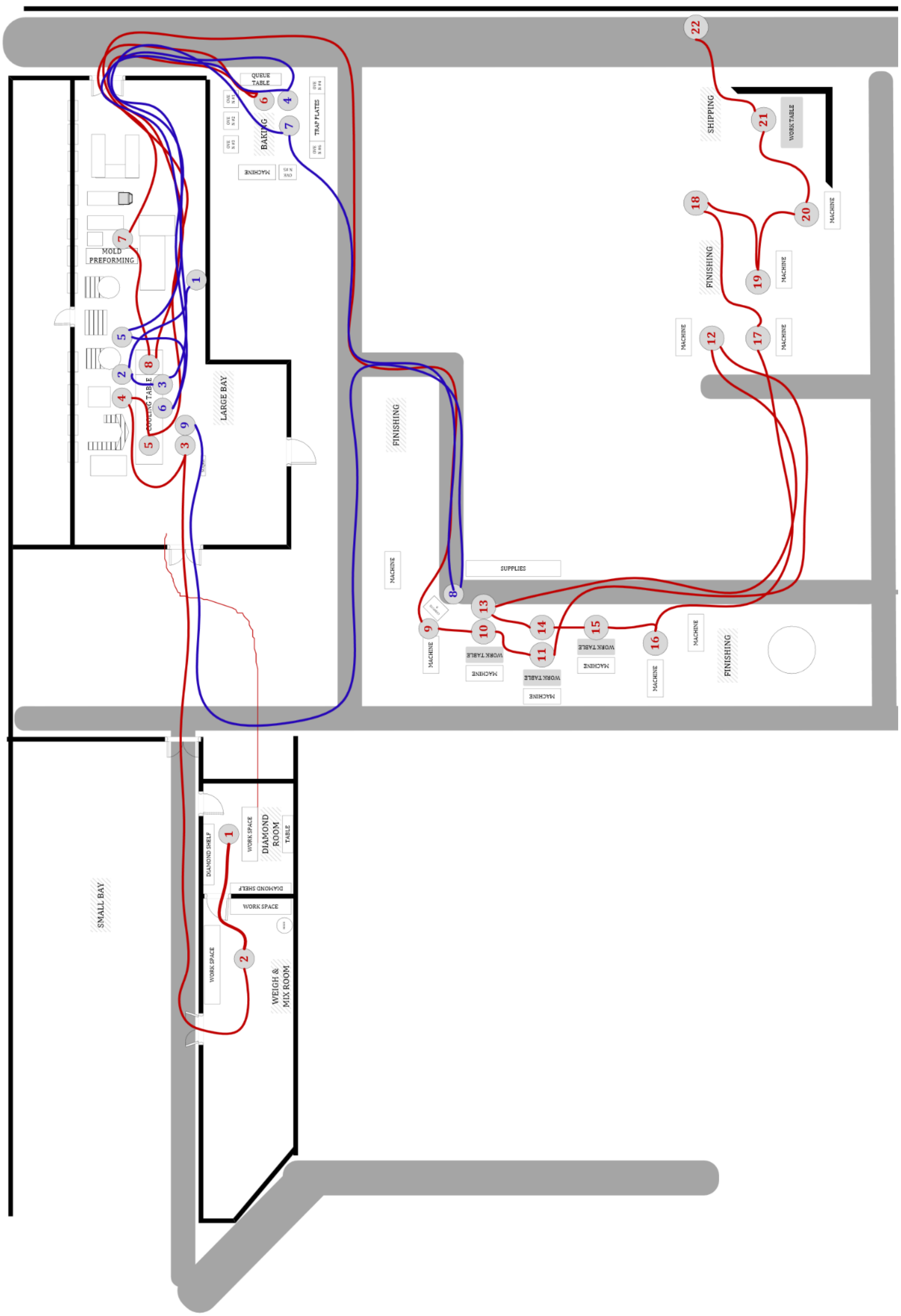


Figure 14. Spaghetti Diagram of Travel Distances Between Operations.

4.5 Current State Value Stream Map

Using the values that were developed from the observed data, the team created a current state value stream map. The first step to creating a value stream map is to construct a flow chart of the current process. The flowchart helps to identify the movement of the materials through the process. Another benefit of constructing a flow chart is to identify how parts travel, whether it is by hand, cart, or forklift. Due to the size of the wheels, the majority of travel between processes is via cart or forklift. The only instance where things are moved by hand is when it is still in an abrasive mixture state.

The tracking sheets were another tool the team utilized when mapping out the flow of materials. In addition to using the tracking sheets for mapping the flow, the team used tracking sheets to collect data for the queue times for different steps in the process. More information on queue times, delays in the system, and cycle times were collected through interviews and various spreadsheets provided by the Saint-Gobain management. Observations from the team as well as the data from the spreadsheets were combined to create the baseline values that were used on the current state value stream map. The information displayed on the value stream map was specific to DC-30 large resin grinding wheels.

The value stream map shows that the large resin grinding wheels have a lead time of 820.6 hours, or approximately 34 days, but the processing time is a mere 96.6 hours. This leaves approximately 720 hours left for the part to be moving or sitting in a queue. These numbers were calculated based on averages of values collected from tracking sheets from the floor, as well as provided production data that was collected through the manufacturing software ShopVue. Outliers that were statistically significant ($\alpha = 0.05$) were removed for the purpose of calculating these averages. The large difference between lead time and processing time indicates that the wheels are spending most of their time waiting in queues.

An important factor to note is that since all of the wheels are made to order, they're not all manufactured exactly the same way. This value stream map shows a parent-child wheel in which a preform must be molded and several parts will be cemented together to create the final product. For parent-child assemblies such as this one, the process is nonlinear, as the weighing and mixing of the diamonds can take place as the preform is being molded and baked.

Since not all wheels are manufactured the same way, not every wheel will go through every step of this process, nor will the process times always be the same. For example, the mix for some wheels needs to age for longer than others before molding, and sometimes cement curing takes longer than the typical 24 hours. As a result, the values on this map will not be applicable to every wheel, and therefore, neither will the total lead-time. These times are averages for the large resin wheel process.

Figure 15. Current State Value Stream Map.

4.6 Future State Value Stream Map

The purpose of developing a future state value stream map is to identify realistic goals and improvements that can be made based on the current state (Plenert, 2012, p. 187). The current state combined with reasonable ideas based on the resources of the company and lean tools equals the future state (Storch 2010). The first step is to create several action items to focus on, taking into consideration factors such as implementation difficulty, cost, time span, and overall impact on the process (Locher, 2008). These changes typically include things such as reducing the cycle time, reducing the number of steps in the process, improving quality, changing scheduling, and introducing kanbans (Abdulmalek & Rajgopal, 2007). These kanbans are visual signals to evoke an action. Lastly, in order to update the current state value stream map to a future state value stream map, values are updated (such as process or queue times), and kaizen bursts are added to highlight specific areas in the process where changes should be made. These kaizen bursts are rapid improvement efforts to remove waste from the system. After the future state is completed, the team compared the overall process times between the current state and the future state to calculate the percent reduction in overall lead-time.

For the future state value stream map for Saint-Gobain, we chose to focus mainly on reducing queue times. The team understood that reducing process times is outside the scope of this project because it would most likely require new machinery or entirely new production methods. Also, based on the complexity of the wheels and the fact that not all wheels go through the exact same steps to be manufactured, the team chose not to focus on changing the number of steps in the process either. Instead, a majority of the current state queue times were significantly longer than they needed to be, while others were too short, causing the process to get further behind. These discrepancies in process time cause the required time between steps to be different from what is scheduled. In terms of kaizen events, it is important to increase operator accountability for logging their work times throughout all steps of the process, as well as increase accountability for working by FIFO. Specifically to baking, the team suggested that the ovens run more often, even when the ovens are not completely full.

Based on the future state recommendations, the new processing time would remain 96.6 hours, and the queue time would be 228 hours, for a total time of 324.6 hours, or 13.53 days. This is a 60.44% overall decrease from the current state. See Figure 16 for a copy of the future state value stream map.

Figure 16. Future State Value Stream Map

4.7 Backwards Scheduling

The current scheduling process that Saint-Gobain uses is backwards scheduling. In this process, the program starts with the anticipated date of completion for the order and then works backwards through all the steps in the process at the end of the program, the late start of the order is calculated. However, the program does not calculate the early start date, or the earliest day that the order can be started. Therefore, there are a certain amount of days that are wasted because production will start on the late start and not the early start (see an example in Appendix F). In this example, you can see that there are 6 unused and wasted days in the beginning of the process.

Backwards scheduling works by starting at the final operation with the promised completion date. Then, the preceding operation's start time is calculated by looking at when the following operation begins and subtracting the duration of the operation. This process continues until the beginning of the schedule, where the latest start and finish times are calculated. Forwards scheduling works by starting the first operation at day 0, right when the order is placed. Then, the following operation would begin once the previous operation was completed, and so on until the end of the process. If there were any operations going on simultaneously, the following operation would start once the longest operation was completed. Therefore, at the end, the process will begin and end on the earliest date possible (see Figure 17 below).

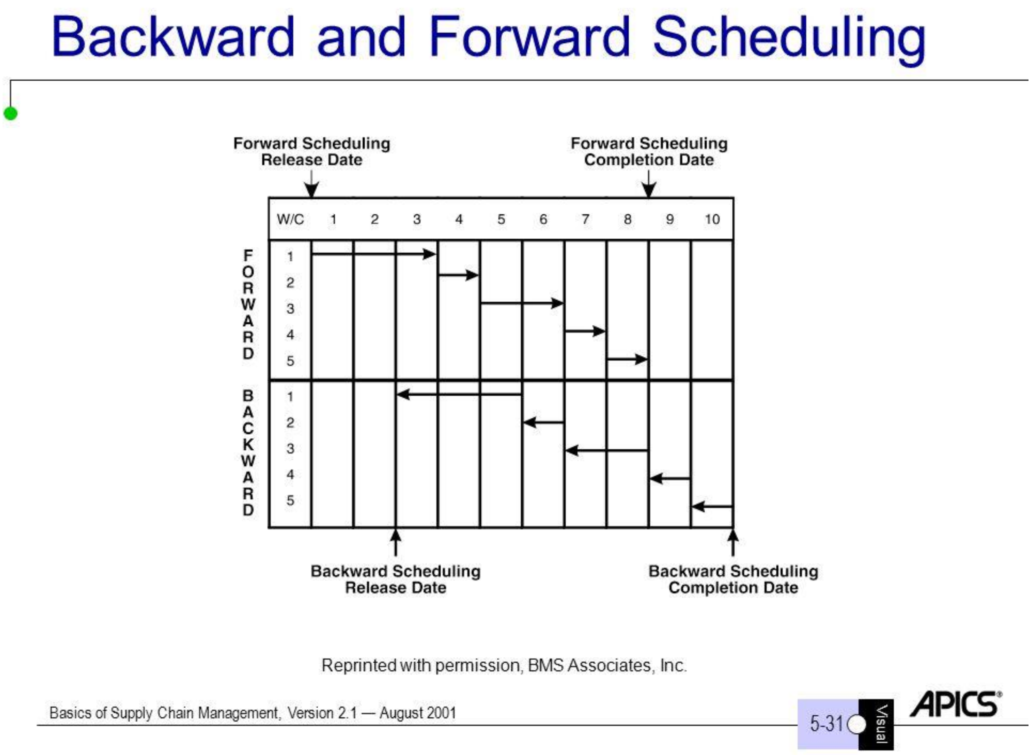


Figure 17. Backwards vs. Forward Scheduling. Source: (Basics of Supply Chain Management. Version 2.1, August 2001).

After speaking with the Manufacturing Manager, some insight was gained as to the specific areas of the schedule that are creating these delays. The first source of delay is the printing of the order checks. After the orders are received from the customers, it takes about 2 days until the checks are printed, as checks are only printed once per day in the morning at 5 AM, and are then distributed to the floor at 10 AM. Furthermore, once the checks are printed, it takes an additional 2 days until production of the order actually begins. If the checks were printed immediately and production began the day after checks were printed, this change alone would save 3 days on the front end of the production schedule.

Another issue with the scheduling stems from the fact that the automated system that produces the schedule for each wheel sometimes is not accurate. For example, scheduling Side to 0.002 one working day after Baking is not always realistic, because baking can take anywhere from 16 to 37 hours; however, the automated system does not account for this range and will always schedule Side to .002 for the next day. The scheduling system also assumed unlimited resources, which frequently causes issues in Molding, as they only have 8 presses to mold in. Molding generally takes a full day, and scheduling more wheels to be molded per day than the number of presses available creates a significant bottleneck. Additionally, some orders require multiple of the same wheel to be made then cemented together, but typically there is only one mold for each size so it is not realistic to mold multiple of the same wheel in one day. By generating unrealistic queue and production times, it's nearly impossible not to get behind. On the other hand, there is usually a full day allotted between Weigh Diamond and Weigh & Mix, even though Weigh & Mix could theoretically happen immediately after Weigh Diamond. This adds unnecessary wait time.

4.8 Arena® Model

Arena® is a versatile simulation software that enables manufacturing organizations to increase their throughput time, identify process bottlenecks, improve logistics, and evaluate potential process changes (Elam, Anderson, Lamphere, & Wilkins, 2011). Arena® allows users to model and analyze process flow, packaging systems, job routing, inventory control, warehousing, distribution, and staffing requirements. The primary reason we are utilizing Arena® as a program is because it allows the test of new process alternatives that have a potential to contribute to increased throughput, reduced work in progress, elimination of bottlenecks, and the optimization of resource utilization.

Arena® is relatively simple software to use and allows users to customize parameters such as resources available, workers schedules, hours of operations, materials, route hours, among other useful factors. These features have the ability to provide Saint-Gobain with valuable insight on how to pursue making changes to the current state operations without incurring the cost or risk associated with the physical implementation. Additionally, simulation modeling has the ability to provide production planners insight into forecasting and planning. After running an Arena® model, results and specific performance measures, such as queue time, value added vs. non-value added time, transfer time, machine utilization, and average total time, are displayed for analysis.

While there are many different ways to represent a model in Arena® software, we chose to use the Basic Process panel because it provides the highest level of modeling. The Basic Process Panel allows the creation of high-level models in a quick and easy way. The basic building blocks for Arena® modules are called modules and there are two kinds: flowchart and data. We used a combination of the Create, Separate, Process, Batch, and Dispose flowchart modules because they allow a great deal of flexibility and provide all the detail required for a simulation project. The data modules we used were Entity, Resource, Schedule, and Set. In Figure 18 below, you can see what shape is corresponded with each flowchart module.

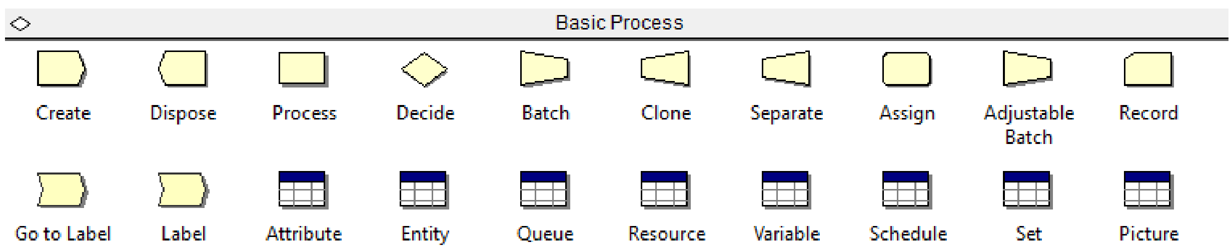


Figure 18. Modules of Basic Process Panel in Arena®.

Each Arena module is parametrized by associated dialog boxes. Descriptions for each module that we used from the Basic Process panel is as follows:

- **Create Module:** Generates a stream of arrivals of Arena® entities (jobs, people, messages, etc.)
- **Dispose:** Entities that enter it are simply discarded
- **Process:** Processes Arena® entities
- **Separate:** Has a feature call *Duplicate Transaction*, where is creates a duplicate of itself
- **Entity:** Can see and edit aspects of the entities in a model
- **Resource:** Allows determination of characteristics of each Resource in a model, such as whether its capacity is fixed or varies according to a schedule
- **Schedule:** Ability to set schedules for individual operators or machines
- **Set:** Ability to group machinery and use shared resources across operations

The Create module is known as the "birth" node for arrival of entities to a model's boundaries. In terms of our model, the Create module simulates an order for a large resin-grinding wheel being placed. The new order then moves into a Separate module, where the entity is duplicated and split into both a wheel and a preform process. After this, the wheel and preform move into their respective operations.

The team used the same data given to us for the value stream maps to create the simulation model. Each Process module reflects probability distribution calculated for each individual operation. It also takes into account the number of machines and/or operators for that operation, in addition to shift schedules. The model is able to recognize shared resources, so it takes into account that preforms and wheels both utilize the ovens and presses.

Figure 19 and Figure 20 show our Current State Arena® Model and our Future State Arena® Model, respectively. The major difference between our current state and future state models is the removal of the preform operations. With the future state model, we operate under the assumption that preforms can begin to be issued from stock instead of created when an order is placed.

The output from our current state model indicated that the total output for 90 days is 70 wheels, with a single wheel taking 758 hours to be completed. The future state model had improved output, with 77 wheels created in 90 days, and a single wheel taking 737 hours to complete. This increases production by 10% in addition to reducing the amount of hours it takes to produce a wheel. The current state model indicates that after a wheel goes through the "Weigh Diamond" operation, the queue for "Preform Molding" is approximately 375 hours. It's clear from the simulation that issuing preforms from stock has the opportunity to reduce the throughput time by quite a lot of time, because a wheel cannot move into pressing and molding the diamond until the preform is ready.

A separate change that was made to the current state map is reducing the amount of wheels an oven needs to have before running it. When the model was changed to reduce oven capacity from 20 wheels to 10, there was a 7% increase in production, with 75 wheels being produced in 90 days. The utilization of the ovens went from an average of 28% to an average of 51%, which means the ovens were being used more, and were able to help increase production of large resin grinding wheels.

Issuing preform from stock and running the ovens more often is just a few examples of the power that Arena® has when simulating potential changes to a process. With additional data, such as data collected over the course of a year, it would be possible to build an even more accurate model that would have the ability to analyze and test several bottlenecks that cause severe congestion in different areas on the production line. Having operators indicate the time as well as the date that they complete an operation will lead to better statistical analysis for future simulation modeling. Purchasing a commercial license for a simulation software such as Arena® would be a worthwhile investment for testing changes to the current state process.

Figure 19. Current State Arena® Model.

Figure 20. Future State Arena® Model.

4.9 Financial Analysis

To analyze the financial impact of the recommendations for Saint-Gobain, the team considered the improvement of the throughput time, as well as areas for capital investment opportunities. Based on recommendations regarding scheduling and reduction of queue times, it is expected that the manufacturing process will be completed 60% faster on average.

Since all of the large resin wheels Saint-Gobain manufactures are made-to-order, each wheel has its own unique cost to manufacture, as well as its own selling price. The team was provided with data for all large resin sales that were sold in 2016 and through October 2017, including the sale price, the cost of manufacturing, and profit. The profit for these orders ranges from -$22,000 to $26,000 and each order consisted of 1-5 wheels; in total, 819 wheels were sold in 2016. There are several reasons why the profit margin is oftentimes negative; wheels are sometimes given to customers for free to compensate them for production issues, as a replacement for recalled products, or for evaluation purposes.

Based on the proposed reduction in cycle time between the current state value stream map and the future state value stream map, the calculated increase in production is shown in Equation 1 and Equation 2:

$$Increase\ in\ Production = \left[\frac{(Current\ Production)}{100\% - Reduction\ in\ Lead\ Time}\right] - Current\ Production$$

Equation 1 Formula to Calculate Increase in Production Volume.

$$Increase\ in\ Production = \left[\frac{819\ wheels\ per\ year}{100\% - 60\%}\right] - 819 = \frac{1228}{year}$$

Equation 2. Calculated Increase in Production Volume.

With an average of an additional 409 wheels able to be manufactured each year, if customers' orders were increased due to the increased capacity for production, the company could expect an increase in profit of approximately $409,000 annually. This is based off the average profit of all wheels sold in 2016, which was calculated to be approximately $1,000 per wheel. This accounts for wheels sold at a loss for promotional purposes.

$$Potential\ Increase\ in\ Profit = Increase\ in\ Production * Average\ Profit\ per\ Wheel$$

Equation 3. Calculated Increase in Production Volume.

$$Potential\ Increase\ in\ Profit = 409\ more\ wheels\ per\ year * \$1{,}000\ average\ profit = \frac{\$409{,}000}{year}$$

Equation 4. Calculated Increase in Production Volume.

Current Production	819 wheels/year
Reduction in Cycle Time	60%
Increase in Production	409 wheels/year
Profit	$1,000 per wheel
Increase in Profit	$409,000 per year

Table 1. Expected Increase in Production & Profit

Saint-Gobain does have a specific amount allocated in their budget each year to be used for capital investment, and the company is planning to purchase a CNC machining center and a grinding machine in the near future. Each machine will cost between $500,000 and $750,000, depending on the features of the machine. While it is unknown at this time where in the production process the machines will be used or what current machinery they may end up replacing, the goal of the new equipment is to reduce lead-time (Capital Purchasing Engineer, Personal Communication, November 15, 2017).

In order to understand the financial impact of this investment, the following estimates were developed. These estimates are based off the following assumptions:

- The cost for both machines will be approximately $1,250,000. This assumes that both machines are purchased at the midrange of the two price points that were provided, or $625,000 each.
- The estimated increase in annual profit is $409,000. It's assumed that this is due to the reduced lead time that may lead to an increase in sales.
- Acquisition, installation, and startup costs are accounted for in the total cost of the machinery.

- There will not be any maintenance costs for the machinery, and that the potential earnings generated by the proposed increase in production remains constant each year.

Using a minimum acceptable rate of return of 8%, which is commonly used for the purchase of new manufacturing equipment, the discounted payback period was calculated as follows in Equation 5:

Present Worth of Cost = -$1,250,000 + $409,000(F/P, 8%, n)

n = 5 years = -$1,250,000 + $409,000(1.469) = -$649,179

n = 10 years = -$1,250,000 + $409,000(2.159) = -$366,969

n = 15 years = -$1,250,000 + $409,000(3.172) = $47,348

Equation 5. Formula to Calculate Present Worth.

As the present worth becomes a positive value between 10 and 15 years, the breakeven point falls within this period. Using the Excel function NPER as shown in Equation 6, the exact period in years can be calculated.

=NPER(interest_rate, payment, present_value, future_value)

=NPER (8%, 0, $409000, $1250000) = 14.516 years

Equation 6. Formula to Calculate Number of Periods for an Investment in Excel

As seen in Equation 6, the discounted payback period for the investment is approximately 14.5 years. This aligns with the present worth cost calculation, with the breakeven point falling between 10 and 15 years.

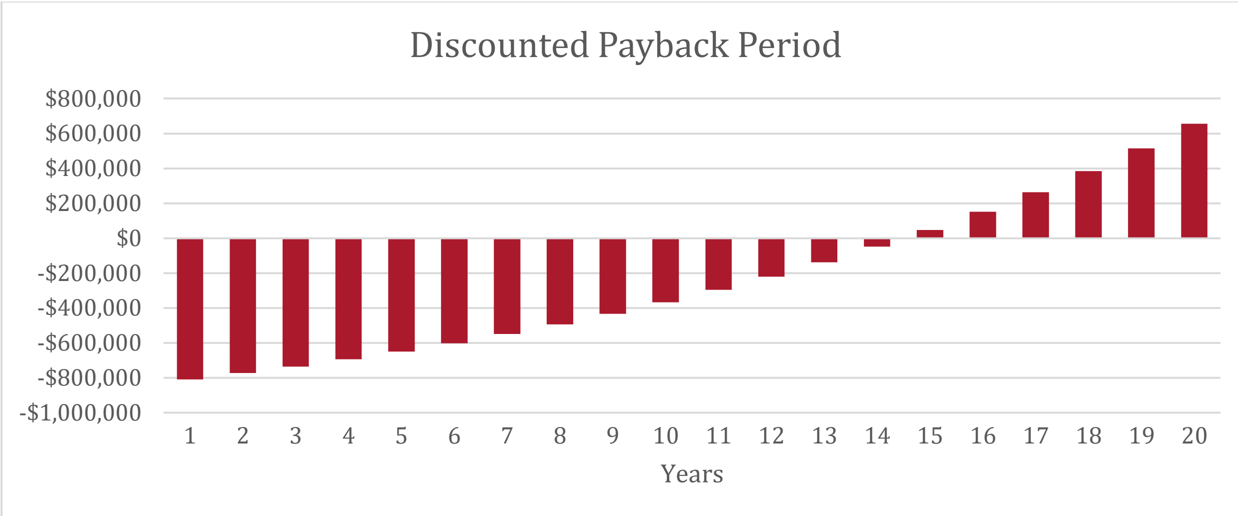


Figure 21. Cash Flow Analysis.

With this $1,250,000 capital investment purchase and an expected increase in profit of $409,000 annually, it would take approximately 14.5 years for Saint-Gobain to break even with the purchase, as shown in Figure 18. While the upfront cost of the investment is very high compared to their yearly revenue, the cost has been accounted for in Saint-Gobain's annual budget, and will be further justified by this expected increase in profit.

Chapter 5: Recommendations

Once the data collection, analysis of the observations, and results occurred, the team was able to develop key recommendations for Saint-Gobain to implement after the completion of this project. When implemented, these recommendations will aid in the reduction of the throughput time for the large resin grinding wheels. There are two main recommendations as well as some additional minor recommendations that can benefit Saint-Gobain. The following table summarizes these recommendations.

Recommendation	**Summary**
Restructure Production Schedule	Switch from a backwards scheduling method to forwards scheduling
Increase Frequency of Running Ovens	Run the ovens even if they are not completely full in order to get wheels through the process at a faster rate
Issue to Stock Preform Molds	Keep the preform molds with the highest demand in stock in order to eliminate the need to mold the preform at the beginning of the process.
Restructure Employee Work Schedule	Have a full second shift and implement written work schedule
Replace Old Machines and Reorganize Floor Plan	Utilize capital investment budget to replace outdated machines and reorganize Large Bay
Increase Safety	Protective barrier and better signage around the hot wheels in molding room

Table 2. Summary of Recommendations.

5.1 Restructure Production Schedule

One major recommendation for Saint-Gobain is to restructure the scheduling of the grinding wheel production. Currently, Saint-Gobain is using backwards scheduling, which produces a late start production date. The backwards scheduling results in a loss of days on the front end, meaning the wheel is not started in production as soon as it is ordered. The team recommends that Saint-Gobain use a forward scheduling program to utilize these days, which will better meet the customer's demand. This will not increase the lead-time for the customer, as the goods issue date of the wheel will not change. Rather it will give Saint-Gobain a better chance of meeting the original promise date.

5.2 Bake Fewer Wheels More Often

Currently, the ovens are only turned on to bake once they are full. Each oven can fit about 20 wheels, and the wheels will sit in the ovens until they are full and ready to bake. The ovens are initially turned on around 2:00PM and emptied around 3:00AM two days later. These parts must be cooled before they are removed from the oven. Some parts are extremely thin and must be held in traps, which need a longer cool time before they are removed. When these parts are finally cooled and removed (around 4 hours later), the parts are removed and either sent back to molding (if it was a preform mold) or sent on to finishing. These subsequent processes cannot handle the influx of parts to the system, and the process will become a bottleneck. If the ovens were to be run without being full, it could reduce the amount of hours wasted waiting for the oven to fill, and could create less of a bottleneck for the operators in finishing and molding.

5.3 Stock Commonly Used Preform Molds

In order to reduce the time spent waiting for preform molds to be finished, the most commonly used preforms could be manufactured in large quantities and kept in stock. In 2016, wheels made using the top three most common preforms accounted for 11% of sales revenue.

Currently, the preforms take 3 days to complete. There are potential delays that can occur in this process, particularly in waiting for the preform mold to bake. If there is a delay, the production of the wheel cannot move forward past the weighing and mixing of the diamond until the preforms are finished. Based on the current scheduling method, molding the preform can add up to 5 days to the overall lead-time. If the mold/press operators could take a preform from stock, the 3 days spent creating the preform and the queue days could be eliminated, and the operators could continue the production of the wheel immediately.

5.4 Restructure Employee Work Schedule

The fourth recommendation is to add a full second shift of employees, opposed to the one and a half shifts that Saint-Gobain has now. Through conversations with employees and managers, the team has determined that some of the key bottleneck locations do not have as many operators as needed in order to meet demand. By increasing the number of employees working on these operations, Saint-Gobain can reduce the bottleneck processes. Furthermore, the team recommend the implementation of a written schedule to keep track of what employees are working at which station, and how many employees are needed per process. This will help determine where the employee is needed, and will allow for flexibility within each shift to account for bottlenecks. Another recommendation is that another employee be assigned to turn preform molds, as conversations with the Molding Team Lead indicate that getting preform molds turned on time is a bottleneck (Molding ATL, Personal Communication, September 20, 2017).

5.5 Utilize Capital Investment Budget

The fifth recommendation is that Saint-Gobain should use their capital investment budget to replace old machines and reorganize floor space. Much of the technology in the superabrasives plant is out of date. This equipment needs improvements. After speaking with the Capital Purchasing Engineer, the team believes it could be useful to consider new machines that can do two or more different jobs. Multi-functional machines would be beneficial because there is limited floor space. Additionally, reorganizing the large bay room and improving the technology in it with a tower storage system could reduce the amount of time operators spend moving the wheel around the room (Capital Purchasing Engineer, Personal Communication, October 4, 2017).

The Capital Purchasing Engineer also pointed out that Saint-Gobain has automated mixing in some other processes. It could be beneficial to implement this process to the superabrasives at this site in order to improve both the quality and process speed. (Capital Purchasing Engineer, Personal Communication, October 4, 2017.

5.6 Increase Safety

The final recommendation for Saint-Gobain is regarding safety concerns. The team observed that wheels cooling in the molding room are left in open areas, exposing employees working in the area to a potential burn hazard. While only one burn has been reported in this area in the past three years, there may be more unreported instances (Safety Engineer, Email Correspondence, November 14, 2017). This one reported incident was categorized as a TF3 incident, meaning that on-site first aid was recommended. Based on the incident report, it does appear that the cause of the burn was a lack of protective barrier between the operator working near the mold and the hot mold itself. Solutions to this safety concern can include things such as warning signs or a physical barrier around the hot wheels.

Chapter 6: Conclusion

The team worked with Saint-Gobain personnel with the goal of reducing the total lead-time for the large resin superabrasive grinding wheels by identifying opportunities for process improvement. By identifying methods to reduce bottlenecks, or rate limiting steps, the grinding wheel production process can become more efficient. With an axiomatic design decomposition, data analysis from production data spreadsheets, as well as operator and manager interviews, the team was better able to understand the cause of the bottlenecks. In addition, the team used several lean tools including fishbone diagrams, spaghetti diagrams, and value stream maps to verify the current state of the company and identify the biggest opportunities for improvement.

The results showed that due to the nature of the business, certain inefficiencies are created when generating the production schedule. Each of the wheels are different sizes and, therefore, require different process times, making it difficult to create a level schedule. The use of a future state value stream map and Arena® simulation model helped identify these rate-limiting steps and provide recommendations based on changing different variables in the current process. By implementing these recommendations, Saint-Gobain should be able to focus their efforts and implement changes on processes that have been identified as having the biggest opportunities for improvement.

There are a few different conclusions that are drawn from the above analysis. If backwards scheduling is continued to be used for the large resin wheels, then the parts will continue to be late. The current system allows for much time to be lost at the beginning of the process and does not account for long queue times later in the system. Making modifications to the system of scheduling could benefit Saint-Gobain in the end in order to meet the delivery dates that are promised to their customers.

In addition, the baking process currently is the longest process, taking more than two days to complete. One option Saint-Gobain could try to mitigate this time wasted is to bake less wheels more often. This could mean running the machines more often but not at full capacity. Another option Saint-Gobain has is stocking the most commonly used preform molds. By stocking these preform molds, this eliminates a molding and baking step from the operations subsequently reducing up to 5 days in the lead time, which can be allocated to a different part of the process. Different scenarios are simulated using the Arena® software to understand which might provide the shortest throughput time.

Based on these conclusions, the team conducted a financial analysis for the company. By reducing the throughput time, there is a possible increase in sales revenue of $460,000 per year. By implementing the changes recommended by the project team, Saint-Gobain could potentially cut their lead-time on many products by 60%. This offers major savings to the company in the end.

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Appendices

Appendix A: Bottlenecks

Appendix B: Grinding Wheel Process

Appendix C: Operator Survey Questions

Coded Survey Responses (Operators)

Appendix D: Management Interview Questions and Answers

Capital Purchasing Engineer

Manufacturing Manager (responsible for staffing)

Quality Manager

Production Scheduling

Materials Manager

Coded Interview Responses (Managers)

Appendix E: Spaghetti Diagram Distances

Preform

Wheel

Appendix F: Backwards Scheduling Example

Appendix G: Presentation for Sponsor