



8-2014

Optimizing Boat Hull and Deck Mold Storage Scheduling with Linear Programming

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I am submitting herewith a thesis written by Tron Bjorn Dareing entitled "Optimizing Boat Hull and Deck Mold Storage Scheduling with Linear Programming." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

Rupy Sawhney, Major Professor

We have read this thesis and recommend its acceptance:

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Accepted for the Council:

Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

Optimizing Boat Hull and Deck Mold Storage Scheduling with Linear Programming

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Tron Bjorn Dareing
August 2014

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ABSTRACT

With a wide range of products, Sea Ray uses a vast amount of large boat molds for each of the different boat models. Storing and transporting these molds can be an issue with introducing high variability in the production process. One of the largest problems deals with the utilization of the employees' time with the large amount of boat production. Having the boat molds being ready for production is a critical part of the manufacturing of quality boats. There is non-value added time spent on preparing the molds for the lamination process and storing them in various areas. This problem arises from an unstandardized method of picking and storing hull and deck molds unrelated to the production schedule.

In order to improve this scenario, the production team needs to know what molds are needed for production, where the molds are located, and that the right maintenance has been conducted. The project scope focused on the hull and deck mold lamination process in the lamination building. This process starts from the pulling of the hull and deck molds from storage to when the part is removed from the mold and taken back to storage or production prepping. Linear programming was applied to minimize the cost of the transportation and preparation of the hull and deck molds as well as mold maintenance. Utilizing linear programming, an optimal mold storing schedule was developed based off of the production schedule and storing constraints.

After running the model, there was a direct connection between the storing of the molds and the production schedule. The same production demand for the week could change based on how the production was scheduled each day. Even though higher production yielded a higher total cost, the total cost could be decreased by having molds be continuously used for production. The model used to optimize the mold scheduling could actually be used to schedule the daily production. With the implementation of a standardized mold scheduling system, total weekly costs can be decreased as well as the non-value added time of the mold transportation and maintenance employees.

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CHAPTER I

INTRODUCTION AND GENERAL INFORMATION

Introduction

Sea Ray is an American manufacturer, operating as a part of Brunswick Boat Group, of pleasure boats that are sold and shipped around the world. Its products range from sport boats to cruisers and everything in between. Sea Ray designs in house and markets over 40 models of boats that can range in size from 18 to 62 feet in length. Based out of Knoxville, TN, Sea Ray has two operating factories in Tennessee and two in Florida. One of these manufacturing facilities lies in Vonore, TN next to Lake Tellico.

The Vonore facility oversees the production of many models of boats that can change from year to year. All of the manufacturing from the seats to the assembly of the boats are completed and tested in house. With such a high quality product, most of the manufacturing is based off of manual labor. Since Sea Ray manufactures and assembles each of its products, large amounts of assets are used and stored on site at the Vonore location. One of the major assets that are being used consistently are the production molds for the hull and deck of the boats.

With the economy recovering from the recession, Sea Ray has experienced a steady amount of business and has a constant production of boats on its manufacturing lines. In order to keep up with this demand, production schedules are made weekly for every model of boat that is going to be produced based off of a yearly forecast. Each boat model can be customized based on color and accessories. This creates the need for various molds for each model type. The large demand creates challenges for Sea Ray with its limited amount of resources in production time and facility space. One area of opportunity is the utilization and storage of its molds. With such a variety of molds to store on site, many challenges are faced in storing and maintaining them for current and future production. In order to understand these challenges it is important to have a grasp on the lamination process used for producing boat hulls and decks.

The lamination process of boat molds is a common practice in boat manufacturing. Figure 1 below shows the basic pieces of the process for the resources. The hull and/or deck mold (see appendix for picture) is supplied from inside or outside storage, the recon maintenance department (PI), or the temporary maintenance station by the production line. The hull and deck molds are then sent through the lamination process with five different stations creating the hull or deck inside the mold. Once the product is ready, it is pulled out from the mold and is moved to the hole cutting station (see appendix for picture). The hull and deck molds can then get stored in inside or outside storage, go to the recon maintenance department, temporary maintenance, or get sent to the waxing station.

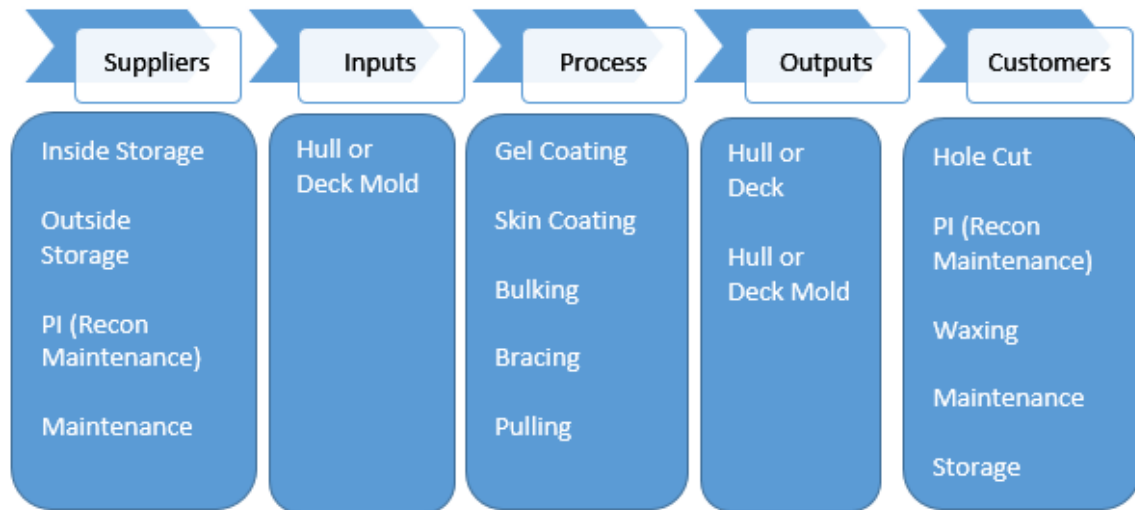


Figure 1. SIPOC Diagram

Figure 2 below goes into more detail on the flow of the hull and deck molds and the decisions behind the different steps. As mentioned before, molds at some point start in storage whether the storage is inside or outside of the lamination building. Once the mold is picked, if it was stored outside certain preparation steps are needed to get the mold ready for lamination such as removing vacuum covers, getting the mold to room temperature, or removing any water inside the mold. If the mold is damaged, repairs need to be conducted before the mold is used for production. Certain molds have different requirements on the number of uses before needing to be waxed for lamination. This varies based on boat model and whether the mold is a hull or deck. After the waxing station, the mold is then ready to go through the lamination process of gel coating, skin coating, bulking, bracing, and finally pulling the product from the mold. After the product is removed, the mold then has to be stored inside or outside based on storage availability. If the mold does need to be stored outside then the mold has to go through prepping procedures in the recon maintenance department before getting stored outside (See appendix for picture). This includes covering the mold with a vacuum cover and taping for mold protection. As can be seen, there are many decision steps that may or may not be value added depending on the connection between the mold and the production schedule.

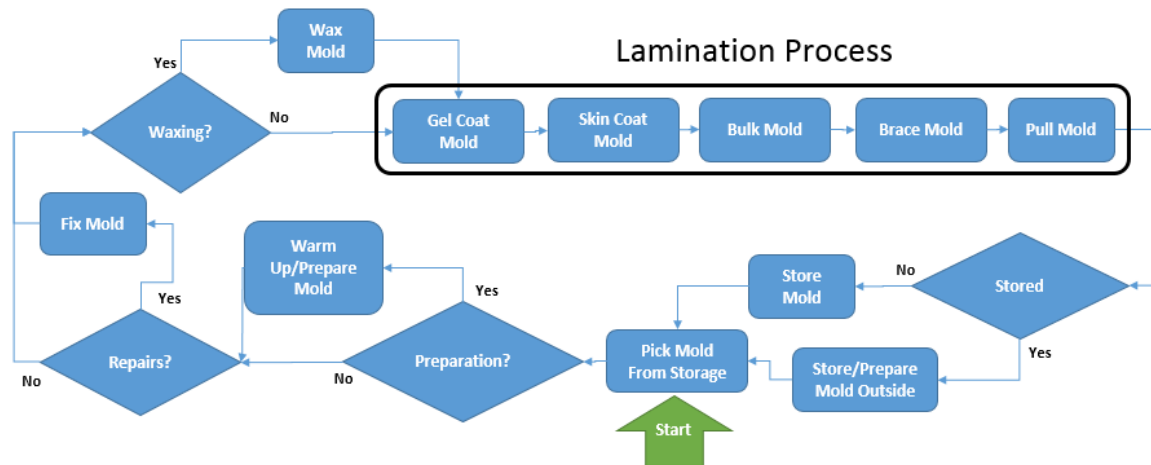


Figure 2. Lamination Flow Chart

The utilization of employees is key to meeting the production schedule. Whether employees should be repairing molds or preparing them for outside storage is an important decision since both options take large amounts of time with multiple employees. Currently Sea Ray has three dedicated storage areas for the hull and deck molds as can be seen below in Figure 3.

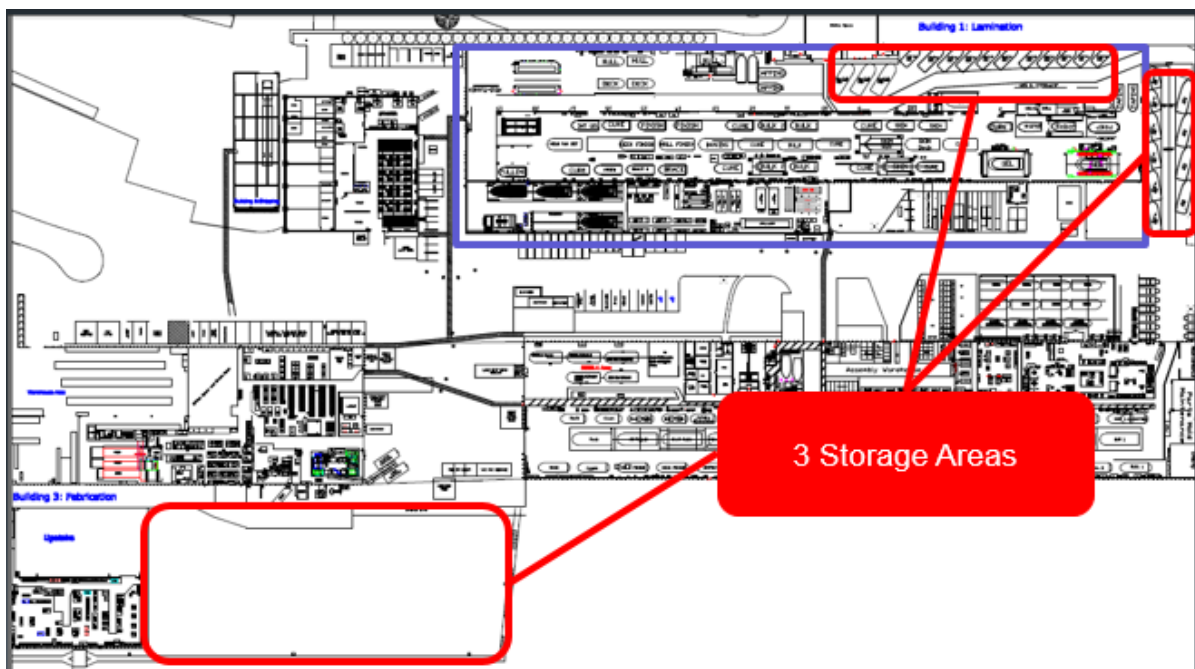


Figure 3. Facility Layout

Figure 3 shows the lamination building as highlighted in blue. This is where the lamination process is carried out. Also inside the lamination building is a storage area dedicated for hull and deck molds in the upper right hand corner. This is the most ideal area for storing molds since it is heated and weather protected. This allows for the molds to be easily transported and prepared if at all for the lamination process. With the molds being weather protected inside the lamination building, no time is needed to prepare the molds with a vacuum cover for storage protection. Figure 4 is a more in depth look of the inside storage layout with the orange boxes highlighting mold storing slots (not the actual number of slots). The transportation time is negligible to transport the molds to the taping station in front of gel coating before beginning the lamination production process. These molds will have the lowest preparation time out of the three storage areas. The lamination building can fit around 22 hull and deck molds in the designated area depending on the particular models of molds being stored. Since the mold sizes can vary in size by ten feet, the amount of mold spaces change and there are no designated slots on the ground for the molds.

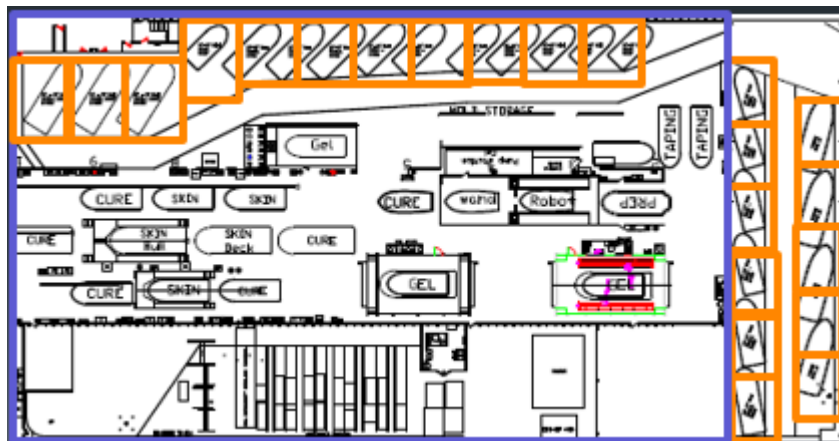


Figure 4. Inside Storage Layout

The second most ideal storage area for molds is on the right side of the lamination building on its outside shown in Figure 3. The side storage area is basically a fully covered room with some insulation on the walls. This allows the molds to be weather protected, but the room is not heated. These molds also do not need to be covered with a vacuum cover since the storage is fully covered from the weather. This storage area allows for ten hull and deck molds to be stored. As can be seen in Figure 4, the transportation time is still only a few minutes to take a mold and bring it to the taping station in front of gel coating.

The third and last area to store molds is on a hill outside as can be seen in Figure 3 in the lower left hand corner. Storing the molds outside is the least ideal option. Even though the molds are made out of strong materials, they can still get

damaged from the weather and during transportation. In order to protect the molds, three to four PI employees have to vacuum cover the molds which takes anywhere from 30 to 40 minutes. Once the molds are covered with plastic, the molds then have to be transported to the hill on a large forklift going all the way across the campus which takes 20 to 30 minutes. It is especially dangerous for the molds in the winter when the molds become more brittle from the cold and experience stress fracturing during transportation. This then entails the molds to either be sent to recon for full repairs or to the maintenance station for temporary repairs adding more prep time to the process. With these extra steps of prepping the molds with vacuum covers and transportation, it costs over \$100 to store a mold outside. If the molds are stored outside, the vacuum covers can be blown off from the high speed winds on the hill top and water can collect in the molds. This requires the forklift operator to turn the mold on its side, dump as much water out as possible, and then have the recon team in maintenance spend up to two hours to pump the rest of the water out.

Going into the project, the problem was known that workers were having non-value added time in the mold storing process. This was a symptom to some root causes. In order to find the root causes of the problem, a fishbone diagram was created in Figure 5 and Figure 6. Five categories were used to discover what was causing the operators to have non-value added time in the process: machines, methods, materials, environment, and manpower. Figure 5 shows the machines, methods, materials, and environment categories while Figure 6 shows the manpower category.

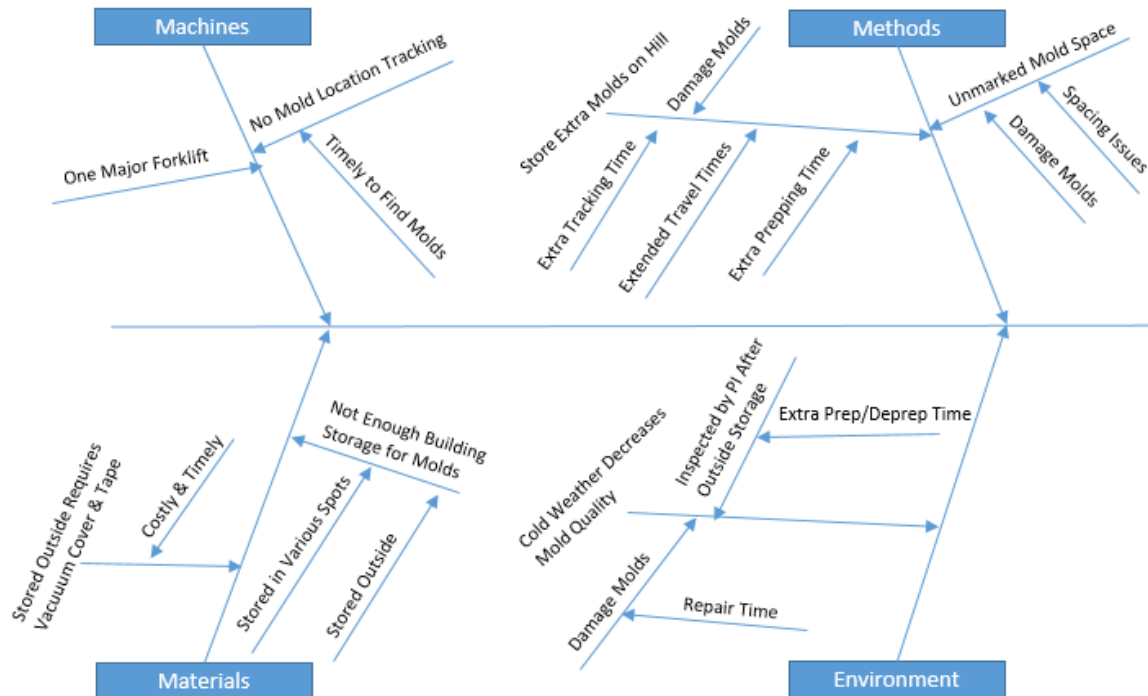


Figure 5. NVA Machines, Materials, Methods, and Environment

Looking at the machines category in Figure 5, the restrictions were that there is only one large forklift to transport the molds to the outside storage and there is no system in tracking where the molds are. The forklift operator has an idea of where the molds were stored last but there is no tracking system as to where the molds actually are. The methods category dealt with the common procedure of storing molds outside when there is no inside or side storage available as well as having unmarked mold space in the marked mold storage areas. When the molds are stored on the hill there is a lot of added time to the process with extra tracking time, preparation time, extended travel times, as well as having damages from weather and transportation. The materials category deals mainly with the limitation of inside storage as well as the extra materials needed to store the molds outside such as vacuum plastic and tape which are costly. The main effect from the environment category was that the quality of the molds decrease when being stored outside which leads to extra repair time and preparation/depreparation time for the molds.

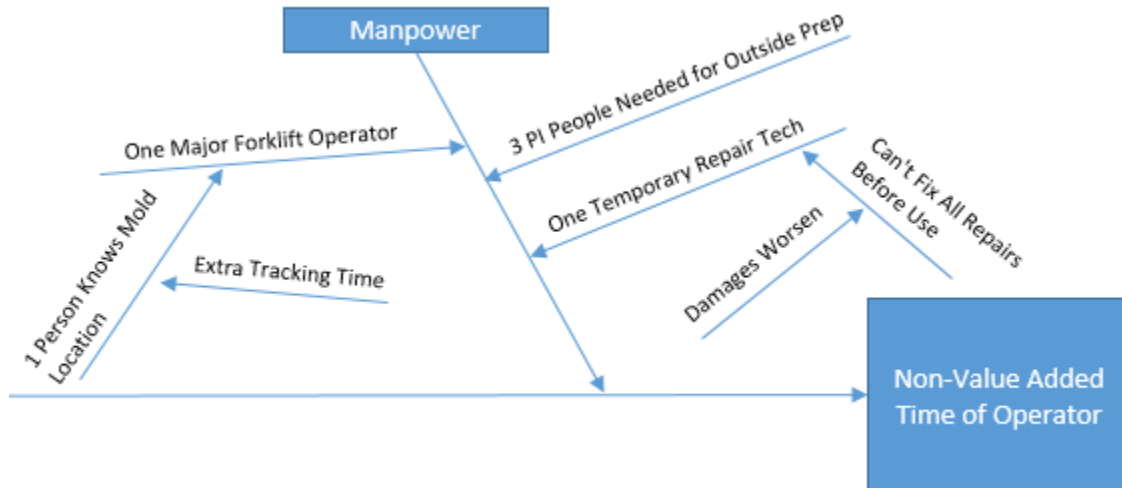


Figure 6. NVA Manpower

Figure 6 shows the effects of having the constraints of the one outside forklift operator, three PI workers needed for preparing the molds to be stored outside or for the lamination process, and having one repair technician put temporary patches on the molds before the lamination process. The major forklift operator may not always know where the molds are located in the three storage areas which leads to extra tracking and travel time. If the forklift operator is not present then even more time is spent searching for the molds. After analyzing the five categories, the area that could see improvement without additional resources is the methods category. This is the area of focus of the project in creating a standardized method of storing molds.

Problem Statement

Sea Ray is experiencing certain employee departments spending time preparing and transporting molds for outside storage when this may not be the most optimal option. Some molds are stored outside on the hill since there is no room inside the lamination building or side storage area when the molds are needed for production the next day. This adds additional time to the cycle time of the product with these extra steps. The daily production schedule drives the demand for specific molds but does not always sync with the open storage space. In this way, the goal is to minimize the non-value added time of the forklift operator and PI employees by creating a connection between the production schedule and the storing of the molds. This project is defined from when a mold is picked from storage to when the part is pulled from the mold and sent back to storage.

Research Objective

There are many different tools available to apply lean concepts to solve this problem. The tool that this project utilizes is linear programming to find an optimal way to store the molds. Various options were considered in finding a solution. One option was to build a 60 by 100 ft² heated storage building to store the extra molds; however after looking at the cost to build this structure and the cost to store a mold outside, this option seemed infeasible for the time frame of this project. Another common practice in storing molds is utilizing vertical or slanted storage for the molds. This also was infeasible and physically restrictive since the large forklift would not be able to fit inside the lamination building. The focus of this project was then to optimize the storing methods using the current resources of the facility. This would be done through developing a linear program with Matlab considering the storing constraints and variables, while using CPLEX to solve the linear program. From this project, Sea Ray could then use a storing schedule based off the production schedule to decide where to store certain molds each week. Linear programming has been applied to many different fields but not specifically to boat mold scheduling. In this case, a unique and new application of linear programming is applied to a recurring problem for a major boat manufacturing company. The goal is to apply linear programming to decrease the costs and increase the efficiency of a recurring process for a local Tennessee company.

Research Design

Methodology of the Model Design

When designing a model to simulate a process or be used for actual production, it is important that certain steps are followed to ensure that the model is validated and credible by the users of the model. As Averill Law describes, "Validation is the process of determining whether a simulation model is an accurate representation of the system, for the particular objectives of the study" (Law, 39). Only a valid model can be used to base decisions on for future actions that will produce reasonable results. Many model designers may omit this validation stage after the model has been created as extra time or money may be needed. These considerations for validation should be introduced at the beginning of the model building process. The validation process can vary in time based on how complex the observed system is. Another important factor when building a model is to understand that the model is an approximation of an actual system. No matter how many resources are put into building a model, the model will never be able to implement all of the different variables the complex actual system faces. Models should also be created for a specific set of defined objectives. The model has to have clear objectives in order to be able to validate the model (Law, 39).

Besides validating a model, the model also has to go through an accreditation. "Accreditation is the official certification (by the project sponsor) that

a simulation model is acceptable for a specific purpose” (Law, 40). The actual users of the model who sponsor the model creation have to accept the outputs as being correct. This is very important since large amounts of resources may be put into the implementation of an output from the model. Someone has to be responsible for the decisions made based off of the model. Having these important factors in mind, the model developer can then follow a seven step approach for building a successful model (Law, 40).

Before building the model, two seven step methodologies were taken into consideration for the development of the model based on simulation modeling from Law and linear programming from Winston. Law suggests that a successful approach for creating a simulation model consists of these seven steps: formulate the problem, collect data and construct an assumptions document, validate the assumptions page, program the model, validate the programmed model, design, conduct, and analyze the outputs, and document and present the results (40-41). Winston developed a similar methodology for building a linear program: formulate the problem, observe the system, formulate a mathematical model of the problem, verify the model and use the model for prediction, select a suitable alternative, present the results and conclusion of the study to the organization, and implement and evaluate recommendations (Winston, 5-7). Even though Law uses the other approach for simulation there are many similarities and benefits that can be achieved by combining Law’s approach with Winston’s. In this way, aspects of both approaches were used when developing the optimization model in order to ensure the model’s validity and credibility. These steps are discussed throughout this paper.

Data Collection Methods

Before beginning this project, management knew that mold storage was a constant struggle, which the lamination workers had grown accustomed to. Dealing with this situation made it hard for a new method to be developed that introduced a more standardized mold storing process. In this way, having an outside analysis of the situation became a great way to gain new insight on what is actually causing non-value added time for the maintenance and forklift operators. The only way to understand the situation was to talk with the process managers to understand the lamination process as well as to talk with the maintenance personnel and forklift operator to understand the current mold storing method. Law refers to these personnel as subject-matter experts (SME’s), and suggests that meetings with SME’s as well as with the decision makers on a regular basis are critical in developing a valid and credible model (42).

In collecting data, a developer can come across some difficulties such as: dealing with non-useful information, data in an incorrect format, rounding errors embedded in the data, and data containing a bias from self-interest. After knowing these types of areas for introducing incorrect data, steps can be put in place to ensure these types of errors are mitigated or eliminated (Law, 45-46). The

developer made sure these factors were clear to the SME's when collecting the data. The lamination process and the mold storing method were the two pieces of information to figuring out why molds were stored the way they are currently.

The process managers were first consulted since understanding the modern boat lamination process was important in order to comprehend their current operations as well as the project goals and issues (Law, 43). Having management back a project is crucial for any project's success or implementation later. A common lean technique, gemba, was used to walk through the lamination process consulting both process managers and line workers for multiple days with different boat models (Liker, 224). In this way the model developer could understand how each of the subsystems act. Once a solid grasp of the lamination process was understood, the key employees dealing with storing the molds were consulted.

The maintenance team deals with maintaining the hull and deck molds as well as prepping the molds for outside storage or for the lamination process. In order to maintain the molds, they have to conduct routine repairs at the cost of being able to use the mold for the production of another boat part. These repairs can take days depending on the severity of the damage. Having the molds spend a minimal amount in down time is crucial for meeting the production schedule. The damages come from usage in the lamination process or from transportation from outside storage. Damages from the lamination process can hardly be avoided but the damages from transportation can be. Consulting these maintenance workers over the course of a few days showed the reasons behind the downtime of the molds from being stored outside. To further delve into the damages from transportation, the mold forklift operator was consulted.

The forklift operator was consulted for one day. This led to the understanding of the way the molds react to different temperatures and factors caused by the outside environment. The outside environment has a direct effect of when a mold is ready to be used for the lamination process. If the mold is stored outside but was damaged from the weather, then the mold spends down time in maintenance being prepared for the lamination process. This can be prevented sometimes if the mold was known to be needed in the future and necessary preparations could have been made. Then the mold could go directly from storage to the lamination process line immediately and meet the production schedule. After consulting the maintenance team and forklift operator, a cost based on past times was assigned to the movement of the molds which is later discussed in the assumptions section.

The data gathered was based off of historical data or collected data from the consulted employees when used in the model. This process of consulting, gathering data, and sharing ideas with management was conducted over the course of a few months. More information was gathered than needed but all aspects of the problem were considered with management. This information could later be used to improve the basic mold storage scheduling model produced in this paper.

Variables

The purpose of developing a model for this project is to know, based on the production schedule, which specific hull and deck molds to use for the lamination process for the day. The model will also determine the optimal storage of the hull and deck molds based on future production from the production schedule. Since each boat model has various amounts of molds for the hull and deck, there is a decision of which specific molds to use to complete the hull and deck products. Currently, the lamination process is based off of which molds are available with no standardized tracking method. The week before the production week, a daily production schedule is created from a scheduling manager specifying the particular molds to use. These molds can be located in any of the storage areas and may not have the required time to allow the mold to be ready for production the next day.

This new model will standardize this mold process by tracking which molds are available for production for a period of 16 days or one month. The differences each day in the model are the specific hull molds and deck molds utilized. The hull and deck molds are the variables based on which molds are used for a specific day's production as well as the specific area to store them. This is what the model will determine based off of the various production constraints. A further discussion of the decision variables are discussed in Chapter 3 in the Nomenclature section.

Constraints

In order for the model to choose the optimal hull and deck molds for the lamination process, a certain set of constraints are defined based off of the collected data and consultation from the production managers. These constraints are defined in more detail in Chapter 3, Model Constraints section. The major constraint groups that must be met are production constraints, storage constraints, and the amount of mold asset constraints.

The production process provides certain constraints in the process of choosing a hull and deck mold. In order to meet customer demands, the defined daily production schedule must be satisfied. A hull and deck mold must be seized in order to complete each model boat demand for the month. This is a key constraint to the model. During the production day, certain hull and deck molds are used for production in the lamination process and thus cannot be used again until the molds have completed the lamination process. This creates a constraint on how many times per week a mold can be used in the lamination process.

Along with the production constraints, there are constraints created from the storage areas. Currently there are only two areas to store molds inside a building (inside the lamination building and the side storage building). The rest of the molds are stored outside in a designated lot. There are no other areas to store the molds which are considered in this model. Since these areas are confined, there are only a certain amount of molds that can fit in the storage areas. The lamination building can hold a defined number of molds as well as the side storage building. The outside storage area has plenty of room to store the rest of the molds. Currently

molds are allowed to stay in an inside storage area for any amount of time. This can cause molds that are used more frequently to be stored outside if the inside storage areas are fully occupied.

The last set of constraints that were considered are the finite amount of mold assets available. There are only a certain amount of molds available for production. Additional molds created are not considered in this model. There are a defined amount of models which Sea Ray can produce. Each of these models has a restricted amount of hull molds and deck molds which can produce the model boat (see the Hull and Deck Table Index in the appendix). In some instances, two boat models can share hull molds. Deck molds are never shared between boat models. This sharing of hull molds between boat models happens in less than 20% of the boat models. Models that are produced more frequently can have molds go back into the lamination process just as the molds complete the process. This coincides with the production capacity constraint mentioned previously. In this model, Sea Ray is constricted to the current amount of mold assets defined in the beginning of the project.

CHAPTER II LITERATURE REVIEW

Background

In order to improve a manufacturing system, it is important to understand the science behind manufacturing processes. A manufacturing process is dynamic and constantly changing. To be able to react properly to these changes, management needs to understand the causes and effects of these varying factors in the manufacturing processes. This chapter will discuss the science behind a manufacturing system, how certain aspects affect the system, and ways to improve the system based on defined metrics. Once the science behind a manufacturing system is understood, a model can be designed incorporating other similar studies in operations research to improve the manufacturing system. These two pieces will justify the model design and the course of this project.

Factory Physics

Basic Factory Dynamics

Sea Ray boats has designed their manufacturing site as a product-oriented layout. Each production or lamination line is dedicated to produce certain boat models with the necessary tools and manpower. This lamination process is the first subassembly for creating a finished boat. As mentioned in Chapter 1, the process begins with the selection of a hull or deck boat mold being prepared for the lamination process, and ends with the preparation of the hull or deck boat mold for storage or further production. Even though the process may seem complicated, there is a simple relationship used in manufacturing to relate three measurable metrics to various production situations. John Little created this manufacturing relationship between throughput, WIP (work in process), and cycle time called Little's Law, which remains true for any type of manufacturing process (Hopp, 239). Understanding this basic relationship can greatly affect the operations in the lamination process.

$$WIP = (Throughput) * (Cycle Time) \quad (1)$$

The first term, WIP, means "...all the product between, but not including, the ending stock points" (Hopp, 230). For the scope of this model, this means all of the boat models in the lamination process to when the part is pulled from the mold. For the purpose of this project, the lamination process itself was not altered and so the WIP is assumed to remain constant. As defined in *Factory Physics*, throughput is "The average quantity of good (non-defective) parts (the manager does have control over quality) produced per unit time" (Hopp, 229). Ideally, Sea Ray would like to have a high throughput in order to meet customer demands. This

makes meeting the production schedule very critical to maintaining a steady demand. Boat product rework is a constant problem when looking at throughput. The boat product can go smoothly through the lamination process, but may still spend large amounts of time going through rework. This can be caused from damages to the mold or production errors. This in turn increases the cycle time. The third parameter, cycle time, is defined "...of a given routing is the average time from release of a job at the beginning of the routing until it reaches an inventory point at the end of the routing (i.e. the time the part spends as WIP)" (Hopp, 230). If the amount of damages to the mold during storage and process preparation can be reduced, then the cycle time for the boat models can be decreased. This is a key metric for the study of this project to reduce in order to improve the lamination process for Sea Ray. Another important relationship is a manufacturing system's service level.

$$Service\ Level = P\{cycle\ time \leq lead\ time\} \quad (2)$$

As defined in *Factory Physics*, "The lead time of a given routing or line is the time allotted for production of a part on that routing or line" which is typically a management constant (Hopp, 230). A higher service level means that Sea Ray has a more responsive production line. This emphasizes the importance of reducing the lamination process's cycle time since this will also increase the lamination process's service level.

Variability Basics

Once the relationships between the manufacturing metrics were understood, the next step was learning what causes changes in a manufacturing process. Having a low cycle time is ideal but a similar throughput can be achieved with a high amount of WIP and extended cycle times. The reason low cycle times are preferred is because of variability in the manufacturing process. *Factory Physics* describes variability as "...the quality of non-uniformity of a class of entities" (Hopp, 265) which in this case would be boat model products. Variability should not be confused with randomness. Randomness can occur from lack of information or natural randomness. Randomness then introduces variability into a process.

Variation is either controllable or naturally random. Controllable variation is caused from manufacturing decisions, while random variation is not predictable. Mold defects can occur based on random variation in the lamination process or controllable variation of being stored in the different storage locations. There is a decision placed to store the mold outside which has the possibility of being damaged from the environment. It is random if molds are damaged by the environment but the probability is much higher when stored outside. This means that storing a mold outside introduces variability into the lamination process which

is ultimately detrimental to the lamination process and the boat product. With this in mind, the goal is to decrease the amount of controllable variation by decreasing the amount of times highly utilized molds are stored outside (Hopp, 265-266).

Factory Physics describes the most common types of variability as: natural variability, random outages, setups, operator availability, and rework (Hopp, 271). For this project, variability from rework can be directly caused from the location of where the molds are stored. Rework variability increases the WIP and cycle time of the lamination process. This is due to boat products having to spend extra time in the PI maintenance station fixing damages which, in many cases, is due to damages to the hull and deck molds. Conducting rework on the products or maintenance of the molds which could have been prevented causes a loss in process capacity. These maintenance and rework employees could be spending their time on non-controllable damages. This would in turn increase the throughput of the lamination process. If these damages are not caught early in the process, then these can carry further down the manufacturing line to the assembly process where it is much more expensive to fix. According to *Factory Physics*, "Waiting time is frequently the largest component of cycle time" (Hopp, 302). Having the boat products sit in rework increases the wait time between the lamination process and the assembly process.

Flow variability is the introduction of variability in a station early in the manufacturing process which affects other stations further down the process (Hopp, 277). Since damages on the mold introduce variation in the first step of the lamination process, this increases the variability to the downstream stations in the lamination process. Now that the areas where variation can be introduced are known, the next section will discuss the ways to control and decrease the variation.

Corrupting Influence of Variability

With the different types of variability, there are three ways or combinations for a manufacturing line to buffer variability: inventory, capacity, and time (Hopp, 309). Currently, time is the main buffer for the variability in the lamination process. Extra time is given in the cycle time for repair allowances. This shows that "Increasing variability always degrades the performance of a production system" (Hopp, 309). Buffers are put in place for production lines as a result of variation. In this case, the goal is to reduce the line cycle time by reducing variability introduced by mold damages. "Arrival variability can be reduced by decreasing process variability at upstream stations, by using better scheduling and shop floor control to smooth material flow, eliminating batch releases, and installing a pull system" (Hopp, 344). With a more uniform mold arrival schedule, the mold readiness at the arrival to the lamination process should be more predictable. Decreasing the variability in the lamination process will then decrease the line cycle time as well as increase the throughput and service level.

Scheduling with Linear Programming

In the last few decades, companies have been using information to increase the efficiency of their processes in order to get an edge on their competitors. This makes collecting and using the right data crucial for a business to stay ahead of competition. Analytics of large amounts of information has been a big push recently. Companies are finding that sharing information throughout their departments allows for an easier mitigation of risk and more optimal assignment of assets. This allows a company to not only sustain its business but excel in a constantly changing competitive environment. With more information and the right analysis, a company can make strategic decisions on day to day operations. These daily processes tend to have patterns or correlations which can be used to get a desired output or adapted to better fit a company's needs. This comes from the understanding of the causal relationships between process events. Once employees understand why events are happening, steps can be implemented to better support a controlled process (IBM Corporation, 2-8). Many times problems are known in a process but companies find it challenging to assign values to these problems without a model. Building these models can clarify a manager's understanding of the process (Rehn, 1382). This is the mindset behind operations research.

Linear programming looks at these causal relationships in a process and finds the optimal way to satisfy the process constraints to get a desired outcome. A similar example of weekly and daily scheduling with linear programming was done at McDonalds for developing employee work schedules. In this case, a computer based employee scheduling program was created to replace creating the schedules manually which took up to eight hours. The McDonalds manager would forecast hourly sales and satisfy the demand with personnel labor hours for one week. This scheduling time of the manager was considered to be non-value added time. The manager could instead be focusing more on the operational activities of the restaurant. The goal of the project was to: decide on a mathematical model that could solve the number of variables, create a low cost for the needed computer hardware and software, have an easy to use interface for managers, and to significantly drop the needed man hours to create an employee schedule. They broke the model into two network flow sub-problems of assigning people each day for that week and the hourly shift for those days (Love, 21-25).

After the program ran, a report would analyze the alternatives to further meet the workers preferences and worker skill requirements in work areas. Once the model's outputs were approved by the different restaurant managers, considerable effort was spent on creating an easy to use user interface. Multiple choice menus were used so a person with little to no computer experience could understand. The users could also manually change the constraints to better suit their particular restaurant's needs. Along with an easy to read report output, the model was well received by the restaurant managers. This new scheduling program significantly reduced the time to create a weekly schedule as well as

increased the quality of the schedule. The program also would have similar outputs from various managers which created a more standardized process (Love, 26-27). This situation with McDonalds closely resembles the mold storage scheduling problem faced by Sea Ray.

Another more recent study of weekly demand and personnel scheduling with flexible adjustments was conducted using a three sub-problem approach with mixed integer linear programs. In this situation, a work force schedule was done manually taking on average four hours to complete. A model was then designed in steps which used the output from the previous model. The weekly demand for the number of employees was created from an hours per employee per day schedule. From that, a daily demand was made. The rough hours per employee timetable was created from a three dimensional binary matrix which took into account worker abilities, availabilities, and the work planning. The second mixed integer linear program created a weekly schedule for every employee. These two mixed integer linear programs were run every week for planning purposes but a daily roster was needed to be created every day based on the previous two outputs. In this case a third mixed integer program was designed to give specific time slots for the workers. After each of the three outputs, the user was allowed to adjust the model if necessary. Ultimately the model helped to reduce the scheduling time for the managers and offer a less costly work schedule. This model not only produced a weekly labor schedule but a daily schedule as well. Management could use the weekly schedule while operations management could use the daily schedule (Ladier, 278-291). This concept of having a weekly and daily schedule for management and operations could be a very beneficial way for Sea Ray to analyze its reports.

A mixed integer linear model was also used for scheduling postal workers for weekly tours. A branch and price algorithm was used to match labor demand with the available workers' schedules in half hour increments. The employees were separated into two categories: regular workers (regular shifts) and flexible workers (flexible and varying shifts). To formulate the model, a small amount of sub-problems were solved for every category of worker but a master problem created a bound to ensure the computer could solve it as a linear program. Since the linear program is bound by the master problem, the solution has tighter lower limits for every node and is solved faster. One sub-problem dealt with the regular workers and the other dealt with the flexible workers. When dealing with the master problem, a best-node-first was chosen for simplicity over a depth-first search in the decision tree. The most amount of computer processing time was spent on the flexible worker sub-problem. In this case, all of the sub-problems were solved until optimality. They found that certain constraints had more effect on a workforce which in this case was the lunch break requirements by the unions. (Brunner, 129-148). Sea Ray could use this information to know what factors have a drastic effect on the lamination process.

Another application of labor schedule modeling was looking at workforce flexibility through cross-training and job rotation. In the past, cross-training

scheduling was dealt with by stochastic programming which omitted the factors of job rotation, and workers' remembering/learning labor skills over time. The problem was then modeled to minimize total cost of assigning workers to tasks, rotation between jobs, and deciding a schedule, if needed, for training. There were three stages for the search heuristic in the model: initiation, constructive, and improvement. The initiation stage was used to solve the minimum rotation interval. With that, the constructive stage randomly generates a feasible worker schedule. The improvement stage looks at the feasible solutions created in the constructive stage and finds the assignment with the best quality and adjusting accordingly. The model found schedules with high quality in a short amount of time. This model also found sensitive factors in the model which would change the total cost. The model shows that an optimal solution can be found in a quick manner and what factors should be analyzed that affect the total cost of scheduling (Azizi, 260-273).

Looking at a production process, John Deere was able to use a simulation model for its Augusta plant to produce a production schedule and pay wages based on how well the plant workers met the outputted production schedule. After facing delays in their assembly line, a model was implemented with a new conveyor system. The production staff began creating a model which took in to consideration: the recent model production, the variations associated with each tractor model, and the necessary production line workers. The model created a production schedule for the next day based on the previous day's production and the forecasted demand. The production line staff ran this model daily to determine what model tractors needed to be made for the day and based how much the production line workers were paid on how well they met the daily production schedule. John Deere found that Excel was an ideal user interface to input the necessary production line information and an output animation to follow what the ideal production should look like. An output report was also produced for easy interpretation of the production staff based on the past feedback given from the production staff to the developer. John Deere found that the new model increased productivity, increased understanding of cause and effect relationships in the production process, and that modeling is an effective tool to analyze and improve a production process (Rehn, 1380-1384).

CHAPTER III MATERIALS AND METHODS

Research Assumptions

There are many factors that contribute and influence the mold lamination process. Perfectly modeling a complex scenario such as this is impossible, but the criticality comes from whether "...the differences between the model and the system are significant enough to affect any conclusions derived from the model" (Law, 44). In order to get a feasible solution within a short amount of computer processing time, a few assumptions had to be made. Knowing the model's limitations is important when using the output for implementation in the future (Law, 43). There were many factors considered when creating the costs for non-value added time.

In order to quantify the reduction in transportation and maintenance non-value added time, a cost was applied to the movement of a mold to and from the lamination building. This cost was based off of employee labor hours, maintenance, and material cost. It is important to note that the damages to a mold from weather and transportation make up a large portion of a mold's non-value added time. The mold maintenance cost was broken up into either major or minor repair costs which occurred from the location of the mold as well as the frequency it has been used.

Since the transportation time from inside storage to the lamination process was negligible and no materials were used, no cost was occurred for the movement of a mold from inside the lamination building to the lamination process or vice versa. The only cost for a mold being stored inside for multiple time periods was from the major and minor repair costs. Since the inside storage is the optimal location to store a mold, the maintenance repair cost was low compared to the other costs. The major and minor repair costs were broken up so that the cost occurred each day a mold was in the inside building which produced a final cost of \$14. Consideration was taken as to not double penalize a mold for being stored inside after a mold was moved inside from outside storage. Costs also occurred when molds were moved to outside storage and from outside storage to the lamination building.

For a mold moving from outside storage to inside storage, a portion of the cost was from the forklift operator transporting the mold to the lamination building. Removing the mold's vacuum cover took a negligible amount of time and was negated from the cost. Sometimes molds stored outside have their vacuum covers removed and get filled with water. When this happens, it can take up to two hours with one employee to pump out the water. Since this is a rare occurrence, a weight was assigned that this occurs ten percent of the time. The rest of the labor cost was based on an hourly wage of \$17 per hour and a constant 20 minutes to retrieve and transport the mold. This produced a cost of \$11.50 each time a mold is moved to outside storage. The majority of the move in costs came from the major and

minor repair cost. As mentioned earlier these repair costs were created so that each time a mold was moved to inside storage a maintenance cost occurred. With the combination of the maintenance and labor cost the move in cost totaled \$68.

The largest cost for a mold happened when a mold was moved to outside storage. The move out labor cost portion had the same transportation cost just mentioned as well as a preparation labor hour cost. The process of covering the mold with the plastic cover took around 35 minutes with three to four employees. For this, 3.5 employees were assumed with 35 minutes labor time per mold with the \$17 per hour wage rate. The second portion of a mold moving outside cost came from the materials used to cover the mold. The plastic wrap and packing tape were estimated on the mold's length. In this case a 35 foot mold was used to estimate the cost. Since the molds vary from 30 feet to 40 feet in length, the difference in the costs were negligible. This then totaled to a cost of \$106 per mold moved to outside storage.

After observing the mold storing process for multiple days, a finite number of mold storage slots were defined for the lamination building and the side storage building based on a consistent storing pattern. The size of the molds do vary from 30 to 40 feet which causes the amount of mold slots used for storing molds to vary. However, the 40 foot boats are almost always stored outside or a slim amount stored in either inside storage areas. The amount of space available inside was then used for the 30 to 35 foot molds. The amount of each type of mold did vary slightly per week, but 22 open mold storage slots were assumed as dedicated storage for the lamination building. The side storage building also had a very consistent amount of 10 mold slots being used to store 30 to 35 foot molds. Since the transportation and preparation time differences between inside storage in the lamination building and the side storage building, the two storage areas were considered to be a single inside storage location. The outside storage had ample room to store molds so no constraint was placed on the amount stored in the outside storage area.

The amount of boats per model forecasted to be produced for the year was assumed to remain constant when this model was developed. This future production schedule was based off of a yearly demand which is then translated into a daily production schedule for one month. Since the work week consists of four ten hour days, a monthly schedule was assumed to be 16 days. The daily production schedule is a major constraint for the movement of the molds and is assumed to remain unchanged. The model can be used for future mold storage scheduling based off of a continuation of a monthly production schedule.

There has been a near constant amount of models used for production in the past. If a new model boat is designed, this new model typically replaces the older version. As models phase out new similar models are created to replace them. This being the case, the amount of models of boats was considered to be constant as well as the number of molds.

Research Hypothesis

After analyzing the lamination and mold storing process, there should be a direct connection between the area of storage of a mold and the ability to meet the production schedule. Knowing this connection can lead to an improvement in overall operations. If a mold is known to be needed for production and is placed in the inside storage areas, then there will be a decrease or minimal amount of downtime for maintenance, thus being able to meet the production schedule at a higher efficiency. This downtime for a mold is associated with non-value added time for the maintenance team and the forklift operator. If the costs of movement of a mold between inside and outside storage areas are minimized, then the non-value added time of the maintenance team and the forklift operator should be decreased as well.

Model Formulation

Model Structure

A common method for solving optimization problems is using a tool called linear programming. A linear program is a model that maximizes or minimizes a linear function of decision variables based off of a set of linear equations or linear inequalities with non-negative decision variables. A certain case of linear programming happens when all of the variables are non-negative integers. When every variable is non-negative and an integer, the formulation is an integer program. For this mold scheduling problem, events either occur or do not occur. This meant that all of the decision variables were binary. When every variable is binary the model is a binary integer problem. This model was developed as a binary integer program where the optimal solution has the lowest objective function value in the feasible region (Winston, 49-53). To solve the binary integer program, CPLEX software was used. CPLEX is a quick optimization solver software that uses optimizers developed from the simplex algorithms as well as others. CPLEX was chosen based on the speed of solving a model with the amount of variables.

Nomenclature

Indexes:

Table 1. Model Index Definitions

Index Symbol	Definition
i	Mold ID number, $i = 1, \dots, 95$
j	Model ID number, $j = 1, \dots, 25$
t	Time number in days, $t = 1, \dots, 16$

There are three indexes used in this model: boat molds, boat models, and time frame. The mold index i represents the specific hull or deck mold being chosen for an action. There are 47 hull molds and 48 deck molds available for production in this model. The first 47 values of i represent the hull molds, while the remaining 48 i values represent the deck molds. The model index j represents the particular model type needed for production. The 95 molds make up the 25 different types of boat models currently in production. This means that models can contain multiple hull and deck molds. There are also instances where hull molds are shared between models. For a better look at the model and mold assignments see the Hull and Deck Table Index in the appendix. The index t represents the time frame of the model in days. Sea Ray operates on a four day production week. The model is designed to schedule for a period of one month which in this case is 16 days.

Decision Variables:

Table 2. Model Decision Variable Definitions

Decision Variable	Definition
$StoredIn_{i,t}$	<i>Mold i is stored in an inside storage area at day t, $StoredIn_{i,t} \in \{0, 1\}$</i>
$StoredOut_{i,t}$	<i>Mold i is stored in an outside storage area at day t, $StoredOut_{i,t} \in \{0, 1\}$</i>
$BeingUsed_{i,t}$	<i>Mold i is used in production at day t, $BeingUsed_{i,t} \in \{0, 1\}$</i>
$MoveIn_{i,t}$	<i>Mold i is moved to an inside storage area from an outside storage area at day t, $MoveIn_{i,t} \in \{0, 1\}$</i>
$MoveOut_{i,t}$	<i>Mold i is moved to an outside storage area from an inside storage area or from the production line at day t, $MoveOut_{i,t} \in \{0, 1\}$</i>

In this model there are five binary decision variables for each mold: $StoredIn_{i,t}$, $StoredOut_{i,t}$, $BeingUsed_{i,t}$, $MoveIn_{i,t}$, and $MoveOut_{i,t}$. The first three variables deal with which state the mold is in. The last two deal with the movement of the mold between storage areas. Each mold can be in one of three states: $StoredIn_{i,t}$, $StoredOut_{i,t}$, and $BeingUsed_{i,t}$. $StoredIn_{i,t}$ happens when mold i is located in inside storage at time t . $StoredOut_{i,t}$ is when mold i is located in outside storage at time t . The last state a mold can be in for a day is $BeingUsed_{i,t}$. $BeingUsed_{i,t}$ describes a mold i at time t undergoing the lamination process (production). For this model, the lamination process for each mold has a length of two days. Since the exact inter-arrival times for each model j for each time t are

unknown, the best way to demonstrate the production time a mold spends in the lamination process was to assume a production length of two days.

The last two decision variables represent the movement of molds between the two large storage areas; inside and outside. $MoveIn_{i,t}$ decides which mold i at day t to move to inside storage. This is dependent upon the daily production schedule. If mold i is needed for production at time $t + 1$ then the mold used for production is moved to inside storage at time t . This is to ensure the proper preparation and maintenance can be conducted on mold i so mold i can be ready for production. These preproduction actions can be items such as: repairs, waxing, and ensuring the mold is at a safe production temperature. $MoveOut_{i,t}$ decides which mold i at day t to move to outside storage. This is used when a mold is not constantly being used for production. Molds that are needed for production are needed to be stored inside with higher priority over molds that are not needed for multiple days. A mold can be moved to outside storage after it has finished production or if it is sitting in inside storage.

Objective Function

$$\begin{aligned} Min z = & Cost1 \sum_{i=1}^{95} \sum_{t=1}^{16} MoveIn_{i,t} + Cost2 \sum_{i=1}^{95} \sum_{t=1}^{16} MoveOut_{i,t} + \\ & Cost3(\sum_{i=1}^{95} \sum_{t=1}^{16} (StoredIn_{i,t} - MoveOut_{i,t})) \end{aligned} \quad (3)$$

Table 3. Model Costs Definitions

Cost	Description
$Cost1 = \$68$	$MoveIn \text{ Cost} = (Labor \text{ Cost}) + (Minor \text{ Repair Cost Outside Storage}) + (Major \text{ Repair Cost Outside Storage})$
$Cost2 = \$106$	$MoveOut \text{ Cost} = (Material \text{ Cost}) + (Labor \text{ Cost})$
$Cost3 = \$14$	$StoredIn \text{ Cost} = (Minor \text{ Repair Cost Inside Storage}) + (Major \text{ Repair Cost Inside Storage})$

The objective of this model is to minimize the total cost of moving molds to/from inside and outside storage as well as the maintenance cost of storage for one month. This is done by assigning a cost for each type of mold movement. $Cost1$ is associated with the movement of a mold to inside storage from outside storage. $Cost1$ is based off of the maintenance team and forklift operator labor cost along with the major and minor damage repair cost from the mold being stored outside. $Cost2$ represents the cost of moving a mold from inside storage or the production line to outside storage. $Cost2$ is the summation of the mold covering material cost and the labor cost. $Cost3$ is the last cost which deals with the molds being stored inside. Molds that are stored inside can still experience major and

minor damages. However, these damage costs are much lower than the maintenance costs that come from molds being stored outside. The inside storage cost occurs each day a mold is stored inside. The objective function (equation 3), sums the total cost for every mold moved each day for one month. The goal is to minimize this transportation and maintenance cost while satisfying the production constraints.

Model Constraints

Table 4. Parameter Descriptions

Parameters	Definition
$Parameter1_{i,t}$	<i>If mold i is BeingUsed or StoredIn at time t and StoredOut at time $t + 1$ then $Parameter1_{i,t} = 1$, otherwise 0, $Parameter1_{i,t} \in \{0, 1\}$</i>
$Parameter2_{i,t}$	<i>If mold i is Being Used at time $t + 1$ then mold i is either StoredIn at time t or BeingUsed at time t. $Parameter2_{i,t}$ is used with a big M to ensure the constraints are not broken, $Parameter2_{i,t} \in \{0, 1\}$</i>
$Parameter3_{i,t}$	<i>If mold i is StoredIn at time t and BeingUsed at time $t + 1$ then, $Parameter3_{i,t+2} = 1$, otherwise 0, $Parameter3_{i,t} \in \{0, 1\}$</i>

When developing the model, three parameters had to be created in order to make the model linear. The parameters were used when an extra variable was needed to complete a linear constraint. These three parameters are defined in Table 4. $Parameter1_{i,t}$ is used in equations 10, 11, 12, 13, and 14. In order to satisfy a linear “or” and “and” constraint, $Parameter1_{i,t}$ was created. $Parameter1_{i,t}$ is binary and is one when mold i is stored outside at time $t + 1$ and either being used for production or stored inside at time t . If neither of the cases are true then $Parameter1_{i,t}$ is zero. A further explanation is given later. $Parameter2_{i,t}$ is a binary variable used in equations 16 and 17, which are linear “or” constraints. If mold i is in production at time t then mold i had to be either stored inside at time t or being used for production at time t . $Parameter2_{i,t}$ is used with a “big M ”, large number, to ensure that if one variable is one then the other must be restricted to zero. $Parameter3_{i,t}$ is used in equations 25, 26, and 27 as a binary variable to represent a mold i being used for production at time $t + 2$. A mold i is in production at time $t + 2$ if mold i was stored inside at time t and used in production at time $t + 1$. If one or both of the cases are not true then $Parameter3_{i,t+2}$ is equal to zero. These parameters are further explained under the equations they are in. The model

constraints were developed using the decision variables and the parameters described. A full list of the model formulation is given in the appendix.

$$StoredIn_{i,t} + StoredOut_{i,t} + BeingUsed_{i,t} = 1 \quad (4)$$

The first constraint, equation 4, deals with the state of mold i at time t . In this model, mold i can only be in one of three states at time t : $StoredIn_{i,t}$, $StoredOut_{i,t}$, or $BeingUsed_{i,t}$. A mold can't be in multiple storage areas at the same time nor be in a storage area while it's being used for production. Since each of the variables are binary, the constraint only allows one of the variables at time t to be one while the remaining are zero.

$$a * b = c \quad (5)$$

$$a + b - c \leq 1 \quad (6)$$

$$-a - b + 2c \leq 0 \quad (7)$$

$$StoredOut_{i,t} + StoredIn_{i,t+1} - MoveIn_{i,t+1} \leq 1 \quad (8)$$

$$-StoredOut_{i,t} - StoredIn_{i,t+1} + 2 * MoveIn_{i,t+1} \leq 0 \quad (9)$$

In order to associate a cost to when a mold is moved to inside storage, a binary variable $MoveIn_{i,t}$ was created. A mold would only be moved to inside storage if a mold was stored in outside storage at time t and then stored in inside storage in time $t + 1$. This meant that the mold i had to be moved inside. The nonlinear equation of if event a and event b happen then event c occurs is shown in equation five. However, in order to keep the program linear, equation five had to be separated into two linear inequalities shown in equations six and seven. These generic variables were then translated into the event variables of the model shown in equations eight and nine (Bisschop, 83-84).

$$BeingUsed_{i,t} - Parameter1_{i,t} \leq 0 \quad (10)$$

$$StoredIn_{i,t} - Parameter1_{i,t} \leq 0 \quad (11)$$

$$Parameter1_{i,t} - BeingUsed_{i,t} - StoredIn_{i,t} \leq 0 \quad (12)$$

$$StoredOut_{i,t+1} + Parameter1_{i,t} - MoveOut_{i,t+1} \leq 1 \quad (13)$$

$$-StoredOut_{i,t+1} - Parameter1_{i,t} + 2 * MoveOut_{i,t+1} \leq 0 \quad (14)$$

In order to associate a cost with moving a mold to outside storage, a variable $MoveOut_{i,t}$ was created. However, a mold could be moved outside under multiple factors. A mold could be used for production at time t and then in outside storage at time $t + 1$ for a mold to be moved outside at time $t + 1$. A mold could also be stored inside at time t and stored outside at time $t + 1$ which also meant a mold was moved outside at time $t + 1$. This $MoveOut_{i,t}$ event occurred from an "either-

or” constraint with the combination of an “and” constraint. In this case a parameter, $Parameter1_{i,t}$, had to be created to represent if either $BeingUsed_{i,t}$ occurred or if $StoredIn_{i,t}$ occurred. Equations 10, 11, and 12 ensured that $Parameter1_{i,t}$ only occurred when either $BeingUsed_{i,t}$ or $StoredIn_{i,t}$ occurred. Then the same and constraint logic with equations eight and nine were used to create equations 13 and 14.

$$\sum_{i=1}^{95} \sum_{t=1}^{16} MoveIn_{i,t} + \sum_{i=1}^{95} \sum_{t=1}^{16} MoveOut_{i,t} \leq 20 \quad (15)$$

Equation 15, restricts the maximum number of molds that can be moved in one day. The movement of molds between the inside storage area and the outside storage area is done with one large forklift. Only this forklift can move the molds between these storage areas. If molds are moved from inside storage to the production line, smaller lifts are used to tow the molds. There are multiple smaller lift machines and operators that can complete this task. Since there is a ten hour work day, the large operator can only move a certain amount of molds each day. This constraint restricts the number of molds moved between storage areas. In this case, an estimated 20 molds are allowed to move each day. The forklift operator should not be overburdened with moving around an unrealistic amount of molds but also have the capacity to move molds to meet production.

$$BeingUsed_{i,t+1} - StoredIn_{i,t} + M * Parameter2_{i,t} \leq M \quad (16)$$

$$BeingUsed_{i,t+1} - BeingUsed_{i,t} - M * Parameter2_{i,t} \leq 0 \quad (17)$$

$$f(x_1, x_2, \dots, x_n) \leq 0 \quad (18)$$

$$g(x_1, x_2, \dots, x_n) \leq 0 \quad (19)$$

$$f(x_1, x_2, \dots, x_n) \leq My \quad (20)$$

$$g(x_1, x_2, \dots, x_n) \leq M(1 - y) \quad (21)$$

There can be two states for a mold to be in at time t in order to be used for production at time $t + 1$. The mold can be either stored inside at time t or being used at time t . This created a scenario in integer programming called an “either-or” constraint. To create an “either-or” constraint, two constraints need to be added to the model. For instance, if two constraints are given (18 and 19), and the designer wanted to ensure that at least one is fulfilled then two additional constraints need to be added (20 and 21). M is a large enough number that makes sure that the constraints are satisfied with every value of each variable. When $y = 1$, $f \leq M$ and $g \leq 0$ which satisfies equation 19. The opposite is true when $y = 0$, $f \leq 0$ and $g \leq M$ which satisfies equation 18. Using this format, equations 20 and 21 were developed using an arbitrary M value of 50 and $y = Parameter2_{i,t}$ (Winston, 487-488).

$$\sum_{i=1}^{95} \sum_{t=1}^{16} \text{StoredIn}_{i,t} \leq 32 \quad (22)$$

After observing the mold storage process over many days, an average of 22 molds were stored inside the lamination building and ten molds stored inside the side storage building. The molds do range in size from 30 to 40 feet, but in order to build a standard model an average was used. This restriction on the inside storage area made it important that molds needed for production were stored inside the day before production. If molds were not needed for production then they were moved to outside storage. Equation 22 binds the number of molds being stored inside at time t to 32 molds.

$$\sum_{i=1}^{47} \sum_{t=1}^{16} \text{BeingUsed}_{i,t} = \sum_{j=1}^{22} \sum_{t=1}^{16} P_{j,t} \quad (23)$$

As mentioned earlier, models can contain multiple hull and deck molds while even sharing hull molds with other models. The other constraints dealt with the molds, but a constraint was needed to link the hull molds with their respective models. Equation 23 links the production of model j at time t to the available hull molds i . $P_{j,t}$ is the production demand for model j at time t . Since there are three pairs of models that share hulls, the production demand for the shared models j were added together and had a total of 22 models with unique hulls. For a better insight into the indexing of the molds and the sharing of the hull molds between models, see the Hull and Deck Table Index in the appendix. For instance, models three and four share three hull molds. The production demand for model three is added to the production demand of model 4 to get a total production demand for the shared hull molds. From the three hull molds, the production demand of models three and four had to be met. The hull molds are indexed as the first 47 molds. The summation of the hull molds being used for production at time t had to be equal to the production demand for model j at time t .

$$\sum_{i=48}^{95} \sum_{t=1}^{16} \text{BeingUsed}_{i,t} = \sum_{j=1}^{25} \sum_{t=1}^{16} P_{j,t} \quad (24)$$

There was a similar need to link the deck molds to the models that needed to be produced. The difference between the hull molds and the deck molds is that there is no sharing of deck molds between models. This meant that there was a unique production demand for each model j at time t . Models could also experience having a multiple number of deck molds. In this way, the summation of the deck molds being used for production at time t had to be equal to the production demand for model j at time t . The deck molds were indexed as the last 48 molds. Equation 24 links the production demand of models to the associated deck molds.

$$StoredIn_{i,t} + BeingUsed_{i,t+1} - Parameter3_{i,t+2} \leq 1 \quad (25)$$

$$-StoredIn_{i,t} - BeingUsed_{i,t+1} + 2 * Parameter3_{i,t+2} \leq 0 \quad (26)$$

$$Parameter3_{i,t+2} - BeingUsed_{i,t+2} \leq 0 \quad (27)$$

Since production takes around 12 hours and the work day is ten hours, a constraint had to be created to ensure that the molds stayed in production for two days. The molds could start production at any time during the first day of production, and then would need to be in production for part of the second day. This meant that if mold i was stored inside at time t and it was in production at time $t + 1$, then the mold would need to be used for production at time $t + 2$. This is the same as if event a and event b happen then event c occurs case as mentioned with equations eight and nine. The nonlinear equation is shown in equation five, and the two generic linear inequalities are equations six and seven. However, for this constraint a new variable, $Parameter3_{i,t}$, was created to represent a mold being in production at time $t + 2$. Equations 25 and 26 were developed from equations eight and nine. Equation 27 ensures that if $Parameter3_{i,t+2}$ does happen (value is one) then $BeingUsed_{i,t+2}$ occurs (value is one). After the model was formulated with the objective function along with each of these variables, the model was then programmed in Matlab and solved with CPLEX.

CHAPTER IV MOLD STORAGE SCHEDULING RESULTS

Model Verification

When building the model, it was important to understand that there was no mold storing system to compare the model to. In order to verify that the model worked mathematically correct, a smaller sample model was created. The full model which includes 95 molds and 16 days of production had 12,160 variables. This is a large output of variables to examine, but if a smaller version was created then the user could see the movement and storage for each mold on each day. This sample model was developed with 10 molds, 3 models, and 4 days of production. In order to create a smaller simulation of the full model, the same constraints as mentioned in the previous section were used with the only difference being the number of molds that were allowed in inside storage for each day. Since 34% of the molds can be stored inside in the full model, only four molds were allowed to be stored inside in the sample model. The constraint and right hand side (RHS) matrices for both the sample model and the full model were created in Matlab, and solved using CPLEX. The output from CPLEX was then sent back to Matlab to show the results.

Another aspect of simulating the full model was the categorization of the molds in the sample model. In the full model, each boat model has various amount of hull and deck molds with some models sharing hull molds as can be seen in the Hull and Deck Table Index in the appendix. To have a close representation of each of these model differences, a categorization of the molds was organized as shown in Table 4 below. Model 1 experienced no sharing of hull molds with other models but had multiple number of hull and deck molds available for production. To introduce hull mold sharing, models 2 and 3 shared their hull molds but had different amounts of deck molds.

Table 5. Sample Model Mold Categorization

	Number of Hull Molds	Number of Deck Molds
Model 1	2	2
Model 2	3	1
Model 3		2

Once the molds were categorized, the numbering of the molds had to be known to interpret the model output. The numbering of the molds in the sample model are shown below in Table 5. In both the sample model and the full model, the hull molds were numbered first and the deck molds were numbered after the hull molds. In the sample model, there were an even number of hull and deck

molds, each containing five molds. This is similar to the full model where there are 47 hull molds and 48 deck molds.

Table 6. Sample Model Mold Description

Model Number	Molds Type	Mold Number
1	Hull	1
	Hull	2
2 & 3	Hull	3
	Hull	4
	Hull	5
1	Deck	6
	Deck	7
2	Deck	8
3	Deck	9
	Deck	10

Once the model was shrunk to accommodate the number of molds, a GUI (graphical user interface) was developed for the model. Creating a user interface was critical to quickly and easily change the production demand for the week and see the corresponding output. Careful consideration was taken to design the interface so that only the needed output information was shown. A picture of the blank user interface can be seen in the appendix. One substantial output that management would want to know would be the weekly total cost for the storing of the molds. This was presented in a text box in the sample model. Besides knowing the weekly cost, seeing how the molds were moved between storage areas based on production was key to verifying the model. Three different areas were created containing ten entities, one for each mold. The three areas were: inside storage, outside storage, and production. Each mold had one entity box in each of the three areas. The entity box would show the mold number based on the location of the mold since each mold can only be in one of the three areas. Toggle buttons were used to change the mold locations for each of the four days. To see the connection between the model demand and the mold location, the categorization of the molds was also shown as static text.

To use the interface, all the user had to do was input the production demand for each of the three models for every day in the week. Once the production demand was put in, the user pushed the “Run Mold Scheduling” button, which solved the sample mold storage scheduling model. If a solution is found a message box appears that says “Solution Found.” If no solution could be calculated, the message box presented “Infeasible: No Solution Found.” This way the user would know a constraint is being broken by the input of the production demand. Once a solution was found, the user could then toggle through each day in the week to see where each mold is located.

Now that the user can see how the molds were stored, the model was analyzed to ensure that each of the constraints mentioned above were not broken. After multiple scenarios were input into the user interface, the model was verified to work as designed. These results were compared with the actual process done in the facility. With the user interface, it was easy to understand and see the logic behind the model. These results confirmed that the logic from the model was in fact similar to the processes currently used.

Trends in Output

While verifying the model with different production inputs, a few trends were noticed between the varying amounts of production. One trend dealt with how the molds were stored when their models were produced compared to molds that were not used for production. Molds that were used for production tended to stay in the inside storage area even after they were used for production even if there was no future demand. However the molds that were needed to be stored inside before production had priority over molds that had just completed production.

Another trend noticed was that the model would try to use molds in production continuously when matching the production demand. Instead of moving another mold inside to use for production, a mold of the same model and mold type leaving production would reenter production. This means that a mold would enter production for two days and then on the third day return back to production if there was demand. This continuous production would eliminate the movement cost of molds as well as the daily cost for a mold to be stored inside.

There were also trends in the total cost based off of storage scheduling and production scheduling. One cost recurring trend was noticed when molds were produced at the end of the week compared to the beginning of the week. With the same production demand for the week, molds that were produced earlier in the week had a lower total cost than a production of the same demand completed later in the week. The model placed molds inside a day or days before the mold would actually be used for production. The mold would then occur the daily inside storage costs since the molds needed for production would start off stored inside. When production is done early in the week, the molds would be stored inside, but spend the majority of time in production thus negating the inside storage cost. So if the molds could spend more time in production then the total cost would be decreased. This confirmed the result mentioned previously of the model sending molds after completing production back into production the next day when possible.

Another result was noticed whenever the production increased the total cost increased. This was from the increase in the movement of the number of molds from inside storage and outside storage as well as more molds sitting in inside storage. However, there could still be high production but have a low total cost if molds were used continuously. High production did bring a higher total cost, but if the molds were used continuously the total weekly cost could actually be lowered.

After noticing these trends, the full model was solved using CPLEX. Without a user interface, analyzing the full model's output was more challenging, but the same mathematical logic was being used. This confirmed, based on the models, that there is a direct connection between the costs of mold storage scheduling and the production scheduling. Costs could be saved using mold storage scheduling over an unstandardized method. However, since production dictated the mold storage schedule, the production schedule could now be optimized taking into consideration the costs of mold storage scheduling. The same model for optimizing mold storage scheduling could actually be used to optimize the production schedule.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

With a high volume of production, Sea Ray was facing non-value added times from the mold transportation and maintenance employees. These non-value added steps were from an inefficient method of moving the hull and deck molds to and from production. The movement of molds was unstandardized and thus molds were placed in areas of most convenience to the mold movers. Molds could be placed inside and remain there with no production for days. However, some molds were moved outside after production since the inside storage area was at full capacity, but would be needed the next day. Data was collected by observing the manufacturing and mold storage processes as well as conversing with the employees who conduct these tasks. A total cost was calculated to measure the amount of non-value added time of the employees. Even though there was no current storing method to compare to, the awareness of the total cost was beneficial to the company. With the data, two linear models were created: a full model and a sample model. The full model contained all 95 of the molds, but it was challenging to understand the logic behind the model from the large number of molds. A sample model with 10 molds and a user interface was created to understand the logic as well as make observations.

After analyzing the full model and sample model, there was a direct link between the mold storage scheduling and the production schedule. Molds were moved inside a day early to ensure all of the proper maintenance was complete before entering the production line. When molds were not used for production they remained in outside storage. A balance was needed when scheduling the production demand to ensure the constraints would not be broken. As the production volume increased the model would continuously use the same molds in production. This continuous production led to a decrease in the total cost for the week. Using this scheduling model, the daily production could be optimized based off of the total cost of storing the molds. This was a hidden benefit from creating the mold scheduling model. Further research can be done to not only have an optimized mold schedule, but an optimized production schedule as well based off of minimizing costs.

Recommendations

The importance of projects such as this is to take the ideas and continuously improve them. Creating a link between the mold storage schedule and the production schedule was a first step in improving the manufacturing processes. The next step should be to implement these storing methods into the current system. Having the acceptance of the workers is also a key factor in having a successful implementation of the methods. The transportation workers should understand the link between the mold storage schedule and the production

schedule. These workers should also understand the costs and benefits of using these methods. Workers will back a new method if they understand the reason behind the method creation. In this way, training should be given to the transportation workers on the downsides of storing molds outside and the extra work needed to be done on the actual boat product. If the transportation workers knew that saving a few minutes for them would exponentially increase the amount of time for a fellow worker in the maintenance department more care would be taken to store the molds in the best location.

If more investment could be placed into developing the full model with a functioning user interface, then a daily mold storing schedule could be created along with a daily production schedule. The full model is already created, but just needs a user interface. This would ensure that the highest quality molds are being used for production. Higher quality molds in production mean less damages to products and less non-value added time of the maintenance workers. The full model interface could also decrease the amount of time that the production planner spends creating the daily production schedule. Using the user interface, in minutes the planner can go through multiple scenarios and find the optimal production schedule that decreases the total cost. These improvements could give Sea Ray an edge over their competitors.

Future Work

Building the sample model and full model is just the first step in improving the mold storing schedule. These models can see more improvement to yield a better solution. One factor that can be added to improve the model would be to have the same model hulls and decks be stored next to each other. This way the mold transporter would spend less time looking for where each of the molds are to move them. After the model has been used multiple times, models that are used more frequently can be tracked to see how many inside storage slots are typically used in a week and have that area designated for these models. This would also decrease the time to find the molds needed or production. These designated areas can change from week to week based off of the production schedule.

As mentioned earlier, there needs to be a user interface created for the full model. The Sea Ray managers should be consulted to ensure that the user interface is exactly what they want. The user interface in the sample model is a starting point for the design of the full model's user interface. Ideas can be taken from this design and expanded to create a more improved interface. Having a successful user interface would not only decrease the costs of storing molds, but also decrease the time the production planner takes to create the daily production schedule. An optimal production schedule can be created from the model to have the lowest total cost. If the inputs for optimal production weeks can be stored, then a database can be built on the best setups for producing models. This database can be updated and changed as the production changes over time.

Besides having a user interface, management could also benefit from having a report created from the model. This report can easily show which molds are stored at what location at what time. Graphical analysis can be created to track the total costs and compare them to the actual costs of the production. This way management can see the trends of costs over the weeks and act accordingly. The comparison of the model to the actual production process can also be used to update the model to make it more valid. Even though this project was just the beginning, the benefits of improving the mold scheduling model and implementing it can out-weigh the costs.

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APPENDIX

Picture of Hull Mold



Picture of Deck Mold



Picture of Vacuum Covered Hull Mold in Outside Storage



Picture of Hull Part Removed From Hull Mold



Hull and Deck Mold Table Index

Type	Hull		Deck	
j	Start i	End i	Start i	End i
1	1	5	48	52
2	6	9	53	56
3	10	12	57	57
4	10	12	58	61
5	13	16	62	62
6	13	16	63	66
7	17	19	67	69
8	20	20	70	71
9	21	21	72	72
10	22	23	73	74
11	24	25	75	76
12	26	27	77	78
13	28	29	79	79
14	30	30	80	80
15	31	31	81	81
16	32	33	82	83
17	34	36	84	85
18	37	39	86	86
19	40	40	87	87
20	41	43	88	90
21	41	43	91	91
22	44	44	92	92
23	45	45	93	93
24	46	46	94	94
25	47	47	95	95

Model Formulation

Objective Function:

$$\begin{aligned} \text{Min } z = & \text{Cost1} \sum_{i=1}^{95} \sum_{t=1}^{16} \text{MoveIn}_{i,t} + \text{Cost2} \sum_{i=1}^{95} \sum_{t=1}^{16} \text{MoveOut}_{i,t} + \\ & \text{Cost3} * \sum_{i=1}^{95} \sum_{t=1}^{16} (\text{StoredIn}_{i,t} - \text{MoveOut}_{i,t}) \end{aligned}$$

Subject to:

$$\begin{aligned} & \text{StoredIn}_{i,t} + \text{StoredOut}_{i,t} + \text{BeingUsed}_{i,t} = 1 \\ & \text{StoredOut}_{i,t} + \text{StoredIn}_{i,t+1} - \text{MoveIn}_{i,t+1} \leq 1 \\ & -\text{StoredOut}_{i,t} - \text{StoredIn}_{i,t+1} + 2 * \text{MoveIn}_{i,t+1} \leq 0 \\ & \text{BeingUsed}_{i,t} - \text{Parameter1}_{i,t} \leq 0 \\ & \text{StoredIn}_{i,t} - \text{Parameter1}_{i,t} \leq 0 \\ & \text{Parameter1}_{i,t} - \text{BeingUsed}_{i,t} - \text{StoredIn}_{i,t} \leq 0 \\ & \text{StoredOut}_{i,t+1} + \text{Parameter1}_{i,t} - \text{MoveOut}_{i,t+1} \leq 1 \\ & -\text{StoredOut}_{i,t+1} - \text{Parameter1}_{i,t} + 2 * \text{MoveOut}_{i,t+1} \leq 0 \\ & \sum_{i=1}^{95} \sum_{t=1}^{16} \text{MoveIn}_{i,t} + \sum_{i=1}^{95} \sum_{t=1}^{16} \text{MoveOut}_{i,t} \leq 20 \\ & \text{BeingUsed}_{i,t+1} - \text{StoredIn}_{i,t} + M * \text{Parameter2}_{it} \leq M \\ & \text{BeingUsed}_{i,t+1} - \text{BeingUsed}_{i,t} - M * \text{Parameter2}_{it} \leq 0 \\ & \sum_{i=1}^{95} \sum_{t=1}^{16} \text{StoredIn}_{i,t} \leq 32 \\ & \sum_{i=1}^{47} \sum_{t=1}^{16} \text{BeingUsed}_{i,t} = \sum_{j=1}^{22} \sum_{t=1}^{16} P_{j,t} \\ & \sum_{i=48}^{95} \sum_{t=1}^{16} \text{BeingUsed}_{i,t} = \sum_{j=25}^{25} \sum_{t=1}^{16} P_{j,t} \\ & \text{StoredIn}_{i,t} + \text{BeingUsed}_{i,t+1} - \text{Parameter3}_{i,t+2} \leq 1 \\ & -\text{StoredIn}_{i,t} - \text{BeingUsed}_{i,t+1} + 2 * \text{Parameter3}_{i,t+2} \leq 0 \\ & \text{Parameter3}_{i,t+2} - \text{BeingUsed}_{i,t+2} \leq 0 \\ & \text{StoredIn}_{i,t} \in \{0, 1\} \\ & \text{StoredOut}_{i,t} \in \{0, 1\} \\ & \text{BeingUsed}_{i,t} \in \{0, 1\} \\ & \text{MovedIn}_{i,t} \in \{0, 1\} \\ & \text{MovedOut}_{i,t} \in \{0, 1\} \\ & \text{Parameter1}_{i,t} \in \{0, 1\} \\ & \text{Parameter2}_{i,t} \in \{0, 1\} \\ & \text{Parameter3}_{i,t} \in \{0, 1\} \end{aligned}$$

Sample Model Empty User Interface

Mold Scheduling Days

Day 1

Day 2

Day 3

Day 4

Production Data Input

	Day 1	Day 2	Day 3	Day 4
Model 1	-	-	-	-
Model 2	-	-	-	-
Model 3	-	-	-	-

Total Cost

-

Number of Models Starting Production on Each Day

Run Mold Scheduling

Model 1 Molds

Mold 1

Mold 2

Mold 6

Mold 7

Model 2 Molds

Mold 3

Mold 4

Mold 5

Mold 8

Model 3 Molds

Mold 3

Mold 4

Mold 5

Mold 9

Mold 10

Molds Stored Inside

-

-

-

-

-

-

-

-

-

-

Molds Stored Outside

-

-

-

-

-

-

-

-

-

-

Molds Being Used for Production

-

-

-

-

-

-

-

-

-

-

Sample Model User Interface Output

Mold Scheduling Days

Day 1

Day 2

Day 3

Day 4

Production Data Input

	Day 1	Day 2	Day 3	Day 4
Model 1	1	0	1	0
Model 2	1	0	0	0
Model 3	0	1	0	1

Total Cost

196

Number of Models Starting Production on Each Day

Run Mold Scheduling

Model 1 Molds

Mold 1

Mold 2

Mold 6

Mold 7

Model 2 Molds

Mold 3

Mold 4

Mold 5

Mold 8

Model 3 Molds

Mold 3

Mold 4

Mold 5

Mold 9

Mold 10

Molds Stored Inside

Mold1

-

Mold3

Mold4

-

-

-

-

-

Mold10

Molds Stored Outside

-

-

-

-

-

-

Mold7

-

Mold9

-

Molds Being Used for Production

-

Mold2

-

-

Mold5

Mold6

-

Mold8

-

-

VITA

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