Proceedings of the 2015 International Conference on Operations Excellence and Service Engineering
Orlando, Florida, USA, September 10-11, 2015

Optimal Hull and Mold Storage in a Lean Boat Manufacturing

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Abstract
The manufacturing process of pleasure boats is standardized among manufacturers. However, this research has been conducted on linking the production schedule with hull and deck mold storing using bi-level optimization. In this case, there was a limited amount of space to store boat molds inside the production building, while the remaining molds were stored outside. Boat molds that were stored outside experienced more damages and more frequent repair times. In order to decrease the non-value added time and cost of the maintenance and transportation of molds, a linear model was developed which synced the mold storage with the production schedule. The model created a mold storing schedule that allowed for enough time to ensure the molds were ready for production, while decreasing the non-value added times and maintenance cost.

Keywords
Warehousing, Optimization, Boat Manufacturing, Linear Programming

1. INTRODUCTION

In most of the industries mold storage and movement is not a big concern because molds are fixed or there is not a big cost related to their movement. In manufacturing of pleasure boats, molds cannot be fixed because of the variety of types. On the other hand movement cost cannot be neglected because of the size of each mold. In addition to that, every movement and warehousing condition may cause failures or conditions that impose maintenance cost.

This paper addresses this problem and optimizes the cost of storage based on number of movement, maintenance and repair cost. There are valuable researches on optimized warehouse locations (Ulungu 1994), warehouse configuration (Sweney 1976) and optimal warehousing and storage assignment (Hausman 1976), but the current problem is inherently different from other storage and warehousing problems because of the special connection between warehousing and production.

There are many examples in industry dealing with assigning employees or work based on time constraints such that these types of problems are known in operations research as scheduling problems (Azizi 2013),(Brunner 2012),(Ladier 2008),(Love 1990),(Rhen 2000). In order to ensure the hull and deck boat molds were ready for production on time, a storage schedule had to be created based on the boat model production schedule. Maintenance cost was also considered in objective function. There was also a need to reduce the variability in the steps before and after the lamination process in order to have reduced inventory and higher throughput (Hopp 2011). This lamination process for a boat model is the first step in the boat building process so any variability introduced here will continue to increase further down the boat manufacturing process (Hopp 2011).

A common method for solving optimization problems such as scheduling is to use 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 (Winston 2004). In this case, the model was completely based on if-else events in the process occurred or do not occur. This meant that all of the decision variables are binary. When every variable is binary the model is a binary problem. The model was developed as a binary integer program where the optimal solution has the lowest objective function value in the feasible region (Winston 2004). To solve the combinatorial optimization model, CLEX® solver was used. CPLEX® is a fast and powerful 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.

2. METHODOLOGY

To solve and develop the linear model, a multistep process was used based on an operations research perspective as well as a simulation model perspective (Law 2008),(Winston 2004). These processes focused on the collection of useful data and validating the model for successful future use (Law 2008),(Winston 2004). Many companies collect large amounts of data but the benefits come from the accuracy of the data as well as how it is used (IBM 2011). After analyzing the lamination and mold storing process using Gemba techniques, there was an assumption that there is a direct connection between the area of storage of a mold and the ability to meet the production schedule (Liker 2008). 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 area, 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.

3. Mathematical Modeling

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 from Table V. The index t represents the time frame of the model in days. The boat manufacturer 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.

Table 1. Index Definition

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

3.1. Objective function

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. Cost1 is the middle value of the three costs. 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, which is the largest of the three costs. Cost3 is the last and lowest 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 (1), 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.

$$Min\ z = Cost1 \sum_{i=1}^{95} \sum_{t=1}^{16} MoveIn_{i,t} + Cost2 \sum_{i=1}^{95} \sum_{t=1}^{16} MoveOut_{i,t} + Cost3 * \sum_{i=1}^{95} \sum_{t=1}^{16} StoredIn_{i,t} - MoveOut_{i,t} \tag{1}$$

Table 2. Cost Description

Cost	Description
$Cost1$	$MoveIn\ Cost = (Labor\ Cost) + (Minor\ Repair\ Cost\ Outside\ Storage) + (Major\ Repair\ Cost\ Outside\ Storage)$
$Cost2$	$MoveOut\ Cost = (Material\ Cost) + (Labor\ Cost)$
$Cost3$	$StoredIn\ Cost = (Minor\ Repair\ Cost\ Inside\ Storage) + (Major\ Repair\ Cost\ Inside\ Storage)$

Table 3. Decision Variable Definition

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

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: $StoredIn_{i,t}$, $StoredOut_{i,t}$, or $BeingUsed_{i,t}$.

$StoredIn_{i,t}$ is 1 if 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 being used 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.

3.2. Mold in only one state constraint

The equation (2), 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 or 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.

$$StoredIn_{i,t} + StoredOut_{i,t} + BeingUsed_{i,t} = 1 \tag{2}$$

3.3. Mold move inside constraints

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 was converted to multiple linear inequalities shown in equations (3) and (4) (Bisschop 2012).

$$StoredOut_{i,t} + StoredIn_{i,t+1} - MoveIn_{i,t+1} \leq 1 \tag{3}$$
$$-StoredOut_{i,t} - StoredIn_{i,t+1} + 2 * MoveIn_{i,t+1} \leq 0 \tag{4}$$

3.4. Mold move outside constraints

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 move to outside storage 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 $t+1$. $Parameter1_{i,t}$, had to be created to represent if either $BeingUsed_{i,t}$ occurred or if $StoredIn_{i,t}$ occurred. Equations (5), (6), and (7) ensured that $Parameter1_{i,t}$ only occurred when either $BeingUsed_{i,t}$ or

$StoredIn_{i,t}$ occurred. Equation (8,9) show that if a mold was being used or stored inside at time t and at time t+1 it is in outside storage $MoveOut_{i,t+1}$ has to be 1 otherwise 0.

$$BeingUsed_{i,t} - Parameter1_{i,t} \leq 0 \quad (5)$$
$$StoredIn_{i,t} - Parameter1_{i,t} \leq 0 \quad (6)$$
$$Parameter1_{i,t} - BeingUsed_{i,t} - StoredIn_{i,t} \leq 0 \quad (7)$$
$$StoredOut_{i,t+1} + Parameter1_{i,t} - MoveOut_{i,t+1} \leq 1 \quad (8)$$
$$-StoredOut_{i,t+1} - Parameter1_{i,t} + 2 * MoveOut_{i,t+1} \leq 0 \quad (9)$$

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3.5. Beginning Mold Production Constraints

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. M is a large enough number that makes sure that the constraints are satisfied with every value of each variable. Using a "big M" format, equations (10) and (11) were developed with an arbitrary M value of 50 and $Parameter2_{i,t}$ (Winston 2004).

$$BeingUsed_{i,t+1} - StoredIn_{i,t} + M * Parameter2_{it} \leq M \quad (10)$$
$$BeingUsed_{i,t+1} - BeingUsed_{i,t} - M * Parameter2_{it} \leq 0 \quad (11)$$

3.6. Mold Two Day Production Constraints

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 $t + 2$. For this constraint a new variable, $Parameter3_{i,t}$, was created to keep the mold being in production line at time $t + 2$. Equations (12) and (13) were structured the same as (3) and (4). Equation (14) ensures that if $Parameter3_{i,t+2}$ is one then $BeingUsed_{i,t+2}$ occurs (value is one).

$$StoredIn_{i,t} + BeingUsed_{i,t+1} - Parameter3_{i,t+2} \leq 1 \quad (12)$$
$$-StoredIn_{i,t} - BeingUsed_{i,t+1} + 2 * Parameter3_{i,t+2} \leq 0 \quad (13)$$
$$Parameter3_{i,t+2} - BeingUsed_{i,t+2} \leq 0 \quad (14)$$

3.7. Mold Transportation Constraint

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.

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

3.8. Mold Inside Storage Capacity Constraint

After observing the mold storage process over many days, an average of 32 molds were stored in inside storage. 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 (16) binds the number of molds being stored inside at time t to 32 molds.

$$\sum_{i=1}^{95}\sum_{t=1}^{16} StoredIn_{i,t} \leq 32 \quad (16)$$

3.9. Mold Production Constraints

There last constraint guarantees that correct mold is at production line at the pre specified time. 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 (17) links the production of model j at time t to the available hull molds i. $P_{j,t}$ is the scheduled production 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 Table 4 (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.

$$\sum_{i=1}^{47}\sum_{t=1}^{16} BeingUsed_{i,t} = \sum_{j=1}^{22}\sum_{t=1}^{16} P_{j,t} \quad (17)$$

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 scheduled production for model j at time t. The deck molds were indexed as the last 48 molds. Equation (18) links the production demand of models to the associated deck molds.

$$\sum_{i=48}^{95}\sum_{t=1}^{16} BeingUsed_{i,t} = \sum_{j=1}^{25}\sum_{t=1}^{16} P_{j,t} \quad (18)$$

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®.

4. RESULTS

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 sample model was created. The full model which includes 95 molds and 16 days of production had 12,160 variables. The constraint and right hand side (RHS) matrices for were created in Matlab®, and solved using CPLEX®. The output from CPLEX® was then sent back to Matlab® to show the results.

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. 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 on 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.

5. Conclusion

Based on the results, there is a connection between the mold storage scheduling and cost of storage as well as 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.

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Appendix

Table 4. Hull and Deck Mold 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

j	Start i	End i	Start i	End i
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

Biography

Mostafa GhafooriVarzaneh is a PhD student in Department of Industrial and System Engineering at University of Tennessee-Knoxville. He holds a B.S. in Electrical Engineering-Power Systems from Amirkabir University of Technology

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Rapinder Sawhney is a Professor & Heath Fellow in Industrial and Systems Engineering at the University of Tennessee, Knoxville. He earned B.S. and M.S. in Industrial Engineering and Ph.D. degrees in Engineering Science and Mechanics from the University of Tennessee, Knoxville in 1981, 1984 and 1991 respectively. He was a Weston Fulton Professor and Department Head during 2010-2013. He is also a faculty for the newly created Center for Interdisciplinary Research and Graduate Education (CIRE) in Energy and the director of Centre for Advanced Systems Research and education (CASRE). His current research focuses on trying to use technology and innovation to enhance organizational productivity. His research group at this moment consists of 40 Postdocs, Ph.D. and Master students. He has published significant journal papers, conference papers and has submitted for 5 patents. His funded research projects are in the millions of dollars. He has worked with over 200 companies and is a recipient of various awards (Boeing Welliver Fellow, Alcoa Faculty Award, IIE Lean Teaching Award, Reuben Harris Award, and Accenture Teaching Excellence Award).

Tron Dareing graduated from the University of Tennessee in 2014 with a MBA and a MS in industrial engineering. Industrial engineering thesis research focused on linear programming with an application in boat mold storage scheduling. He previously worked as a quality engineer with Schlumberger on the product life cycle of fracking pumps in the oil and gas industry. Tron is currently working at MAHLE as an industrial engineer concentrating on process improvement on automotive piston manufacturing lines.