ME 555

# Final Project

## Warehouse Design Optimization

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**4/23/2014**

**Abstract**

The project is focused on optimizing the design of a basic pallet warehouse to minimize construction and lease costs. As the transportation costs for raw materials or finished products increases over time companies are expanding their warehouse networks. The main shift has gone from large scale operations that provided storing economies of scales to smaller warehouses located closer to the final customer and therefore reducing the dependence on gas prices and maximizing full truck loads. By optimizing the design of the warehouse to an estimated demand volume, companies can significantly reduce their construction costs and improve their warehouse networks. Some of the anticipated challenges will be to work with different quotes from different vendors as well as the physical limitations of some of the equipment that is required to operate a facility. The results of the project will help a company determine what is the minimal cost to build a warehouse, the dimensions required to cope with demand and provide information on incremental costs for some of the constraints.

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# Introduction

Currently there is a great deal of focus on lowering the cost of distribution, especially in retail distribution. Companies such as Amazon, Zappos, Quidsi and many more are changing the traditional retail business industry into an e-commerce industry. This transformation has been enabled by the low cost of distribution, which derives from the accurate positioning of warehouses and supply chain networks. As e-commerce tries to reduce delivery times and remove barriers between themselves and brick and mortar stores, smaller more convenient warehouses will be required. The motivation for this project is to develop a tool that can be used to determine what is the ideal size and location of such warehouses. The optimization project will minimize costs while keeping the historical demand in perspective. As a result we will have a model that depends on demand and cost input variables to determine the ideal warehouse size.

Once a company has grown to a national or global scale one of the first issues it has to resolve is where they should locate their next warehouse or operations facility. Most companies' initial operations are selected because of the proximity to the owner, initial location of parent company or regional geographic advantage but if the company is successful it has to choose it next location wisely. Several factors come into consideration for the location of a company's operations for example customer location, cost of capital, real estate, infrastructure, operational feasibility, etc. For this project we will focus only on the real estate cost and construction cost for the estimated new location and compare it to a turnkey alternative solution. Our objective is to determine the optimal dimensions of a warehouse with a capacity for a given monthly demand standardized in pallets at a given cost per square feet of real estate and construction material.

Some of the tradeoffs in building a warehouse are the wider a warehouse the less need for high storage racks and lower investment costs. But if a warehouse decides to grow vertically it can reduce its square feet area and therefore reduce its lease and maintenance cost. For this problem statement we will disregard the maintenance cost for the total area and the cost of forklifts. The cost of the forklifts was not taken into consideration because each forklift model has different capabilities and would create and our model would not have any discrete solutions.

Our objective therefore is to minimize the construction and land lease for 10 years for a specific demand of 10,000 standard size pallets. The model warehouse will need to handle an average amount of standard sized pallets per month and they will be stored in vertical racks. Each rack will be able to hold up to 4 pallets and all of the rack will have standard dimension. The variables for the model will be the number of racks that will be placed along the main three axis in the model. The main axis will be called length, width and height. Each rack has a specific dimension for width, depth and height.

Our parameters will be the cost of leasing a square feet of land, the material cost of:

- Building a square foot of wall
- Material cost of a square foot of ceiling
- Number of pallets that flow through the warehouse each month.
- Rack has a capacity of 4 pallets.

The constraints that will determine the feasibility of the warehouse design are:

- The total demand in one month has to be stored within the warehouse.
- The forklifts are only high enough to reach three pallet levels high
- Each rack has to be spaced at least 3 meters from the next one alongside it (Richards, 2011)
- The initial model will use wide CBT aisle forklifts (Picture 1)
- Loaded pallets are 48” long, 40” wide and 48”high
- The area of the ceiling has to be the same as the area of the floor
- Racks have to be at least one pallet deep and two pallets wide

*Figure 1 – CBT forklift* Source: Crown Equipment Corp

For this model we will assume that the product suffers from very little seasonality. All product can be stores in the previously mentioned pallet dimensions. The cost of capital to the company is 0% therefore there is not decrease in value of the money over time. The labor costs are constant and we can always increase and reduce labor accordingly. There is a trained workforce and the warehouse will start running the same month of its completion. We can also assume that the rack have no maintenance cost once installed. All of the area under the lease is part of the warehouse.

# Design Problem

## Problem Statement

The design problem is to optimize the size of the warehouse to accommodate the established demand per month and minimize the cost of construction and lease of land for 10 years. Some of the tradeoffs in the design include the cost per construction and the lease of the land. If the building is tall the amount of land that has to be leased is smaller, but the cost of building a square foot of wall might upset the savings on the lease. Also there is a limit on the amount of racks that can be stacked, this will also affect in which direction the number of racks expands.

## Mathematical Model

### Notations

| Symbol | *Description* | Unit | Type |
|---|---|---|---|
| **L** | *Length Dimension* | Racks | Variable |
| **W** | *Width Dimension* | Racks | Variable |
| **H** | *Height Dimension* | Racks | Variable |
| **D** | *Demand per month* | Pallets | Parameter |
| **Fc** | *Front wall cost* | $ / ft^2 | Parameter |
| **FLc** | *Floor cost* | $ / ft^2 | Parameter |
| **Sc** | *Side wall cost* | $ / ft^2 | Parameter |
| **Cc** | *Ceiling cost* | $ / ft^2 | Parameter |
| **Rc** | *Rack cost* | $ | Parameter |
| **Rl** | *Rack length capacity* | pallets | Parameter |
| **Rw** | *Rack width capacity* | pallets | Parameter |
| **Rh** | *Rack height capacity* | pallets | Parameter |
| **Tc** | *Turnkey Cost* | $ | Parameter |

### Objective function

The objective function is to minimize the cost of construction and lease of land for a 10 year period using the tree dimensions of the warehouse walls as variables, L, W, H. Each side of the building has a specific cost that can vary depending on the vendor.

**Objective Function**

$$\text{Min} \quad 1062 \cdot L \cdot H + 1833 \cdot H \cdot W + 724 \cdot L \cdot W + 559.5 \cdot L \cdot W \cdot H + 365{,}904$$

**Constraints**

$$L, H, W > 0$$

1. **Demand**

$$L \cdot H \cdot W \geq 2{,}500$$

2. **Maximum Height**

$$8 \cdot H \leq 35$$

3. **Turnkey option**

$$1062 \cdot L \cdot H + 1833 \cdot H \cdot W + 724 \cdot L \cdot W + 559.5 \cdot L \cdot W \cdot H + 365{,}904 \ \leq \ 5{,}022{,}600$$

4. **Optional**

$$L, H, W = \ Integers$$

## Model Analysis

All of the cost for the walls have been aggregated into a standard cost per square feet of one side of the building. For this exercise we used the following parameters that were extracted from industry averages. Having an aggregate number helps simplify the calculations and also is more similar to real industry quotes. Construction companies, material distributors, and retailers generally charge per square feet of material. Since this is a warehouse design almost all of the area in each wall is very similar. Therefore it makes sense to simplify and use an average cost per side.

Another simplification that was take into account was that the average area of a rack include the area required for the forklift to function. This means that the minimum 3 meters required by the forklift to move pallets from the racks are included in the 13.3 f/rack dimensions on the width of each rack. This helped reduce the number of constraints on the number of aisled required in the warehouse. If a new forklift is considered for the warehouse that does not require the 3 meter wide aisle, all we need to do is to reduce the width of the aisle. Also the current land for lease has a value of $0.28 per ft^2, which would make the cost to lease the 130,680 ft^2 lot for 10 years a total of $365,904.0 that need to be added to the final construction lot. (www.loopnet.com, 2014)

| **Construction Costs** | **$ / ft^2** |
|---|---|
| Front/Back Wall[1] | 8.25 |

[1] Wall Cost; Masonry Advisory Council; http://www.maconline.org/tech/design/tall.pdf

| | |
|---|---|
| Floor[2] | 3.80 |
| Side Wall[3] | 8.25 |
| Ceiling[4] | 3.04 |

| | |
|---|---|
| **Cost per rack[5]** | $ 559.5 |

| **Dimensions** | **ft / rack** | **# Pallets** |
|---|---|---|
| L | 8.0 | 2 |
| W | 13.3 | 1 |
| H | 8.0 | 2 |

# Design Optimization

## Optimization results

The optimized solution was obtained using excel solver with the standard LSGRG nonlinear algorithm. This excel solver feature comes with the basic excel package and provides a user friendly interphase. The model evolved slightly from the original design. Fir the first design model the variables were intended to be the linear feet assigned to each side of the building. The combination of the sides of the building would provide the total area of each side of the building. Once the total area was obtained it would be divided by the area a rack would occupy in that direction. The division would provide the maximum number of racks required. Constraint would have to be placed to limit the amount of racks and it was very difficult to include the number of aisle and the minimum spacing required for each rack.

Since standardizing the volume and areas of each side and racks was complicated the standard measure unit was transferred to the dimensions of a basic rack. The minimum space required for an aisle was included in the dimensions of the rack and therefore the variables were changed to the number of racks that would be placed along each axis. This shift simplified the variable setting and once the number of racks was determined they were converted to linear feet by multiplying the number of racks along that axis times the size of each rack. All racks are placed in the same direction with the largest side of the racks parallel to the length axis of the warehouse. Fig. 2 is a representation of the locations of the racks.

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[2] Cement Slab Cost; Homewyse; http://www.homewyse.com/services/cost_to_install_cement_slab.html
[3] Wall Cost; Masonry Advisory Council; http://www.maconline.org/tech/design/tall.pdf
[4] Roof Costs is 80% of floor costs (Calin M. Popescu, 2003)
[5] Pallet Cost; Grainger; http://www.grainger.com/product/HUSKY-Pallet-Rack-WP33735/_/N-mkcZ1z07nbn?_=1398013344907&redirect%3Dsolenoid%3D%3D%3D%3D%3D=&s_pp=false#nav=%2Fproduct%2FHUSKY-Pallet-Rack-WP33735%2F_%2FN-mkcZ1z0kinvZ1z0lipvZ1z07nbnZ1z0ne4u%3FR%3D21E934%26_%3D1398013369454%26redirect%253Dsolenoid%253D%253D%253D%253D%253D%3D%26s_pp%3Dfalse

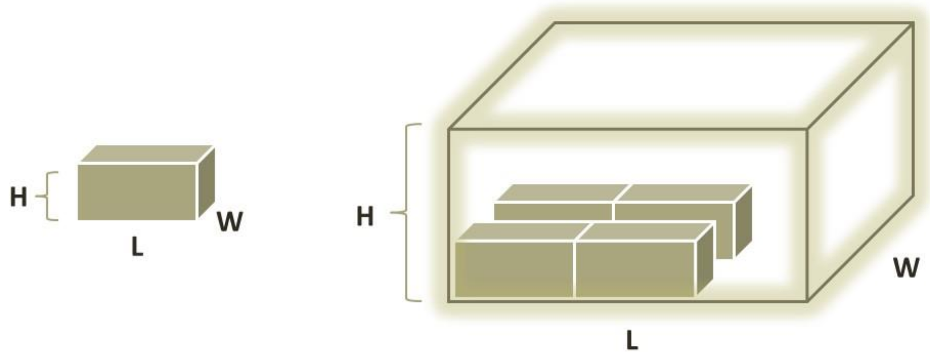


*Figure 2 Layout of racks inside warehouse*

A summary of the optimal solution for the optimization problem can be found below in Fig. 3. The optimal solution states that the warehouse should be 30.9 racks in length, 18.5 racks in width, and 4.4 rack in height. The minim cost of the warehouse design is $2,467,105. The optimal solution is $2,555,495 lower than the turnkey solution, $5,022,600 (www.Loopnet.com, 2014), and the active constraint is the total height of 35 ft. The pallet capacity constraint should also be an active constraint since it's cell value is 2,500 racks but since it is not an integer solution it has some decimal points as slack and therefore for the excel solver is not an active constraint.

Objective Cell (Min)

| Name | Original Value | Final Value |
|---|---|---|
| Objective Function | 380,332 | 2,467,105 |

Decision Variable Cells

| Name | Original Value | Final Value | Type |
|---|---|---|---|
| Pallet capacity L | 3 | 30.9 | Normal |
| Pallet capacity W | 2 | 18.5 | Normal |
| Pallet capacity H | 1 | 4.4 | Normal |

Constraints

| Name | Cell Value | # Constraint | Status | Slack |
|---|---|---|---|---|
| Objective Function | 2,467,104.7 | 3 | Not Binding | 2,555,495 |
| Total Ft H | 35.0 | 2 | Binding | - |
| Pallet capacity | 2,500.0 | 1 | Not Binding | 0 |

*Figure 3 Optimization model results*

Sensitivity Analysis

In the sensitivity analysis we can determine how much the active constraints contribute to the model. In this case, if the maximum height constraint were to increase by one feet we would have savings of $7,844. If the rack capacity were to increase by one rack the total cost would increase as well by $783.43 Fig. 4. The sensitivity analysis is very useful when evaluating constraints to determine if the effort or investment to change the constraint is worth it. With the model's sensitivity we can easily determine if investing in reach forklifts that can lift pallets to larger heights than 7m are worth the investment. An example in this case would be that if a reach truck can increase the maximum height to 36 ft but costs more than $7,844 it would not be worth to make the switch from CBT forklifts. Additionally, if management is analyzing the option of increasing the storage capacity by one rack but those four extra pallets would not generate more revenue than $783.43 then it would not be profitable to increase the capacity. It also helps to keep in mind that this is a simplified model and solution. There are several factors that are not taken into account which management should always keep in mind and think of how the constraints affect the external factors.

Objective Cell (Min)

| Name | Final Value |
|---|---|
| Objective Function | 2,467,104.70 |

Decision Variable Cells

| Name | Final Value | Reduced Gradient |
|---|---|---|
| Pallet capacity L | 30.87 | - |
| Pallet capacity W | 18.51 | 0.58 |
| Pallet capacity H | 4.38 | - |

Constraints

| Name | Final Value | Reduced Gradient |
|---|---|---|
| Objective Function | $ 2,467,104.70 | $ - |
| Total Ft H | 35.00 | (7,844.87) |
| Pallet capacity | 2,500.00 | 783.43 |

*Figure 4 Sensitivity analysis*

The following Fig. 5 shows if the variables are adequately constrained and what would be the limits for each variable that would comply with the current constraints. Since the pallet capacity in H is constrained by an outside factor such as a forklift height its range is very limited. Variables L and W have more options for potential values. Having more alternatives in with these two variables is very important since most of the warehouses will have to adapt to the terrain available, some warehouse might be landlocked and additional constraints along the length or width dimension can decrease the upper limit.

| Decision Variable | Value | Lower Limit | Objective Result | Upper Limit | Objective Result |
|---|---|---|---|---|---|
| Pallet capacity L | 30.87 | 30.87 | $2,467,104.70 | 71.15 | $5,022,600.00 |
| Pallet capacity W | 18.51 | 18.51 | $2,467,104.70 | 42.66 | $5,022,600.00 |
| Pallet capacity H | 4.38 | 4.38 | $2,467,104.70 | 4.38 | $2,467,104.70 |

*Figure 5 Variable upper and lower limits*

## Parametric Study

The current optimal solution design is a warehouse that is equally long and wide. The design shows there is a direct relationship between the linear feet of a warehouse side and the cost. In the initial case the four sides of the warehouse had the same cost per square feet. Therefore the parametric study consisted of a series of runs with different values in cost for the sides and front/back wall of the warehouse. The cost variations fluctuated +/-5% for each side and the results can be seen in Fig. 6. The following matrix shows the different cost in the objective function for the nine scenarios and the variations in each variable for each scenario Fig. 7.

| **Scenarios** | Front Wall | **-5%** | **0** | **+5%** |
|---|---|---|---|---|
| Side Wall | | **7.84** | **8.25** | **8.66** |
| -5% | 7.84 | 1 | 2 | 3 |
| 0 | 8.25 | 4 | 5 | 6 |
| +5% | 8.66 | 7 | 8 | 9 |

| **$ / Ft ^2** | Front Wall | **-5%** | **0** | **+5%** |
|---|---|---|---|---|
| Side Wall | | **7.84** | **8.25** | **8.66** |
| -5% | 7.84 | 2,452,842 | 2,459,882 | 2,466,748 |
| 0 | 8.25 | 2,459,882 | 2,467,104 | 2,474,149 |
| +5% | 8.66 | 2,466,748 | 2,474,149 | 2,481,367 |

*Figure 6 Parametric objective function results*

| Scenario | L | W | H | Total Pallets |
|---|---|---|---|---|
| 1 | 31 | 19 | 4 | 2500 |
| 2 | 30 | 19 | 4 | 2500 |
| 3 | 29 | 19 | 4 | 2500 |
| 4 | 32 | 18 | 4 | 2500 |
| 5 | 31 | 19 | 4 | 2500 |
| 6 | 30 | 19 | 4 | 2500 |
| 7 | 32 | 18 | 4 | 2500 |
| 8 | 32 | 18 | 4 | 2500 |
| 9 | 31 | 19 | 4 | 2500 |

*Figure 7 Variable Variations*

The parametric study shows that the objective function changes depending on the cost per square feet of wall. Even if two walls suffer and increment of 5 % if the other two walls have a decrease of 5% the solution would be better than the objective function. This tradeoff in cost can be counterbalanced with more square feet attributed to the lowest costing wall and compensate for the increment in the other walls cost. By using this parametric study the warehouse managers should try to decrease the cost of the front/back walls and maybe place more reinforcements on the side walls. The results can be generalized as the higher cost per square feet of a wall the less area that wall should have.

## Discussion

The results of the optimization study indicate that as the cost of building a wall increases the total area of wall corresponding to that cost will decrease. The current model has assumed that there is no difference in cost between the side walls and the front and back walls therefore the optimal design is a square based building. There are two active constraints that determine the minimal and maximum area of the warehouse. The average number of pallets per month that have to be stored limits the minimum area of the warehouse from decreasing to zero, since it is a cost minimization problem . The maximum height constraints limits the maximum height of the building to 35 feet, which would be the maximum physical constraint for the CBT forklifts to work with. The model does encounter some practical constraints that limit the flexibility of the design. If your warehouse is too long and only one aisle wide it will result very impractical, since it would take too much time to sort and collect the different materials. Also there is a limit to the strength of the walls in a structure. Especially in locations were the weather plays a significant factor in the maintenance of the stored material. If the warehouse is located in a region that suffers from extremely low temperatures, management might want to reduce the total area of walls since each square foot would have to be insulated.

The next steps to improve the model is to include different rack locations within the warehouse and use different rack types. There are gravity racks that do not require as many forklifts and conveyor belt systems that influence the storage time and transportation cost within the warehouse. Additionally, the model could include dummy variables to compare objective functions for different height restrictions. Different forklift models can reach different heights and also have cost differences. It would be interesting to include the cost of the forklifts and the maintenance of the total warehouse area. This will help determine what type of vendors could provide a cost effective solution to the operating needs of the warehouse.

## References


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# Appendix

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Objective Function | $2,467,104.70 | | | | | | | |
| | | | | | | | Demand | |
| | | L | W | H | | | Racks | Pallets |
| | Rack capacity | 30.9 | 18.5 | 4.4 | 2499.997917 | > = | 2500 | 10,000 |
| | Pallets | 2 | 1 | 2 | 4 | | | |
| | Ft / Pallet | 8.0 | 13.3 | 8.0 | | | | |
| | Total Ft | 247.0 | 247.0 | 35.00 | | | | |
| | | | | <= | | | | |
| | Maximum | | | 35.00 | | | | |
| | Total Ft^2 | 60,994.32 | | | | | | |
| | | Area | Sides | Cost | Total Cost | | | |
| Front/Back Wall | L*H | 8,643.63 | 2 | $ 8.3 | $ 142,620.0 | | | |
| Floor | L*W | 60,994.32 | 1 | $ 3.8 | $ 231,778.4 | | | |
| Side Wall | W*H | 8,644.29 | 2 | $ 8.3 | $ 142,630.7 | | | |
| Ceiling | W*L | 60,994.32 | 1 | $ 3.0 | $ 185,422.7 | | | |
| Racks | | | | $ 559.5 | $ 1,398,748.8 | | | |
| | | | | Total Cost | $ 2,101,200.7 | | | |
| **Land Lease Information** | | Ft ^2 | $ / Ft ^2 | Total Lease | 10 yr investment | | | |
| 30980 Industrial Rd, Livonia, MI 48150 | | 130,680 | $0.28 | $36,590 | $ 365,904.0 | | | |
| **Turnkey Lease option** | | Ft ^2 | $ / ft^2 | $ / Year | 10 yr investment | | | |
| Total Ft^2 | | 100,452.0 | 5 | 502,260.00 | $ 5,022,600.0 | | | |

*Figure 8 Excel Model for Warehouse design*

| **Build Warehouse** | **Lease Warehouse** |
|---|---|
|   |  |
| 30980 Industrial Rd, Livonia, MI 48150 | 5949 Jackson Road, Ann Arbor, MI 48103 |