A Structured Comparison Study on Storage Racks System

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Abstract: One of the most important decisions in warehouse and distribution center is the selection of the storage mode. Mostly, current warehousing practice is based on rules-of-thumb in pallet selection. The result can be useful but not repeatable in other projects. In addition, the warehouse research area almost focuses on overall layout and warehouse strategy and routing problems and rarely mentioned the structured method or tools to support the selection of storage racks. In this paper, a structured method is developed to compare the space utilization and the handling requirements based on product profiles. The product profiles include product mix, cycle stock and safety stock characteristics of each SKU. It creates simulation model to display the real operation of warehouse and analyzed the experiment results to compare 3 types of storage mode. However, each storage mode has its advantages and specific suitability of products. Single deep pallet racks allow random access with lower initial cost. The random access allows sharing among SKUs and therefore requires fewer storage locations. The Gravity flow racks allow higher density storage and reduced travels for its gravity move. The Drive-in racks allow a lift truck to drive within the rack frame to access the interior loads. The simulation experiment under the same product profile to makes three systems comparable. The experiment results indicated that Gravity racks system has more benefits on responding speed and travel saving under the same product profile design among three storage racks systems.

Keywords: Warehouse, single-deep pallet racks, gravity racks, drive-in racks, synchronized replenishment, SIMIO

1. Introduction

Warehouses and distribution centers (DCs) play more and more important role in modern society. For each company, the most fundamental idea is of the management of two resources: space and time (that is labor or person-hours) [1]. Warehouse and DCs allow enterprise to keep competitive by matching the supply with customer demand as well as consolidating products. Although the automatic intensive storage and retrieval systems, such as ASRS, allows enterprise realize automation, the general single deep racks, gravity racks and drive-in racks are still widely used in warehouse and DCs. In this paper, it compares 3 popular storage modes in space requirement and travel distance of handling operation.

Single-deep pallet rack, which has also known as selective rack, is the most common type of racks used in warehouses and DCs currently. The selectivity allows space sharing in SKUs with random access. In addition, single-deep rack incurs lower installation cost and easier to achieve modularization of system. However, it provides the lowest-density storage of any pallet racking system [2].

Gravity flow racks has lines with rollers which enable pallets to be put-away at one side and retrieved from the other side. The design can potentially reduce travel by forklifts during handling operation. A gravity flow rack particularly adapted for stocking and vending liquids [3]. This type of racks system is very practical to optimize the effectiveness of the JIT production. They provide high density storage and separate the traffic for storage and retrieval [4].Gravity flow racks support FIFO discipline and therefore suitable for dated goods. The amount of travel reduction depends on the flow volume in the DC and the layout [5]. Without space sharing among SKUs which cause the gravity flow racks may waste space. The utilization mainly depends on cycle stock and safety stock setting of product.

Drive-in, also known as drive-through rack, allows a lift truck to drive within the rack frame to access the interior loads; but, again to avoid double handling, all the levels of each lane must be devoted to a single SKU [1]. The product also can be moved according to FIFO policy. Additionally, drive-in racks system has some concerns in storage and retrieval process. It has more skill requirement of forklift driver because of its layout and the driver need to navigate within the lane. That will cause the enterprise higher labor cost than other types of pallet rack systems.

Therefore, the three types of rack systems have their specific application condition depending on the product profiles. The product profiles include volume flow, safety stock and cycle stock. However, current warehousing practice is mostly based on rules-of-thumb and simplistic ratios as well as extensive analysis of product mix, storage and material flow characteristics. The analysis can be useful but no repeatable in next projects. In addition, the warehouse research field almost focuses on overall layout and storage strategy and pick-path optimization problems and rarely mentioned the selection method or tools to support the selection of storage racks. Lots of researchers study on warehouse optimization. Jin GU., summarized in their paper that warehouse design involves five major decisions including determining the overall warehouse structure, sizing and dimensioning the warehouse and its departments, determining the detailed layout within each department, selecting warehouse equipment and selecting operational strategies [6] [7]. It is hard to build up a specific mathematical model for racks selection. Simulation-based analysis and optimization appears as a better choice to solve current problem as compared to the use of analytical approaches [8] [9] [10]. Jong FO., they developed a structured method to compare the initial and operating costs, the space, and the handling requirements and conducted two cases studies to demonstrate the effectiveness of this structured method for comparison [5]. This paper provided structured method for practitioners to make more reasonable decisions firstly. The further research has been done on basis of it. The simulation models have been created to analyze the space requirement and travel difference among single-deep rack, gravity rack and drive-in rack systems.

2. Mechanical Structure and Applicability

The three types of rack systems have their specific application condition according to their mechanical structure. They have different requirements in space, labor, travel and equipment [1]. It presents the racks mechanical structure and different applicability in this section.

Single-deep rack stores pallets in one deep. The racks allow pallet independently accessible so that any SKU can be carried from any location at any level. This structure gives picker complete freedom to retrieve any individual pallet. Therefore, the sequence of storage and retrieval process can be random. However, it also requires more aisle space to access any pallet. The lane can also consist two single-deep which known as double-deep rack to reduce aisle space. But it has concern about double-handling and slightly need more work to store and retrieve pallet. Single-deep rack system provides the lowest-density storage of any pallet racking system.

Gravity flow rack is deep lane rack in which the shelving is slanted and lines with rollers, so that when a pallet is removed, gravity pulls the remainder to the front [1]. This enables the storage and retrieval operations without interfering each other. But this cause one lane to storage only the same SKU which makes it’s appropriate to store high throughput and less variety items. Generally, the storage depth of gravity flow rack is limited to about eight pallets because of weight conversations.
Drive-in rack is the simplest kind of a static block storage system. The rack supports form vertical aisles for the rack feeders [11]. It allows forklifts to drive within the rack frame to access the interior loads. The system is operated solely with front stackers and accessed from the side. The unification of isles and lane makes drive-in rack system higher space utilization. However, it does not enable the flexibility of access that other types of pallet rack achieve. It requires a more skilled forklift driver to do the storage and retrieval operation for its difference to navigate within the lane which makes more labor cost [12]. This storage mode is also suitable to the high throughput items.

3. Mathematical modeling of space requirement

In this section, it develops the mathematical models to estimate the minimum space requirements of gravity racks, drive-in racks and single-deep racks.

The notations are as follows.

- \( n \): The number of SKUs.
- \( l \): The constant aisle width with the number of pallet width.
- \( s_s \): The safety stock level of SKU.
- \( c_s \): The cycle stock level of SKU.
- \( G_m \): The minimum space requirement of gravity racks.
- \( D_m \): The minimum space requirement of drive-in racks.
- \( k_i (t) \): At time \( t \), the number of pallets that SKU holding.
- \( a_i \): The inventory starting point of each year.
- \( b_i \): The replenishment batch size for SKU.
- \( D_i \): The demand of SKU experiences per day.
- \( o_i \): The total number of SKU orders per year.
- \( a_s \): The average space for SKU needs under perfect synchronization.
- \( T S_1 \): The total space that SKUs need in the case with perfect synchronization when replenishment size is 1 pallet for single-deep racks.
- \( T S_2 \): The total space that SKUs requirement in the case that SKUs with the same order frequency and cycle stock under the best arrangement assumption.
At any given time, each lane in gravity flow rack can only hold one SKU and one SKU may occupy more than 1 lane. There is no share between different SKUs. Therefore, the unfilled lanes will exist always. In order to modeling the space requirement, it assumes that each SKU uses only one lane. It must satisfy the maximum SKU space requirement. Thus, the total space that gravity flow racks need is:

\[ G_m = n(2l + \max(cs_i + ss_i)) \]  

(1)

3.2 Minimum space requirement modeling of drive-in racks

The forklifts drive within the rack frame to access the interior loads and unload. It assumes each lane in drive-in rack only hold one SKU too. There is no aisle space needs for forklifts. In order to modeling the space requirement, it sets each SKU uses only one lane. So, the total space that drive-in racks need is:

\[ D_m = n \max(cs_i + ss_i) \]  

(2)

3.3 Minimum space requirement modeling of Single deep pallet racks

The space requirement has related to the size of replenishment. In order to modeling the minimum space requirement, it assumes that the replenishment operation is synchronized with the order picking process. In this way, the space utilization will be perfectly 100%. But in practice, this may hardly to realize.

3.3.1 The replenishment size is 1 pallet

Suppose \( SKU_i \) holds \((ss_i + cs_i)\) pallet locations initially. After 1 time period, that is \( \frac{1}{D} \) days, one location becomes empty, and \( SKU_i \) uses \((ss_i + cs_i) - 1\) locations. So in the \( j^{th} \) period, \( SKU_i \) uses \((cs_i + ss_i - (j - 1)) \left( \frac{1}{2}l + 1 \right) \frac{1}{D} \) pallet space. Then it gets the average space that \( SKU_i \) occupies by summing the pallet space that \( SKU_i \) needs through time periods and dividing it by time.

\[ a_{si} = (ss_i + \frac{1}{2}(cs_i + 1)) \left( \frac{1}{2}l + 1 \right) \]  

(3)

It assumes the replenishment is synchronized in 1 pallet, so sum equation (3) to obtain the total space requirement.

\[ TS_i = \left( \sum_{r=1}^{r} ss_i + \sum_{r=1}^{r} \frac{1}{2}(cs_i + 1) \right) \left( \frac{1}{2}l + 1 \right) \]  

(4)

3.3.2 The replenishment size is more than 1

It illustrates the space requirement of 2 SKUs with the same profile, that is the same cycle stock and safety stock and both replenishment period is 0.5 year. There has space sharing between them. The combined space requirement depends on the time arrangement of replenishment operation.

The Figure 3 to Figure 5 displays the inventory levels of three cases. In the figures, the \( X \) axis is the time of 1 year and the \( Y \) axis is the level of inventory. In addition, the red line represents the inventory of \( SKU_1 \), the blue curve represents the inventory of \( SKU_2 \) and the black one shows the combined inventory of 2 SKUs.

It sets the replenishment time of \( SKU_1 \) without changing and only varies the time of \( SKU_2 \). By combining the inventory, it can find the benefits of synchronization. For \( SKU_1 \), the replenishment time of is January and June. In Figure 3, the replenishment time for \( SKU_2 \) is March and September and the maximal combined inventory is 175 pallets.

![Fig. 3. Replenishment case 1](image-url)
In Figure 4, the replenishment of 2 SKUs is the same and it can get the worst synchronization condition. The maximal combined inventory is 200, which is biggest among all cases.

![Fig. 4. Replenishment case 2](image)

Figure 5 shows the situation that SKU \(_2\) is replenished in February and August.

![Fig. 5. Replenishment case 3](image)

As is shown in above figures, the managers of distribution center can develop the warehouse space utilization by arranging the replenishment time to maximize the sharing among all SKUs. It is difficult to calculate the space requirement of single-deep racks for the sharing. At the beginning of 1 year, SKU \(_i\) occupy \((ss_i + Di)\) pallets location. It uses a fluid model here. That is, it treats SKUs as a continuously divisible fluid. At time \(t = 0, 1, \ldots, 1\), SKU \(_i\) holds

\[
k_i(t) = (ss_i + cs_i) - \left(\left(t_o_i - a_o_i\right) - \left[t_o_i - a_o_i\right]\right)
\]

(5)

Because \(K_{ss}\) is a floor function, the problem is difficult to solve. For simplification, it tries to get the lower bound of space requirement under the best synchronization and with the same profile among SKUs. And the schedule of replenishment can be staggered so that the SKUs use the least amount of space [5].

Under synchronize replenishment assumption, let \(o_i = a\), \(b = b\), \(i = 1, \ldots, n\) \(\alpha_i = \frac{i - 1}{n - 1}\). Thus, the space requirement of all SKU is:

\[
TS_i = \left(\sum_{i=1}^{n} ss_i + \frac{1}{2} c(n + 1)\right)\left(\frac{1}{2} t + 1\right)
\]

(6)

4. Simulation modeling

Even though warehouses can serve quite different ends, most share the same pattern of material flow [13]. There are two core operations in distribution center, storage (includes retrieval) and picking [14]. The product takes place through the following physical processes in warehouse.

![Fig. 6. Physical processes in warehouse](image)
This paper develops the model to simulate the real operations in warehouse with forklifts to achieve the material handling inside. However, the operations in warehouse are complex and the simulation scale also has limitation.

It conducts a real case which has 40 SKUs in 4 classes, 432 storage locations. Each class has different SKU profile and primary inventory, which will be listed below.

Therefore, in order to guarantee the result meaningful, it needs to do some assumptions and simplification for simulation model to compare 3 rack systems under the same situation.

Initially generate the same amount of each SKU with the same storage allocation strategy.

- The same order frequency
- The same safety stock for each SKU
- The same handling ability and capacity and the speed of forklift
- The path distance all in the same proportion with reality
- The forklifts are always in good condition

SIMIO is a simulation modeling framework based on intelligent objects [15] [16]. Each of these objects represents a physical component in the real system. This warehouse resources considered includes palletizer, racks, forklifts, SKU, and others as listed in Table 1.

<table>
<thead>
<tr>
<th>Objects in real process</th>
<th>Objects in SIMIO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inbound Palletizer</td>
<td>Source</td>
</tr>
<tr>
<td>SKU maker</td>
<td>Server</td>
</tr>
<tr>
<td>Racks</td>
<td>Server</td>
</tr>
<tr>
<td>Storage location</td>
<td>Server</td>
</tr>
<tr>
<td>Outbound conveyor</td>
<td>Sink</td>
</tr>
<tr>
<td>Forklift inbound and outbound</td>
<td>Vehicle</td>
</tr>
<tr>
<td>Forklift route</td>
<td>Path</td>
</tr>
</tbody>
</table>

SIMIO supports 3D graphics and animation [17]. In fig 2, there is screenshot example for the single-deep racks model.

SIMIO framework is focus on object-based modeling. It also supports a seamless use of multiple modeling paradigms including event, process, object and agent-based modeling [8] [19] [20]. Firstly, it builds the rack system with blank racks in 4 groups. Secondly, it starts the initialization of storage allocation according to the stock original configuration from external data. And then, each SKU will on shelves automatically. After that, the orders will come into the system in normal distribution and processing event will check the replenishment point. If the current inventory less than the safety stock, the replenishment process starts until all orders out of system. The flow chart below presents the framework of simulation.
5. Experiments and analysis

The comparison of Single-deep racks and Gravity flow racks and Drive-in racks focus on the storage location’s utilization or space utilization and the travel distance of inbound and outbound handling operations. In order to present the performance difference of three type racks system, it builds the simulation model of systems under SIMIO. By tracking all SKUs inventory summation level changing and inbound and outbound forklifts travel distance, it can achieve the comparison of space utilization and travel distance of 3 systems.

It sets each order arrives random with an exponential time. The ride capacity of inbound forklift is 2 SKU one time and 1 SKU for outbound forklift. For the replenishment rule, it uses the (R, S) strategy which is checking the inventory continuously and replenishing just in time with the fixed maximum inventory level for each SKU. We used csv file to record the inventory of whole warehouse with time interval of 5 minutes. The working time is 24 hours every day. After running 1 week, it generated the result report automatically. It uses MATLAB to analyze the collection data and draw the inventory tracking curve as bellows. From the description in section 2, both Gravity flow racks and Drive-in racks can save travel because of the mechanical structure.

![Fig.8. Simulation flow chart](image)

![Fig.9. All SKUs inventory summation level tracking curve](image)

In figure 9, the X-axis represents the time and the interval time is 5 minutes. Y-axis is the inventory level. The blue curve is the inventory level of Single-deep racks. The red one is the Gravity racks and the other one belongs to the Drive-in racks. From the figure above, it shows how the inventory summation level changes from beginning to steady state.

The inventory level can be divided into 3 stages. In first stage, the inventory in warehouse is enough to satisfy the order demand. And 3 racks almost decrease with the same speed until reaching the replenishment point at 20h5min. It defines the first stage is the consumption stage. In second stage, the inventory level of each system begins to rise because of the replenishment operation. From the curve above, it can be seen the rising of inventory level with different speed. Obviously, the Gravity racks rises faster than the others and it reaches to the steady stage firstly. The inventory level of Drive-in racks and Single-deep racks run almost the same in this stage. It defines this stage is the replenishment stage. In the third stage, it has been found the 3 racks systems all become steady. And the level of inventory has a little difference with 3 systems. For the Single-deep rack is higher than the others. The Gravity rack is the lowest level. And the inventory level of Drive-in rack is between in Single-deep and Gravity rack. We define this stage is the steady state.

From the inventory level curves above, we found the Gravity rack reaches the steady state firstly mainly because the replenishment operation is faster than the others. Due to the gravity flow benefits and the loading and unloading operation simplicity, the Gravity rack has a little advantage than Single-deep rack and Drive-in rack in space requirement and responding speed under the same SKU profile design.

The simulation model can also record the throughput and travel distance of each forklift. Through the recording results, the travel distance benefits of each rack system will be showed as bellows.

![Fig.10. All SKUs inventory summation level tracking curve](image)

For Gravity racks, the travel saves in 2 ways. One is the automatic move by gravity in the direction from receiving to shipping. The other one is the reduction in size of facility. Drive-in racks save the travel mainly in the reduction of isles. However the handling operation of Drive-in forklifts takes more time than others for its mechanical structure which causes the higher utilization of forklifts. The travel saving can present in the result above. For Gravity flow racks, the outbound travel saves 25.2% with the Single-deep racks and the inbound travel saves 22.3%. The Drive-in racks save 13.3% in outbound process and 6.71% in inbound direction. The forklift utilization can also present the travel benefits of systems. The utilization of outbound forklift of Single-deep racks is 92.5% with idle time is 12.57 hours. The Gravity rack is 84.3% with idle time is 26.4 hours. And the Drive-in rack is 89.3% with idle time is 18 hours.
6. Conclusions

In this paper, the structured mathematical models are developed to estimate the lower bound in space requirements in single deep racks, gravity flow racks and drive-in racks system. For the selective racks system, it considers the space sharing among SKUS based on the product profiles. It conducts simulation models and compares three rack systems in space utilization and travel distance by tracking their storage and retrieval operation data. The changing of inventory summation level can be divided into 3 stages and the results show gravity flow racks system reached steady state faster than the others. Although the results indicates the Gravity flow racks has benefits in space utilization and travel, but the performance of storage and retrieval operation in fixed racks system are affected by routing plan, storage allocation and other storage strategies. The paper simplifies this problem with assumption and limitation of products mix and scale. The results indicate that our models provide some useful insights in selection of storage racks.

References