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Optimizing Replenishment Strategies For Fixed And Dynamic Bin Systems In Prime Locations In A Warehouse

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Abstract:
Efficient inventory replenishment is critical for ensuring smooth warehouse operations and meeting customer demand. This paper presents a logic flow for replenishment process from reserve to prime locations for both fixed and dynamic bin systems in prime location of the warehouse. It also compares the flow, highlights the advantages, and outlines the methods for upgrading from fixed to prime bin systems. Fixed bin systems are straightforward but struggle to handle fluctuating demand, while dynamic bin systems offer flexibility by adjusting storage allocation based on factors such as demand and available space. The study introduces key methods like criticality scoring and proximity-based bin selection to improve replenishment decision-making. It also addresses challenges such as demand variability, space constraints, and operational setbacks. The proposed logic aims to provide practical solutions for optimizing replenishment strategies in warehouses, enhancing overall efficiency and adaptability.

Keyword: *Inventory Management, Replenishment Strategies, Prime Location, Reserve Location, Warehouse Operations, Criticality Scoring, Proximity-Based Bin Selection, Storage Optimization.*

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I. Introduction

Efficient inventory management is critical for ensuring smooth warehouse operations, especially in today's fast-moving and competitive industries. Replenishment strategies play a key role in maintaining adequate stock levels, preventing delays, and optimizing space utilization. Fixed bin systems, commonly used in warehouses, assign specific storage locations for each product. While simple and easy to manage, these systems often struggle to adapt to fluctuating demand and dynamic operational needs.

This paper examines fixed bin and dynamic bin replenishment methods in warehouse. It suggests the logical progression for replenishment from reserve inventory to prime inventory, along with decision-making strategies during operational difficulties and product availability issues.

The research also investigates essential elements such as demand fluctuations, restocking frequency, category significance, and the ranking of storage areas. It presents useful tools like criticality scoring for items and proximity-based bin selection, highlighting the importance of modern warehouse management systems for immediate decision-making.

This paper presents a structured framework for implementing dynamic replenishment strategies to improve flexibility and efficiency, and it offers insights into optimizing warehouse operations by contrasting the benefits and drawbacks of fixed and dynamic systems.

II. Literature Review And Background

Efficient inventory management constitutes a fundamental element of contemporary warehouse operations, wherein replenishment strategies assume a critical function in preserving operational continuity, mitigating delays, and maximizing space utilization.

Within a warehouse, reserve locations serve as designated areas for the storage of substantial quantities of products in bulk, whereas prime locations consist of smaller, readily accessible zones situated in proximity to the picking and packing areas, designed for expedited order fulfilment. The process of replenishing stock from reserve to prime locations is imperative to guarantee that inventory remains consistently available in prime areas for swiftly moving orders. Given the spatial constraints of prime locations, it is necessary to conduct regular restocking from the reserve to prevent stock depletion. This methodology fosters operational efficiency by ensuring that prime locations are perpetually prepared for immediate utilization while employing reserve locations for the accommodation of excess inventory. It further enables the warehouse to handle sudden increases in demand and optimize the space for smooth and fast operations. In short, replenishment ensures that warehouses can meet customer needs without delays while managing space effectively.

Figure 1: Reserve location

Figure 2: Prime location

This study explores fixed bin and dynamic bin replenishment strategies in prime storage locations from reserve locations, addressing critical factors such as demand variability, replenishment frequency, and zone prioritization, all within the broader context of advanced warehouse management systems. The literature provides insights into these aspects and highlights the ongoing transition toward dynamic approaches for improved efficiency.

Fixed bin systems, characterized by pre-assigned storage locations, have been widely adopted for their simplicity and ease of implementation. However, studies have noted their rigidity and limited adaptability to fluctuating demands and dynamic operational requirements [1]. In contrast, dynamic bin systems allocate storage locations based on real-time data and operational priorities, offering superior flexibility and space utilization [2]. These systems are particularly effective in handling variable demand patterns and optimizing picking processes, although they require advanced WMS and higher initial investments [3]. The comparison between these systems highlights the trade-offs in cost, complexity, and scalability. Demand variability significantly impacts replenishment strategies, necessitating adaptive mechanisms to ensure inventory levels align with consumption patterns. Research has proposed predictive models leveraging historical demand data to mitigate stockouts and overstocking [4]. Additionally, the integration of safety stock calculations and reorder point formulas, as detailed in classical inventory management theories, remains central to replenishment decision-making [5]. This study builds on these principles to propose a logical flow for replenishment initiation and decision-making during operational setbacks. Proximity-based bin selection, rooted in minimizing travel distances for picking and replenishment, has been extensively discussed in the literature. Clustering algorithms and spatial proximity metrics have demonstrated effectiveness in reducing operational inefficiencies [6]. Furthermore, criticality scoring systems, incorporating demand criticality, replenishment frequency, and category priority, enable prioritization of high-impact products, aligning replenishment strategies with business goals [7]. This approach enhances the responsiveness of warehouse systems to real-time operational needs. The evolution of WMS has been integral to the implementation of dynamic bin systems. These systems integrate real-time data, predictive analytics, and automation to facilitate dynamic storage allocation and replenishment [8]. Studies have emphasized the role of IoT, RFID, and AI-driven algorithms in enhancing decision-making capabilities, thus transforming traditional warehousing practices [9]. However, the adoption of these technologies is contingent on cost considerations and the scalability of operations. This study synthesizes existing research on fixed and dynamic bin replenishment systems, emphasizing the importance of adaptability, data-driven decision-making, and efficient resource utilization. By addressing the limitations of fixed systems and leveraging advanced technologies, dynamic replenishment strategies hold promises for optimizing warehouse operations and meeting the demands of modern supply chains.

III. Methodology

Verification process for replenishment initiation in fixed bins.

Initial logic checks for replenishment of prime location from reserve location.

If

The quantity in prime Location ≤ reorder point quantity

$Q_1 \ldots\ldots + Q_i \leq ((Dn \times LT) + Ss) = RP$

$\left(\sum_1^i Q_i\right) = Q_b \leq RP$ ---------- (1)

1.Qi - This represents the quantity of a particular article stored in a bin. It's essentially the amount of that article you have in stock at a given location.
2. LT – Lead time for replenishment. [Typically, it will range between 1 to 3 days]
3. Q1, Q2, ..., Qi - These are individual quantities of the same article in different bins. The formula considers the cumulative quantity of the article in multiple bins (from Q1 to Qi) when determining if it meets the demand forecast.
4. ∑Qi = Qb: This is the summation symbol (∑) indicating that you should add up the current inventory in the bins (Q1, Q2, ..., Qi) to get the total quantity available for that specific article in prime location.
5. Dn - This represents the demand for the article within a particular time period. You've mentioned different scenarios:
- n = 1...31 - This implies daily demand. You are considering demand on a day-to-day basis for up to 31 days.
- n = 1...5 - This represents weekly demand. You're looking at demand for up to 5 weeks.
- n = 1...12 - This signifies monthly demand. You're considering demand over a span of up to 12 months.
6. Ss – Safety stock. This is considered in the reorder point calculation.
7. RP – Reorder point, the point at which the replenishment is triggered.
Then,
The quantity in reserve location needs to be replenished to the bins in the prime location.

Fixed bin replenishment logic: From reserve to prime location

The replenishment process for fixed bins, emphasizing how the indent creation occurs from one specific bin in the reserve location to the prime location:

In warehousing operations, certain articles or products are designated to be stored in specific bins within the prime location area. These bins have a predefined maximum capacity denoted as WM (Maximum quantity of an article that can be occupied in a bin).
- QA (Current available quantity): This represents the quantity of the article currently present in the designated bin within the prime location.
- QB (Remaining Quantity): This signifies the remaining space in the bin where more of the article can be stored. It is calculated as the difference between the maximum capacity WM and the current available quantity QA,
i.e., QBi = WMi – QAi ---------- (2)

The objective of replenishing goods in fixed bins is to ensure that these bins are consistently stocked to meet demand. The replenishment process follows these steps:
For the articles which satisfied the condition mentioned in formula 1.
we need to check whether we have enough quantity in the reserve location for replenishment.

we can calculate the total replenishment quantity QBrep by subtracting the current inventory in the prime locations (Qb) from the reorder point RP for the article with minimum replenishment quantity defined that avoids small replenishment requests.

$QB_{rep} = \max(RP - Q_b, Q_{b\ min})$

$QP_{rep} \geq QB_{rep}$ ---------- (3)

QP_{rep} (Total quantity available for replenishment): This is the total quantity of the article that is available in the reserve location.

$Q_{b\ min}$: minimum replenishment quantity that avoids small replenishment requests. The replenishment triggers only when the required quantity exceeds this threshold.

If the articles satisfy this second equation, then the article is qualified for replenishment and the next step is to choose the prime location.

Criteria for selecting prime locations for fixed bin replenishment

Determine the remaining quantity (QB_i) for each bin in the prime location, calculate the remaining space QB_i by subtracting the current available quantity QA_i from the maximum capacity WM_i.

$QB_i = WM_i - Q_b$ ---------- (4)

Where i = bin number

$QB_1 + QB_2 + \ldots\ldots\ldots.. QB_i = QB_{rem}$

QB_{rep} need to be replenished in the bins (prime location), the QB_{rem} is the space which need to be filled.
The bins having the least QB_i will be the first-choice bins for replenishment.
Prioritize bins such that $QB_1 \leq QB_2 \leq \ldots \leq QB_n$.

Criteria for selecting reserve locations for fixed bin replenishment

Suppose there are p different reserve locations, each containing the same article. Let QP_p represent the total quantity of the article in reserve locations p. To determine which reserve location to choose for creating an indent, we prioritize based on the quantity available. Specifically, we select the reserve location that has the least quantity when compared to other locations with the same article. (This is for apparel, footwear). When it comes to cosmetics, FMCG, medicine and other areas where we deal products with expiry dates the FIFO need to be followed, we need to give first preference to the reserve location based on the date of incoming and then the reserve quantity need to be considered for prioritization. So, first filter based on GRN date and then the reserve location having the minimum quantity need to be selected. And there are products which follow LIFO such as glass, ceramics etc. for these products we need to give first preference to the reserve location based on the date of incoming such as FIFO model and then the reserve quantity need to be considered for prioritization.

We need to consider the reserve location p_i where min (QP_p) for all p

This identifies the reserve location p_i with the minimum quantity (QP) of the article.

Indent Creation: Once we have identified the reserve location with the minimum quantity, we proceed to create an indent from that reserve location to the prime location.

Multiple reserve locations (p) are available, prioritize based on:

1. FIFO (First-In-First-Out)

Priority Reserve location p_i = min (GRN Date) and min (QP_p).

2. LIFO (Last-In-First-Out)

Priority Reserve location p_i = max (GRN Date) and min (QP_p).

3. Lowest Available Quantity for other items:

Priority Reserve location p_i = min (QP_p).

The, another scenario where the FIFO is considered, and if we have many reserve locations which has the same GRN date for the same article, then among the reserve locations having the same GRN date the lowest available quantity should be considered as the reserve location for replenishment.

Priority Reserve Location (general) =

{

min (GRN $Date_p$) and then min (QP_p) for FIFO/LIFO.

min (QP_p) if GRN date is same for all the locations (FIFO/LIFO).

min (QP_p) if non-FIFO/LIFO.

Where:

GRN $Date_p$: Goods Receipt Note Date for reserve location p.

QP_p: Total quantity of the article available in reserve location p.

p: Reserve location index (e.g., p_1, p_2, … p_n).

Replenishment indent creation process

When sufficient quantity is available in reserve location for replenishment

Initial Indent Calculation:

Determine the initial replenishment quantity (QI_i) required from the selected reserve location (p_i). This is calculated by subtracting the remaining space in the selected prime location (QR_i) from the minimum quantity available at the reserve location:

QI_i = min (QP_p) - QR_i ---------- (5)

Comparison with Next Prime Location:

If the calculated replenishment quantity (QI_i) is greater than or equal to the remaining space in the next prime location (QR_2), proceed to create a new indent for the next prime location.

If QI_1 is less than QR_2, it indicates that the current reserve location (p_i) is depleted, and the next reserve location (p_{i+1}) with the minimum quantity (min (QP_{pi+1}) is selected for replenishment.

Continuation of the Process:

The indent creation process continues iteratively, ensuring that available space in the prime location is filled systematically.

Reserve locations are selected in order of priority based on the minimum available quantity, and the process repeats until the prime location is fully replenished for that article or all reserve locations are exhausted.

This method ensures that reserve locations are prioritized based on available quantities, and indents are created in a structured manner to replenish prime locations efficiently.

When available quantity in reserve location for replenishment reaches zero

When the reserve location does not have enough quantity to fulfil the replenishment demand for a specific article, the following steps occur:

$QP_{rep} < QB_{rep}$ ---------- (6)
The system identifies the article as critical and triggers a red alert indicating the inability to meet demand.

Replenishment Indent to Inbound Staging Area: The system generates a replenishment indent for the inbound staging area, checking for the availability of the same article waiting for put-away.

If the article is found in the inbound staging area, the criticality of the situation is assessed. The system evaluates how soon the prime location will go out of stock after replenishment.

$T_{crit} = \frac{QB_r}{RP}$ ---------- (7)

T_{crit} = Time (in days, weeks, or months) until the prime location goes out of stock after replenishment.
QB_r = Quantity in the prime location after replenishment.

After calculating the T_{crit} for all the articles, the articles need to be sorted in ascending order based on the T_{crit} and the importance of put away needs to be given in the same order. If the article is unavailable in the inbound staging area, a notification is sent to the demand and supply team to alert them about the upcoming out-of-stock situation for the article.

Insufficient space in prime location for fixed bin replenishment

When the fixed bins in the prime location cannot accommodate the replenishment demand, the replenishment strategy needs to align with the demand cycle to maintain inventory levels for picking and dispatching.

Demand and replenishment cycle alignment: The replenishment cycle (C_{rep}) must match the demand cycle (D_n), which could vary:

- Daily Demand: n=1...31days.
- Weekly Demand: n=1...5 weeks.
- Monthly Demand: n=1...12 months.

Check if Demand Exceeds Fixed Bin Capacity:
$RP > QB_{rep}$ ---------- (8)
If the fixed bins cannot hold the demand capacity based on the replenishment cycle, then
Option 1: Adjust the replenishment frequency (F_{rep}) based on demand (D_n) and dispatch rate (R_{dis}):

$F_{rep} = \frac{R_P}{R_{dis}}$ ---------- (9)

Option 2: Increase the number of fixed bins for the article.
Trigger: Increase Fixed Bins for Article
Option 3: If neither replenishment cycle adjustment nor adding fixed bins is feasible:
Trigger: Reserve Picking for Article

Exception – when bins chosen for replenishment are blocked

The picking, inventory cycle count and replenishment should go hand in hand and it should not be a hierarchical process rather it should be a simultaneous process.

The system should create the indent for the bins (b) even if they have pick or inventory block. But it should not allow the system to account the items until the inventory or pick block or put-away block is removed. In this way the replenishment team can pick the items and keep it ready for replenishment from the reserve location, but will only be able to account the items once these blocks are removed.

Additional considerations and challenges in fixed bin replenishment

Demand Variability: The discussed method assumes demand forecasts (D_n) are accurate. Any significant deviation from forecasts could disrupt the methodology. Adaptive mechanisms or buffers might be necessary to overcome the disruption.

If the D_n is variable then in the case of fixed bins there is a major challenge to replenish the products as per the fluctuating demand. To overcome this issue, the demand variability of the article needs to be studied using past few days, few weeks, last year same time data and for the items with high inconsistency in demand reserve buffer bins in the prime location to accommodate sudden spikes in demand.

Replenishment cycle (Frep): Adjusting replenishment cycles based on dispatch rates (R_{dis}) works on paper, but the feasibility of frequent cycles needs evaluation for operational efficiency and cost. Man power utilization, resource allocation and availability are very important for defining replenishment cycles, and it also involves cost. So, before taking the decision of adjusting the replenishment cycles the cost benefit analysis (Perform an analysis to determine the trade-offs between operational cost and the benefits of meeting fluctuating demand) need to be done and then based on the analysis the decision need to be taken.
Finally, the integration with warehouse management systems is crucial for practical implementation.

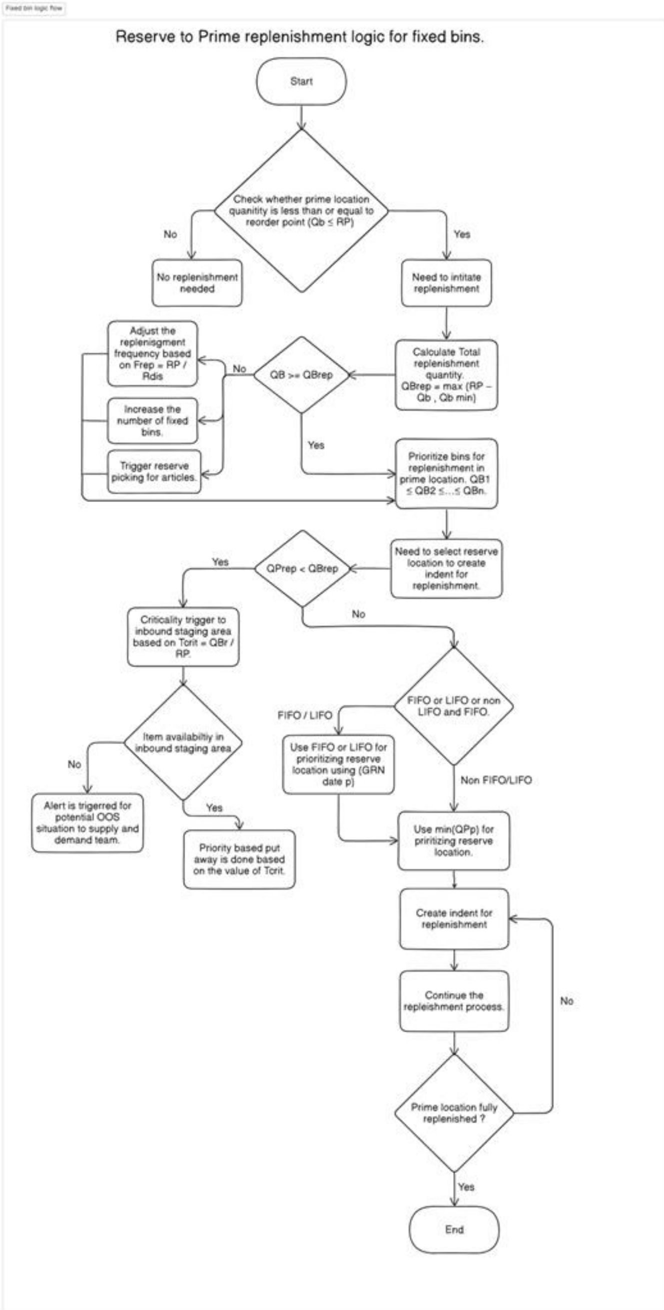

Figure 3: Reserve to prime replenishment logic for fixed bins

Dynamic bin replenishment Logic: From reserve to prime location

In a fixed bin system, articles are assigned to a predetermined number of bins, whereas dynamic bin replenishment involves dynamically allocating and reallocating bins based on factors such as demand, available space, and replenishment priorities. This approach optimizes storage allocation in warehouses by considering various aspects, including warehouse layout, the proximity of empty bins or bins already containing the same article requiring replenishment, demand patterns, resource availability, and capacity utilization. Before replenishing bins in prime locations from reserve storage, these factors are carefully evaluated to ensure efficiency.

The logic used to initiate replenishment in dynamic bin replenishment is the same as that used in fixed bin replenishment:

$Q_b \leq RP$ ---------- (1)

Where:

Q_b: Current quantity in prime location bins.

RP: Reorder point, calculated as $RP=(D_n \cdot LT) + S_s$ where D_n is demand and LT is lead time, and S_s is safety stock.

For the qualified products, the replenishment quantity is calculated using the formula:

QB_{rep} = max (RP – Q_b, $Q_{b\ min}$) ---------- (2)
Where:
QB_{rep}: Total replenishment quantity required.
$Q_{b\ min}$: Minimum replenishment quantity to avoid small replenishment requests.
This logic is identical to the one employed in fixed bin replenishment systems.

The next step in this process to identify the bins in the prime location for replenishment from the reserve location. In this case we don't have any fixed bins, here the bins are selected dynamically.

Most distribution centers and warehouses assign specific storage locations for item categories. Replenishment for a product prioritizes bins within the prime location assigned to its category.

Determining the relative criticality score of the product

The criticality of a product is calculated using 3 important factors which is demand criticality, replenishment frequency and category priority.

Pcrit (Criticality of a product) = (α × (Demand criticality)) + (β × (replenishment frequency)) + (γ × (Category priority)) ---------- (10)

α, β, and γ is the weighting factors based on operational focus.

α: Demand Criticality is given priority because it directly reflects customer requirements. Products with high demand variation are more likely to face stockouts, making them critical for replenishment.

Demand criticality:

Average daily demand of the product / Average daily demand of all the qualified products for replenishment.

Demand criticality: $\frac{D_d(P_i)}{D_d}$ ---------- (11)

Where:
D_d: Average daily demand of the product.
P_i: Product i considered for replenishment
P: All the products that is considered for replenishment.

Scaled demand criticality (SDC): $\frac{D_d}{Max(D_d)}$ ---------- (12)

Where:
Dd: Average daily demand of the product.
Max (Dd): Maximum daily demand of the product.

β: Replenishment Frequency accounts for operational constraints such as manpower and replenishment cycles. Higher frequency indicates better responsiveness but can strain resources. On a specific day what is the replenishment frequency. This number is will generally be 1 or 2 times based on the operational constraint.

Scaled replenishment frequency (SRF): $\frac{F_{rep}}{Max\ Cap\ F_{rep}}$ ---------- (13)

Where:
F_{rep}: Replenishment frequency number
Max Cap F_{rep}: Maximum replenishment frequency number when warehouse operating at maximum capacity.

γ: Category Priority (CP) reflects strategic importance, ensuring that business-critical or high-margin products receive attention. The priority number is defined for every product by the category team. It ranges from 0 to 100.

Scaled category priority (CP): $\frac{\text{Category Priority}}{100}$ ---------- (14)

The relative weight

Total Replenishment factor (TRF): SDC + SRF + SCP ---------- (15)

Demand weight factor (α): $\frac{SDC}{TRF}$ ---------- (16)

Replenishment frequency factor (β): $\frac{SRF}{TRF}$ ---------- (17)

Category priority factor (γ): $\frac{SCP}{TRF}$ ---------- (18)

α, β, and γ is scaled using TRF so that the sum of α, β, and γ need to be 1.

After calculating the $Pcrit_p$ for each product, we need to calculate the relative criticality score $Crit_r$ by considering the cumulative Pcrit of all the products which is qualified for replenishments.

$Crit_r = \frac{Pcrit_P}{\sum_{i=1}^{n} Pcrit_i}$ ---------- (19)

Where:
$Crit_r$: Relative criticality score of the product
$Pcrit_P$: Criticality of the product
n = Total number of products in the queue for replenishment.

Categorizing prime location zones based on Pcrit value

Based on the Pcrit value the product need to be assigned to priority segments.

The category zones need to be divided into 3:

- Front Zone (ZF): Closest to the outbound staging area; highest priority.
- Middle Zone (ZM): Moderately accessible; medium priority.
- Back Zone (ZB): Farthest from the outbound staging area; lowest priority.

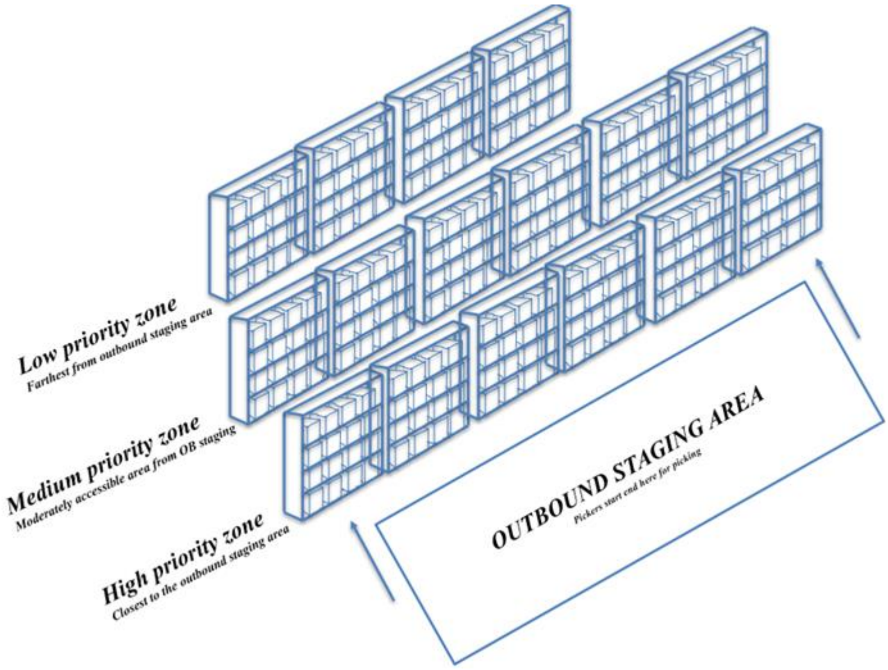

Figure 4: Priority based picking zone

The bins also need to be mapped to these zones, which will allow the system to select the bins based on the priority.

If the Pcrit value is greater than 1 standard deviation of the mean of Pcrit values of all the products in the category then it comes under highest priority.

If the Pcrit value is between mean of Pcrit value and 1 standard deviation of the mean of Pcrit values of all the products in the warehouse then it comes under medium priority.

If the Pcrit value is less than the mean of Pcrit values of all the products in the category then it comes under lowest priority.

The 1 standard deviation considered here, can also be 1.5 or 2 or n …… based on the industry requirements.

So based on the Pcrit value the bins which are mapped to the concerned priority zones will get assigned to this product.

Selection of bins in prime location for replenishment based on priority zones

If the criticality of the product has not changed and if the item is currently placed in the right picking zone as per the criticality, then we need to allocate bins already having the product and then if needed empty bins which is near the existing bins with the product are selected and replenished to minimize picking time. Based on the warehouse layout it can differ, but most of the warehouses have rack bin system.

Scenario 1: If the product's priority zone changes based on its Pcrit value, check for bins in the newly assigned zone that already contain the product selected for replenishment.

Scenario 2: If the product's priority zone remains unchanged, verify if there are bins in the current assigned zone that already contain the product chosen for replenishment.

In both scenarios calculate remaining quantity (QB_i) in each bin within the respective zone where the product is stocked, this is done by subtracting the current available quantity QA_i from the maximum capacity WM_i.

$QB_i = WM_i – Q_b$ ---------- (4)

Where i = bin number

$QB_1 + QB_2 + \ldots\ldots\ldots.. QB_i = QB_{rem}$

QB_{rep} need to be replenished in the bins (prime location), the QB_{rem} is the space which need to be filled.

The bins having the least QB_i will be the first-choice bins for replenishment.
Prioritize bins such that $QB_1 \leq QB_1 \ldots \leq QB_n$

Calculation of empty bins allocated to a product based on $Crit_r$

If $QB_{rep} > QB_{rem}$

Number of empty bins required (EB_i) = $\frac{QB_{rep} - QB_{rem}}{WM\ of\ the\ product}$ ---------- (20)

WM – total units of the product that the bin can hold.

This is the base requirement for empty bins (EB_i)

When dynamically replenishing bins, it's essential to impose a cap on the number of empty bins allocated for a single product. This ensures efficient use of space, accounts for operational constraints, and accommodates other products in the queue for replenishment. The cap should consider critical factors like product criticality, replenishment frequency, manpower availability, and resource constraints. So, few constraints are considered to this base value of empty bins (EB_i) to give an allocation of empty bins to all the products waiting in the queue that need to be replenished.

We should then use $Crit_r$ to allocate the empty bins in the prime location by multiplying the $Crit_r$ value of the product with total number of empty bins available.

$EBin_a = (EB_i) \times Crit_r$ ---------- (21)

Where:

$EBin_a$ = Empty bins assigned

If $EB_i \leq EBin_a$, then we can proceed to next step, but if the actual need for empty bins is greater than empty bins assigned ($EB_i > EBin_a$) then we need to collate the products satisfying this condition and sort them based on the value of $Crit_r$.

A trigger should be sent to the inventory team which will have the product, empty bins needed and its $Crit_r$ value information.

Based upon this information, inventory team should act upon and provide the confirmation to proceed with replenishment indent creation process.

Scenario 1: Inventory team can confirm to proceed with replenishment indent with the available empty bins and provide the ETA for the confirmation for the remaining empty bins.

Scenario 2: Inventory team will not provide confirmation for the replenishment indent creation until all the required empty bins are listed in the system for the product.

So, the products satisfying the condition check $EB_i \leq EBin_a$, only upon the confirmation from inventory team, it goes to the next step.

Selection of empty bins in prime location for replenishment in priority zones

We need to select the empty bins based on the criticality of the product, if Pcrit value is greater than 1 standard deviation of the mean of Pcrit values of all the products in the category then it comes under highest priority then allocate bins in Front Zone (ZF).

If the Pcrit value is between mean of Pcrit value and 1 standard deviation of the mean of Pcrit values of all the products in the warehouse then it comes under medium priority, then allocate it to Middle Zone (ZM).

If the Pcrit value is less than the mean of Pcrit values of all the products in the category then it comes under lowest priority, then allocate it to Back Zone (ZB).

The 1 standard deviation considered here, can also be 1.5 or 2 or n …… based on the industry requirements.

So based on the Pcrit value the bins which are mapped to the concerned priority zones will get assigned to this product.

Scenario 1: If the product's priority zone changes based on its Pcrit value, check for bins in the newly assigned zone that already contain the product selected for replenishment.

Scenario 2: If the product's priority zone remains unchanged, verify if there are bins in the current assigned zone that already contain the product chosen for replenishment.

In both scenarios locate the empty bins near to the bins with the product i. First, we need to check the same shelf. If unavailable, check the same rack. If unavailable move to opposite racks, same aisle, adjacent aisles, and so on. In a rack-bin system, select bins closest to the existing cluster of bins containing the article. Nearest bins are prioritized based on their spatial relation to occupied bins.

Steps to identify the Cluster of Bins with the Item:

- Identify all bins already containing the item, b_i, and their positions in the warehouse layout (e.g., rack, aisle, shelf).
- Represent these bins as a cluster C: {b1, b2, ………...bi}

And each location b_i has a location coordinate (x_i, y_i, z_i)

- Identify all the empty bins in the defined category zone of the article bej
- For each empty bin bej , calculate the distance to the cluster C. Use the minimum distance to any bin in the cluster as the proximity metric:

$D_j = \min \{\text{Distance } (be_j, b_i) \mid b_i \in C\}$ ---------- (22)

Distance between the bins in cluster and the empty bins can be calculated using a Euclidean distance,

$D_{ij} = \sqrt{(x_j - x_i) + (y_j - y_i) + (z_j - z_i)}$ or ---------- (23)

or Manhattan distance.

$D_{ij} = |x_j - x_i| + |y_j - y_i| + |z_j - z_i|$ ---------- (24)

After calculating the distance from the cluster C to every identified empty bin, we need to prioritize the selection of the bins. Sort the empty bins be_j by their proximity D_j to the cluster C.

$be_1 \leq be_2 \leq be_3 \ldots\ldots\ldots$ bej

Select the empty bin be_j with the smallest D_j for replenishment.

Create replenishment indent for the selected empty bin be_j and update the cluster C to include it:

$C \longleftarrow C \cup \{be_j\}$---------- (25)

After adding a bin to the cluster, recalculate the proximity to the remaining empty bins. This iterative approach ensures that bins are selected based on their closeness to the updated cluster, reducing picking time by keeping the same product stocked near each other.

If there are no existing bins in the current or previously assigned priority zones, directly reference the $EBin_a$ value to determine the number of bins required. Allocate these bins for replenishment using the proximity method, prioritizing the closest available bins to optimize efficiency.

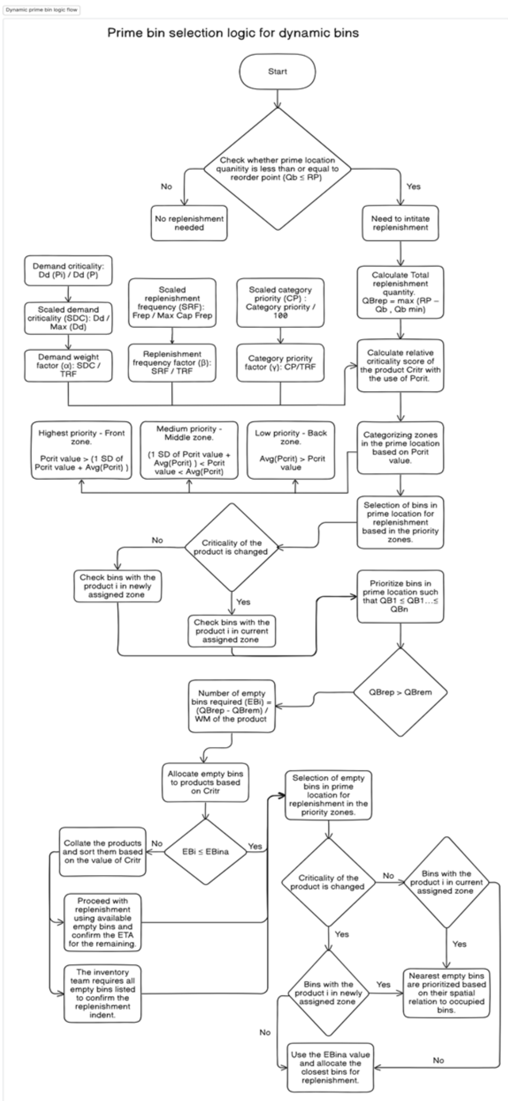

Figure 5: Prime bin selection logic for dynamic bins

Choosing the reserve location for dynamic bin replenishment

1.Multiple Reserve Locations: Suppose there are p different reserve locations, each containing the same article. Let QP_p represent the total quantity of the article in reserve locations p.

2.Priority Based on Quantity: To determine which reserve location to choose for creating an indent, we prioritize based on the quantity available. Specifically, we select the reserve location that has the least quantity when compared to other locations with the same article. (This is for apparel, footwear). When it comes to cosmetics, FMCG, medicine and other areas where we deal products with expiry dates the FIFO need to be followed, we need to give first preference to the reserve location based on the date of incoming and then the reserve quantity need to be considered for prioritization. So, first filter based on GRN date and then the reserve location having the minimum quantity need to be selected. And there are products which follow LIFO such as glass, ceramics etc. for these products we need to give first preference to the reserve location based on the date of incoming such as FIFO model and then the reserve quantity need to be considered for prioritization.

We need to consider the reserve location p_i where min (QP_p) for all p

This identifies the reserve location p_i with the minimum quantity (QP) of the article.

Indent Creation: Once we've identified the reserve location with the minimum quantity, we proceed to create an indent from that reserve location to the prime location.

Multiple reserve locations (p_n) are available, prioritize based on:

- FIFO (First-In-First-Out)

Priority Reserve location p_i = min (GRN Date) and min (QP_p).

- LIFO (Last-In-First-Out)

Priority Reserve location p_i = max (GRN Date) and min (QP_p).

- Lowest Available Quantity for other items:

Priority Reserve location p_i = min (QP_p).

The, another scenario where the FIFO is considered, and if we have many reserve locations which has the same GRN date for the same article, then among the reserve locations having the same GRN date the lowest available quantity should be considered as the reserve location for replenishment.

Priority Reserve Location (general) =

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min (GRN $Date_p$) and then min (QP_p) for FIFO/LIFO.

min (QP_p) if GRN date is same for all the locations (FIFO/LIFO).

min (QP_p) if non-FIFO/LIFO.

Where:

GRN $Date_p$: Goods Receipt Note Date for reserve location p.

QP_p: Total quantity of the article available in reserve location p.

p: Reserve location index (e.g., p_1, p_2, … p_n).

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When sufficient quantity is available in reserve location for replenishment

Initial Indent Calculation:

Determine the initial replenishment quantity (QI_i) required from the selected reserve location (p_i). This is calculated by subtracting the remaining space in the selected prime location (QR_i) from the minimum quantity available at the reserve location:

QI_i = min (QP_p) - QR_i ----------

Comparison with Next Prime Location:

If the calculated replenishment quantity (QI_i) is greater than or equal to the remaining space in the next prime location (QR_2), proceed to create a new indent for the next prime location.

If QI_1 is less than QR_2, it indicates that the current reserve location (p_i) is depleted, and the next reserve location (p_{i+1}) with the minimum quantity (min (QP_{pi+1}) is selected for replenishment.

Continuation of the Process:

The indent creation process continues iteratively, ensuring that available space in the prime location is filled systematically.

Reserve locations are selected in order of priority based on the minimum available quantity, and the process repeats until the prime location is fully replenished for that article or all reserve locations are exhausted.

This method ensures that reserve locations are prioritized based on available quantities, and indents are created in a structured manner to replenish prime locations efficiently.

When available quantity in reserve location for replenishment reaches zero

When the reserve location does not have enough quantity to fulfil the replenishment demand for a specific article, the following steps occur:

$QP_{rep} < QB_{rep}$ --------- (6)

The system identifies the article as critical and triggers a red alert indicating the inability to meet demand.

Replenishment Indent to Inbound Staging Area: The system generates a replenishment indent for the inbound staging area, checking for the availability of the same article waiting for put-away. If the article is found in the inbound staging area, the criticality of the situation is assessed. The system evaluates how soon the prime location will go out of stock after replenishment.

$T_{crit} = \frac{QB_r}{RP}$ ---------- (7)

T_{crit} = Time (in days, weeks, or months) until the prime location goes out of stock after replenishment.

QB_r = Quantity in the prime location after replenishment.

After calculating the T_{crit} for all the articles, the articles need to be sorted in ascending order based on the T_{crit} and the importance of put away needs to be given in the same order. If the article is unavailable in the inbound staging area, a notification is sent to the demand and supply team to alert them about the upcoming out-of-stock situation for the article.

Difference between prime location fixed bin and dynamic bin strategy

Fixed bin and dynamic bin systems differ significantly in their structure, functionality, and adaptability, making each suitable for different operational needs. Fixed bin systems assign specific, predefined locations for items, offering simplicity and ease of implementation. This makes them ideal for warehouses with stable and predictable demand. However, their rigid nature limits flexibility and adaptability. If demand fluctuates or inventory levels change significantly, fixed bins may lead to inefficiencies. These systems are cost-effective and straightforward, requiring minimal investment in technology and resources, making them appealing for smaller or less dynamic operations.

On the other hand, dynamic bin systems are highly flexible and designed to adapt to real-time needs. Instead of being restricted to fixed locations, items are stored based on current demand, available space, and operational priorities. This flexibility allows dynamic bins to handle fluctuating demand patterns effectively, ensuring optimal space utilization. By dynamically assigning storage locations, these systems reduce travel time for picking, improving operational efficiency. However, implementing a dynamic bin system is more complex and requires advanced warehouse management software for real-time data integration and decision-making. The setup and maintenance costs are higher, as it involves sophisticated algorithms and additional training for staff.

Fixed bin systems are simpler and less resource-intensive, with lower implementation costs. However, they may struggle to meet the demands of fast-changing environments or situations where space and resources need to be optimized dynamically. Dynamic bin systems, while requiring greater investment, offer significant advantages in scalability and efficiency. They excel in environments with high variability, allowing warehouses to respond quickly to changing inventory profiles or sudden demand spikes.

The choice between fixed and dynamic bin systems depends on the specific requirements of the operation. Fixed bins work best for stable demand scenarios where simplicity and predictability are priorities. Dynamic bins, however, are better suited for complex, high-variability environments where adaptability and efficiency are critical. A hybrid approach combining the stability of fixed bins with the adaptability of dynamic bins can often provide the best of both worlds, ensuring that warehouses operate efficiently while meeting diverse demands. Ultimately, the decision should be guided by the scale, demand variability, and available resources.

Upgrading fixed bins to dynamic bins strategy

Upgrading a fixed bin system to a dynamic bin system can significantly improve warehouse efficiency and flexibility. The transition requires careful planning, new technologies, and redesigned workflows. The first step is to assess the current warehouse setup. This involves understanding storage needs, analyzing inventory patterns, and identifying inefficiencies in the fixed bin system. Common issues like underutilized space, difficulty in managing fluctuating demand, or inefficient picking processes should be noted. This assessment will form the foundation for designing the dynamic system.

Next, upgrading the technology infrastructure is crucial. A robust warehouse management system is essential for enabling real-time tracking and dynamic bin allocation. The WMS should be capable of integrating with other systems such as inventory management and demand forecasting tools. Additional technologies, such as barcode scanners, RFID tags, and IoT devices, can enhance visibility and accuracy by providing real-time data on inventory levels and bin utilization. These tools ensure the system has the information needed to allocate bins dynamically.

Once the technology is in place, the next step is to create a dynamic allocation strategy. This involves setting rules for assigning bins based on factors such as demand patterns, product turnover rates, and proximity to picking areas. For instance, high-demand or fast-moving items should be placed closer to the picking zones to reduce travel time, while less critical items can be stored farther away. Space utilization is another important consideration; bins should be allocated in a way that minimizes empty or underused space while leaving some flexibility for future adjustments.

The warehouse layout must also be restructured to support the dynamic bin system. Divide the warehouse into zones based on product priorities, such as high-priority zones for frequently picked items and lower-priority zones for slower-moving inventory. Group similar or frequently picked items together to create clusters that reduce travel time during picking operations. Additionally, leave some bins unassigned to allow for flexibility in real-time adjustments.

Staff training is a key part of the transition. Employees must be educated on the new dynamic system and trained to use updated tools and technologies, including the WMS. Simulating real-world scenarios can help teams familiarize themselves with the new workflows and identify any potential challenges before full implementation.

The transition should be gradual, starting with a small section of the warehouse. This allows for testing the system, gathering feedback, and refining the processes before expanding to the entire operation. Monitoring performance during this phase is critical. Key metrics such as picking time, space utilization, and replenishment accuracy should be tracked to measure the effectiveness of the system. Use the feedback to optimize the allocation rules and improve the WMS algorithms.

Finally, the system should be continuously monitored and optimized. Regularly review operational data to identify areas for improvement. Update algorithms and allocation rules to adapt to changing inventory profiles or demand patterns. By following these steps, a fixed bin system can be successfully upgraded to a dynamic bin system, improving flexibility, space utilization, and overall efficiency.

IV. Conclusion

This study highlights the critical role of efficient replenishment strategies in optimizing warehouse operations. By comparing fixed and dynamic bin systems, it becomes evident that dynamic strategies provide superior flexibility and adaptability to fluctuating demand and operational priorities. The proposed frameworks for replenishment initiation, bin allocation, and reserve location prioritization offer actionable insights to enhance inventory management efficiency. Dynamic bin systems leverage advanced technologies such as WMS, IoT, and data-driven decision-making to address the limitations of fixed systems, enabling real-time adaptability and improved space utilization. While implementing such systems requires higher initial investments and training, their long-term benefits in scalability and operational efficiency outweigh these challenges. The research emphasizes the importance of criticality scoring, proximity-based bin selection, and adaptive mechanisms to accommodate demand variability and resource constraints. Additionally, integrating predictive analytics and continuous system optimization can further enhance the efficacy of these strategies, ensuring warehouses remain agile and responsive in a competitive landscape. Future work could explore the integration of machine learning algorithms for demand forecasting and replenishment decision-making, as well as the application of dynamic bin strategies across diverse industries with varying storage needs. By combining technological advancements with structured methodologies, warehouses can achieve unprecedented levels of efficiency, meeting the demands of modern supply chains.

V. Limitations And Future Research Directions

Although inventory replenishment strategies have advanced significantly, challenges still remain. One major limitation is the reliance on accurate and timely data. If data is incomplete or delayed, replenishment decisions can be disrupted, resulting in either too little or too much inventory. Dynamic systems, while offering better efficiency, require sophisticated software and significant computing resources to make decisions in real time. For smaller businesses, these requirements may be too expensive or difficult to implement.

Another challenge is effectively predicting future demand. While some systems use historical data to improve replenishment accuracy, unexpected changes in demand or supply chain delays can still cause problems. Additionally, there is limited integration of pricing strategies with inventory replenishment. Aligning pricing with inventory levels could improve decision-making, but this is not yet common practice.

Future research can focus on making dynamic systems simpler and more affordable so that smaller businesses can adopt them. Machine learning and AI could improve demand forecasting and help make smarter replenishment decisions in real time. Combining these technologies with "digital twins -virtual models of warehouse operations can allow businesses to test replenishment strategies without disrupting their actual operations.

Another idea is to develop hybrid systems that combine the simplicity of fixed bins with the flexibility of dynamic bins. These systems could provide a balanced approach, suitable for warehouses with different needs. Sustainability should also be considered in future designs, such as reducing waste and energy use during replenishment activities.

Finally, dynamic systems need to scale better for larger supply chains. Using cloud-based technologies and distributed computing could make these systems easier to expand and manage. Future studies could also design industry-specific replenishment systems tailored to the needs of sectors like healthcare, e-commerce, and manufacturing. By addressing these challenges, future developments in inventory replenishment can make systems more flexible, cost-effective, and capable of meeting the changing demands of modern supply chains.

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