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Pallet-Layer Batching to Reduce Changeover Losses on a High-Mix Polyvinyl Chloride Fittings Packing Line: A Replenishment-Band Rule and Simulation Study

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Abstract

In polyvinyl chloride (PVC) pipe-fittings manufacturing, and similar high-mix, make-to-stock industries, packing lines often run under minimum–maximum (min–max) control. The production batch of each stock-keeping unit (SKU) is set implicitly by the difference between its maximum level and its reorder point. Set without reference to the unit load, these replenishment bands are often a fraction of a pallet, which multiplies changeovers. This study formalizes a pallet-layer batching (PLB) rule that rounds each band to a whole-layer unit load under a changeover-frequency ceiling (τ) and re-sets the control levels under a safety-stock retention floor (φ). Master data for the 304 SKUs of a packing line in a PVC pipe-fittings plant with more than 6,000 SKUs were evaluated by finite-capacity Monte Carlo simulation against the existing levels, manual layer rounding, the economic order quantity, a monthly fixed cycle and a cost-optimal menu selection. The existing levels committed 70% of scheduled time to changeovers. PLB (τ = 1.5, φ = 0.7) reduced changeover time to 55 h per month (12.8% of scheduled time), 63% below manual layer rounding, with a 100% fill rate, 2.1% more inventory and a total changeover and holding cost within 1.5% of the cost-optimal policy, without requiring cost data.

Keywords: *Changeover, Lot Sizing, Monte Carlo Simulation, Overall Equipment Effectiveness, Polyvinyl Chloride Pipe Fittings.*

INTRODUCTION

Background

In polyvinyl chloride (PVC) pipe-fittings manufacturing, product variety is high: the plant studied here carries more than 6,000 stock-keeping units (SKUs), 304 of which are packed on a single line. Overall equipment effectiveness (OEE) expresses the productive share of the scheduled time of a line as the product of availability, performance and quality factors [1,2]. On lines that switch frequently between products, changeovers are usually the largest availability loss, and a residual loss per changeover remains even after set-up reduction programs based on the single-minute exchange of die (SMED) method [3–6]. Once changeover duration has been reduced, the number of changeovers becomes the next variable to address, and that number is governed by the batch size.

On make-to-stock packing lines, batch size is seldom planned as such; it follows from the replenishment parameters stored in the enterprise resource planning (ERP) system. Under minimum–maximum (min-max) control, a production order is released when the inventory position of a SKU falls to its reorder point, and the quantity ordered restores the inventory position to the maximum level. The smallest order this logic can generate is therefore the difference between the two levels, referred to here as the replenishment band, which is in effect the minimum batch the system releases. These levels are typically set from coverage and service considerations, without reference to the unit load, that is, the carton, layer or pallet in which the product leaves the line.

The mismatch has two consequences. When the band is smaller than a pallet layer, each order requires a changeover for a fraction of a pallet, which raises the number of changeovers and leaves partial pallets in the warehouse. The band also determines the cycle stock: widening it to a unit load raises inventory unless the trigger levels, the reorder point and the safety stock, are lowered at the same time. Planners often resolve this tension informally by rounding order quantities up and overriding the system values, which separates the executed plan from the documented control logic.

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Related Work

Lot sizing with set-up costs or times has an extensive literature: Copil et al. [7,8]. Minimum order quantities and batch multiples appear as supplier-imposed constraints in joint replenishment [9], as full-batch replenishment in lot sizing with batch ordering [10], and in the (r, nQ, T) periodic-review policy, in which orders are integer multiples of a base batch [11]. Pallet geometry is addressed by the pallet-loading problem [12,13], and palletized transport costs have been embedded in stochastic inventory models as stepwise cost functions [14]. In these studies, the unit load is a cost step or a packing problem; its link to the min-max parameters that drive replenishment on a capacity-constrained line has not been examined, and the OEE literature treats the number of changeovers as an input [1,4].

Periodic-review (R, s, S) and order-up-to policies[15-17], safety-stock determination [18], rolling-horizon re-planning [19,20] and sales and operations planning [21,22] address how control parameters are set and revised. Product variety has been associated with poorer cost, lead-time and inventory performance [23–26]. Discrete-event simulation is commonly used to evaluate such policies on an existing line: Loacker et al. [27] reported that halving a minimum order quantity at a food manufacturer increased set-up time by 31%, and line-level digital twins increasingly incorporate such models [28]. Total productive maintenance addresses the equipment-related component of availability [29].

A rule is therefore required that rounds the replenishment band of each SKU to a whole-layer unit load, allocates the band increase between the trigger levels and the maximum level, and is evaluated under finite capacity.

Contribution

This paper formalizes such a rule, termed pallet-layer batching (PLB), from a manual reparameterizationexercise on the packing line of a PVC pipe-fittings plant, and evaluates it by finite-capacity MonteCarlo simulation on master data for the 304 SKUs packed on that line. Four questions are addressed: the reduction in changeover time; the inventory cost of the rule and the share recovered by the allocation step; the sensitivity of the results; and the position of the rule relative to established lot-sizing policies on a common cost basis.

MATERIALS AND METHODS

Line and SKU Portfolio

The study line packs small molded PVC pipe fittings into retail cartons, which are stacked on pallets in a fixed pattern for each carton class. Master data were extracted for all active SKUs on the line (304 SKUs in seven carton classes), identified as SKU-001 to SKU-304 and classes A to G (Table 1). Each carton class fixes the pieces per carton (5–200), cartons per layer (6–54) and layers per pallet (6–8), so the pieces per layer and per pallet are known integers for every SKU. For each SKU the existing levels (safety stock, SS; reorder point, ROP; maximum level, Max), the average monthly demand in a low and a high season, and the unit cost ($0.1–1.8 per piece) were available. SKUs with a demand record for only one season were treated as non-seasonal.

The existing band, the difference between the maximum level and the reorder point, has a median of 0.09 pallet (interquartile range 0.04–0.40) and is a whole number of layers for only 5.9% of SKUs (Fig. 2a). The line operates three 8-h shifts on five days per week; a planned availability factor of 0.85 for breaks, preventive maintenance and minor stops gives 1,224 min of scheduled time per day and 428 h per 21-day month. A changeover takes 15 min in the base case (10–30 min in the sensitivity analysis). The nominal packing rate depends on the carton class (Table 1). At these rates the run time required by demand is 55 h in a low-season month and 90 h in a high-season month, 13–21% of the scheduled time.

Table 1. SKU portfolio and line parameters used in the simulation (master data of the studied line).

Item	Value
Plant portfolio / active SKUs on studied line / carton classes	more than 6,000 / 304 / 7
Pieces per carton	5–200 (median 25)
Cartons per layer; layers per pallet	6–54; 6–8
Pieces per pallet	420–43,200 (median 4,320)
Monthly demand per SKU, low / high season (pieces)	42–154,642 / 42–211,234
Total line demand, low / high season	1.44 M pieces (35.2 k cartons) / 2.47 M pieces (58.7 k cartons)
Existing band b = Max − ROP (pallet fraction)	median 0.09, IQR 0.04–0.40; whole layers for 5.9% of SKUs
Unit cost ($ per piece)	0.1–1.8 (mean 0.36)
Shift pattern; planned availability	3 × 8 h, 5 days/week; 0.85 (1,224 min/day, 428 h/month)
Changeover duration (base; range)	15 min (10–30 min), sequence-independent
Nominal packing rate by carton class (cartons/min)	A 15; B, C, G 12; E, F 10; D 8 (sensitivity: 0.5–1.0 × nominal)
Daily demand model	Negative binomial, mean D/21, dispersion k = 2 (1–4); high season April–September
Horizon; warm-up; replications	15 months of 21 working days; 3 months; 20 (10 for sensitivity), common random numbers

The Pallet-Layer Batching Rule

Figure 1 summarizes the rule, which consists of five one-time steps applied to each SKU and one daily operating step. All quantities are expressed in pieces, and $\lceil x \rceil$ denotes rounding x up to the next integer.

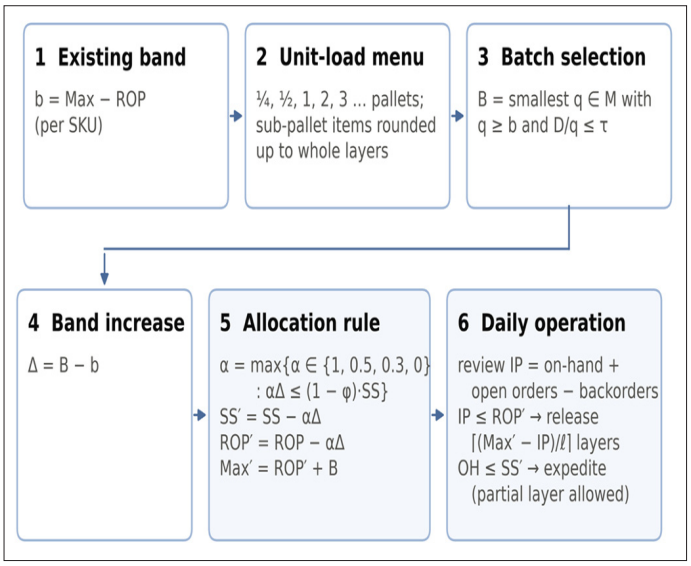


Fig. 1. The pallet-layer batching (PLB) rule. Steps 1–5 constitute a one-time reparameterizationof each SKU; Step 6 is the daily min–max review with layer-rounded order quantities and the safety-stock exception.

Step 1 (existing band). The existing band is

b = Max − ROP,

where b is the existing band (pieces), Max is the existing maximum level (pieces) and ROP is the existing reorder point (pieces).

Step 2 (unit-load menu). The admissible batches form the unit-load menu

$$M = q(¼), q(½), q(1), q(2), \ldots,$$

where f is the pallet fraction (pallets), $q(f) = \lceil fL \rceil \ell$ is the corresponding batch in pieces rounded up to whole layers, L is the number of layers per pallet and ℓ the number of pieces per layer. A quarter pallet is the smallest standard unit load; single layers are permitted only under the exception in Step 6.

Step 3 (batch selection). The new batch (B) is the smallest menu item that covers the existing band under a changeover-frequency ceiling τ:

$$B = min q \in M: q \geq b and D/q \leq \tau,$$

where q is any batch in the menu M (pieces), D is the mean monthly demand of the SKU (pieces per month), D/q is the expected number of changeovers if the SKU is produced in batches of q (changeovers per month), and τ is the changeover-frequency ceiling (changeovers per SKU per month). The first condition ensures that the new batch covers the existing band; the second prevents high-demand SKUs from being changed over more than τ times per month.

Step 4 (band increase). The band increase is

$\Delta = B – b,$

where Δ is the band increase (pieces); because $B \geq b$, Δ is never negative.

Step 5 (allocation). The band increase is absorbed partly by lowering the trigger levels and partly by raising the maximum level:

$$SS' = SS - \alpha\Delta, ROP' = ROP - \alpha\Delta, Max' = ROP' + B,$$

where SS is the existing safety stock (pieces); SS′, ROP′ and Max′ are the new safety stock, reorder point and maximum level (pieces); and α is the share of Δ taken from the trigger levels (dimensionless, $0 \leq \alpha \leq 1$): with α = 1 the maximum level is unchanged, and with α = 0 the trigger levels are unchanged. The share is chosen as

$$\alpha = max\alpha \in 1{,}0.5{,}0.3{,}0: \alpha\Delta \leq (1 - \varphi)SS,$$

where φ is the safety-stock retention floor (dimensionless, $0 \leq \varphi \leq 1$), the minimum fraction of SS that must be retained; αΔ is the reduction of the safety stock (pieces); and (1 − φ)SS is the largest reduction permitted (pieces). The expression selects the largest admissible share whose reduction does not exceed this limit; with φ = 0.7 the safety stock may be reduced by at most 30%. The four admissible values are the allocation patterns used by the planner. The gap ROP − SS, which covers demand during the production lead time, is unchanged, and all levels are rounded up to whole cartons.

Step 6 (daily operation). At the start of each working day the inventory position of every SKU is reviewed:

IP = OH + OO − BO,

where IP is the inventory position (pieces), OH the on-hand stock (pieces), OO the quantity in open production orders (pieces) and BO the backordered quantity, demand received but not yet supplied (pieces). When the inventory position IP falls to ROP′, an order of

$n = \lceil (Max' - IP)/\ell \rceil,$

layers is released, where n is the number of layers required to restore the inventory position to Max′; by construction, $n\ell \geq B$. An order is expedited when on-hand stock reaches SS′ (OH ≤ SS′), that is, moved to the front of the production sequence; if no order is open, an order of Max′ − IP rounded up to whole cartons is released and expedited, the only case in which a partial layer is produced. The remaining orders are sequenced by run-out time,

r = OH/d,

where r is the run-out time (working days), the number of days the on-hand stock would last, and d is the mean daily demand of the SKU (pieces per day).

Steps 1–5 are change only ERP parameters; Step 6 is the existing minimum–maximum logic of the ERP system with a layer-rounded order quantity and an expedite flag, so no

additional planning software is required. With τ = 1.5 and φ = 0.7 the rule reproduces the planner's manually chosen batches exactly for 50% of the 304 SKUs and within one menu step for 96%, and agrees with the planner on whether the trigger levels were lowered for 91%. The resulting batch distribution is shown in Fig. 2.

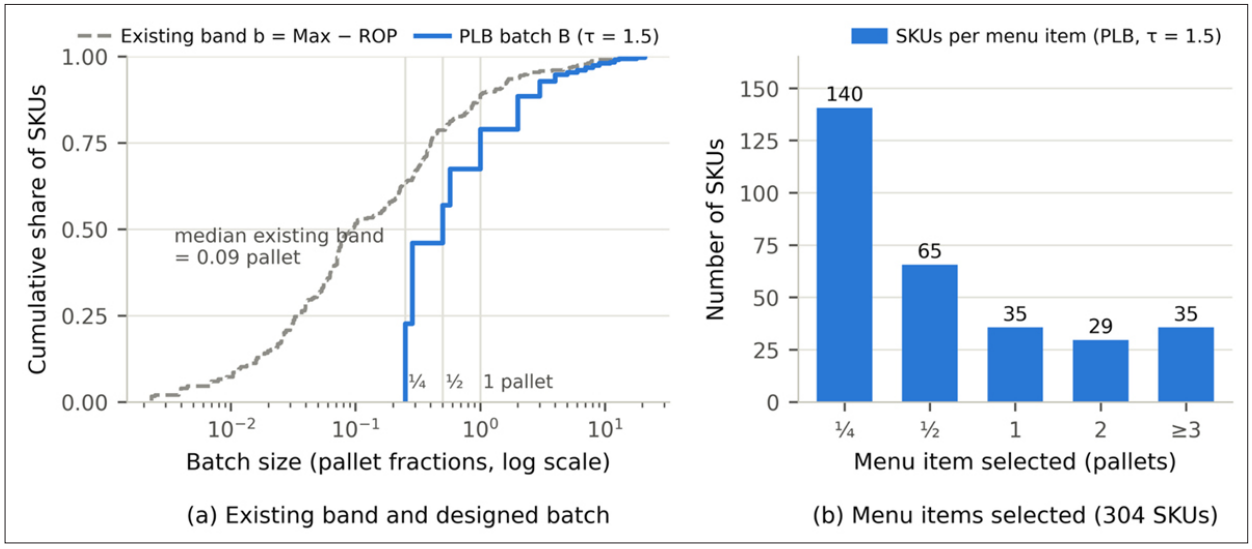


Fig. 2. (a) Cumulative distribution of the existing band b = Max − ROP and of the new batch B across the 304 SKUs, expressed in pallet fractions (logarithmic scale). (b) Unit-load menu items selected by the rule with τ = 1.5.

Simulation Model

A finite-capacity, daily-bucket MonteCarlo simulation of the single line was implemented in Python 3.11 with the NumPy and SciPy libraries. Daily demand for each SKU follows a negative binomial distribution with

$$\mu = D/21,\ \sigma^2 = \mu + \mu^2/k,$$

where μ is the mean daily demand in the season in force (pieces per day), D the mean monthly demand of that season (pieces per month), 21 the working days per month, σ^2 the variance of daily demand (pieces^2) and k the dispersion parameter (dimensionless); smaller k gives more variable demand. The high season runs from April to September. With $k = 2$ the coefficient of variation (standard deviation divided by mean) is approximately 0.7 for high-demand and 1.0 for low-demand SKUs.

Each day the review of Step 6 is applied to all SKUs, after which the open orders are produced in sequence. The line time occupied by an order is

$$t = c + x/\rho,$$

where t is the line time (min), c the changeover duration (min), x the order quantity (cartons) and ρ the nominal packing rate of the carton class (cartons per minute). An order that cannot be completed within the day continues on the following day without a second changeover. Completed quantities fill backorders first; unmet demand is backordered. Changeovers are sequence-independent. The same review, expediting and sequencing logic is applied in every scenario.

The horizon is 15 months of 21 working days, of which the first three months are a warm-up period excluded from the statistics. Twenty replications were run per scenario with common random numbers, so that policies are compared on identical demand realizations; results are means with 95% confidence intervals, and differences were tested with paired t-tests. Under the existing levels, the model generated 1,326 changeovers per month in July–September, close to the approximately 1,300 recorded on the line in the third quarter of 2026.The outputs are listed in Table 3; they include the changeover share of scheduled time (an availability loss in OEE terms), the unit fill rate (the fraction of demand met from stock without delay) and the monthly cost

$$C = KN + hV,$$

where C is the total monthly cost ($ per month), K the cost of one changeover ($ per changeover), N the number of changeovers per month, h the monthly holding cost rate (fraction of inventory value per month) and V the average on-hand inventory value ($). The changeover cost is the labor of the four-operator crew at $20 per hour for the duration of the changeover ($20 in the 15-min base case), and the holding rate is 20% of unit cost per year (h = 0.0167 per month); the same cost basis applies to every scenario. A deterministic benchmark is also reported:

$$N_0 = \Sigma\, D/B,$$

where N_0 is the number of changeovers per month if every order equaled exactly one batch, summed over all SKUs.The simulation code, SKU master data and simulation outputs are provided as Supplementary File S1.

Scenarios

Table 2 lists the scenarios. S1 and S2 apply the existing levels

with orders rounded up to whole cartons and to at least one whole layer (manual layer rounding), respectively; S3 is the proposed rule; S4 restricts the menu to whole pallets; and S5 assigns the entire band increase to the maximum level (α = 0), which isolates the effect of the allocation step. Sensitivity runs (10 replications each) vary the changeover duration (10, 15 and 30 min), the achieved packing rate (0.5, 0.75 and 1.0 times nominal, representing performance losses), the demand dispersion (k = 1, 2 and 4), τ (1 to 4) and φ (0.5 to 1.0), one factor at a time.

Three benchmark policies, S6-S8, position the rule against established methods on the same model, data and cost basis. All three observe the obsolescence limit of the line, under which stock unsold after three months is written off, by restricting each batch to at most three months of mean demand wherever a single layer permits. S6 applies the economic order quantity,

$$Q_E = \sqrt{(2DK/h_u)},$$

where Q_E is the cost-minimizing batch (pieces) and h_u the holding cost per piece per month ($ per piece per month), the product of h and the unit cost; Q_E is rounded down to whole layers (at least one), so that neither the economic quantity nor the three-month limit is exceeded, and the control levels are re-set with the allocation step. S7 is a monthly fixed cycle, the periodic-review order-up-to policy [15]: each SKU is reviewed on a fixed working day, with the SKUs spread evenly over the 21 days, and ordered up to SS + D in whole layers. S8 selects for each SKU the item of the extended menu {one layer, ¼, ½, 1, 2, … pallets} that minimizes $K{\cdot}D/q + h_u q/2$, the monthly changeover plus holding cost of batch q, subject to the three-month limit; it is the best choice available to the PLB rule when costs are known, and its levels are re-set with the allocation step. Line capacity was verified not to be binding for any of the three.

Table 2. Simulated scenarios.

Scenario	Description	Control levels
S1	Existing levels, order quantity rounded up to whole cartons	SS, ROP, Max unchanged
S2	Existing levels, every order rounded up to at least one whole layer (manual layer rounding)	SS, ROP, Max unchanged
S3	PLB: unit-load menu {¼, ½, 1, 2, 3, …} pallets in whole layers, τ = 1.5, φ = 0.7	Re-set by Step 5 (Section 2.2)
S4	PLB with the menu restricted to whole pallets {1, 2, 3, …}	Re-set by Step 5 (Section 2.2)
S5	PLB with the unit-load menu, entire band increase on Max (α = 0)	SS, ROP unchanged; Max′ = Max + Δ
S6	Economic order quantity, rounded down to whole layers (at least one), capped at three months of demand	Re-set by Step 5 (Section 2.2)
S7	Monthly fixed cycle: each SKU reviewed on a fixed working day each month and ordered up to SS + D in whole layers	SS unchanged; order-up-to level SS + D
S8	Cost-optimal choice from the extended menu {one layer, ¼, ½, 1, 2, … pallets} under the three-month limit	Re-set by Step 5 (Section 2.2)

RESULTS AND DISCUSSION

Batch Design

With τ = 1.5 the menu assigns a quarter pallet to 140 SKUs, a half pallet to 65, one pallet to 35, two pallets to 29 and three or more pallets to 35 (Fig. 2b); the median batch is four layers. The allocation step lowered the trigger levels for 222 of the 304 SKUs (α = 1 for 68, 0.5 for 90 and 0.3 for 64) and assigned the entire band increase to the maximum level for 82, most of which are low-demand SKUs whose quarter pallet is large relative to their safety stock. At the design level, the safety-stock investment decreases from $535k to $452k (−15.5%), the cycle stock (half the batch) increases from $81k to $174k, and the investment at the maximum level increases from $853k to $955k (+12%).

Base-case Comparison

Table 3 and Fig. 3 present the base-case results. Under the existing levels (S1) the deterministic benchmark implies approximately 2,790 changeovers per month; because the daily review releases at most one order per SKU per day, the line executes 1,199 changeovers per month, 70.0% of scheduled time, against 55–90 h of run time. The fill rate remains at 100% only because the existing safety stocks are large.

Table 3. Base-case results (mean ± 95% confidence interval over 20 replications; intervals smaller than the last digit shown are omitted). Design values are deterministic.

Output	S1 Existing levels	S2 Manual Layer Rounding	S3 PLB	S4 Full pallet	S5 PLB (α=0)
Changeovers per month	1,199 ± 1	594 ± 1	219	106	219
Changeover time (h per month)	299.7 ± 0.3	148.4 ± 0.2	54.7 ± 0.1	26.6 ± 0.1	54.7 ± 0.1
Changeover share of scheduled time (%)	70.0 ± 0.1	34.7 ± 0.1	12.8	6.2	12.8
Line utilization (%)	86.8 ± 0.1	51.5 ± 0.1	29.7	23.3 ± 0.1	29.7
Unit fill rate (%)	100.0	100.0	100.0	100.0	100.0
Stock-out SKU-days per month	0.9 ± 0.1	0.1	0.0	0.0	0.0
Expedited orders per month	83.7 ± 1.2	26.9 ± 0.6	7.4 ± 0.3	2.7 ± 0.2	7.4 ± 0.3
Mean order size (layers)	2.7	5.4	14.7	30.4 ± 0.1	14.7
Maximum changeovers in a day	70.2 ± 0.4	47.3 ± 1.1	21.9 ± 0.8	13.6 ± 0.6	21.9 ± 0.8
Open orders at end of horizon	0	0	0	0	0
Average on-hand inventory ($k)	759	778	794	1,086 ± 1	877
Deterministic benchmark Σ D/B (changeovers per month)	2,788	644	274	171	274
Design safety stock ($k) / Max level ($k)	535 / 853	535 / 853	452 / 955	463 / 1,194	535 / 1,038

Rounding every order up to a whole layer (S2) halves the load to 594 changeovers and 148 h per month (34.7% of scheduled time). The PLB rule (S3) reduces the load to 219 changeovers and 55 h per month (12.8% of scheduled time), 82% below the existing levels and 63% below S2 (both P < 0.001). The busiest day involves 22 changeovers compared with 47 (S2) and 70 (S1), expedited orders fall to 7 per month, and the fill rate is not significantly different from S2 (P = 0.11). Average on-hand inventory is $794k, compared with $778k under S2 and $759k under S1, increases of $17k (2.1%) and $35k (4.6%) respectively (both P< 0.001); the 15.5% reduction in safety stock offsets most of the additional cycle stock. The simulated number of changeovers is 20% below the deterministic benchmark of 274 because orders released below the reorder point exceed B by the shortfall.

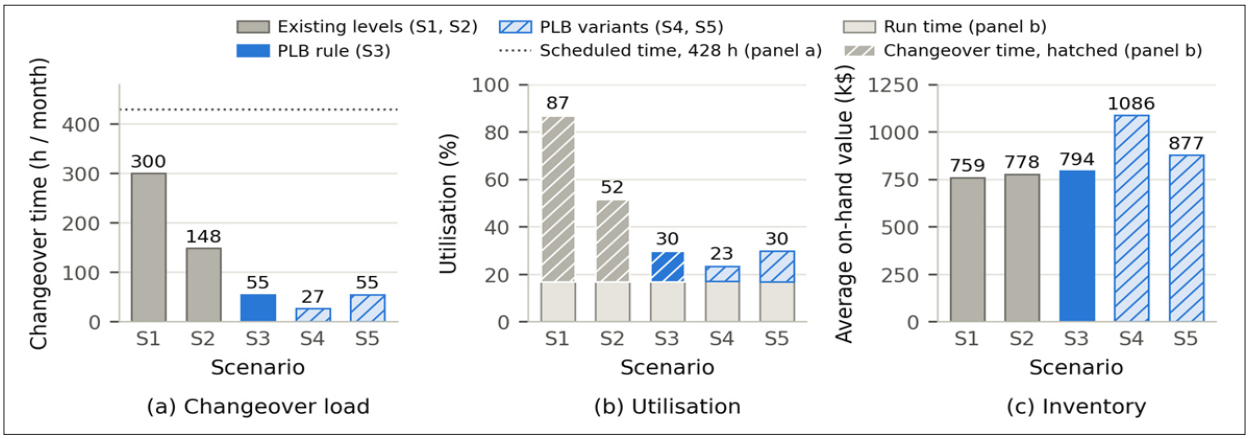


Fig. 3. Base-case comparison of scenarios S1 to S5: (a) changeover time per month against the scheduled time of 428 h; (b) line utilization divided into run time (plain) and changeover time (hatched); (c) average on-hand inventory valued at unit cost.

Restricting the menu to whole pallets (S4) removes a further 113 changeovers per month (28 h) but raises inventory to $1,086k, 37% above S3. Assigning the entire increase to the maximum level (S5) leaves changeovers unchanged and raises inventory to $877k; the allocation step therefore recovers $83k, or 10.5% of the on-hand value, with no change in expedited orders or fill rate.

Sensitivity

Figure 4 shows the trade-off between changeover time and inventory for the rule. Raising τ from 1.5 to 4 adds 99 changeovers (25 h) per month while inventory changes by less than 1%, because smaller batches also imply smaller band increases and smaller safety-stock reductions; lowering τ to 1.0 removes 49 changeovers (12 h) per month at the cost of a 5.7% increase in inventory. The safety-stock retention floor φ affects inventory almost exclusively: φ = 0.5 gives $758k and φ = 1.0 (no reduction of the trigger levels) $877k, with the same changeovers, fill rate and expedited orders, which indicates that the existing safety stocks (median cover 25–35 days) exceeded what the observed service level required.

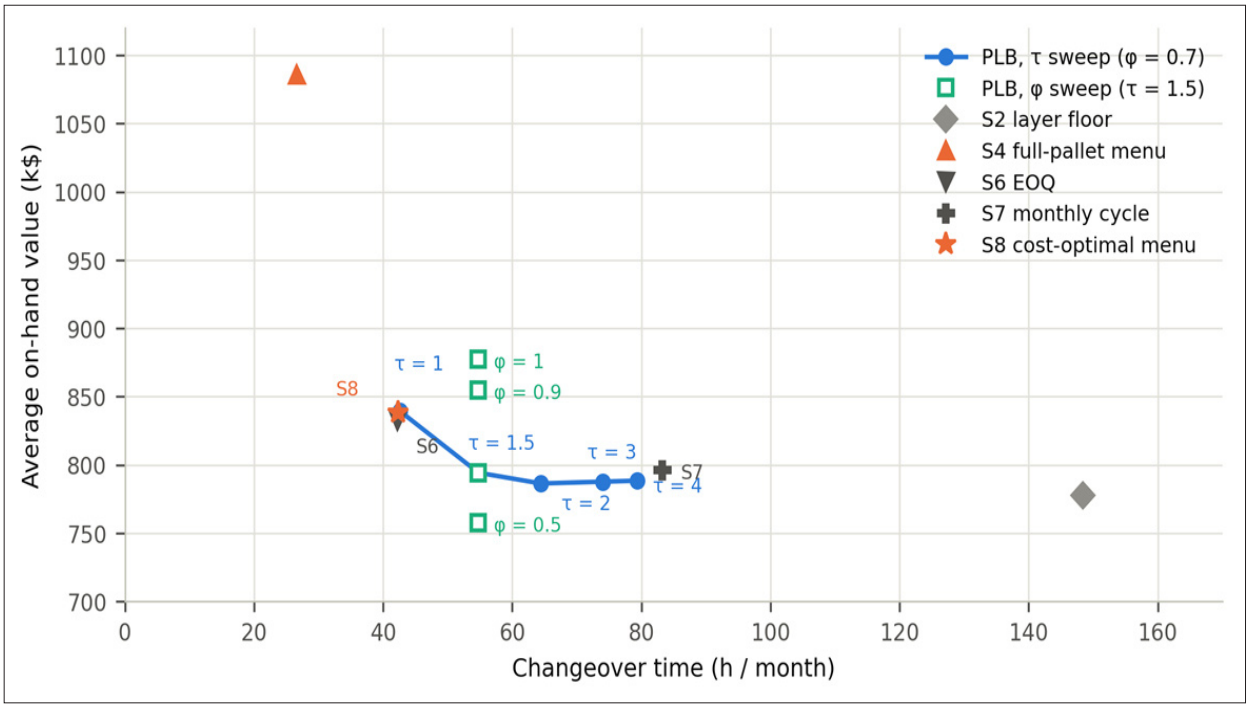


Fig. 4. Changeover time against average on-hand inventory for the PLB rule as τ and φ are varied (10 replications per point), with S2, S4 and S6–S8 for reference.

Table 4 and Fig. 5a show the effect of changeover duration and achieved packing rate. With a 10-min changeover the existing levels still consume 47% of scheduled time; with a 30-min changeover they saturate the line (utilization 99%, fill rate 29%), and the manual layer-rounding practice reaches 86% utilization with 73 expedited orders per month, whereas the PLB rule remains at 26% of scheduled time and 43% utilization with full service. A lower achieved packing rate changes utilization but not the number of changeovers: at half the nominal rate the existing levels run at 99.5% utilization with 1,111 expedited orders per month, against 47% and 7 under the PLB rule. Demand dispersion has little effect on changeovers (217–220 per month) and changes expedited orders from 11 (k = 1) to 6 (k = 4) per month. Changeovers follow the season (Fig. 5b): 180 (low season) and 257 (high season) per month under PLB, against 1,070 and 1,328 under the existing levels andagainst 500 and 687 under manual layer rounding.

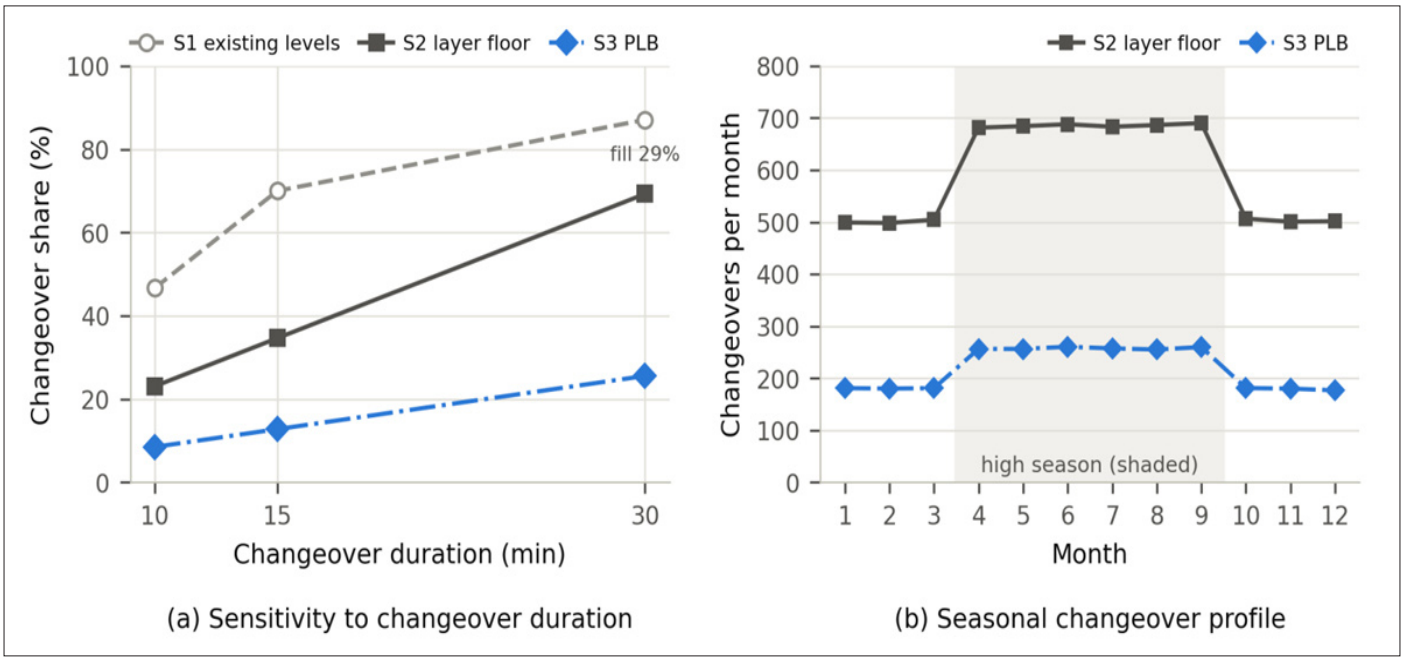


Fig. 5. (a) Changeover share of scheduled time against changeover duration for S1, S2 and S3; the saturation point is annotated with the unit fill rate. (b) Monthly changeover profile over the year for S2 and S3 (base case, 20 replications); the shaded area marks the high season.

Table 4. One-factor sensitivity of S1, S2 and S3 to changeover duration, achieved packing rate and demand dispersion (10 replications; means).

Factor	Scen.	CO per month	CO share (%)	Util. (%)	Fill rate (%)	Exp. per month	Inv. ($k)
c = 10 min	S1	1,200	46.7	63.5	100.0	82	761
	S2	593	23.1	39.9	100.0	27	778
	S3	219	8.5	25.4	100.0	7	794
c = 15 min	S1	1,200	70.0	86.8	100.0	84	759
	S2	593	34.6	51.5	100.0	27	778
	S3	219	12.8	29.7	100.0	7	794
c = 30 min	S1	746	87.1	98.9	29.3	1,207	58
	S2	593	69.3	86.1	100.0	73	755
	S3	219	25.6	42.5	100.0	7	794
Rate factor 0.5	S1	1,156	67.5	99.5	99.4	1,111	455
	S2	593	34.6	68.3	100.0	27	777
	S3	219	12.8	46.6	100.0	7	794
Rate factor 0.75	S1	1,200	70.0	92.5	100.0	513	699
	S2	593	34.6	57.1	100.0	27	778
	S3	219	12.8	35.3	100.0	7	794
Rate factor 1	S1	1,200	70.0	86.8	100.0	84	759
	S2	593	34.6	51.5	100.0	27	778
	S3	219	12.8	29.7	100.0	7	794
k = 1	S2	577	33.7	50.5	100.0	37	779
	S3	217	12.7	29.5	100.0	11	795
k = 2	S2	593	34.6	51.5	100.0	27	778
	S3	219	12.8	29.7	100.0	7	794
k = 4	S2	602	35.1	52.0	100.0	23	777
	S3	220	12.8	29.7	100.0	6	794

Note: c, changeover duration; rate factor, achieved packing rate as a fraction of the nominal rate; k, demand dispersion; CO, changeovers; CO share, changeover share of scheduled time; Util., line utilization; Exp., expedited orders; Inv., average on-hand inventory value.

Comparison with Benchmark Policies

Table 5 and Fig. 6 compare the rule with the benchmark policies. The economic order quantity (S6) and the cost-optimal menu selection (S8) give almost identical results: 169 changeovers per month and a total cost of $17,252–17,357 per month. The PLB rule with $\tau = 1.5$ lies within 1.5% of the cost-optimal menu ($17,615 per month; paired difference $257, $P < 0.001$) and within 2.1% of the economic order quantity, with 5% less inventory and 50 more changeovers per month. With $\tau = 1.0$ the rule coincides with both cost-based policies (Fig. 4), so the cost-optimal batch is reachable through the single parameter τ without cost data. The monthly fixed cycle (S7) performs worst of the benchmarks, with 333 changeovers and 64 expedited orders per month, because a fixed review day cannot respond to demand variation within the cycle, and a total cost 14.8% above S8. Manual layer rounding (S2) costs 43% more than S8 and the existing levels (S1) more than twice as much, because under both the changeover labor exceeds the holding cost.

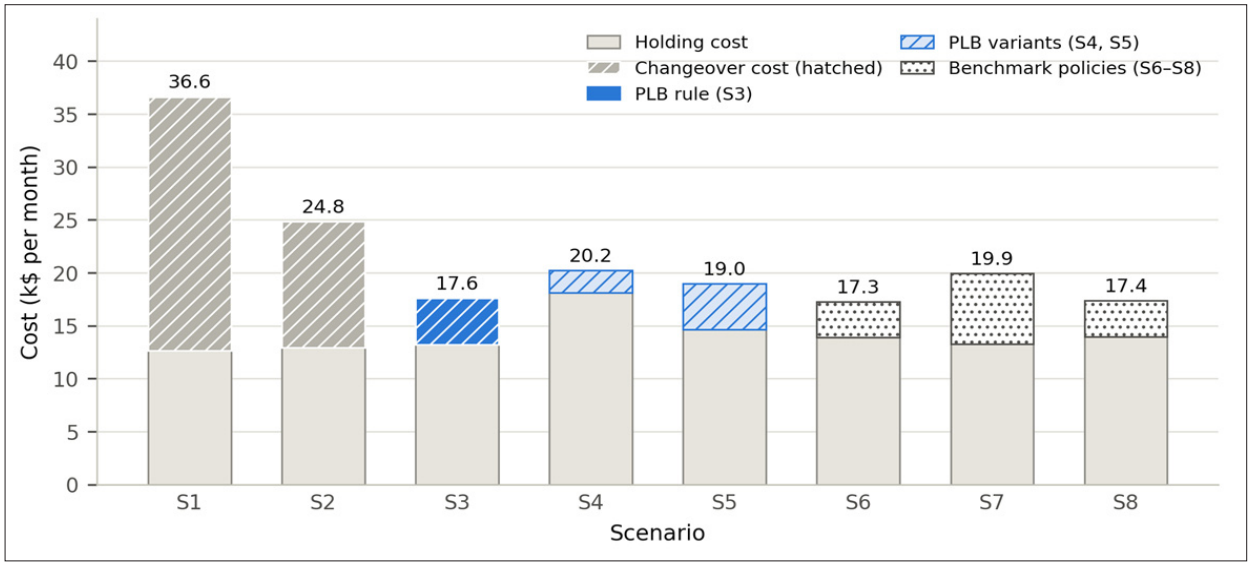


Fig. 6. Monthly changeover cost (hatched) and holding cost (plain) by scenario under the common cost basis ($20 per changeover, 20% holding rate per year); labels give the total in k$ per month.

The obsolescence check shows one departure from the cost-based policies: under PLB 24 of the 304 SKUs receive a batch exceeding three months of mean demand, because a quarter pallet is the smallest menu item, whereas S6-S8, which admit single layers, leave only the 8 SKUs for which even one layer exceeds the limit. Admitting single layers for these SKUs would remove the difference; together they account for fewer than 10 changeovers per month.

Table 5. Comparison of the PLB rule with the benchmark policies (mean ± 95% confidence interval over 20 replications; intervals smaller than the last digit shown are omitted). Costs use $20 per changeover and a holding rate of 20% of unit cost per year.

Output	S2 Manual layer rounding	S3 PLB	S6 EOQ	S7 Monthly cycle	S8 Cost-optimal
Changeovers per month	594 ± 1	219	169	333 ± 1	169
Changeover time (h per month)	148.4 ± 0.2	54.7 ± 0.1	42.2 ± 0.1	83.2 ± 0.2	42.3 ± 0.1
Changeover share of scheduled time (%)	34.7 ± 0.1	12.8	9.8	19.4	9.9
Line utilization (%)	51.5 ± 0.1	29.7	26.7	36.3 ± 0.1	26.8 ± 0.1
Unit fill rate (%)	100.0	100.0	100.0	100.0	100.0
Expedited orders per month	26.9 ± 0.6	7.4 ± 0.3	4.6 ± 0.2	63.5 ± 0.6	4.9 ± 0.2
Mean order size (layers)	5.4	14.7	19.0 ± 0.1	9.7	19.0
Average on-hand inventory ($k)	778	794	833	796	838
Changeover cost ($ per month)	11,875 ± 19	4,377 ± 7	3,375 ± 6	6,656 ± 13	3,385 ± 6
Holding cost ($ per month)	12,960 ± 2	13,238 ± 4	13,878 ± 5	13,269 ± 5	13,972 ± 7
Total cost ($ per month)	24,835 ± 18	17,615 ± 8	17,252 ± 7	19,925 ± 14	17,357 ± 9
Total cost relative to S8 (%)	+43.1	+1.5	-0.6	+14.8	+0.0
SKUs whose batch exceeds three months of demand	8	24	8	8	8

DISCUSSION

Four findings emerge. First, on the PVC pipe-fittings line studied, the replenishment band functioned as an implicit lot-sizing policy: with a median band of 0.09 pallet, the existing levels committed 70% of the scheduled time to changeovers, consistent with the approximately 1,300 changeovers per month recorded on the line, and the line saturated when the changeover lasted 30 min or the achieved rate fell to half of nominal.Second, manual layer rounding would halve the changeover load,but the PLB rule removes a further 63% of changeover time; the gain arises from the changeover-frequency ceiling τ, which moves medium- and high-demand SKUs from a single layer to a half, one or several pallets, and from the unit-load menu, which eliminates partial-pallet batches. Third, the inventory cost of the larger batches is small when the band increase is allocated subject to the safety-stock retention floor, because coverage-based safety stocks tend to be generous for the SKUs whose bands are widened most; the allocation step recovered 10.5% of the on-hand value without affecting service. Fourth, the rule

comes within 1.5–2.1% of the cost of the economic order quantity and of the cost-optimal menu selection using only the pallet pattern and a changeover-frequency ceiling, and coincides with them at $\tau = 1.0$; τ therefore substitutes for the cost ratio K/h_u that the economic order quantity requires, an advantage where changeover and holding costs are not tracked.

A practical implication concerns capacity: with the proposed batches the line is occupied for 30% of a three-shift pattern, so under the assumptions of the model the demand could be packed in approximately one shift, whereas the existing levels require all three. The results are consistent with previous work [27], and the residual changeover losses reported after SMED programs [3,6] are incurred per event; changeover time is the product of frequency and duration, so 219 changeovers of 15 min take less time than 594 of 10 min (Table 4). In lot-sizing terms the rule is a heuristic for a capacitated multi-item problem with batch-size constraints [7,8,10]; it preserves the (s, S) structure that the ERP system already executes [15,16] and is closely related to the (r, nQ, T) policy of Christou et al. [11], with the base batch determined by the unit load rather than by cost.

The study is limited to a single PVC pipe-fittings line with sequence-independent changeovers, a fixed nominal packing rate per carton class, fixed seasonal demand means without trend or promotions and labor-only changeover cost, and warehouse space is not costed. The benchmark policies were compared at the base-case load (about 27% utilization), and on a more heavily loaded line the longer runs of cost-based batches could delay other SKUs and reduce service. In addition, τ and φ were selected to reproduce the planner's plan rather than optimized, and post-implementation data are not yet available. Ongoing work will validate the simulated reduction against the OEE record of the line, set τ and φ by SKU class, incorporate sequence-dependent changeovers and cost warehouse pallet positions, for instance within a planning digital twin [28].

CONCLUSION

Under minimum–maximum control, the replenishment bands of a high-variety packing line act as a de facto lot-sizing policy, and when set without reference to the unit load, they generate changeover loads that absorb most of the available capacity. The pallet-layer batching rule converts each band into a whole-layer unit load under a changeover-frequency ceiling (τ) and re-sets the control levels under a safety-stock retention floor (φ). On data for 304 SKUs from a PVC pipe-fittings packing line, it reduced changeover time by 63% relative to manual layer rounding and by 82% relative to the existing levels, to 12.8% of scheduled time, with the fill rate at 100%, inventory up by 2.1%, and a total changeover and holding cost within 1.5% of a cost-optimal policy without cost data. The rule needs no additional software, is reproducible from existing ERP parameters and pallet patterns, and its two parameters make explicit a trade-off that is otherwise resolved informally.

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