Demand Driven Inventory Replenishment Strategy Combining Demand Information by CUSUM in Semiconductor Industry

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Abstract. The product in semiconductor industry is known to have its property in long production lead time, short life cycle and fluctuating demand. It is very difficult to manage the inventory effectively through the classic replenishment strategies due to the complexity of exploring managing parameters. On the other hand, demand driven inventory replenishment approach combined with buffer management suggested by the Theory of Constraints (TOC) has been demonstrated to be a good alternative to manage such inventory. This paper applied the concept of cumulative sum (CUSUM) approach, a sequential analysis technique used in quality control, to enhance the effectiveness of the demand-driven inventory replenishment strategies. Market forecasts provided by downstream customer and product demand trend are both considered in this approach to make better judgement on the replenishment decision. Real cases in managing finished wafers are analyzed. The results showed that our approach is an effective way to enhance the effectiveness of the demand-driven inventory replenishment method proposed by TOC in terms of obtaining higher service level with lower inventory.

Keywords: Theory of constraints、Demand-Pull、Buffer Management、CUSUM

1. INTRODUCTION

Goldratt and Cox (1984) proposed TOC, a method of controlling the bottleneck in the system to control the whole system. With the growing popularity of TOC in the practitioner, Goldratt (1994) then proposed to use demand-pull replenishment strategy combined by buffer management (short as DPBM hereafter) to be applied in supply chains. This method allows every member in the supply chains to set a proper inventory (named target buffer), which is large enough to cover the demand during replenishment lead time, to fulfill demand from the downstream customers. Once the target buffer is established, inventory replenishment is driven by the real demand and the target buffer is adjusted based on the status of inventory to ensure the amount of inventory carried is appropriated. In order to managing the target buffer, the buffer is evenly divided into three sections: red, yellow and green. Red section is below one third of target buffer, yellow section is between the one third and two third of target buffer and the green section is above two third of target buffer. When the inventory on-hand level penetrates the red section, it means that the inventory is too low thus target buffer needs to be increased to avoid out-of-stock situation. When the inventory on-hand level stays in the green section, it means that the inventory kept is too much thus target buffer needs to be decreased to avoid overstock.

DPBM is known to its simplicity and has been acknowledged by many industries in practice. Chang, et al. (2007) introduced demand pull strategy to the film transistor liquid crystal display (TFL-LCD). Huang et al. (2008) use demand pull strategy and buffer management in the construction of TFT-LCD to manage steel reinforcement and concrete material. Wu et al. (2010) consider the production lead time and constraints of capacity when using demand pull strategy. Considering that different product has different production lead time and the capacity is limited, their research has proposed a replenishment frequency. The replenishment frequency can meet the real situation better. Different from those traditional inventory replenishment strategies such as (s, S), (s, Q), (R, S) models that required complicated settings in parameters, DPBM is executed based on the follow three parameters (hereafter refer to DPBM parameters): (1) the size of the initial target buffer, (2) the timing to adjust the target buffer, and (3) the adjustment of buffer size. TOC suggests the rules of thumb to determine the timing of buffer adjustment as well as the size of buffer adjusted: raise the target buffer by 1/3 of its original when the on-hand inventory level reaches the red section; decrease the target buffer by 1/3 of its original when the on-hand inventory level reaches the green section (Schragenheim, 2007). When the rule-of-thumb DPBM parameters are not effective enough, one of the alternatives is to tune those parameters to fit different demand patterns of different product. However, lack of proper tool, fine-tuning DPBM parameters is a time-consuming process. Thus Hung et al. (2010) constructed a decision support system for decision makers to quickly search for appropriate DPBM parameters to manage semiconductor inventory at wafer level. Using this decision support system, Chang et al. (2014) explored the historical demands for forty-five products in a wafer foundry. They found that classical DPBM approach works well for some of these products, however, for rest of them, classical DPBM approach fail to find effective parameters to achieve the goal set for managing those finished-processing wafers. Chang et al. (2014) regarded the reasons that classical DPBM approach is not very effective for those products that have long product lead time (usually 9 weeks in a wafer foundry), highly fluctuating demands and short product life cycle.

In order to enhance the classical DPBM approach, Chang et al. (2014) used the market demand forecasts provided by customers to change the buffer management mechanisms on DPBM parameters. By learning the future demand ahead of time, the decision maker can adjust the buffer through altering the order quantities to achieve higher service level using fewer inventory compared to using the classical DPBM approach. However, their approach only adjust the DPBM parameters based on the demand forecasts without considering the trend shown in the historical demands.

In this paper, we proposed to use CUSUM (Cumulative Sum) (Page,1954) in the DPBM approach to explore the demand trends reveal from both the historical demands as well as the market forecasts. CUSUM is a method original used in quality control chart to detecting small variations in a manufacturing process. By cumulative observations over a period of time in the past, a small deviation may be reflected as a big abnormal signal. When the cumulative sum exceeds a pre-determined threshold, an alarm rings and the cumulative sum will be reset to continue monitoring the process (Montgomery, 2007). The proposed approach considers both historical data and market forecasts provided by customers and applied the concept of CUSUM to see if there exists certain trends in the demand. Along with the expected inventory level, the replenishment rules were designed so that the decision maker can make early respond to the trends to avoid over- or under- stock situation. In particular, this paper focuses on the finished-good management in a wafer foundry. The rest of the paper is organized as follows. Section 2 described the settings of the study problem. Section 3 presented the proposed approach. In Section 4, several real cases were analyzed to show the effectiveness of the proposed approach. Section 5 concluded this paper.

2. PROBLEM DESCRIPTION

This research discuss the manufacturing of fabrication and management in wafer finished goods. The purpose is to satisfy customer orders and lower the chance of out of stock. On the other hand, lower inventory to reduce cost. Wafer manufacturing factory (abbreviate as factory) puts wafers to a storage location after they are finished processed by various machines in the factory. This storage location is called as “warehouse” in this study. The wafers stored in the warehouse are subject to ship for further processing such as packaging and assembly by other facility upon customers’ requests (orders). Each finished-processing wafer is very expensive, ranging from thousands of US dollars to tens of thousands of US dollars, depends on the type of products. In each replenishment period, the warehouse ships out the quantity of product required by customer (i.e., the demand) and make replenishment decision to the factory based on pre-determined replenishment rules. The replenishment request made to the factory will received by the warehouse after a pre-determined replenishment lead time. This lead time is actually the time for the factory to manufacture the wafers, which depends on the complexity and urgency of the product as well as the status of the factory, ranging between 5 to 9 weeks or even longer. In this paper, the replenishment lead time is assumed to be fixed since it is actually a controllable factor for a well-managed foundry. In addition, this paper assumed rush order is not allowed and all the replenishment requests will be fulfilled. Moreover, there is no fixed ordering cost for each replenishment decision made by the warehouse. Since all the wafers are customized, backlog is allowed and whatever backlogged needs to be satisfied first. Also, it is assumed that the customer is willing to share the demand of downstream market with the warehouse and will provide rolling forecasts for at least the next product lead time and updated regularly. The minimum time period is a week. That is, the replenishment decision is made each week, and the replenishment time is also expressed in weeks.

3. METHODOLOGY

There's two part of the proposed methodology. The first part constructs various indicators based on CUSUM method to show the demand trends of the product and determine the timing to adjust the buffer. Then a set of replenishment rules are suggested to describe how to make the replenishment decisions. The demand trend indicators are reset each time after the buffer is adjusted to ensure they can reflect to the real demand trend and sense the demand variation.

3.1 Calculation of demand trend

A term called the inventory level determination limit (ILDL) is defined to represent the sum of on-hand and in-transit inventory based on our estimation when considering the market forecasts. This term is similar to the target buffer size in the classical DPBM approach. Before making replenishment decisions, the initial ILDL, i.e., denoted as T_{LT+1}, has to be set first. The purpose of ILDL is to satisfy customer demand and the demand uncertainty within the replenishment lead time (LT). This paper followed the advice given in Schragenheim (2007) to set the initial value of ILDL as the sum of demand during the replenishment lead time multiplied by 1.5 where the sum of demand during the replenishment lead time is determined by the past demand information. However, since the product we are dealing with are all new products with less than 2 years of product life, the past demand information is very limited. Thus this paper used the time between period 1 and period LT as the time to build initial inventory and used equation (1) to calculate T_{LT+1}.

$$T_{LT+1}=(\sum_{j=1}^{j=LT} D_j) \times 1.5 \tag{1}$$

Calculate CUSUM according to history data and adjust the ILDL and replenishment quantity according to expected inventory. The expected demand of every period will change through the time and the predicted demand will update accordingly. Replenishment mode starts when customer pull their demand, trigger the action of replenishment. In each replenishment period j, customer made a shipping request, denoted as D_j and provided demand forecasts for the next LT periods of time. Let $F_{j,k}$, for $k=j+1, \ldots, j+LT$ be the demand forecasts provided by the customer. Let $FOH_{j,k}$ be the projected on-hand inventory of period k based on the rolling forecast given in period j, calculated by equation (2).

$$FOH_{j,k}=\begin{cases} OH_j+FG_k-F_{j,k} \ , \ if \ \ k=j+1 \\ FOH_{j,k-1}+FG_k-F_{j,k} \ \ , \ if \ \ k=j+2,\ldots,j+LT \end{cases} \tag{2}$$

In equation (2), FG_k represent the amount of products scheduled to receive in period k.

Furthermore, on-hand inventory in period j (OH_j) is calculated by (3):

$$OH_j = OH_{j-1} + POR_j - D_j, \forall j \tag{3}$$

In equation (3), POR_j and D_j represent the planned order receipts and the actually demand of period j, $\forall j$, respectively.

This study applied CUSUM to compute the cumulative trend indicators to explore the trends shown in demands. Let $DC^{+}_{Ij,j}$ and $DC^{-}_{Ij,j}$ be the positive and negative trend indicator between period I_j and period j, respectively, in which I_j represents the closest period of time from period j when the trend indicators are reset.

$DC^{+}_{Ij,j}$ is calculate by equation (4).

$$DC^{+}_{I_j,j}=\begin{cases} max[0, D_j-(\mu_j+p_j)] \quad , \ if \ \ I_j=j \\ max\left[0, D_j-(\mu_j+p_j)+DC^{+}_{I_j,j-1}\right] \quad , \ if \ \ I_j\neq j \end{cases}, \forall j \tag{4}$$

Similarly, $DC^{-}_{Ij,j}$ is calculated by equation (5).

$$DC^{-}_{I_j,j}=\begin{cases} max[0, (\mu_j-p_j)-D_j] \quad , \quad if \ \ I_j=j \\ max\left[0, (\mu_j-p_j)-D_j+DC^{-}_{I_j,j-1}\right] \ , \ if \ \ I_j\neq j \end{cases}, \forall j \tag{5}$$

In equation (4) and (5), D_j is the real demand in period j and μ_j represents the target average demand in period j, calculated by equation (6).

$$\mu_j=\begin{cases} \sum_{k=1}^{LT}\frac{D_k}{LT} \ , \ if \ \ j=LT+1 \\ \mu_{j-1}+Q_j \ , \ if \ \ j=I_j \\ \mu_{j-1} \ , \ O.W. \end{cases} \tag{6}$$

In equation (6), the initial target average demand is calculated as the average demand between period 1 and period LT; when the trend indicator needs to be updated, the target average demand needs to be updated as well; otherwise, the target average demand of period j is set the same as period j-1. Q_j in equation (6) is calculated by equation (7).

$$Q_j = \begin{cases} \frac{\sigma_j}{2} + \frac{DC^+_{I_j,j-1}}{N^+_{j-1}} & ,If\ DC^+_{I_j,j-1} > \max[H_{j-1}, DC^-_{I_j,j-1}] \\ \frac{-\sigma_j}{2} - \frac{DC^-_{I_j,j-1}}{N^-_{j-1}} & ,If\ DC^-_{I_j,j-1} > \max[H_{j-1}, DC^-_{I_j,j-1}] \\ 0 & ,\quad O.W. \end{cases} \tag{7}$$

In equation (7), H_j is the threshold used in period j to determine if there is positive or negative trends revealed based on the trend indicators and σ_j is the standard deviation of demands calculated in period j, calculated by equation (8). In this study, we set H_j as $2\sigma_j$.

$$\sigma_j = \begin{cases} \sqrt{\sum_{k=1}^{LT} \frac{(D_k - \bar{D}_k)^2}{LT-1}} & ,if\ \ j = LT+1 \\ \sqrt{\sum_{k=1}^{j-1} \frac{(D_k - \bar{D}_k)^2}{j-2}} & ,if j = I_j \\ \sigma_{j-1} & ,\ O.W. \end{cases} \tag{8}$$

In equation (8), $\bar{D}_j$ is the demand average calculated in period j, as in equation (9).

$$\bar{D}_j = \begin{cases} \frac{\sum_{k=1}^{LT} D_k}{LT} & ,if\ \ j = LT+1 \\ \frac{\sum_{k=1}^{j-1} D_k}{j-1} & ,if\ \ j = I_j \\ \bar{D}_{j-1} & ,O.W. \end{cases} \tag{9}$$

In equation (9), the initial average demand (i.e, $\bar{D}_{LT+1}$) is the average of the demands of the first LT periods; at the time when the trend indicator needs to be updated, the demand average is recalculated using the demands between period 1 and period $j-1$; otherwise, the demand average is just set the same as the one in the previous period. The standard deviation of demand in equation (8) is calculated and updated using the same concept as in equation (9). The initial demand standard deviation is calculated from the demands over first LT periods; at the time when the trend indicator needs to be updated, the standard deviation of demand is recalculated using the demands between period 1 and period $j-1$; otherwise, the standard deviation of demand is just set as the one in the previous period.

N^+_j in equation (7) is the cumulative number of periods when the positive demand trend indicators is larger than 0, calculated by equation (10). Similarly, N^-_j in equation (7) is the cumulative number of periods when the negative demand trend indicators is larger than 0, calculated by equation (11).

$$N_j^+ = \begin{cases} 1, If\ \ DC^+_{I_j,j} > 0 and\ \ N^+_{j-1} > 0 \\ N^+_{j-1} + 1, If\ \ DC^+_{I_j,j} > 0 and\ \ N^+_{j-1} = 0 \\ 0\ \ ,\ O.W. \end{cases} \tag{10}$$

$$N_j^- = \begin{cases} 1, If\ \ DC^-_{I_j,j} > 0\ \ and\ \ N^-_{j-1} = 0 \\ N^-_{j-1} + 1, If\ \ DC^-_{I_j,j} > 0\ \ and\ \ N^-_{j-1} > 0 \\ 0,\ O.W. \end{cases} \tag{11}$$

When the p value in adaptive control chart is $\sigma/2$, in some specific situation can raise the effectiveness of control chart.

In equation (4), p_j is another parameter to determine. This study sets the value pj as $\sigma_j\ /2$ according to the study made by Zimmer, Montgomery, and Runger (2000).

In equation (4), I_j, the closest period of time from period j when the trend indicators are reset, can be expressed as equation (12).

$$I_j = \begin{cases} I_j & ,if\qquad j = LT+1 \\ j\ ,if & DC^+_{I_{j-1},j-1} > max[H_{j-1}, DC^-_{I_{j-1},j-1}] \\ \quad or\ \ DC^-_{I_{j-1},j-1} > max[H_{j-1}, DC^+_{I_{j-1},j-1}] \\ I_{j-1} & ,\qquad O.W. \end{cases} \tag{12}$$

In equation (12), when either the positive trend indicator is greater than the maximum value between the threshold and the negative trend indictor or when the negative trend indicator is greater than the maximum value between the threshold and the positive trend indictor, the demand trend is revealed. Thus the trend indicators need to be reset for later use and I_j is recorded as the time when the indicator is reset.

3.2 Determination of replenishment rules

In each time period j, ILDL T_j is divided into three equal sections: green, yellow and red, from top to bottom. When the on-hand inventory level locates in the section above 2/3 T_j, we said the inventory is in green zone. If the on-hand inventory level locates between 0 and 1/3 T_j, we said the inventory is in the red zone. The inventory is in the yellow zone if the on-hand inventory locates between1/3 T_j and 2/3 T_j. Besides using the positive and negative trend indictors to explore the demand trend, this study also considered the inventory status to propose a set replenishment rules. There are three parts in this set of replenishment rules: (1) rising trend, (2) declining trend and (3) no obvious trend. When $DC^{+}_{Ij,j}>H_j$, we said there exists a rising trend; when $DC^{-}_{Ij,j}>H_j$, we said there exists a declining trend. These replenishment rules are organized in Table 1. The amount of ILDL to adjust when necessary was determined by systematic trials under different demand trends.

Table 1: The proposed inventory replenishment rules

Trend of demand	Replenishment rule	Projected on hand inventory at period j	Actual inventory status at period j	ILDL Adjustment decision	Replenishment decision
Rising trend	rule 1	Greater than 1/2 T_j	Green	Do not make adjustment	Do not make replenishment
	rule 2		Yellow		
	rule 3		Red		Current demand
	rule 4	between 0 and 1/2T_j	Green	Increase T_j by its 1/5	Do not make replenishment
	rule 5		Yellow		Current demand
	rule 6		Red		The amount of adjustment
	rule 7	lower than 0 (i.e., out of stock)	Green	Increase T_j by its 1/5	Current demand
	rule 8		Yellow	Increase T_j by its 1/3	Current demand plus out-of-stock quantity
	rule 9		Red		Adjustment plus out-of-stock quantity
Declining trend	rule 10	greater than 1/2 T_j	Green	Decrease T_j by its 1/3	Do not make replenishment
	rule 11		Yellow		
	rule 12		Red		
	rule 13	between 0 and 1/2T_j	Green	Decrease T_j by its 1/3	Do not make replenishment
	rule 14		Yellow		
	rule 15		Red	Decrease T_j by its 1/5	
	rule 16	lower than 0 (i.e., out of stock)	Green	Do not make adjustment	Current demand plus out-of-stock quantity
	rule 17		Yellow		
	rule 18		Red		
No significant trend	rule 19	greater than 1/2 T_j			Do not make replenishment
	rule 20	between 0 and 1/2T_j			Current demand
	rule 21	lower than 0 (i.e., out of stock)			Current demand plus out-of-stock quantity

3.3 Performance Measures

The performance indicators used in this study to evaluate the effectiveness of the result of inventory management are average inventory (AI), calculated by equation (13), and service level (SL), calculated by equation (14).

$$AI = \frac{\sum_{j=1}^{k} OH_j}{k} \quad (13)$$

$$SL = \left(1 - \frac{\sum_j OS_j}{\sum_j D_j}\right) \times 100\% \quad (14)$$

The average inventory calculates the average inventory on-hand throughout the periods. Service level measured the proportion of demand cannot be satisfied by inventory. In equation (14), OS_j is the out-of-stock quantity of period j, calculated by equation (15).

$$OS_j = \begin{cases} |OH_j| \ , if \ \ OH_j < 0 \ \ and \ \ |OH_j| < D_j \\ D_j, if \quad OH_j < 0 and \ \ |OH_j| > D_j \\ 0, if \ \ OH_j > 0 \end{cases} \quad (15)$$

4. Case Analysis

The study proposed a set of replenishment rules by applying the concept of CUSUM to explore the demand trends by judging from both the history demand and market forecasts provided by customer. In this section, we used real demand information of three products provided by a world-leading wafer foundry (hereafter called Company X) to demonstrate the effectiveness of the proposed approach.

4.1 Demand Characteristics of the Three Products

The demand and product information along with the assumptions made are organized as follows.

1. Length of observing periods: 74 weeks for product A, 76 weeks for product B, 73 weeks for product C.
2. Replenishment lead time : 9 weeks for product A, 9 weeks for product B, 11 weeks for product C
3. The replenishment decision is made each week.
4. Backlog is allowed
5. No rush orders are allowed(i.e.,the replenishment lead time is fixed).
6. The initial warm up time is one replenishment lead time. There is enough time to build up initial target inventory
7. Customer provides the demand rolling forecasts for the next six months each week.

4.2 Analysis of Product A

There are demand information of 74 weeks of product A provided by Company X. Figure 1 depicts the demand of each week. The average and standard deviation of demand are 3747.01 and 935.64, respectively. The coefficient of variation is 0.25. Six-month rolling forecasts of the market are provided by the customer each week but we only consider the forecasts for the next replenishment lead time. The mean absolute percentage error (MAPE) of the demand forecasts of product A is 40.26%.

Figure 1: The 74-week demand information of product A

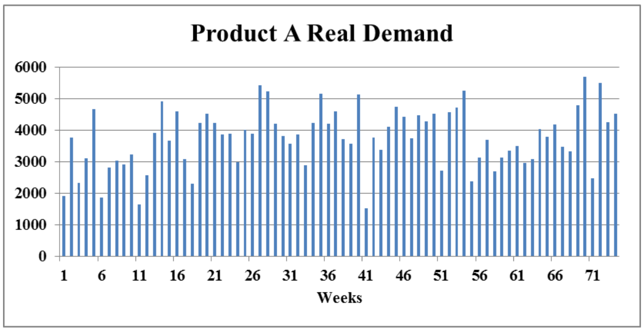


Figure 2 showed the on-hand inventory of each week resulted from using the classical DPBM (denoted as DPBM) and the proposed approach. Although the on-hand inventory between week 20 and week 26 resulted by using the proposed approach is higher than the classical DPBM, starting from week 27, the proposed method is outperformed the classical DPBM in terms of on-hand inventory.

Figure 2: The on-hand inventory of product A by the proposed method and the classical DPBM

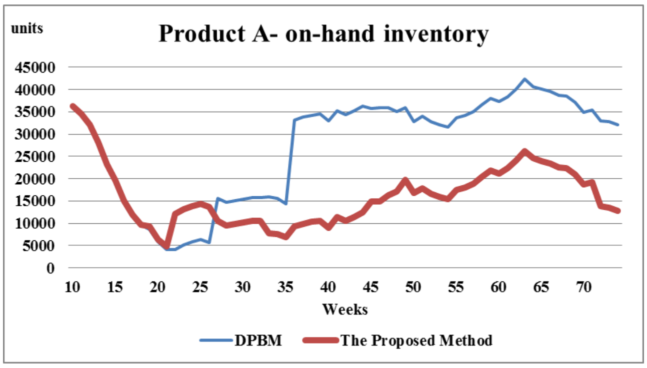


Table 2 The performance indicators of the two approaches of product A

	The Proposed Method	Classical DPBM
Average inventory (AI)	16150.71	27472.98
Service level(SL)	100%	100%

From table 2, the comparison of performance measurement between proposed method and DPBM, under the same service level (100%), the proposed method has significantly lower average inventory than DPBM.

4.3 Analysis of Product B

Demand information of 76 weeks of product B is provided by Company X. Demand of each week is depicted in Figure 3. The average and standard deviation of demand are 1103.36 749.44. The coefficient of variation is 0.68. The MAPE of the demand forecasts of product B is 92.08%

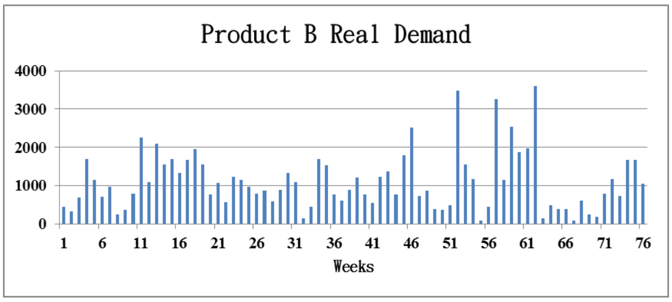


Figure 3: The 76 weeks demand information of product B

Figure 4 is the on-hand inventory resulted from using the proposed method and DPBM. In week 14, both methods face out-of-stock situation. But the proposed method can react to the demand faster and decrease out-of-stock period. From table 5, the proposed method has better performance in service level and average inventory than DPBM.

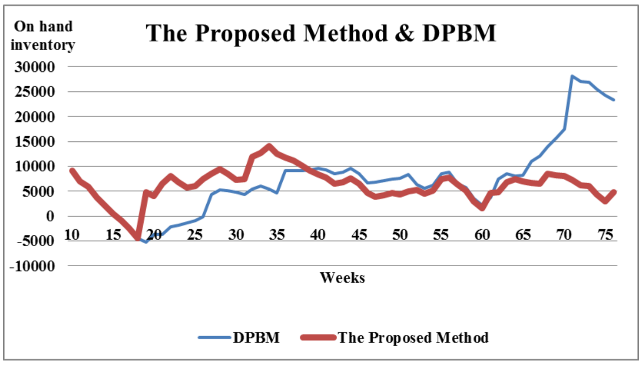


Figure 4: The on-hand Inventory of product B by the proposed method and DPBM

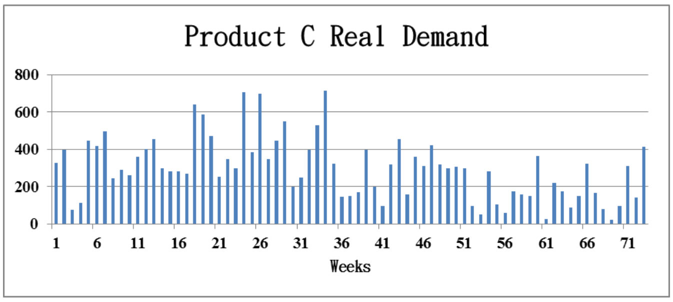
Table3: The performance indicators of the two approaches of product B

	The Proposed Method	Classical DPBM
Average inventory (AI)	6397.70	7802.25
Service level(SL)	93.59%	84.58%

From table 3, the performance indicators show that the overall performance of the proposed method is better than DPBM.

4.4 Analysis of Product C

Demand information of 73 weeks of product C is provided by company X Figure 5 depicts the demand of each week of product C. The average and standard deviation of demand is 296.25 and 163.42. The



coefficient of variation is 0.55. The MAPE of demand forecasts of product C is 121.77%.

Figure 5: The 73 weeks demand information of product C

In the inventory management of product C, figure 6 shows the on-hand inventory using the proposed method and DPBM. In week 28, out-of-stock situation happened using DPBM. The proposed method has reacted to the demand early and no out-of-stock situation happened. After week 33, inventory of proposed method is lower than DPBM.

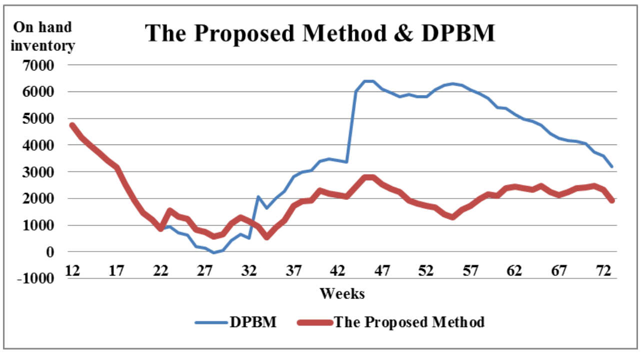


Figure 6 The on-hand inventory of product C of the proposed method and DPBM

Table 4: The performance indicators of proposed method and DPBM- product C

	The Proposed Method	Classical DPBM
Average inventory (AI)	2001.66	3627.66
Service level(SL)	100.00%	99.77%

From table 4, the performance indicators shows that the overall performance of the proposed method is better than DPBM.

5.CONCLUSION

The research proposed applying CUSUM value calculated by history demand to determine the rising or decreasing of demand. Combine the market demand forecast to calculate expected inventory, then use the concept of target buffer to determine ILDL and the section of inventory level. It primary use the advantage when ILDL adjust, CUSUM value can be re-calculated. It is able to detect small variation and combine projected inventory to adjust replenishment.

Through case analysis, the proposed method has better performance than DPBM which simply considers history data. In some products, out of stock happens in both methods. But the proposed method can respond to the trend and decrease out of stock quantity or satisfy customer demand. This is the proof that the proposed method can react to the demand more efficiently.

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