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Enhancement of Theory of Constraints replenishment using a novel generic buffer management procedure

KUO-JUNG YUAN†, SHENG-HUNG CHANG‡ and
RONG-KWEI LI†*

Managing a distribution system requires the right inventory in the right place at the right time. A Theory of Constraints replenishment solution is presented to aggregate inventory buffers at the central warehouse in plant and change the mode of operation from push to pull. The solution is powerful, but the optimal amount of buffer remains undetermined. In Theory of Constraints, choosing a specific buffer size is not crucial if the buffer is accurately monitored in a timely manner. Accordingly, Theory of Constraints is offered a buffer management approach for monitoring the buffer. Such buffer management is feasible and effective but is insufficiently rigorous. This paper elucidates a generic buffer management procedure, based on the concept of Theory of Constraints buffer management that rigorously defines a method of monitoring to size and adjust the buffer. An example demonstrates the feasibility of the proposed generic buffer management procedure.

1. Introduction

As a complex network, a distribution system links a production plant, several regional warehouses and many points of sale by the forward flow of products and the feedback of demand information (figure 1). The need for regional warehouse stems from the need to supply the market very quickly—ideally from the shelf. It is always a very competitive environment—it is sensitive to price, quality, and availability. Even the most stable market is plagued by fluctuations in demand. At any given site those fluctuations may be considerable, even if the global picture suggests a very flat (or, at least, a very predictable) demand.

The goal of every profit-based organization is to make money. So our ultimate purpose is to maximize the profits of a company—in the present as well as in the future. However, this kind of environment emphasizes the inherent conflict (figure 2) between two management approaches:

- Hold high levels of inventory in order to face peaks of demand and to ensure availability.
- Hold low levels of inventory in order to cut expenses, insure quality and reduce returns due to shelf-life, obsolescence, or engineering changes.

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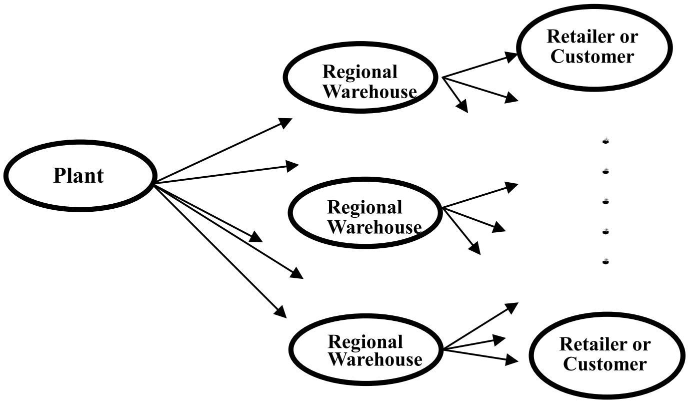


Figure 1. Distribution system.

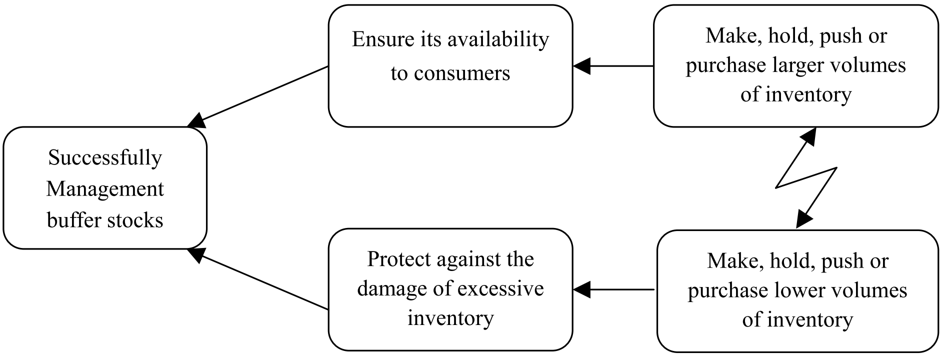


Figure 2. Dilemma of inventory management.

The usual solution is a compromise relying on a better forecast to minimize the risks involved. Most organizations, therefore, tend to push the inventory toward the end user, hoping to be able to meet end-users' demands at the right place and time. However, the replenishment period is long and the plant produces in anticipation of demand, based on forecasts. Consequently, the system always includes a huge inventory and requires continuous expediting, leading to chaos in the system.

The assumptions are that in order to face peaks of demand and to ensure availability we must hold high levels of inventory and tolerate inaccurate forecasting and long replenishment times. Can we break the conflict? Can we do something or change the way we handle distribution so that these assumptions will not be correct?

Yes, the replenishment solution (pull system) in the Theory of Constraints (TOC) claims that the accuracy of the forecast depends on which stage in the distribution system you are talking about. For example, if it is the highest level, the points of sale. What is the accuracy in terms of percentages of the forecast here? It is very poor. However, if we now look at the regional warehouse that supplies, the accuracy is far better than that for the forecast at the selling points level. The same is true when we go from all the regional warehouses back to the plant and we we talk about the total consumption from this vendor. Again, accuracy becomes better.

The TOC replenishment solution utilizes this fact, a solution that we have already. Hold the inventory at the most accurate point. This is not very accurate, but it is the most accurate point of the system. Where is the most accurate point of the system? At the source—at the plant in most cases. That is where we have the biggest aggregation. TOC states that aggregating the inventory and holding it at the plant warehouse (figue 3) not only decouples production disruption from bullwhip effect (Lee *et al.* 1997), but also increases the reliability of the replenishment of the goods to the regional warehouse, by making the replenishment time equal to the transportation time only. It is now not connected to production lead-time any more. In such a case, the reliability of the replenishment is markedly improved such that the regional warehouse can depend on being resupplied. Accordingly, hoarding inventory in the distribution chain is rendered unnecessary and other links need not attempt to overprotect themselves with excessive inventory. The goal of having the right inventory at the right place at the right time can thus be achieved.

The solution is effective. However, determining the right amount of buffer and performing inventory buffer control at the plant warehouse and regional warehouses remains an issue.

Various mathematical methods have been applied to determine optimum buffer size. Park (1993) reviewed a few popular methods, including enumeration, the gradient approach, separable programming, Hooke and Jeaves' search method, factorial design and dynamic programming. Although the buffer can be accurately sized in a number of ways, in TOC choosing the right buffer size is not very important if the buffer is accurately monitored in a timely manner.

Concerning how to monitor inventory buffer accurately in a timely way, Silver *et al.* (1998) reviews the conventional inventory theory and discuss how the fundamental purpose of a replenishment control system is to resolve the following three issues or problems: (1) how often the inventory status should be determined. (2) when a replenishment order should be placed and (3) how large the replenishment order should be. The answer to the problems of how often the inventory status should be determined by specifies trigger rules, by which the replenishment for a batch is generated as soon as a trigger level is reached. These rules can be classified as

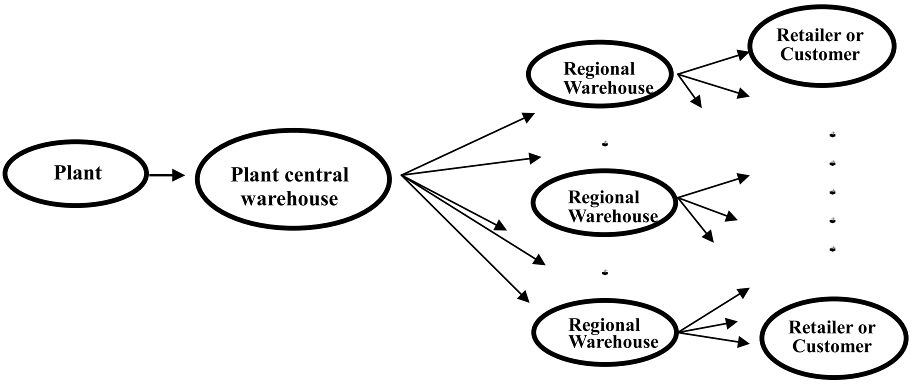


Figure 3. Distribution system (aggregating and holding inventory at plant central warehouse).

either periodic review systems $((R, S)$, (s, Q) policy) or continuous review systems $((s, S)$ and (s, Q) policy).

However, when demand rate varies with the time, the trigger rules should adjust to accompany the demand change. Silver (1978) uses rolling horizon of length $R + L$ (review period and lead time) approach that allows the demand rate vary within the current horizon by using safety stock considerations to decide when to place an order, followed by the deterministic Silver–Meal heuristic to select the size of the then current replenishment. In addition to Silver, Askin (1981) also addressed this problem as well. In a similar field, Vargas and Metters (1996) develops a stochastic version of the Wagner–Whitin model. However, these models has drawbacks from practitioner's standpoint.

Enrhardt and Mosier (1984) suggest a heuristic method, known as the revised power approximation. A somewhat similar approach was presented by Platt *et al.* (1997) who develop an accurate approximation for both s and Q when a fill rate is used. Their approximation can be built on a spreadsheet very easily. Bollapragada and Morton (1993), who developed a myopic heuristic, involved precomputing the (s, S) values for various values of mean demand. However, this heuristic should be avoided if demand is expected to decline rapidly.

Zheng and Federgruen (1991) developed a fast algorithm for finding the optimal s and S for given R and for discrete demand distributions. However, this algorithm, using a programming language, is best developed on a computer rather than a spreadsheet. Banerjee and Burton (1994) suggested some heuristic methods for determining the reorder point in the continuous review context for a product with unequal, discrete stock withdrawals under deterministic conditions. Research efforts in this regard have not been adequate to date. Banerjee and Burton (1996) extended the study and use simulation heuristic procedures to design mechanisms for triggering set-ups of replenishment. Additional related work on this problem includes Ernst and Powell (1995), Morton and Pentico (1995) Anupindi *et al.* (1996).

Simon (1996) proposed a heuristic method for buffer management under the maximization of throughput rate as an objection function to protect the throughput rate of manufacturing area. However, this heuristic method for buffer management would be a deterioration of the responsiveness to customer demands.

The common drawback of the algorithms or heuristic methods addressed above is that they compute s and S at a fixed time. They do not provide a continuous monitor approach to accompany the change of the demand. This will create either excess stock or supply shortage.

TOC involves such a method of buffer management and has three objectives, including protecting throughput, reducing inventory and decreasing operating expenses. The first objective is met by sizing the buffer according to the product of the paranoia consumption during the replenishment time, and a safety factor (1.5). This safety factor intuitively can be understood as follows. During paranoia consumption, the buffer level just before a new production run should be equal to half of the paranoia consumption over the replenishment time. This quantity provides extra protection for unexpected demand and should be enough to recover the buffer level in time, without loss of throughput.

TOC divides the buffer into three controlled zones: green, yellow and red (figure 4). Each zone contains one-third of the buffer. If the buffer drops into the green zone, no action is needed; if it drops further into the yellow zone, warning and

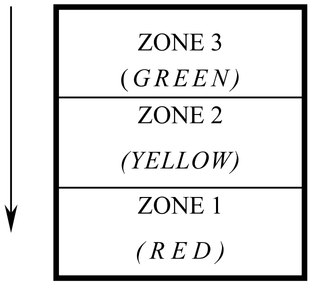


Figure 4. TOC buffer management: three fixed zones.

planning is necessary; and if it drops into the red zone, immediate action must be taken.

According to the three buffer control zones, if the maximum buffer is too large, then the buffer levels will be mostly at the top of the green zone, signalling the need to decrease the buffer size. If the buffer is too small, then the buffer levels will be at the bottom of the yellow zone or, even worse, the buffer will penetrate multiply into the red zone, indicating the need to increase the buffer level. TOC claims that the correct buffer level will be reached after several iterations.

TOC buffer management is also an instrument for reducing operating expenses. Increasing the size of the buffer leads to fewer emergency shipments being required, since the number of penetrations into the red zone is excessive. Operating expenses are reduced because emergency shipments cost much more than regular shipments.

TOC buffer management is feasible and powerful, but is not sufficiently rigorous. A rigorous procedure must be developed to implement the method effectively in the real world, especially if the method is to be computerized. No such method is yet available in the literature. Therefore, this paper proposes a generic buffer management procedure, based on TOC buffer management that will define rigorously a monitoring approach for sizing the buffer, monitoring the buffer and adjusting it accordingly. A generic procedure is one that should be further tuned for application in a specific area. An example illustrates the feasibility of the proposed procedure.

2. Generic buffer management procedure

TOC buffer management involves a three-level buffer control zone, where each layer does not necessarily represent on-third of the buffer, but rather constitutes from 10 to 50%. Therefore, in the generic buffer management procedure, two buffer control zones are proposed: green (maximum buffer size) and red (safety buffer size). Figure 5 shows the two-level generic buffer management control chart. The safety buffer protects the Murphy and should allow timely recovery (e.g. for an emergency replenishment) without loss of throughput. The buffer functions as a warning mechanism. A signal is issued when the buffer consumption penetrates into the safety buffer level and necessary actions are taken. The size of the buffer is the average period consumption rate $\bar{X}$ (estimates from the past N periods) from the next link during the replenishment time. The size of the safety buffer does not affect the maximum buffer size, but does affect the nervous of the system. If the safety buffer size is set too low or too high, then wrong action is more likely to be signalled. The size of the green buffer zone is specified to protect peak consumption and is the weighted average consumption rate $(K\bar{X})$. The weighted K value depends

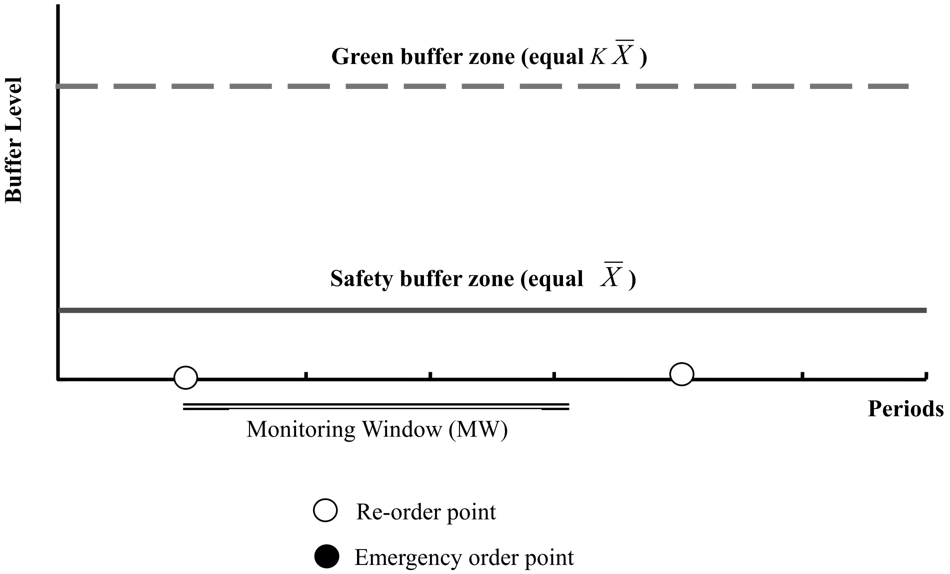


Figure 5. Buffer size (green buffer zone and safety buffer zone).

on the application environment. The size of the green level determines the average amount of the inventory of the system. Again, if the green buffer size is set too low, then penetration into the safety level is more likely; however, if it is set too high, then the inventory cost will be high. Both the green buffer level and the safety buffer level should be adjusted accordingly.

Several variables are defined:

- Replenishment time (R_{LT}): is the normal time required to replenish the order and includes transportation time only.
- Emergency replenishment time (R^E_{LT}): is the shortest time required to replenish the emergency order.
- Order review period (P_{CT}): is the regular time interval between the reorder points. The buffer procedure regularly replaces the order at each order reorder point.
- Monitoring window (MW): time interval that functions as a reference for tracking the buffer consumption status and deciding which action must be taken. The monitoring window should be higher than the average replenishment time between shipments. The monitoring window is reset under the following conditions. (1) During the monitoring window, no safety buffer penetration occurs; the green buffer is adjusted and a new monitoring window is reset at the end of the previous monitoring window. (2) Whenever either the safety buffer level or the green line buffer level is adjusted during the monitoring window, the monitoring window is reset from the period which follows the one in which the buffer was adjusted. Whenever the monitoring window is reset, the buffer consumption status of the previous monitoring window is excluded from the decision regarding this new monitoring window.
- Regular replenishment order quantity (R^q): is the replenishment order quantity at each reorder point. The order quantity is determined by two con-

ditions. Case 1: If the order review period exceeds the replenishment time, then the quantity of the replenishment order is calculated as (green line buffer—current buffer). Case 2: If the order review period is shorter than the replenishment time, then the quantity of replenishment order is calculated as, (green line buffer–current buffer–schedule on-hand).

- Emergency order quantity (R_E^q): is the emergency replenishment order placed when the buffer consumption penetrates into the safety buffer level. The amount of the emergency replenishment order is calculated as, (green line buffer + current buffer)/2.

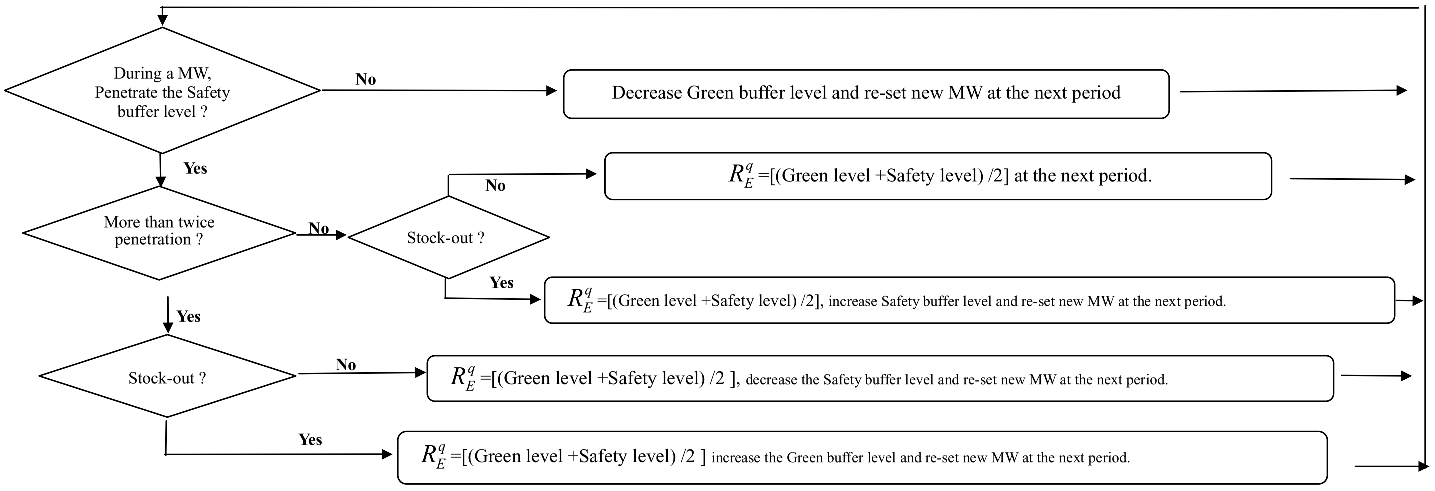
Figure 6 illustrates the flows of the generic buffer management procedure. Two situations activate the flows. In the first, during the monitoring window, either the buffer consumption penetrates into the safety buffer level, or at the end of the monitoring window, the flow of figure 6(a) is activated. In the second, the flow of figure 6(b) is activated when the next re-order point is reached.

Penetration of the safety buffer is first checked for, when the flow of figure 6(a) is activated. If no penetration has occurred, then if the monitoring window has ended, then the green level is decreased, the monitoring window is reset and the next monitor is initiated (figure 7). The green buffer level is reduced because the lack of safety buffer penetration implies that the green buffer line is too high.

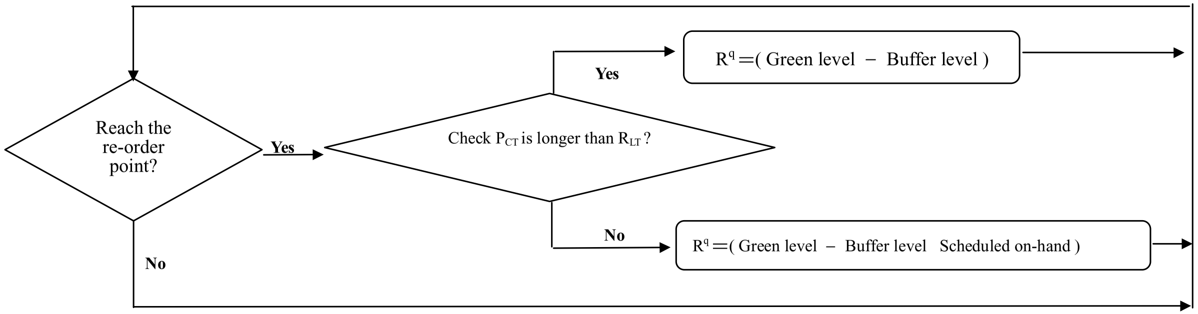
If the safety buffer is penetrated, but this does not represent the second penetration of the safety buffer within the monitoring window, we check if the stock out occurs. If stock out does not occur, only the emergency replenishment order is triggered. The replenishment order quantity equals (green level + safety level)/2, and the replenishment time equals the emergency replenishment time (figure 8). If stock out does occur, an emergency replenishment order of the same amount is triggered but the safety buffer level is increased (figure 9) because both the green and the safety buffer levels are set too low. Adjusting the safety buffer level allows the monitoring window to be reset and the next monitor to be initiated. As stated above, the actual size of the buffer is not critical as long as the buffer status continues to be monitored. Therefore, the extent to which the safety or green buffer levels should be increased or decreased is also subjective.

If the safety buffer is penetrated but it represent the second penetration of the safety buffer within the monitoring window, we check if the stock out occurs. If stock out has not occurred, then an emergency replenishment order is replaced and the safety buffer level is decreased, because in two cases of penetration, the safety buffer level may have been set too high (figure 10). Again, the monitoring window will be reset and the next monitor initiated, since the safety buffer level has been adjusted. If stock out does occur, an emergency order is placed and the green buffer level is increased because the green buffer is too small (figure 11). Again, the monitoring window will be reset and the next monitor initiated since the green buffer level has also been adjusted.

When the flow of figure 6(b) is activated, the order consumption situation is reviewed and the replenishment order quantity is computed. The order is issued to the previous link and expected to be replenished within the replenishment period. The replenishment order quantity falls under one of two cases. In the first, the order review period equals or exceeds the order replenishment time (figure 12) and the replenishment order quantity equals (green line buffer–current buffer). In the second, the order review period is shorter than the order replenishment time (figure 13) and



(a). The adjustment procedure



(b). The re-order point replenishment procedure

Figure 6. Flow of the generic buffer management procedure.

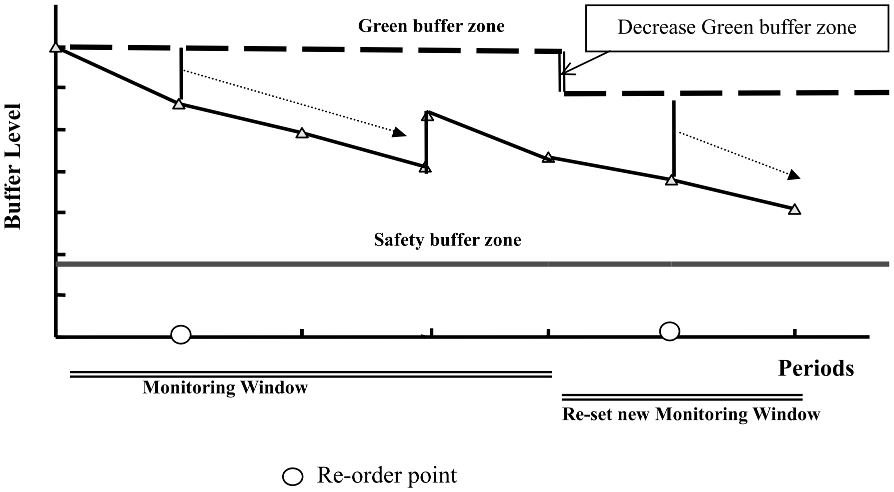


Figure 7. Reduce green buffer zone and reset the monitoring window.

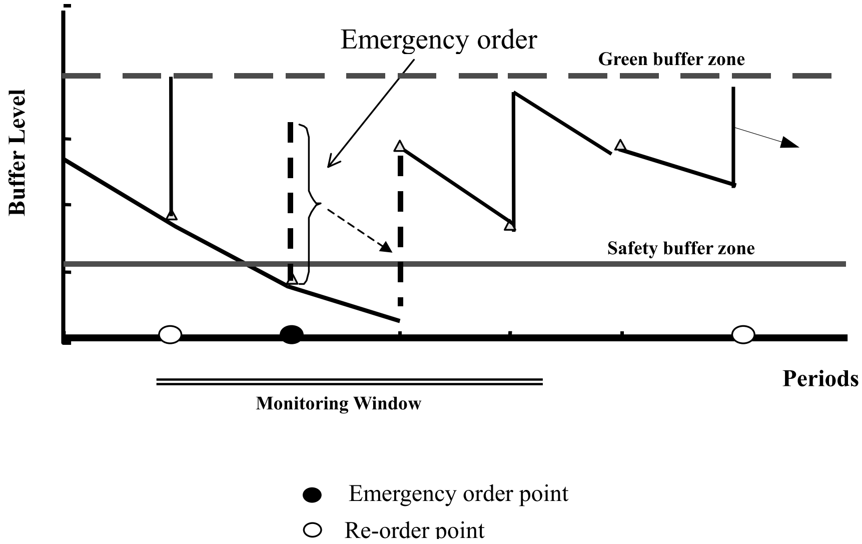


Figure 8. Penetration of the safety buffer level.

the replenishment order quantity equals (green line buffer–current buffer–scheduled on-hand). After the replenishment order is issued, any penetration of the safety buffer within the monitoring window is checked for: if none has occurred, then the green buffer level is reduced (figure 7). Otherwise, no adjustment is made.

3. Example

Figure 14 shows an example to demonstrate the generic buffer management procedure. The replenishment time is set to three periods: the order review period to five periods, the monitoring window to six periods and the emergency order

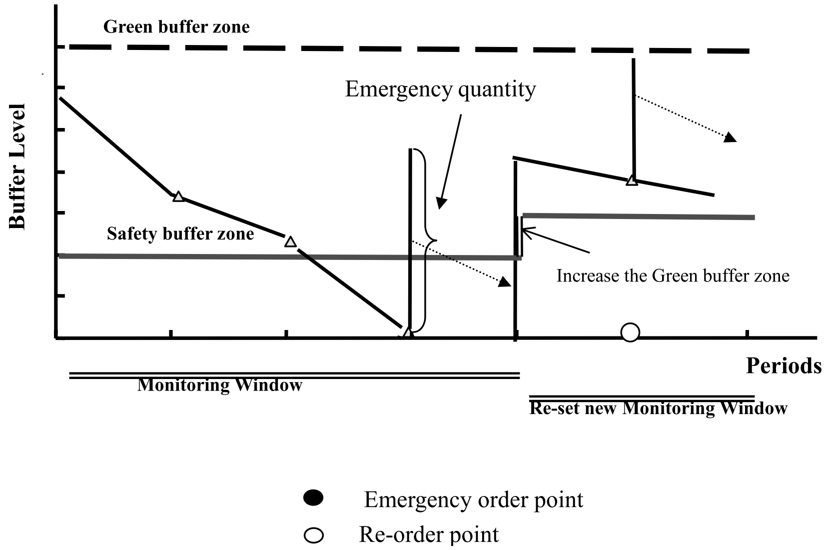


Figure 9. Stock-out, increase safety buffer zone and reset the monitoring window at the next period.

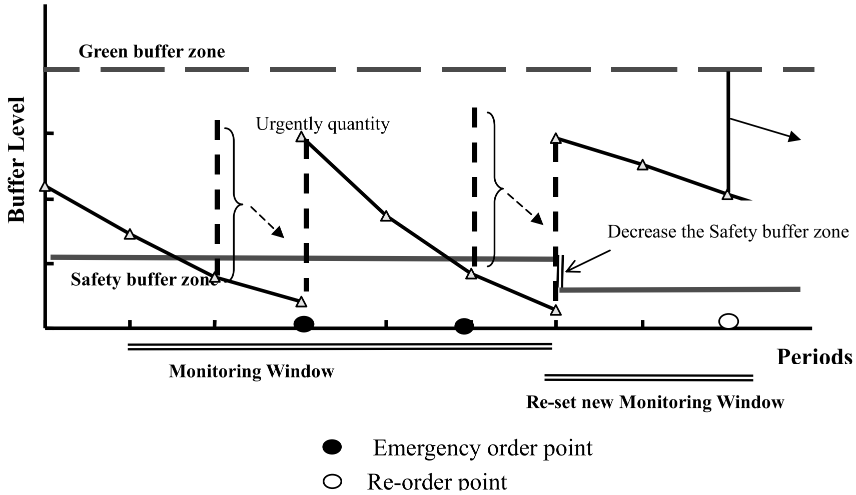


Figure 10. Twice penetration but not stock-out, decrease the safety buffer zone at the next period.

replenishment time to one period. The safety buffer level is assigned, according to the past 16 periods, as one average consumption rate equal to 370 units; the *K* factor is set to 4, such that the maximum buffer size is 1480 units.

Initially, the buffer size at the 17th period is 1230 units and no penetration occurs. When the 18th period, which is an order review period, is reached, the replenishment order quantity is determined to be equal to 485 (1480–995). The buffer size of 995 during the 18th period is equal to the buffer size of previous

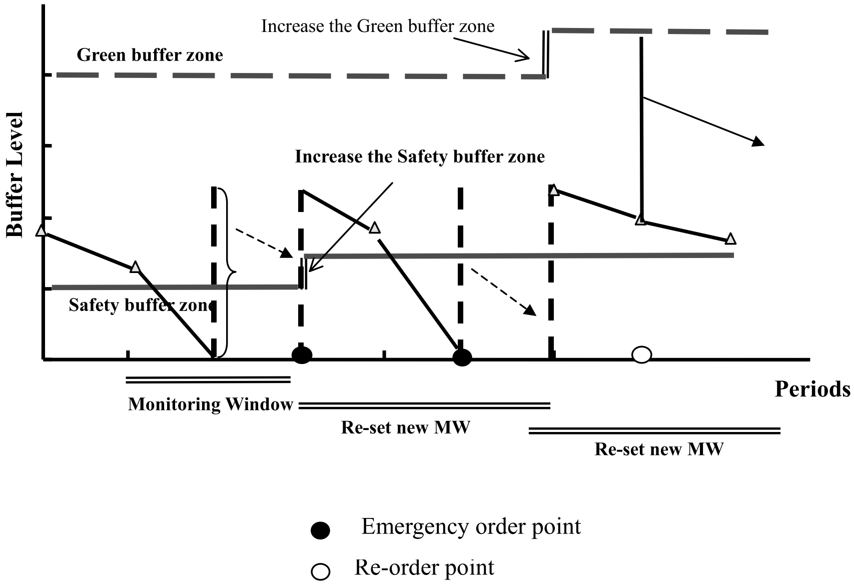


Figure 11. Twice penetration and stock-out, increase the green buffer zone at the next period and reset the monitoring window.

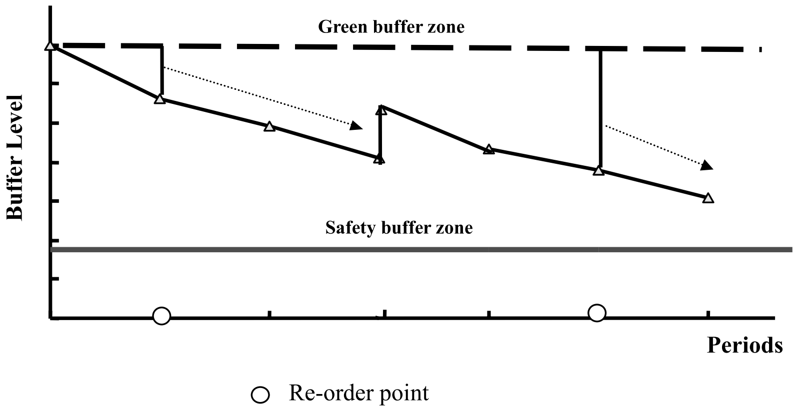


Figure 12. Order review period is equal to or longer than the order replenishment time.

period minus the demand of the 18th period, which is 1230–235. The buffer is still monitored and no penetration occurs during the 19th and 20th periods. The order placed in the 18th period arrives during the 21st, since the order replenishment time is three periods; the buffer is then equal to 935 (645 − 195 + 485).

When the second order review point is reached in the 23rd period during the monitoring window, the safety buffer level is not penetrated, and the green buffer size can be reduced from 1480 to 1300. Accordingly, a new replenishment order quantity is determined, which is 715 (1300–585). A new monitoring window must be reset since the green buffer size has been reduced. The monitoring window starts from period 23.

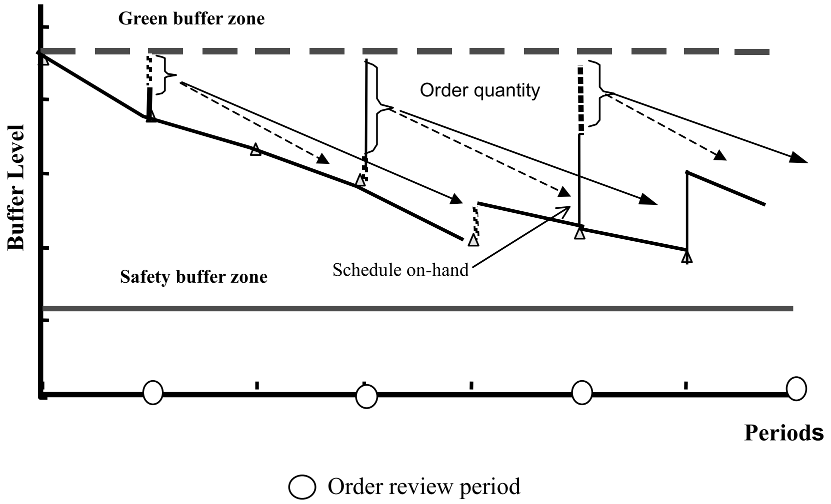


Figure 13. Order review period is shorter than the order replenishment time.

The buffer status continues to be monitored. In period 25, the safety buffer is penetrated, and an emergency replenishment order of 835 units $((1300 + 370)/2)$ is issued, and arrives during the following period. No action other than placing the emergency replenishment order is required since this penetration is the first during the monitoring window. The last replenishment order and the emergency order arrive during period 26, and the buffer are now 926 units $(65 - 689 + 835 + 715)$.

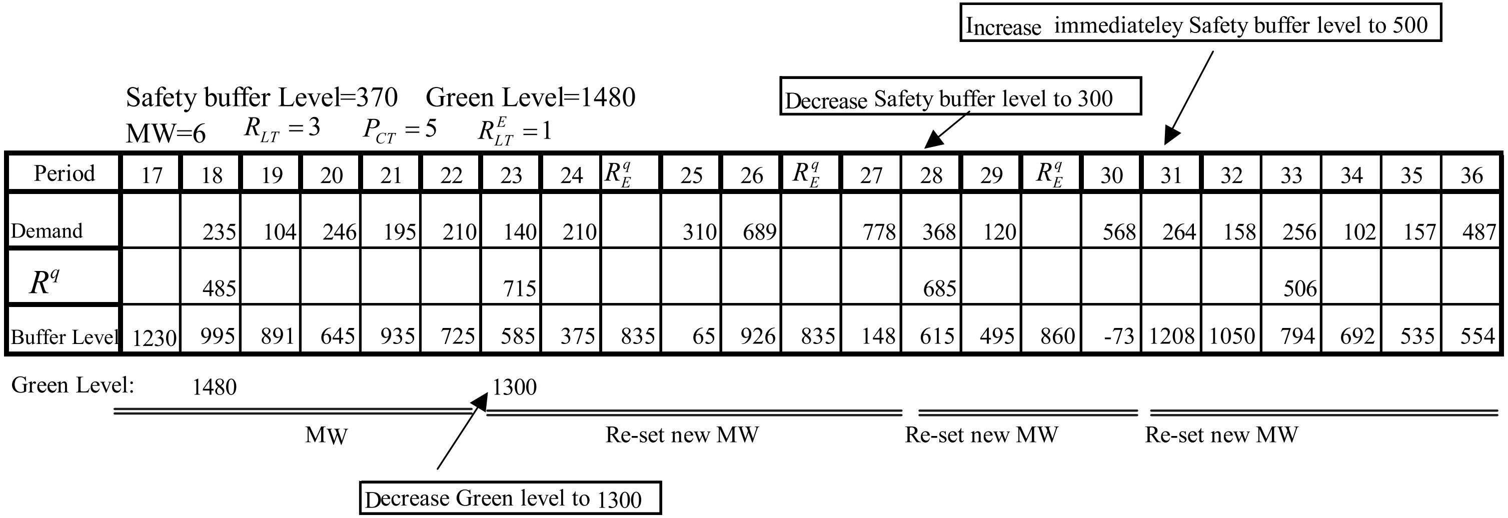
During period 27, a second penetration occurs, and an emergency replenishment order of 685 units is issued. Only the safety buffer level is decreased from 370 units to 300 units since no stock out occurs. Again, the safety buffer level is adjusted, and a new monitoring window must be reset. The monitoring window will start from period 28.

The 28th and 29th periods are as usual. During period 30, a sharp demand peak penetrates the safety buffer again and also causes a stock out problem. An emergency order is placed, and the safety buffer level is increased from 300 units to 500 units. (Again, this is a subjective adjustment.) The safety buffer level is shifted and a new monitoring window must be reset. The monitoring window will start from the 31st period.

4. Comparison

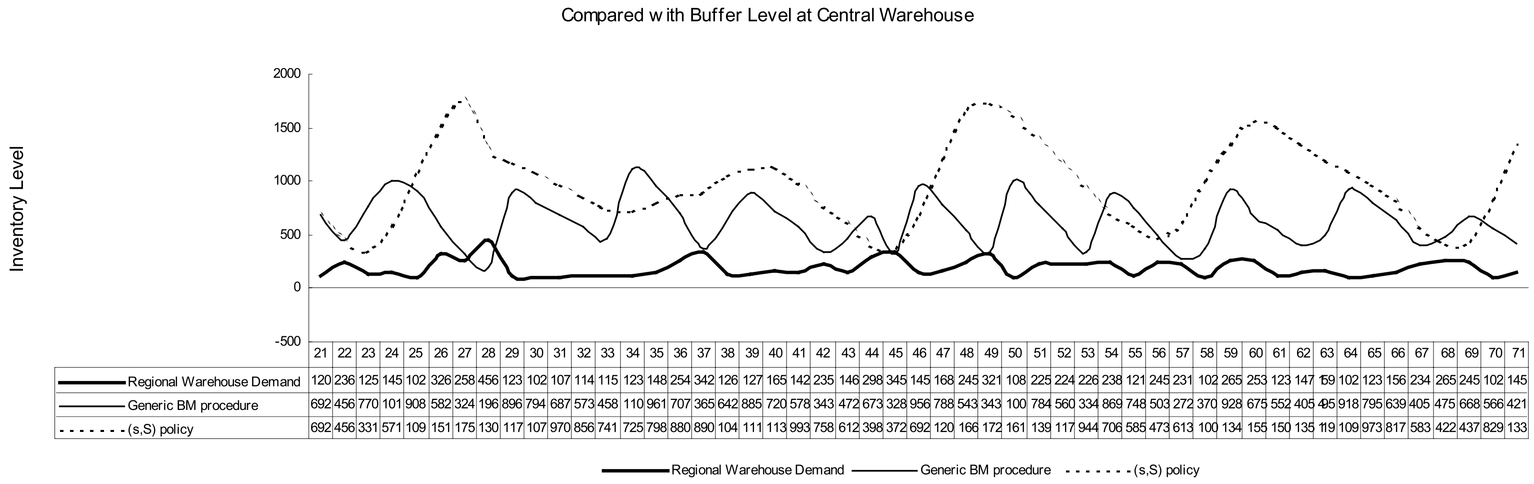
A continuous review system with (s, S) policy is used here to compare with the proposed generic buffer management procedure, and initially we set the buffer size equally for both methods. For the generic buffer management procedure, the order review horizon is set to five periods, the replenishment time is three periods, the urgently replenishment order is one period and the monitoring window is six periods. The green level is set equal to average period demand rope length (from a previous buffer) × 133% (peak usage allowance). For the continuous review system, the replenishment time is three periods, the urgently replenishment order is one period and we assume that no fixed order costs (David *et al.* 2000) where:

$$S = L \times \mathrm{AVG} + z \times \mathrm{STD} \times \sqrt{L}$$



Period	17	18	19	20	21	22	23	24	R_E^q	25	26	R_E^q	27	28	29	R_E^q	30	31	32	33	34	35	36
Demand		235	104	246	195	210	140	210		310	689		778	368	120		568	264	158	256	102	157	487
R^q		485					715							685						506			
Buffer Level	1230	995	891	645	935	725	585	375	835	65	926	835	148	615	495	860	-73	1208	1050	794	692	535	554

Figure 14. Example of a generic buffer management procedure.



	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
Regional Warehouse Demand	120	236	125	145	102	326	258	456	123	102	107	114	115	123	148	254	342	126	127	165	142	235	146	298	345	145
Generic BM procedure	692	456	770	101	908	582	324	196	896	794	687	573	458	110	961	707	365	642	885	720	578	343	472	673	328	956
(s,S) policy	692	456	331	571	109	151	175	130	117	107	970	856	741	725	798	880	890	104	111	113	993	758	612	398	372	692

	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
Regional Warehouse Demand	168	245	321	108	225	224	226	238	121	245	231	102	265	253	123	147	159	102	123	156	234	265	245	102	145
Generic BM procedure	788	543	343	100	784	560	334	869	748	503	272	370	928	675	552	405	495	918	795	639	405	475	668	566	421
(s,S) policy	120	166	172	161	139	117	944	706	585	473	613	100	134	155	150	135	119	109	973	817	583	422	437	829	133

Figure 15. Compared with buffer level at plant central warehouse.

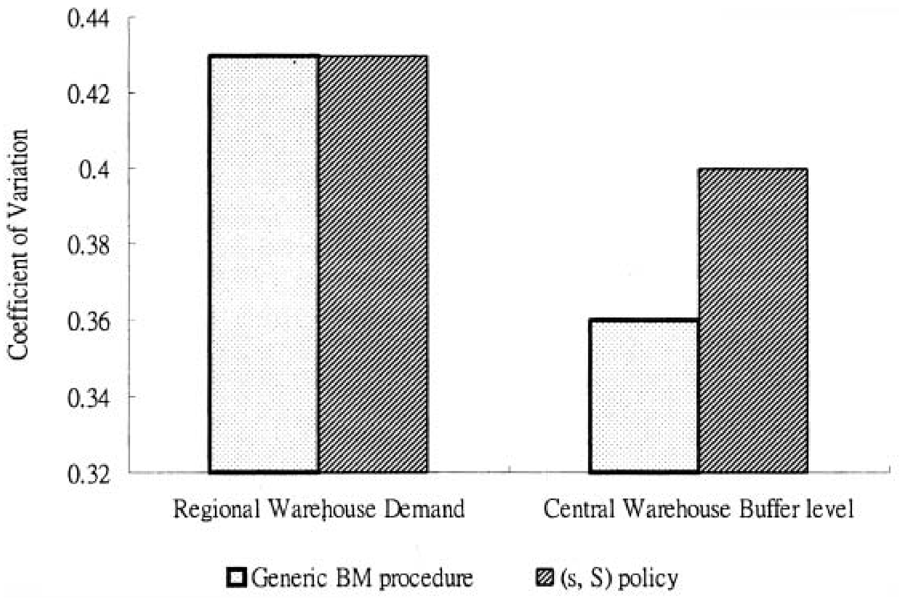


Figure 16. Coefficient of variation of buffer level at the plant central warehouse.

where STD is the standard deviation of period demand, AVG is the average period demand, L is the replenishment lead-time from the previous buffer and Z is the service level.

Demand at the regional warehouse is assumed to be random and a normal distribution, and the service level is set to 99.9% for both methods. The result of the average inventory for the continuous system (s, S) is higher than the generic buffer management procedure. The buffer level at central warehouse for both methods is illustrated in figure 15.

The coefficient of variation is measurement relative to the variation of average buffer inventory. The higher the coefficient of variation, the higher the impact safety stock on the reduction of buffer inventory. Since reduction in average inventory is achieved mainly through a reduction in safety stock, the higher the coefficient of variation, the larger the impact of safety stock on inventory reduction. The result also shows that the coefficient of variation for the proposed generic buffer management procedure is lower than the continuous review system (s, S) policy (figure 16).

5. Conclusion

This paper offered a generic buffer management procedure to enhance TOC replenishment. With the monitoring window review of the green buffer level and red buffer level, the procedure rigorously defined a means of sizing the buffer, monitoring it and correcting it when necessary. An example revealed the feasibility of the procedure. A comparison showed that the proposed buffer management procedure outperforms on buffer control management. Adopting the proposed procedure in a specific application environment is not difficult if the variables are defined according to the application environment.

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