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Dynamic TOC-based approach to planning and controlling accessories in MTO environments

P. Keyvani and M.M. Lotfi*

Department of Industrial Engineering, Faculty of Engineering, Yazd University, Yazd, Iran.

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ABC analysis;
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Abstract. In make-to-order systems, customers expect more freedom to choose the accessories they desire. However, demand variations and internal disorders cause uncertainties. Hence, a different inventory system is required for such items to dynamically manage those variations. In this paper, a dynamic approach based on the theory of constraints is proposed for inventory planning and control of accessories. First, the risk of processing time variation is balanced while keeping cycle time balanced. Second, the ribbons of buffer control charts are determined by a buffer planning model in which a multi-criteria ABC analysis is carried out to apply different customer service levels. To detect demand variations and monitor the buffer, trend of consumption in each monitoring window is carefully traced. In addition, simulation-based procedures are recommended to update control ribbons. The comparison between the performance of the proposed approach and those of common methods using the data of an automobile company, as well as several random test problems, confirms that the total cost and the efficiency of inventory system can be significantly reduced and increased, respectively.

1. Introduction

Inventories hold a strategic position in the operations of manufacturing enterprises. A good inventory management system is utilized to determine the right time to reorder and stipulate how much it requires to be supplied. Companies often need to manage several items in inventory; however, they may not be managed in the same way. In fact, without a structured methodology, it would be difficult to work well. Today, competition, especially in Make-To-Order (MTO) systems, is becoming more and more intense; therefore, the product customization will, indeed, be a necessary engagement for manufacturing companies. In such conditions, accessories, as the optional value-adding attachments to the main products, play an important role in ensuring high satisfaction for customers. Therefore, inventory planning and control of accessories and other items helps provide a good response to the varying requirements of customers.

However, stochastic nature of MTO environments may cause variability in the operational systems as a result of fluctuating demands, setup delays, machine breakdown, material delivery delays, operator delays, etc. [1]. Moreover, customers seek various accessories in different products; hence, the combination of accessories attached to the products frequently changes.

With frequent changes in the product mix, the assembly line may repetitively become unbalanced and the related process variability would be amplified. High variations in the process times and demand trends in MTO environments may lead to an increase in the system costs and customers' dissatisfaction. Companies that could not quickly respond to the fluctuating

*. *Corresponding author.*
E-mail addresses: Parvaneh.Keyvani@gmail.com (P. Keyvani); Lotfi@yazd.ac.ir (M.M. Lotfi)

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environment will be forced to leave competition little by little. This variation, thus, should be managed by a dynamic approach. In this paper, a multi-step approach based on the Theory Of Constraints (TOC) is proposed for dynamic planning and control of accessories in MTO environments.

The rest of the paper is organized as follows. In Section 2, the relevant and supportive body of literature is reported. Section 3 is devoted to the proposed dynamic multi-step approach. Computational experiments are analyzed in Section 4. Managerial insights are presented in Section 5. Finally, this paper closes with the concluding remarks and directions for any future study.

2. Literature review

The existing literature regarding planning and control of accessories is quite limited. Büchel [2] introduced stochastic thinking into MRP by means of a usage ratio for optional components, showing the ratio of demands for the components to the total demands for different final products. He first developed a model so as to determine those factors that influence the parameters of the usage ratio distribution and, then, demonstrated how the stochastic usage ratios might be included in an MRP procedure to reduce demand uncertainty. However, he stated that small usage ratios caused considerable demand variations and made high safety stocks (high inventory costs) necessary, or impaired the delivery performance.

Wang and Hu [3] formulated a (Q, r) model for the correlative demands between the necessary components and the optional components. They incorporated the service costs into the budget constraint in a multi-item inventory control system and proposed two heuristic procedures to solve the model. They [4] presented a multi-item (Q, r) model for the correlative demands between the necessary and optional components. The maximum investment in the inventory was assumed to be random. Notably, they assumed in both papers that the demand for each optional component depends upon the customers' demands and is mutually independent of the other optional components, while the demands of optional components are related together because of their commonality and substitutability characteristics. Moreover, they considered that all the products were bought, did not address the capacity limitations, and did not regard the importance level of inventories in their model. In addition, their system could not dynamically control the inventories. As a result, the proposed model may repetitively become infeasible due to frequent changes in the demands of accessories and should be run again. Lee and Lee [5] developed an approximation for a continuous review inventory system. The demand distribution of subassemblies and accessories was assumed to follow a bivariate normal distribution because of the system interaction between subassemblies and accessories. The problem was difficult to solve due to the bivariate normal distribution.

Notably, as the inherent diversity, the production lines for accessories in MTO systems require to be able to produce various models. In this condition, the well-known mixed Model Assembly Lines (MAL) are used to produce various models of accessories on the same line. The Mixed model Assembly Line Balancing Problem (MALBP) was firstly introduced by Thomopoulos [6,7]. In this regard, a number of research studies have been published; however, none of them considered the impact of variability on the task times. Udayakumar [8] presented a mathematical model to address the impact of variability on the task times in a single model manual assembly line balancing problem. After that, Sharma et al. [9] introduced a heuristic method to balance the risk among the workstations of a single assembly line. Recently, Keyvani and Lotfi [10], concerning the impact of variability on the task times, proposed a heuristic algorithm for risk balancing while simultaneously keeping the cycle time balanced. This paper applies a similar algorithm to balance MAL for producing accessories under MTO environments.

In the past, the standard cost accounting methods were used to establish make-or-buy decisions. However, such methods ignore possible production constraints in determining the total output of the system. Hence, they lead to an increase in the costs and a decrease in the performance. Gardiner and Blackstone [11] proposed a method for incorporating the bottleneck capacity into the make-or-buy decisions; however, it did not ensure the best solution to more complicated problems. They discussed the Contribution Per Constraint Minute (CPCM) criterion. CPCM is the contribution generated when a bottleneck resource contributes one minute to the process of production. They showed that the standard cost method for making an outsourcing decision was inferior to the CPCM. Balakrishnan and Cheng [12] used a spreadsheet-based optimizer for greater effective implementation of make-or-buy decisions. This method is not appropriate for large-sized instances.

To formulate an inventory planning model, distinction should be made among the accessories by applying the distinct customer service levels. Due to the aforementioned characteristics of accessories in the MTO environments, the traditional ABC analysis characterized by a single criterion (usually, annual dollar usage) may fail to provide proper classification in practice. In this regard, the problem of Multi-Criteria Inventory Classification (MCIC) has been addressed by some researchers in the literature. The well-known criteria considered in the literature include inventory costs, part criticality, lead time, commonality, obsolescence, substitutability, scarcity, durability, and stock-out costs [13]. Notably, there are many MCIC methods such as cross-tabulate matrix methodology [14], clustering analysis [15], analytic hierarchy process [16], and heuristic algorithms [17,18]. However, such methods are difficult for the inventory managers to understand and apply.

Recently, Data Envelopment Analysis (DEA) has been widely used in this area. Ramanathan [13] proposed a weighted linear optimization model; however, the model could lead to a situation where an item with a high value and an unimportant criterion is inappropriately classified as a Class-A item. Zhou and Fan [19] extended the same model and provided a more reasonable and encompassing criterion using two sets of weights, the most and the least favorable, for each item. Chen [20] proposed a peer-estimation approach. He determined two common sets of weight for criteria and aggregated the results of the two performance scores in the most favorable and least favorable ways for each item without any subjectivity. However, the method is also complicated and difficult to implement.

Ng [21] proposed a new weighted linear optimization model in order to convert all the criteria of an inventory item into a scalar score. The decision-maker ranked the criteria in descending order in terms of the importance level. The weights were automatically generated when the model was optimized. This differs from other methods such as AHP in which the weights are specified exogenously. Hadi-Vencheh [22] pointed out that the inventory score of an item in [21] was independent of the weights associated with each criterion. This means that the weight of each criterion becomes irrelevant in determining the aggregate score of an item. Babai et al. [23] carried out service-cost performance index analysis of four MCIC models [13,19,21,22]. They concluded that [13] and [19] performed better. In this paper, the model [21] was used to classify the accessories. The results were applied to determine the control ribbon sizes of buffer control charts.

Due to the mentioned variability in the MTO production systems and the order arrivals, the accessories must be dynamically managed. TOC controls the buffer size adjustments by a Dynamic Buffer Management (DBM) technique in which the inventory control is done by some control charts. The charts are divided into three controlling ribbons: green, yellow, and red. Hence, the dynamic control charts of DBM technique are employed in this paper. In this way, the consumption trends are traced in the Monitoring Windows (MW); if any changes are detected, then controlling ribbons are updated. Yuan et al. [24] proposed a generic buffer management procedure. For example, if the red ribbon is penetrated more than one time during an MW and stock out does occur, then an emergency order is placed and the green buffer level is increased. Kaijun and Wang Yuxia [25] introduced three inventory control policies based on the DBM and used a simulation approach to compare them to the (s,S,T) policy. Reyes et al. [26] proposed a model to manage the inventory by DBM. They used the technique of colors and materials reviewed by DBM. This generated 18.7% of annual saving in inventory costs. As found in the previous studies, no method was proposed to determine the length of MW. In addition, the procedures proposed updating the controlling ribbons regardless of the system's conditions. In this paper, some procedures are recommended to update the controlling ribbons using the simulation. In addition, the results of ABC analysis are applied to determine the length of MW.

There are various methods for inventory planning and control such as MRP, JIT, and TOC. MRP naturally tends to hold a large amount of inventory. On the other hand, JIT works well in a balanced environment; however, the MTO production system will frequently become unbalanced due to the variations in the arrival of orders and product mix. TOC, accepting an imbalanced system, is an approach to continuous improvement, originally developed by Goldratt et al. [27]. Recently, it has successfully been applied to the fields such as operations, finance, projects, distribution and supply chains, marketing and sales, and strategy and tactics [28]. Gundogar et al. [29] analyzed spring mattress line of a furniture manufacturing company. The company sought to increase its production output with new investments. The objective was to find the bottlenecks in production line in order to balance the semi-finished material flow. Several different scenarios were tested to improve the manufacturing system.

In the previous works regarding the inventory planning and control, the dynamic nature of accessories in the MTO systems was not considered. In fact, they should be run again after any change in the parameters. For example, they did not address the risk of the inherent variability when balancing the assembly line and determining the make-or-buy decisions. Moreover, they did not take the importance of accessories into account when designing the inventory control system. In addition, in the existing static inventory control charts, changes in the parameters were not recognized while updating the control ribbons in response to the critical fluctuations. Finally, in order to balance the inventory costs, updating the control charts must be done according to the importance level of inventories. To consider the above gaps, in this paper, a dynamic multi-step approach based on the TOC philosophy is proposed to treat the inventory planning and control of accessories in the MTO systems.

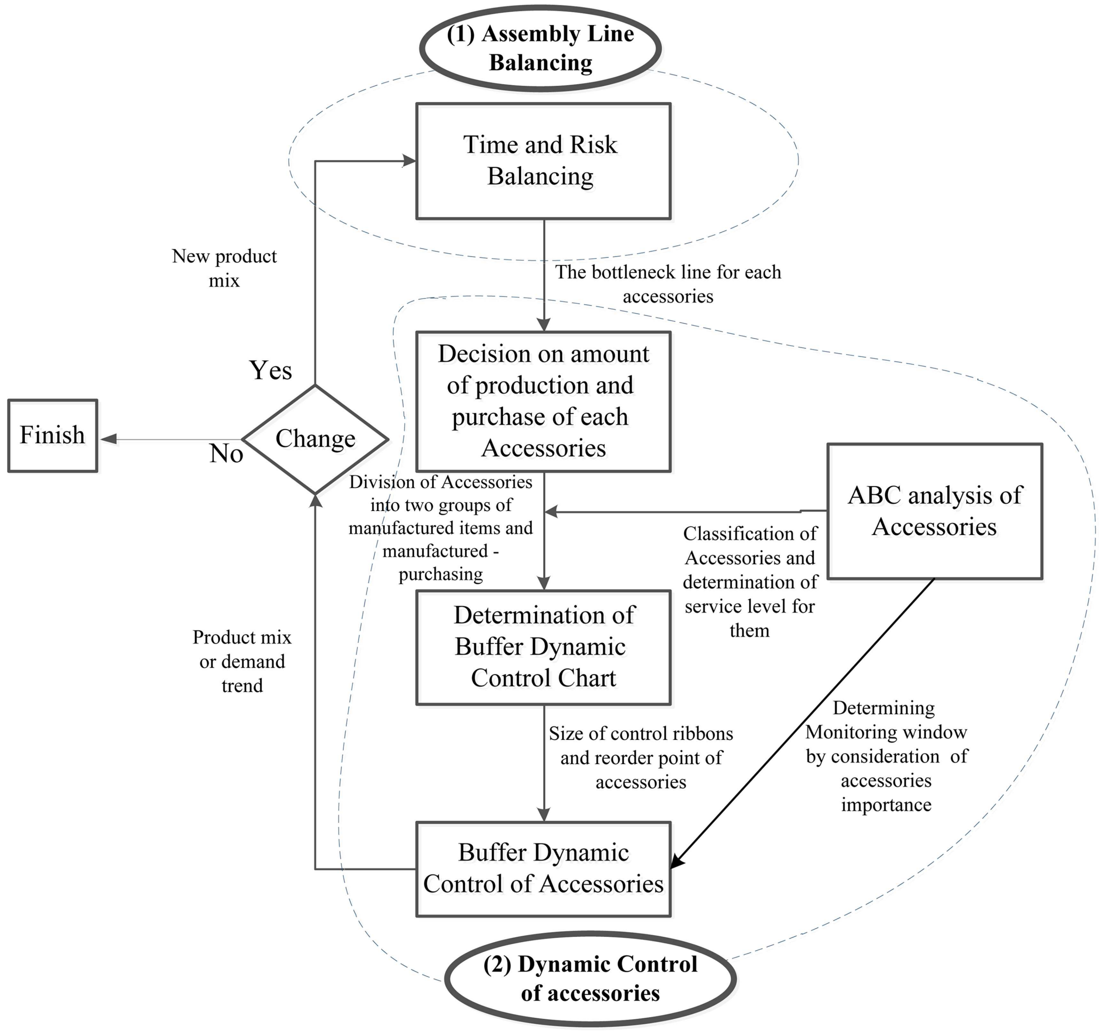

Figure 1. TOC-based approach to dynamic inventory planning and control of accessories.

3. Dynamic TOC-based approach

In this section, the proposed dynamic TOC-based inventory planning and control approach is described. A schematic view is presented in Figure 1.

3.1. Assembly line balancing

In the MTO systems, any order arrival may cause a change in the product mix, which needs the MAL to be rebalanced. To evenly distribute the workload among the workstations, MALBP involving the reassignment of tasks of all the product models is applied [30]. However, as a result of natural variability, the tasks may not be completed in a specific cycle time, causing delays. The larger the variability of task time, the higher the associated risk. Because of the workload variation for different models, this variability would be amplified in MALs. Thus, in addition to cycle time, its risk has to be balanced for increasing efficiency. Risk is the potential loss that occurs when any product model fails to complete in the specific time and the cycle time exceeds the standard time. Most of the recent work studies considered the bottleneck as "a resource already working at its full capacity"; however, if a given non-bottleneck workstation has high variability, there is a significant probability that it will become bottleneck. Consequently, it is critical to consider risk in MALBP together with the cycle time.

3.1.1. The risk-based heuristic algorithm

A risk of task has three components including magnitude, frequency, and exposure. Magnitude is the deviation of actual completion time from the standard time; frequency is the number of times the actual completion time exceeds the standard time, and exposure is the processing time exposed. The risk-based algorithm proposed by Keyvani and Lotfi [10] to balance MAL in the MTO environments is as follows:

1. Inputs: joint precedence diagram of different product models as well as initial time balancing of MAL.

2. Calculation of Risk Index (RI) of each task.
3. Calculation of risk index of each workstation.
4. Calculation of the mean risk of workstations ($\overline{RI}$). If all the workstations have a risk equal to $\overline{RI}$, MAL is balanced; otherwise, the next steps should be taken.
5. Calculation of absolute distance between the risk and mean risk of workstations for workstation k:

$$DRI_K = \left|\overline{RI} - B_k\right| \qquad \forall\ k. \tag{1}$$

6. Balancing the risk in MAL by sharing DRI of bottleneck to the other workstations. Workstation with the maximum value of B_k is denoted as bottleneck. By implementing a trial-and-error approach, additional risk among the workstations is distributed considering the precedence diagram and initial time balancing.
7. Calculation of the new total DRI by Eq. (2). The lower value of DRI means a better balance:

$$DRI = \sum_{k=1}^{K} DRI_K. \tag{2}$$

3.2. Dynamic planning and control of accessories

For dynamic planning and control of the accessories, the following steps (as depicted in Figure 1) should be performed.

3.2.1. Make-or-buy decisions for accessories

For each accessory, first, the Profits Per Minute of Bottleneck (PPMB) are calculated by the output of risk-based balancing algorithm. Then, PPMB is used to optimize the production and purchasing quantity of accessories.

Parameters

q	Accessory
s	Resource
CP_q	Purchasing cost for accessory q
RMC_q	Raw material cost for accessory q
t_{qs}	Required capacity of resource s for producing one unit of accessory q
T_{Cons_q}	Required time of bottleneck for producing one unit of accessory q
AC_s	Available capacity of resource s
D_q	Demand of accessory q

Decision variable

P_q Production amount of accessory q

Proposed model

$$\max\ Z = \sum_q \frac{P_q(CP_q - RMC_q)}{T_{\text{Cons}_q}}. \tag{3}$$

Accordingly, we determine which item is economically eligible to consume the bottleneck capacity.

$$\sum_q P_q t_{qs} \leq AC_s \qquad \forall\ s, \tag{4}$$

$$P_q \leq D_q \qquad \forall\ q, \tag{5}$$

$$P_q \geq 0. \tag{6}$$

Objective function (3) maximizes the total PPMB. The resource constraints are provided in Relation (4). Constraint (5) ensures that the production quantity of each accessory is less than the demands. Notably, if the optimized value of P_q is equal to the demand, it can be fully produced inside the factory. Otherwise, purchasing should, also, be planned. Accordingly, accessories are divided into two groups ($q = a \cup e$; a: set of only-produced accessories, e: set of partly purchasing accessories). It is worth noting that the proposed model is a small-sized linear one; hence, it can easily be solved by the optimization solvers of GAMS programming language.

3.2.2. ABC analysis of accessories

In this paper, MCIC is proposed with respect to four criteria:

1. Annual dollar usage;
2. Commonality;
3. Lead time, positively related to the importance level of each item;
4. Substitutability, which is a negatively-related criterion.

Parameters

j	Criterion
y_{qj}	Value of criterion j for accessory q

Decision variable

w_{qj} Weight of accessory q under criterion j

ABC analysis model [21]

$$\max\ S_q = \sum_{j=1}^{J} w_{qj} y_{qj} \qquad \forall\ q, \tag{7}$$

$$\sum_{j=1}^{J} w_{qj} = 1 \qquad \forall\ q, \tag{8}$$

$$w_{qj} - w_{q(j+1)} \geq 0 \qquad \forall\ j = 0, 1, \cdots, (J-1), \tag{9}$$

$$w_{qj} \geq 0, \qquad j = 1, 2, \cdots, J. \tag{10}$$

Objective function (7) maximizes the weighted score of accessory q as a value between 0 and 1. The larger the value of S_q, the higher the importance level of q. Constraint (8) is determined for normalization. Constraint (9) is aimed at ensuring the sequence of criteria ranking. This model should be run for each q. It is a small-sized continuous linear one; hence, it may be solved easily. The accessories are sorted in descending order of scores. Then, about 5-20% of the accessories with the highest scores are placed in Class A; the next 30-40% is embedded in Class B and the remaining 40-50% in Class C. In this paper, different inventory control systems are proposed for each class.

3.2.3. Buffer planning of accessories

Considering the output of the previous step, an optimization model is proposed to determine the parameters of control chart ribbons. Most companies might not tend to increase the production capacity when the demands are greater than the production rate because it is time consuming, costly, and even bulky. They prefer purchasing or accepting backorder. The assumptions of buffer planning model are as follows:

- Demand rate is distributed normally;
- Production rate is considered deterministic;
- Backorder is permitted;
- Purchasing is done just once in the first period.

Parameters

t_{1a}	Time interval during which accessory a is produced to meet backorder
t_{2a}	Time interval during which accessory a is produced and inventory increases
t_{3a}	Time interval during which accessory a is consumed only and inventory is positive
t_{4a}	Time interval during which backorder for accessory a will occur
ts_a	Setup time of accessory a
A_a	Setup cost of producing accessory a
D_a	Demand average of accessory a
σ_{D_a}	Demand standard deviation of accessory a
P_a	Production rate of accessory a
C_a	Per unit production cost of accessory a
h_a	Per unit holding cost of accessory a
sc_a	Per unit backorder cost of accessory a
tp_a	Production cycle of accessory a
T_{Cons_a}	Available time at bottleneck resource for producing accessory a
α_a	Risk level of accessory a (shortage probability) based on the ABC analysis
$z_{1-\alpha_a}$	Standard normal score of service level for accessory a
L_a	Lead time of accessory a
f_a	Per unit required space of accessory a in warehouse

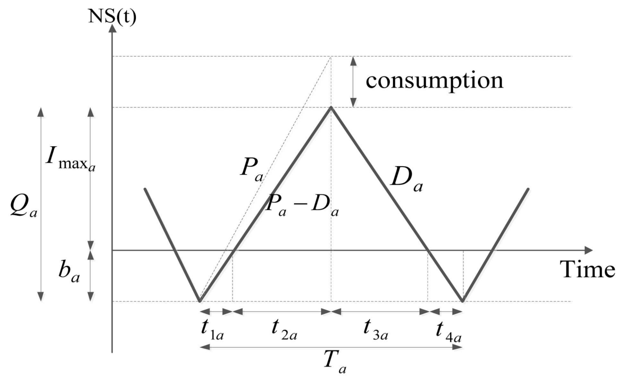

Figure 2. Inventory versus time graph of accessory a.

Decision variables

Q_a	Production quantity of accessory a in each period
b_a	Backorder quantity of accessory a in each period
ss_a	Safety stock of accessory a in each period
rr_a	Order point of accessory a in each period
T_a	Length of period for accessory a (Figure 2)

According to Figure 2, we have:

$$T_a = t_{1a} + t_{2a} + t_{3a} + t_{4a} = \frac{Q_a}{D_a}, \tag{11}$$

$$I_{\max_a} = Q_a \left(1 - \frac{D_a}{P_a}\right) - b_a, \tag{12}$$

$$\overline{I_a} = \frac{I_{\max_a}(t_{2a} + t_{3a})}{2}, \tag{13}$$

$$\overline{b_a} = \frac{b_a(t_{1a} + t_{4a})}{2}. \tag{14}$$

Consequently, cost objective function for only producing accessories is developed in Eq. (15) as follows:

$$Z_1 = \sum_a \frac{1}{T_a} \left[A_{1a} + h_a \left[\overline{I_a} + ss_a\right] + sc_a \left[\ \overline{b_a}\ \right]\right]. \tag{15}$$

Extra notations for partly purchasing accessory e are presented as follows:

A_{1e}	Setup cost of producing accessory e
A_{2e}	Order cost of purchasing accessory e

C_{1e} Per unit production cost of accessory e

C_{2e} Per unit purchasing cost of accessory e

Decision variables

Q_{1e} Production quantity of accessory e in each period

Q_{2e} Purchasing quantity of accessory e in each period

b_e Backorder quantity of accessory e in each period

ss_e Safety stock of accessory e in each period

rr_e Order point of accessory e in each period

R_e Net inventory at the beginning of production cycle for accessory e

y_{1e} Production binary variable of accessory e

y_{2e} purchasing binary variable of accessory e

T_e : Length of period for accessory e

According to Figure 3, we have:

$$Q_{1e} = \frac{(R_e + b_e)(P_e)}{D_e - P_e}, \tag{16}$$

$$T_e = \frac{D_e Q_{2e} + P_e(R_e + b_e - Q_{2e})}{D_e(D_e - P_e)}. \tag{17}$$

Therefore, the cost objective function of partly purchasing accessories is obtained through Eq. (18) as shown in Box I.

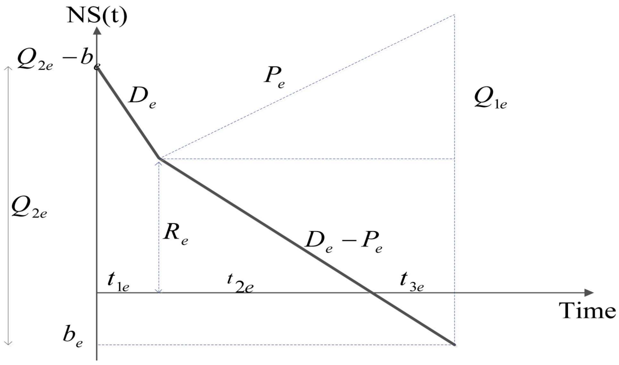

Figure 3. Inventory versus time graph of accessory e.

The proposed model for buffer planning

$$\min \ Z_1 + Z_2, \tag{19}$$

$$\frac{Q_a}{P_a} + ts_a \leq T_{\text{Cons}_a} \qquad \forall\, a, \tag{20}$$

$$\frac{Q_{1e}}{P_e} + ts_e \leq T_{\text{Cons}_e} \qquad \forall\, e, \tag{21}$$

$$\sum_a f_a(I_{\max_a}) + \sum_e f_e(I_{\max_e}) \leq F$$

$$\rightarrow \sum_a f_a\left(Q_a\left(1 - \frac{D_a}{P_a}\right) - b_a\right)$$

$$+ \sum_e f_e(Q_{2e} - b_e) \leq F, \tag{22}$$

$$Z_2 = \sum_e \left[\frac{1}{T_e}\right]\left[(C_{1e}Q_{1e} + C_{2e}Q_{2e}) + (A_{1e}y_{1e} + A_{2e}y_{2e}) + \left(\frac{h_e}{2}\left[R_e\left(\frac{R_e}{D_e - P_e}\right) + \left(Q_{2e} - \left(\frac{Q_{1e}(D_e - P_e) - R_e(P_e)}{P_e}\right) + R_e\right) \cdot \left(\frac{Q_{2e} - \frac{Q_{1e}(D_e - P_e) - R_e(P_e)}{P_e} - R_e}{D_e}\right)\right] + h_e(ss_e + Q_{1e})\right) + \left(SC_e\left[\frac{b_e}{2}\left(\frac{b_e}{D_e - P_e}\right)\right]\right)\right]. \tag{18}$$

Box I

$$\sum_a C_a Q_a + \sum_e (C_{1e} Q_{1e} + C_{2e} Q_{2e}) \leq B, \tag{23}$$

$$p(D_a \leq rr_a) \geq 1 - \alpha_a \qquad \forall\, a, \tag{24}$$

$$p(D_e \leq rr_e + Q_{1e}) \geq 1 - \alpha_e \qquad \forall\, e, \tag{25}$$

$$R_e \leq Q_{2e} - b_e \qquad \forall\, e, \tag{26}$$

$$Q_{1e} \leq M y_{1e} \qquad \forall\, e, \tag{27}$$

$$Q_{2e} \leq M y_{2e} \qquad \forall\, e. \tag{28}$$

F and B are available warehouse space and budget, respectively. Objective (19) minimizes the total inventory costs. Constraints (20) and (21) ensure that the sum of production and setup time is not greater than the bottleneck time. Constraints (22) and (23) are warehouse space and budget limitations. Constraints (24) and (25) show the service level of accessories considering the results of ABC analysis. Constraint (26) indicates the minimum value of net inventory to start production. Constraints (27) and (28) are as-controlled constraints, and M is a big number.

Of note, the chance-constrained programming is used to convert Constraints (24) and (25) to the deterministic equivalents:

$$ss_a \geq z_{1-\alpha_a} \sqrt{L_a} . \sigma_{D_a} \qquad \forall\, a, \tag{29}$$

$$ss_e + Q_{1e} \geq z_{1-\alpha_e} \sqrt{L_e} . \sigma_{D_e} \qquad \forall\, e. \tag{30}$$

Although the model dimension is inherently small, it is quadratic and fractional. In addition, Constraints (22) and (23) are complicated ones. The model is nonlinear and non-convex; therefore, an exact solution is hardly found, even for small-sized instances. Therefore, in this paper, an iterative algorithm is developed.

3.2.4. Iterative algorithm

Decision variable T is a complicated variable; therefore, an upper bound for it is proposed. Then, starting from the upper bound, T decreases with a specified step size until it is greater than zero. The model is solved for each T; the optimum solution is characterized as the minimum value of the objective function. Upper bound for T_e is presented as objective function (31) of the following optimization model:

$$\max\ T_e = \frac{D_e Q_{2e} + P_e (R_e + b_e - Q_{2e})}{D_e (D_e - P_e)}, \tag{31}$$

$$T_e \geq \frac{Q_{2e}}{D_e}, \tag{32}$$

$$T_e \geq \frac{Q_{1e}}{D_e}, \tag{33}$$

$$T_e \leq \frac{b_e + R_e + Q_{1e}}{P_e}, \tag{34}$$

$$T_e \leq T_{G_e}. \tag{35}$$

Constraints (32)-(34) are obtained from Figure 3. Notably, the demand of accessories is fluctuating. In this paper, a periodic review system is used; therefore, T_{G_e} in Constraint (35) is the average number of previous periods where the demand trend of accessory e has changed. For example, if the order review period of one accessory is 5 and demand changes throughout all 3 periods, the order review period should be considered less than 3 periods.

Upper bound for T_a is presented in the form of objective function (36) of the following optimization model:

$$\max\ T_a = \frac{Q_a}{D_a}, \tag{36}$$

$$T_a \leq T_{G_a}. \tag{37}$$

Accordingly, the pseudocode of iterative algorithm is given in Figure 4.

3.2.5. Dynamic buffer control of accessories

It is difficult for many factories to apply the principle of having the right stock in the right place at the right time. They hold high levels of inventory, which is an expensive work. Due to the variability of the production process and demand trend of accessories, buffer management must dynamically be managed. Since the buffer size reflects the consumption pattern, DBM frequently monitors and adjusts (decrement or increment) the buffer size whenever required. The DBM control chart has two parts: ribbons and Monitoring Windows (MW).

Ribbons

As shown in Figure 5, buffer should be divided into the following three controlling ribbons:

1. Green: The ribbon is determined to protect against peak consumption. If the buffer drops into this ribbon, no action is required. Its size has high effect on the system's performance. If the effect is too high, then inventory costs will increase, while if it is too low, buffer level tends towards the red ribbon;
2. Yellow: the intermediate level, where the normal on-hand stock should be; if the buffer drops further into the yellow ribbon, warning and planning will be necessary;
3. Red: Immediate action must be taken. Its size affects the nervousness of the system. If it is too low or too high, wrong action is more likely to be signaled [24,30].

In this paper, green and red ribbons in the first MW are calculated by the buffer planning model.

Input:

$Tmax_a$\Upper bound of T_a

$Tmax_e$\Upper bound of T_e

k\ Step size

Output:

T_a, T_e, SS_a, SS_e, Q_{1a}, Q_{1e}, Q_{2e}, b_a, b_e

Procedure:

1. T_a=$Tmax_a$
2. T_e=$Tmax_e$
3. while T_a>0 do
4. while T_e>0 do
5. Solve model (3)-(8) and save the solution
6. $T_a = T_a - k$
7. $T_e = T_e - k$
8. end while
9. end while
10. Use the solution with the minimum objective function value.

Figure 4. Pseudo code of iterative algorithm.

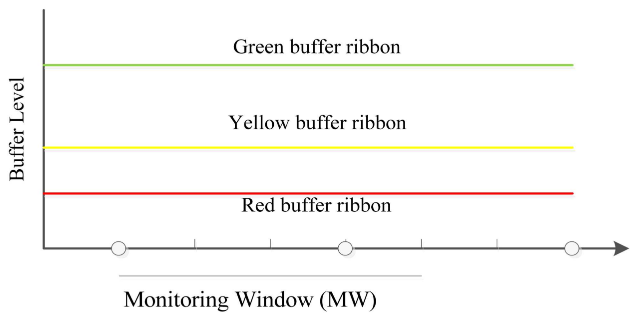

Figure 5. TOC buffer management with three ribbons [25].

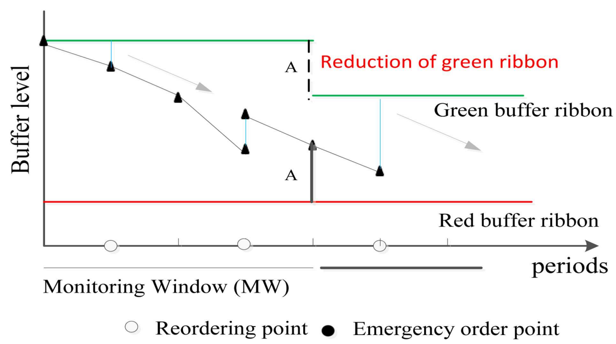

Figure 6. Reducing green buffer zone and resetting MW.

Green ribbon is assumed to be $(ss_a + Q_a - b_a)$ and $(ss_e + Q_{1e} + Q_{2e} - b_e)$ for a and e, respectively. Red ribbon is assumed to be (ss_a) and (ss_e). DBM is applied as a periodic review procedure; at the end of each period, if buffer level is less than green ribbon, order is placed. The order quantity is equal to green ribbon minus the buffer level.

Monitoring Windows (MW)

The buffer consumption trend in each MW is controlled. If any changes are detected in the consumption trend, controlling ribbons will be updated in the next MW. Notably, both high and low control levels exert high costs for the inventory system; therefore, the control level should be consistent with the importance level. Class A should be monitored moment by moment; however, Classes B and C require less control. To do so, considering the system's condition, different procedures should be followed:

A. *No penetration of buffer level to red ribbon during the MW.* It appears that green buffer line is too high; thus, green ribbon is reduced similar to the amount of red ribbon. Then, MW is reset and the next monitoring is initiated, as shown in Figure 6;

B. *Penetrating less than n times to red ribbon without backorder during the MW.* An emergency replenishment order as the amount of red ribbon minus buffer level is triggered, as shown in Figure 7;

C. *Penetrating less than n times to red ribbon with backorder during the MW.* An emergency replenishment order as the amount of red ribbon minus buffer level is triggered. Moreover, red ribbon increases to reach half of the difference between average demand in the current and next periods, as shown in Figure 8;

D. *Penetrating at least n times to red ribbon without backorder during the MW.* Both the emergency

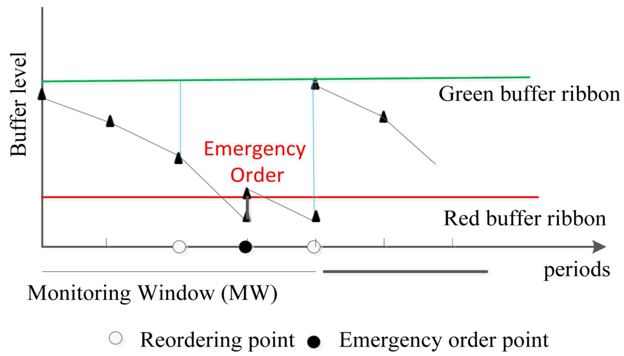

Figure 7. Penetration of the safety buffer level.

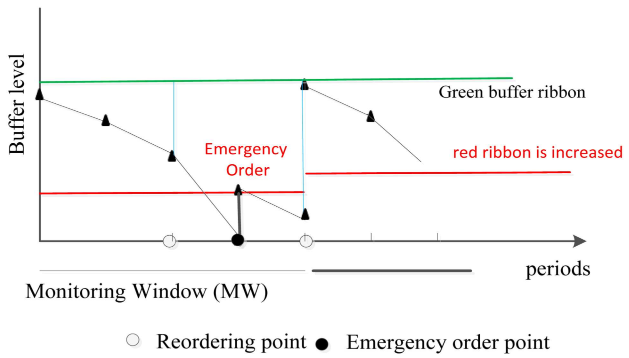

Figure 8. Stock-out, increasing red ribbon and resetting the MW in the next period.

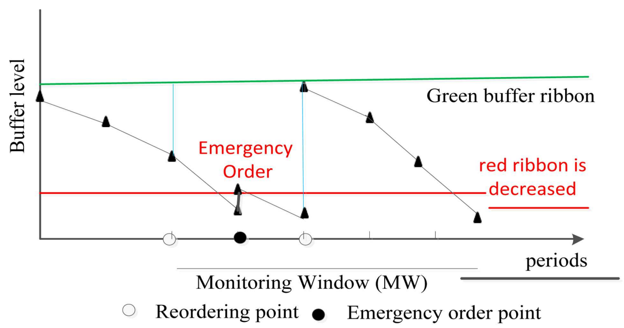

Figure 9. At least n times penetration but not stock-out, decreasing the red ribbon in the next period.

replenishment order is triggered and the red ribbon is reduced to the amount of the emergency replenishment order, as shown in Figure 9;

E. *Penetrating at least n times to red ribbon with backorder during the MW.* An emergency order is triggered. Moreover, green ribbon increases to reach the amount of emergency replenishment order + half of the difference between average demand in the current and next periods, as shown in Figure 10.

4. Computational experiments

To confirm the proper performance of the proposed

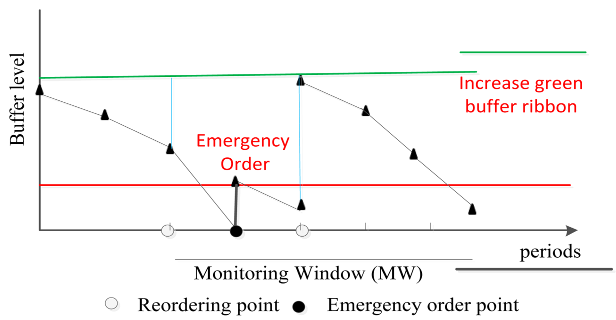

Figure 10. At least n times penetration and stock-out, increasing green buffer zone and resetting MW.

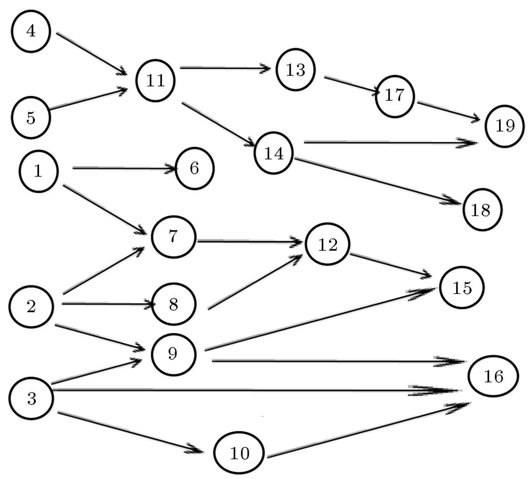

Figure 11. Joint precedence diagram.

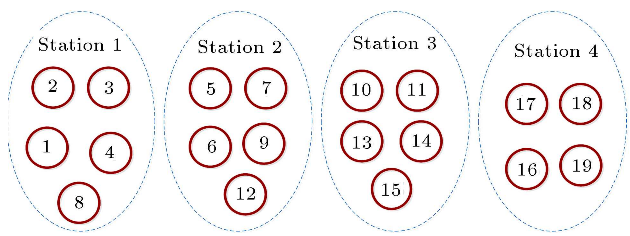

Figure 12. Initial time balancing.

approach, first, a real case is studied. Data is collected in an automobile company. Eight accessories are applied to different product models; accessories can substitute each other, some of which are common in different models. The company's reputation is rapidly decreasing due to the failure to respond to the customers on time.

4.1. Line balancing

The joint precedence diagram of eight accessories is depicted in Figure 11. Standard task times are given in Table 1. Current cycle time is 2.25 min and product mix is (0.20, 0.13, 0.12, 0.15, 0.10, 0.10, 0.10, 0.10). For applying the risk-based heuristic algorithm, the initial solution considering only cycle time is used, as shown in Figure 12. The corresponding risk is calculated in Table 2. As observed, risk of Station 3 is too high due

Table 1. Standard task times.

Task	Accessory							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	0.10	0.20	0.20	0.20	0.20	0.20	0.10	0.20
2	0.40	0.40	0.40	0.40	0.40	0.40	0.30	0.30
3	0.00	0.10	0.10	0.10	0.10	0.10	0.20	0.10
4	0.30	0.30	0.30	0.30	0.40	0.40	0.10	0.10
5	0.20	0.20	0.00	0.00	0.00	0.30	0.30	0.10
6	0.20	0.20	0.20	0.20	0.20	0.20	0.40	0.00
7	0.20	0.20	0.20	0.20	0.10	0.20	0.20	0.20
8	0.00	0.10	0.10	0.00	0.00	0.00	0.00	0.00
9	0.40	0.00	0.30	0.30	0.30	0.30	0.60	0.20
10	0.00	0.30	0.30	0.30	0.30	0.30	0.30	0.50
11	0.20	0.20	0.20	0.20	0.10	0.50	0.50	0.10
12	0.10	0.10	0.00	0.15	0.50	0.10	0.10	0.30
13	0.10	0.10	0.10	0.10	0.10	0.30	0.30	0.20
14	0.20	0.20	0.20	0.00	0.10	0.20	0.30	0.30
15	0.60	0.00	0.10	0.10	0.10	0.40	0.20	0.40
16	0.00	0.30	0.30	0.30	0.12	0.10	0.10	0.30
17	0.10	0.20	0.20	0.20	0.10	0.10	0.30	0.30
18	0.30	0.10	0.10	0.10	0.20	0.20	0.20	0.20
19	0.40	0.10	0.10	0.10	0.10	0.10	0.30	0.50

Table 2. Station risks in initial time balancing.

Station	Task	Risk	Total risk
1	1	1.64	4.26
	4	1.60	
	3	0.00	
	2	1.02	
	8	0.00	
2	9	0.45	3.01
	5	0.70	
	7	0.89	
	6	0.61	
	12	0.36	
3	15	0.57	7.36
	11	1.25	
	10	0.00	
	13	3.24	
	14	2.30	
4	18	1.33	3.40
	17	1.38	
	19	0.69	
	16	0.00	
Total risk (RI)			18.03
Average risk ($\overline{RI}$)			4.51

to Task 13. Risk deviation of each station from $\overline{RI}$ is given in Table 3.

Station 3 is bottleneck; its tasks have the highest variability. Hence, in terms of the precedence diagram and cycle time of 2.25, additional risk of Station 3 is distributed among the other stations (Table 4 and Figure 13). Accordingly, DRI is reduced from 5.712 to 2.53, whereas cycle time does not exceed 2.25 min.

Table 3. Risk deviations from $\bar{R}I$ in initial line balancing.

	Station				
	1	**2**	**3**	**4**	**MAL**
DRI	0.244	1.502	2.856	1.110	5.712

Table 4. Time and risk balancing.

Station	Task	Risk	Station risk	*DRI*
1	1	1.64	4.96	0.46
	2	1.02		
	3	0.00		
	4	1.60		
	5	0.70		
	8	0.00		
2	6	0.61	3.55	0.95
	7	0.88		
	9	0.45		
	11	1.25		
	12	0.36		
3	10	0.00	4.18	0.32
	18	1.32		
	14	2.29		
	15	0.57		
4	13	3.24	5.31	0.81
	17	1.38		
	19	0.69		
	16	0.00		
MAL's DRI				2.53

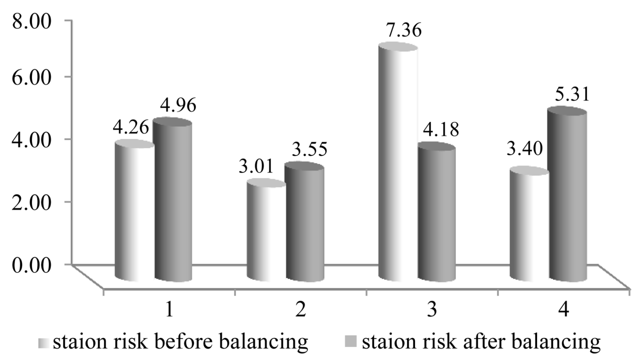

Figure 13. Comparison of station risks after and before risk balancing.

Now, product mix changes to (0.35, 0.10, 0.10, 0.10, 0.10, 0.10, 0.05, 0.10). Then, Station 2 with risk of 5.184 becomes the bottleneck, as given in Table 5. Actual task times of Station 2 for eight accessories indicate bottleneck times in Table 6. These times are used to determine the production and purchasing quantity in the next step.

Table 5. Risk deviation of stations after changing product mix.

Station	Task	Risk	Station risk	*DRI*
1	1	1.835	4.308	0.271
	2	1.690		
	3	0.000		
	4	0.485		
	5	0.298		
	8	0.000		
2	6	1.045	5.184	1.147
	7	0.555		
	9	1.187		
	11	1.288		
	12	1.109		
3	10	0.000	2.548	1.489
	18	0.981		
	14	0.979		
	15	0.588		
4	13	2.714	4.107	0.070
	17	0.319		
	19	1.073		
	16	0.000		
MAL's *DRI*				2.977

4.2. Make-or-buy decisions

Available capacity of each resource is 2400 min per month. The required data are given in Table 7. Solving the model shows that Accessories 3, 4, and 5 can be placed in Group a, while the rest are in Group e (Table 8).

4.3. Multi-criteria ABC analysis

Criteria-related data and normalized data are given in Tables 9 and 10, respectively. Outputs of ABC analysis are shown in Table 11. Accessory 8 gets the maximum score due to the maximum value in the first two criteria. Regarding the company's condition, service levels of

Table 8. Production and purchasing quantity of accessories.

Accessory	PPMB	Production	Purchasing	Group
1	119880	0	100	e
2	254421	0	500	e
3	1043956	400	0	a
4	841514	200	0	a
5	364964	400	0	a
6	152905	270	30	e
7	142740	684	16	e
8	1025000	0	200	e

Table 6. Average actual time of each accessory.

Task	Accessory							
	1	2	3	4	5	6	7	8
6	0.1870	0.2105	0.2015	0.2035	0.1950	0.2030	0.4235	0.0000
7	0.2110	0.2105	0.2185	0.1895	0.1020	0.2020	0.1950	0.2050
9	0.3975	0.0000	0.2860	0.3035	0.3150	0.2950	0.6090	0.1875
11	0.1995	0.1880	0.2040	0.2200	0.1265	0.5015	0.5050	0.1110
12	1.0070	1.0025	0.0000	0.1530	0.4945	0.1065	0.0890	0.2965
Average actual time	2.0002	1.6115	0.9100	1.0695	1.2330	1.3080	1.8215	0.8000
Standard time of station	2.0000	1.6000	0.9000	1.0500	1.2000	1.3000	1.8000	0.8000

Table 7. Required data for make-or-buy decisions.

Accessory	Purchasing cost	Material cost	T_{Cons} (min)	Demand per month
1	180000	60000	2.0020	100
2	260000	150000	1.6115	500
3	650000	300000	0.9100	400
4	650000	250000	1.0695	200
5	300000	150000	1.2330	400
6	140000	60000	1.3080	300
7	190000	70000	1.8215	700
8	420000	400000	0.8000	200

Table 9. Input data of ABC analysis.

Accessory	1	2	3	4	5	6	7	8
Annual dollar usage	27000000	805406000	579120000	175512000	500000000	80000000	6697500	850000000
Commonality	0	1	1	1	1	0	0	1
Lead time (day)	5	5	4	3	4	6	5	4
Substitutability	4	4	4	4	0	1	1	2

Table 10. Normalized data of ABC analysis.

Accessory	1	2	3	4	5	6	7	8
Annual dollar usage	0.0241	0.9471	0.6788	0.2002	0.5850	0.0869	0.0000	1.0000
Commonality	0.0000	1.0000	1.0000	1.0000	1.0000	0.0000	0.0000	1.0000
Lead time	0.6667	0.6667	0.3333	0.0000	0.3333	1.0000	0.6667	0.3333
Substitutability	1.0000	1.0000	1.0000	1.0000	0.0000	0.2500	0.2500	0.5000

Table 11. Outputs of ABC analysis.

Accessory	Score	Class	Service level	$Z_{1-\alpha}$	Accessory	Score	Class	Service level	$Z_{1-\alpha}$
8	1.000	A	99%	2.330	4	0.600	C	96%	1.800
2	0.974	B	98%	2.100	1	0.423	C	96%	1.800
3	0.839	B	98%	2.100	6	0.362	C	96%	1.800
5	0.792	B	98%	2.100	7	0.222	C	96%	1.800

accessories are considered to be 99%, 98%, and 96% for Classes A, B, and C, respectively.

4.4. Buffer planning

Time period is considered monthly here. Parameters of normal demand distribution functions are given in Table 12. Warehouse-required spaces of accessories in Group a are 25, 54, and 36 cm^2 and in Group e are 12, 84, 64, 146, and 74 cm^2, respectively. Total warehouse space is 1500 million cm^2, and total budget is 2000. Costs and input data are shown in Table 13.

Upper bound of T for Groups a and e from the proposed models are 2 and 3 months, respectively. By applying the iterative algorithm, the cost objective function (19) is measured to be 477311; the other results drawn in Tables 14 and 15 are used to determine

Table 12. Normal demand distribution functions of accessories.

Accessory	Distribution function	Accessory	Distribution function
1	$N \sim (100, 50)$	5	$N \sim (400, 20)$
2	$N \sim (500, 60)$	6	$N \sim (300, 10)$
3	$N \sim (400, 30)$	7	$N \sim (700, 40)$
4	$N \sim (200, 15)$	8	$N \sim (200, 9)$

Table 14. Results of buffer planning model for accessories in Group a.

Accessory	Q_a	b_a	ss_a	T_a (month)
3	800	1	29	2
4	400	1	15	2
5	800	1	14	2

Table 13. Input data of buffer planning model.

Accessory	Costs						Production rate per month	Set up time (min)	Lead time (month)
	Holding	Purchasing	Backorder	Ordering	Production	Set up			
1	1.544	180	360	180	90	50	50	2.30	0.2
2	2.008	260	500	300	160	70	300	1.28	0.2
3	4.270	0	1600	0	500	180	500	1.02	0.2
4	4.270	0	1000	0	350	110	350	1.80	0.3
5	2.240	0	700	0	200	110	410	2.00	0.1
6	1.312	140	250	160	80	40	210	1.50	0.1
7	1.602	190	300	250	100	60	500	1.90	0.2
8	2.936	420	1300	900	400	200	100	1.64	0.1

Table 15. Results of buffer planning model for accessories in Group e.

Accessory	Q_{1e}	Q_{2e}	b_e	ss_e	R_e	y_{1e}	y_{2e}	T_e (month)
1	150	150	1	0	149	1	1	3
2	900	600	2	0	598	1	1	3
6	630	270	1	0	269	1	1	3
7	1500	600	3	0	597	1	1	3
8	300	300	1	0	299	1	1	3

Table 16. Results of buffer planning model for dynamic buffer control charts.

Accessory	Importance level	T	Green ribbon	Red ribbon	b	Accessory	Importance level	T	Green ribbon	Red ribbon	b
1	C	3	299	0	1	5	B	2	813	14	1
2	B	3	1498	0	2	6	C	3	899	0	1
3	B	2	828	29	1	7	C	3	2098	0	3
4	C	2	414	15	1	8	A	3	599	0	1

the control ribbons. Notably, safety stock of accessories in Group e is zero because they are purchased in the first period. The required data of control charts for each accessory are given in Table 16.

4.5. Dynamic buffer control

Using the expert's opinions, MW for accessories in Classes A, B, and C is considered within the order review periods of 3, 4, and 5, respectively. Then, the number of penetration times (n) for each class is determined by Monte-Carlo simulation in Excel software. Simulation outputs of an accessory in each class are mentioned.

Accessory 1 belongs to Class C with MW of 5 order review periods. Therefore, penetration of 2 up to 5 times should be simulated. According to Table 17, $n = 2$ has the minimum cost. For Accessory 1, green and red ribbons are 299 and zero, respectively. In the first MW, the trend of buffer level is traced. According to the proposed procedure, since it penetrates more than one time during MW and backorder occurs, an emergency order is placed and the green buffer level is increased to 370. As depicted in Figure 14, in the next MW, fluctuation of buffer level is decreased; however, buffer levels do not penetrate red ribbon. Thus, red ribbon is increased to 15.

Table 17. Simulation outputs of n for Accessory 1 (Class C).

N	Cost of n times penetration
2	52562650
3	52563170
4	107078250
5	105578250

Accessory 5 is in Class B with MW of 4 order review periods. Thus, penetration of 2 up to 4 times is simulated. According to Table 18, $n = 2$ has the

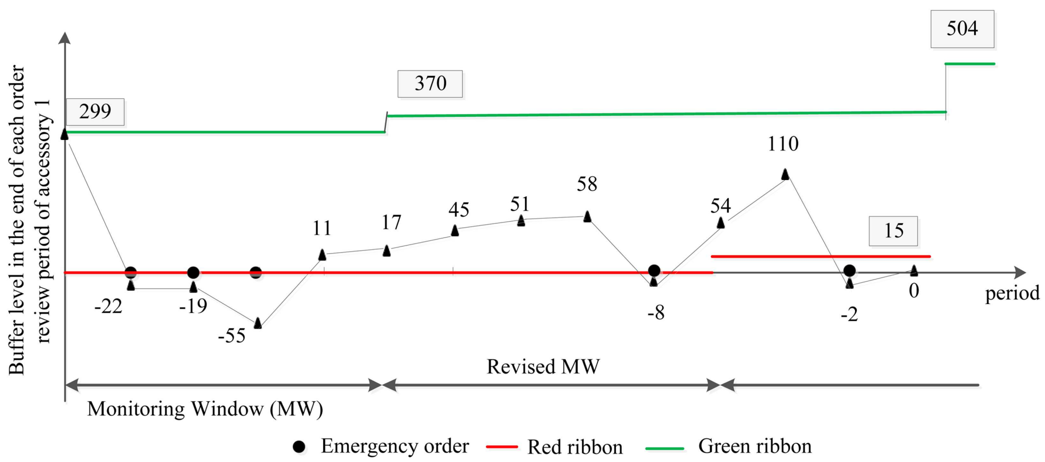

Figure 14. Dynamic buffer control chart of Accessory 1.

Table 18. Simulation outputs of n for Accessory 5 (Class B).

n	Cost of n times penetration
2	234606880
3	242295470
4	242248640

Table 19. Simulation outputs of n for Accessory 8 (Class A).

n	Cost of n times penetration
2	256536260
3	263599690

minimum cost. Dynamic control chart is shown in Figure 15. Note that fluctuations of this item are controlled appropriately after three MWs.

Accessory 8 is in Class A with MW of 3 order review periods. The simulation results given in Table 19 show that $n = 2$ has the minimum cost. Dynamic control chart is shown in Figure 16. Fluctuations of this item are also controlled appropriately after three MWs.

4.6. Comparison of the proposed method and common methods

This company implements Lot For Lot (LFL) method as the current practice. To prove the performance of the proposed approach, it is compared to LFL, Least Unit Cost (LUC), and Least Period Cost (LPC); obtained results are drawn in Table 20 and Figure 17. Of note, the proposed approach decreases the costs of Accessory 8 in Class A by approximately 24% compared to LFL.

The rare and frequent control of each accessory always leads to an increase in costs. Hence, the parameters of inventory planning and control system should be set considering the importance levels. For example, if MW of Accessory 1 is considered to be 3 instead of 5, the corresponding costs will be increased according to Table 21.

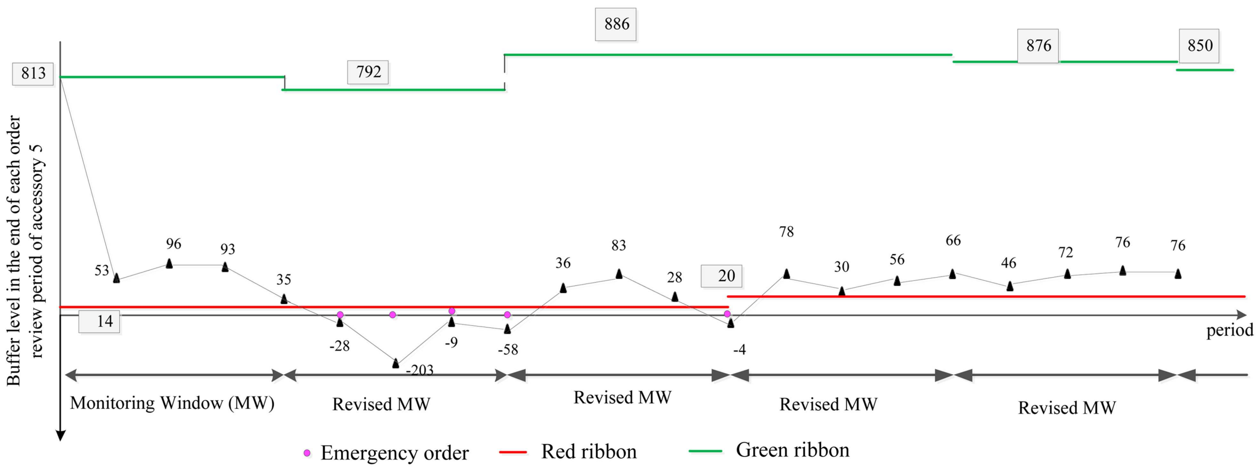

Figure 15. Dynamic buffer control chart of Accessory 5.

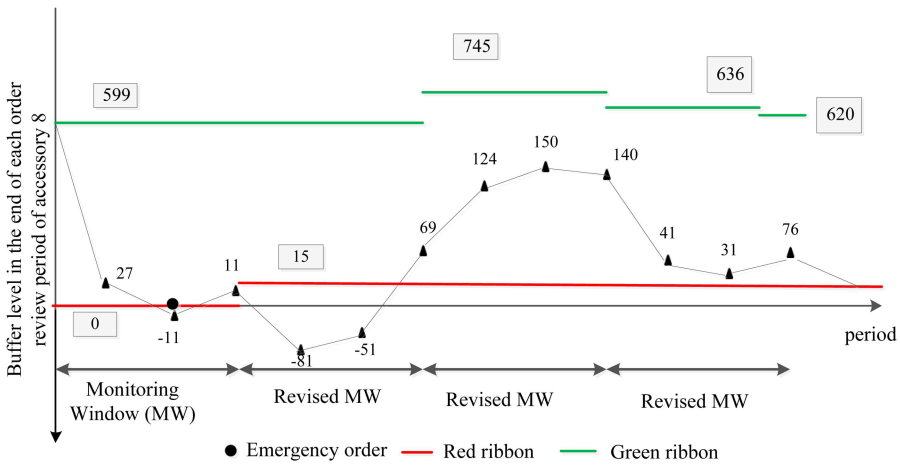

Figure 16. Dynamic buffer control chart of Accessory 8.

Table 20. Comparison of the costs of the proposed approach and common methods.

Accessory	Proposed approach	LFL	LUC	LPC
1	52562650	88520000	72531950	54183550
2	264549610	510900000	323408300	273487700
3	431642100	634700000	634700000	634700000
4	106671940	148400000	148400000	148400000
5	234606880	280900000	280900000	280900000
6	68189680	75250000	75250000	75250000
7	142734240	150500000	150500000	150500000
8	256536260	432600000	275657060	275657060

Table 21. Cost comparison for different sizes of MW.

Accessory	Size of MW	
	5	3
1 (Class C)	52562650	82199800
8 (Class A)	270698390	256536260

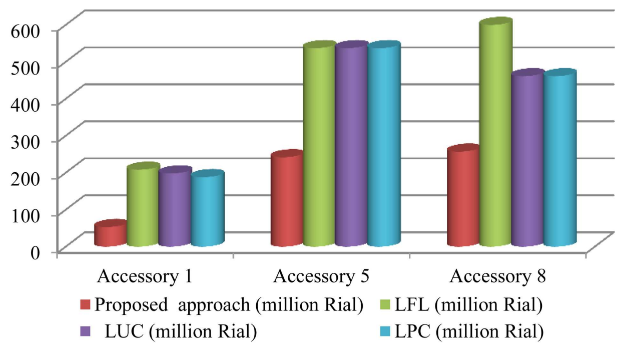

Figure 17. Comparison of the proposed approach and common methods.

4.7. Test problem analysis

In this subsection, a comprehensive analysis of sixteen random test problems of three different sizes is carried out to highlight the advantage of our proposed approach against the common methods. The main specifications of 16 test problems are represented in Tables 22 and 23. The detailed data of test problems may be provided upon the request of interested readers. The results are shown in Table 24. As observed, the total costs of the proposed approach are significantly lower than those of common methods.

To properly compare the total costs, the RD index in the last column is calculated as the relative deviation of the proposed approach from the average of the other three methods in terms of the total costs.

$$RD=\frac{\text{Mean (LFL, LUC, LPC)}-\text{Proposed approach}}{\text{Proposed approach}}. \tag{38}$$

As observed, the total costs of common methods in small-sized instances are 0.03 to 0.32 times greater than those of the proposed approach. These values vary from 0.03 to 0.13 for medium-sized instances and from 0.17 to 0.31 for large-sized instances, respectively.

5. Managerial insights

Accessories play an important role in customers' satisfaction. Productions of these items are susceptible to some variability in customers' demands, production times, and related costs. In this paper, a dynamic TOC-based approach is proposed to deal with the dynamic nature of such items. An automobile company is studied to confirm the performance of the proposed approach. The following results are achieved:

1. In the MTO environments, common approaches to inventory planning and control of accessories could increase the costs greatly as they do not address the corresponding dynamics appropriately;
2. In the mixed-model assembly lines for accessories, considering risk while keeping the cycle time balanced could decrease the risk deviation of line (in our case, 55%). By applying the proposed risk-based heuristic, the variability risk is distributed in assembly line equally;
3. If the monitoring window of buffer control charts is determined to be greater or less than the optimized value, extra costs would be imposed on the system (in our case, 15%). Our results show that the monitoring window should be determined according to the importance levels;
4. The non-optimized number of penetrations into red ribbon could increase the inventory control costs (in our case, 10%). Therefore, after determining the length of MW, the number of penetrations into red ribbon should be monitored dynamically (by simulation);
5. As a result of analyzing 16 test problems, on average, the proposed approach indicates a 17% reduction in the total costs compared to the other common methods. The reasons are as follows:

Table 22. Product mix for 16 test problems.

Accessory	Test problem															
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**
1	0.20	0.20	0.30	0.20	0.30	0.20	0.11	0.30	0.20	0.03	0.10	0.06	0.01	0.03	0.10	0.20
2	0.30	0.30	0.25	0.30	0.30	0.01	0.10	0.10	0.10	0.01	0.30	0.10	0.02	0.01	0.11	0.02
3	0.40	0.40	0.25	0.40	0.30	0.09	0.09	0.01	0.05	0.10	0.02	0.11	0.03	0.05	0.03	0.04
4	0.10	0.10	0.20	0.10	0.10	0.10	0.10	0.18	0.04	0.15	0.02	0.03	0.01	0.30	0.03	0.10
5	—	—	—	—	—	0.09	0.10	0.06	0.08	0.05	0.05	0.03	0.05	0.02	0.01	0.04
6	—	—	—	—	—	0.06	0.06	0.07	0.20	0.09	0.06	0.01	0.30	0.05	0.05	0.08
7	—	—	—	—	—	0.07	0.07	0.10	0.10	0.10	0.10	0.05	0.02	0.10	0.30	0.03
8	—	—	—	—	—	0.1	0.10	0.10	0.10	0.40	0.11	0.30	0.05	0.02	0.02	0.01
9	—	—	—	—	—	0.2	0.20	0.07	0.05	0.02	0.03	0.02	0.30	0.30	0.02	0.02
10	—	—	—	—	—	0.08	0.09	0.01	0.08	0.05	0.03	0.02	0.02	0.02	0.02	0.01
11	—	—	—	—	—	—	—	—	—	—	0.01	0.10	0.02	0.02	0.02	0.02
12	—	—	—	—	—	—	—	—	—	—	0.05	0.05	0.01	0.01	0.01	0.02
13	—	—	—	—	—	—	—	—	—	—	0.01	0.01	0.05	0.02	0.02	0.03
14	—	—	—	—	—	—	—	—	—	—	0.02	0.02	0.10	0.02	0.02	0.08
15	—	—	—	—	—	—	—	—	—	—	0.09	0.09	0.01	0.03	0.24	0.03
16	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.03
17	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.02
18	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.01
19	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.01
20	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.03
21	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.04
22	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.04
23	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.03
24	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.03
25	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.07
26	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.04
27	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.01
28	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.03
29	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.05
30	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	0.01

Table 23. Parameters of uniform distributions for data generation.

Costs (×1000)						Monthly normal demand	
Purchasing	**Material**	**Holding**	**Backorder**	**Ordering/setup**	**Production**	**Ave.**	**Std. dev.**
(2,750)	(6,300)	(1,5)	(100,800)	(10,900)	(90,3500)	(100,600)	(0.02 Ave, 0.20 Ave)

Table 24. Comparing costs of the proposed approach to that of common methods using 16 test problems.

Problem size	Test problem	Proposed approach	LFL	LUC	LPC	RD
Small	1	2845861310	3746940000	3742802600	3742861060	0.32
	2	531247840	606680000	568534160	569012050	0.09
	3	244521330	251640000	251640000	251640000	0.03
	4	128018870	188010000	138633000	138633000	0.21
	5	160053070	210520000	178215500	171249650	0.17
Medium	6	421531197	432260000	432260000	432260000	0.03
	7	512305790	536450000	536450000	536450000	0.05
	8	442186260	496820000	449226180	457621640	0.06
	9	408327850	492670000	441081200	445449600	0.13
	10	380031300	458380000	413705400	409213600	0.12
Large	11	493228622	618300000	593557200	613518500	0.23
	12	832773285	1288270000	958171960	1023256600	0.31
	13	633758693	754490000	733563600	738375400	0.17
	14	675341950	882580000	815705000	697756800	0.18
	15	801783160	1029460000	969205000	974782600	0.24
	16	3134274379	3996992000	3892232220	3875323220	0.25

- Considering risk when balancing the assembly line;
- Incorporating the bottleneck capacity into the make-or-buy decisions;
- Taking the importance of accessories into account in inventory control system;
- Updating the control ribbons in response to the critical fluctuations according to the importance level of inventories.

6. Concluding remarks and future research directions

Intense fluctuations in the demand for accessories cause induced variability; hence, a dynamic inventory planning and control system is required for such items. In this paper, a dynamic TOC-based approach considering the importance level of accessories was proposed. The risk of processing time variation was balanced while keeping the cycle time balanced. By a buffer planning model, the ribbons of buffer control charts were determined in which a multi-criteria ABC analysis was carried out to apply different customer service levels. Trend of consumption in each monitoring window was carefully traced to detect demand variations and monitor the buffer. In addition, some procedures using the simulation were recommended to update control ribbons. Through a real case, the proposed approach was compared to the existing conditions and traditional methods. The results confirmed that this approach could significantly reduce the costs and improve the efficiency of the inventory system. The results were generalized by analyzing 16 random test problems of different sizes. The application of the data mining technique to determine demand change point in control charts and the proposition of a model to simultaneously balance variability risk and assembly line time could serve as proper directions for the future study.

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Biographies

Parvaneh Keyvani received his MSc in Industrial Engineering from Yazd University (2016). Her research interests lie in the area of production planning, inventory control, and multiple criteria decision-making.

Mohammad Mehdi Lotfi is an Associate Professor of Industrial Engineering at Yazd University. His areas of expertise are Operations Management and Project Scheduling. His research interests include optimization, decision tools and quantitative methods in operations management and logistics (especially humanitarian logistics), energy efficiency, and healthcare. He was the project manager of many projects and published more than 40 journal papers. He received his BSc from Sharif University of Technology, and both MSc and PhD degrees from University of Tehran, all in Iran.