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Research Article

Optimizing Safety Stock Levels in Modular Production Systems Using Component Commonality and Group Technology Philosophy: A Study Based on Simulation

Kenneth Edgar Hernandez-Ruiz,[1] Elias Olivares-Benitez,[2] Jose Luis Martinez-Flores,[3] and Santiago Omar Caballero-Morales[3]

[1] *Tecnologico de Monterrey Campus Puebla, Via Atlixcayotl No. 2301, Reserva Territorial Atlixcayotl, 72453 Puebla, PUE, Mexico*
[2] *Universidad Panamericana Campus Guadalajara, Calzada Circunvalación Poniente No. 49, Ciudad Granja, 45010 Zapopan, JAL, Mexico*
[3] *UPAEP University, 21 Sur 1103 Colonia Santiago, 72410 Puebla, PUE, Mexico*

Correspondence should be addressed to Elias Olivares-Benitez; eliasolivares@hotmail.com

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Modular production and component commonality are two widely used strategies in the manufacturing industry to meet customers growing needs for customized products. Using these strategies, companies can enhance their performance to achieve optimal safety stock levels. Despite the importance of safety stocks in business competition, little attention has been paid to the way to reduce them without affecting the customer service levels. This paper develops a mathematical model to reduce safety stock levels in organizations that employ modular production. To construct the model, we take advantage of the benefits of aggregate inventories, standardization of components, component commonality, and Group Technology philosophy in regard to stock levels. The model is tested through the simulation of three years of operation of two modular product systems. For each system, we calculated and compared the safety stock levels for two cases: (1) under the only presence of component commonality and (2) under the presence of both component commonality and Group Technology philosophy. The results show a reduction in safety stock levels when we linked the component commonality with the Group Technology philosophy. The paper presents a discussion of the implications of each case, features of the model, and suggestions for future research.

1. Introduction

Over the past few decades, manufacturing has faced a steady growth in market competition caused mainly by three factors: (1) globalization [1], (2) technological advances, and (3) high demand for customized products [2–4]. To meet this demand and being competitive, the companies have applied as main strategy the offering of a wider variety of products [1, 2, 5–9]. However, having a wider variety of products increases the complexity of the organization because it increases the quantity of parts or components that the company must make or buy.

To meet efficiently the high demand of customized products, some researchers [1, 9, 10] suggest two methods: (1) increasing production capacity and (2) applying modular production systems. Of these strategies, the modular production or *modularity* is the most popular [11, 12]. The basic idea of the modularity is to design modules or components standardized with standard interfaces in such a way that they can be combined in a high number of end products to meet customer requirements [5, 13, 14]. A truly modular production system makes it possible to manufacture custom products and to react quickly to customer requirements with virtually the same features found in the mass production [15–18]. One of the main benefits of modularity is that it leads to a reduction of the stock levels.

By using *Make to Stock* (MTS) and *Assemble to Stock* (ATS) production approaches, a manufacturer can maintain cycle stock levels according to a forecast demand. However, in an environment with uncertainly, forecasts are not reliable. For this reason, the manufacturers use an investment in safety stocks, which allow them to respond effectively to forecast errors and to overcome or mitigate the risk of stock-outs. The strategy most widely used to minimize the safety stock levels in modular production systems is *component commonality,* which replaces two or more parts of an end product by a common part [14, 19–23].

The studies for minimizing the safety stock levels in modular production systems began with Collier [24], who argued that, by increasing the degree of component commonality in a modular production system, the costs of operation and the stocks levels can be reduced because larger production batches are created and standardization improved. Thus, Baker [19] proved that the safety stock levels decrease as much as the degree of commonality increases. Baker et al. [25] examined the effect of component commonality on optimal safety stock levels in two products with a two-level inventory model, showing that replacing two unique parts with a common part results in a smaller requirements for the common part. Gerchak and Henig [20] replicated Baker et al. [25] and showed that in *Assemble to Order* (ATO) systems the stocks of product-specific components always increase when other components are combined with common parts. Gerchak et al. [21] extended the results of Baker et al. [25] in understanding the impact of component commonality on safety stock levels under service level constraints. Hillier [26] analyzed the effects of component commonality in the total cost of a modular production system using a multiperiod model when a common component is significantly more expensive than the unique parts. Chew et al. [27] quantified the impact of component commonality in a two-echelon assembled-to-stock system consisting of several common components and end products. The results showed that when each type of component is shared by at least two end products, the safety stock levels are reduced requiring to be held at a sufficiently high service level. Catena et al. [28] proposed four models with commonality for calculating safety stock levels for subassemblies and manufacturing components under ATO and *Make to Order* (MTO) systems. Persona et al. [29] extended the study of Catena et al. [28] and applied the models in two different industries to prove the reduction in the safety stock levels. Like these works, there are many other studies focused on the effect of the component commonality on safety stock levels in modular production systems such as Gerchak and Henig [30]; Eynan and Rosenblatt [31]; Fisher et al. [32]; Cheung [23].

The main contribution of this work is the proposal of a model that includes Group Technology philosophy (GT) for the computation of safety stock levels in modular production systems. This inclusion extends the previous approaches that only considered component commonality. The mathematical model is tested through the simulation of three years of operation of two modular product systems. For each system, we calculated and compared the safety stock levels for two scenarios: (1) under the only presence of component commonality and (2) under the presence of both component commonality and GT. These scenarios are used to compare the performance of the mathematical model proposed with the traditional model. The results show a reduction in the safety stock levels without affecting the customer service levels (CSL).

The remainder of the paper is organized as follows. Section 2 shows the development of the proposed model. In Section 3 the simulation results are presented. Section 4 discusses the main implications of the model. Finally, Section 5 presents the conclusions and suggestions for future research.

2. Mathematical Model

According to Mikkola [6], the structure of a modular product is divided into four levels of complexity: system, subsystem, modules, and components. However, this structure is determined mainly by organizations considering their production approaches and the intended application of the products. This study divides the modular product into three levels of complexity: system, modules, and components.

A modular products system assumes the existence of

(i) m end products with indexes $l = 1, 2, \ldots, m$;

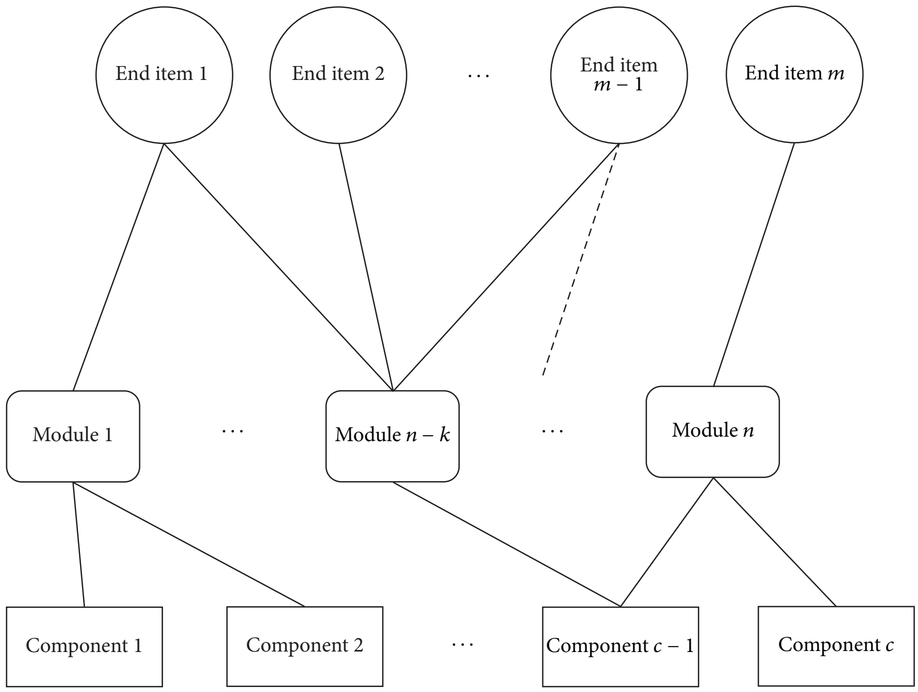
(ii) n modules with indexes $j = 1, 2, \ldots, n$;

(iii) c components with indexes $i = 1, 2, \ldots, c$.

The number of components i required to build one module j is denoted as a_{ij}; and the number of modules j required to build one end product l is denoted as b_{jl}. Figure 1 shows this configuration and the matrices of composition of modules and components.

2.1. Preliminary Analysis. The structure of a modular products system supports managers in determining stock levels, because it allows them to know exactly the number of modules and components they need in an end product. In reality, all manufacturers operate with an investment in inventories, even those organizations that employ the Just-in-Time strategy. These inventories consist of raw material, work in process, products from a reverse logistic system, subassemblies, and end products. All of them are necessary for very specific reasons that, taken together, facilitate efficient performance in organizations. In the ideal case, where a manufacturing system operates in a purely deterministic environment, the forecast demand is not necessary. However, in actual practice, this does not happen; there is always uncertainty in the environment and sudden changes in the customers behavior causing inaccurate forecasts, regardless of the forecasting method used.

It is well known that organizations turn to the preparation of forecasts to determine the future demand for their products. With these forecasts, they adjust their resources and production capacities in order to meet these demands. Because forecast is only approximations, the managers must always take into account a forecast value and a forecast



$$a_{ij} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \cdots & \vdots \\ a_{c1} & a_{c2} & \cdots & a_{cn} \end{bmatrix} \qquad b_{jl} = \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1m} \\ b_{21} & b_{22} & \cdots & b_{2m} \\ \vdots & \vdots & \cdots & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nm} \end{bmatrix}$$

Figure 1: General structure of a modular products system and its matrices of composition.

error as metrics to determine the stocks levels. Therefore, to meet the real demand for a modular product over a period of time t, managers consider a deterministic amount and a random amount of inventory. As a consequence of the random component, safety stocks become necessary in an organization. Safety stocks are inventory that remain to meet the demand that exceeds the forecast in a period of time t. These stocks avoid stock-out costs and lost sales. For an organization, it is important to maintain optimal safety stock levels, because they also generate costs to keep them in the warehouse. It is harmful to have excess inventory when new competing products are introduced because the available inventory becomes obsolete.

In an environment of modular production, where the demand of a product in a period of time t is bigger than forecast demand, the forecast error can be cover by the safety stock as follows:

$$D_t = \omega\mu + \text{SS}, \quad (1)$$

where

- D_t is demand of the period t;
- ω is unit of time (days, weeks, and months) of the period t;
- μ is the average of the forecasted demand;
- SS is safety stock.

Assuming that the demand D_t is normally distributed with mean μ and a variance $\text{var}[D_t]$, by definition of the normal standard distribution and its inverse, the following expression is obtained:

$$D_t = \omega\mu + k\sigma\sqrt{L}. \quad (2)$$

Therefore, the safety stock is defined by the next expression:

$$\text{SS} = k\sigma\sqrt{L}, \quad (3)$$

where

- SS is safety stock;
- k is the safety factor that determines the probability that the real demand of a product is less than or equal to the forecasted demand plus the safety stock;
- L is lead-time;
- σ is standard deviation of the demand.

Indeed, the safety stock SS represents the stock-out in the stock cycle during the period of time between the processes of placing and receiving an order; that is,

$$\text{ROP} = L\mu + \text{SS}, \quad (4)$$

where ROP is the reorder point and μ is the mean of the demand through the planning horizon.

Expression (3) determines the safety stock for an end product, which assumes independence in its demand and does not consider the presence of component commonality. This expression only considers as key metrics the standard deviation and a safety factor k to ensure a certain CSL.

However, in practice, organizations adopt different strategies to reduce the safety stock levels to maintain low costs; to start to reduce them, an organization needs to create an aggregate inventory; this consists in centralizing inventories in a single warehouse, instead of having different storage points. The aggregate inventories generate savings in inventory holding costs; the process of building part families by GT is facilitated and allows the efficient use of the component commonality.

An organization that offers a wide variety of modular products as customized products must maintain an aggregation in inventories. Now, if this organization seeks to reduce the safety stock levels, in addition to this aggregation, it also must consider the application of the component commonality. Then, in this case, Expression (3) can be generalized considering the distribution of the aggregate inventory, which has a normal distribution with an aggregate demand d', a variance $\text{var}[d']$, and a standard deviation σ', as follows in expressions (5). One has

$$d' = \sum_{l=1}^{m} d_l,$$
$$\text{var}\left[d'\right] = \sum_{l=1}^{m} \sigma_l^2 + 2\sum_{l<z} \text{cov}_{lz} = \sum_{l=1}^{m} \sigma_l^2 + 2\sum_{l<z} \rho_{lz}\sigma_l\sigma_z, \quad (5)$$
$$\sigma' = \sqrt{\text{var}\left[d'\right]} = \sqrt{\sum_{l=1}^{m} \sigma_l^2 + 2\sum_{l<z} \rho_{lz}\sigma_l\sigma_z},$$

where ρ_{lz} is the Pearson correlation coefficient between the final products l and z, while the sum of the standard deviations represents those deviations where component commonality exists. From expressions (3) and (5), the safety stock for each final product l into an aggregate inventory of modular products with component commonality can be determined based on the next expression:

$$\text{SS}_l = k\sigma_\alpha \sqrt{L_l} = k\sqrt{\sum_{l=1}^{m} \sigma_l^2 + 2\sum_{l<z} \rho_{lz}\sigma_l\sigma_z}\sqrt{L_l}. \quad (6)$$

When the demands are independent ($\rho_{lz} = 0$) between all end products, expression (6) is simplified as follows:

$$\text{SS}_l = k\sqrt{\sum_{l=1}^{m} \sigma_l^2}\sqrt{L_l}. \quad (7)$$

Expressions (6) and (7) determine the safety stock levels of end products with dependent and independent demands, respectively, considering the use of the aggregate inventories and the component commonality.

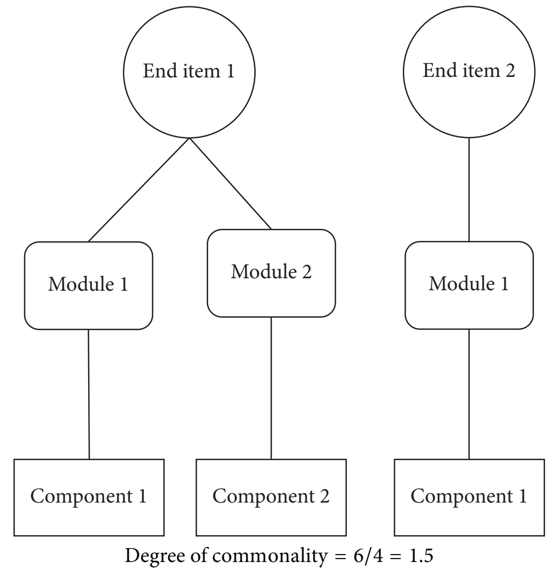


Figure 2: Degree of commonality in two simple modular products.

This preliminary analysis develops expressions (3)–(7) that already have been developed in previous literature. These expressions are presented in this paper because these are the basis to construct the proposed model.

2.2. Proposed Model. Under MTS and ATS production approaches, it is necessary to determine the safety stock levels for each component that exists in a modular products system, and expressions (6) and (7) are the basis for calculation.

To determine the safety stock of each component of a modular products system, we must consider the degree of commonality present in the system. According to Collier [24], the structure of the system determines the degree of commonality; this is defined as the total number of modules and components in the system divided by the total number of distinct modules and components. Figure 2 shows an example of how to calculate the degree of commonality of two modular products.

Considering the existence of modules and common components, expression (6) is adjusted to determine the safety stock levels of each component in the system; therefore, in each term of the expression, we consider the participation of components in modules and modules in end products. The expression developed is as follows:

$$\text{SS}_i = k\sqrt{\sum_{j=1}^{n}\sum_{l=1}^{m} a_{ij}b_{jl}\sigma_l^2 + 2\sum_{j=1}^{n}\sum_{l=1}^{m-1}\sum_{z=2}^{m} a_{ij}^2 b_{jl}b_{jz}\rho_{lz}\sigma_l\sigma_z}\sqrt{L_i}. \quad (8)$$

When there is independence in demands between the end products, expression (8) is simplified as follows:

$$\text{SS}_i = k\sqrt{\sum_{j=1}^{n}\sum_{l=1}^{m} a_{ij}b_{jl}\sigma_l^2}\sqrt{L_i}. \quad (9)$$

Expressions (8) and (9) have been developed in this paper for calculating safety stocks of the components of a modular products system with component commonality and with three levels of complexity. However, the proposed model also suggests the presence of a factor of substitution from the GT philosophy to reduce further the safety stock levels.

2.2.1. Factor of Substitution. The GT is a manufacturing philosophy that brings together the components with similar physical features (shape, size, and manufacturing processes) in part families to take advantages in the optimization of many processes such as lead times, setup times, processing times, labor operations, and reworks. From GT philosophy, we define a *factor of substitution* of a component i as f_{si}, which considers a fraction of substitute components r_i within the part family to which the component i belongs, and by their similarities, the component i can be replaced by them in case of stock-out. An example of substitutes components are two similar screws with different drives in the heads. It assume that this substitution does not affect or change the shape, function, costs, and physical and mechanical properties of the end product. The fraction r_i is defined as follows:

$$r_i = \frac{n_i}{\left(\left(\sum_{i=1}^{c} N_i - 1\right)/C\right)}, \tag{10}$$

where

r_i is fraction of substitution of the component i;

n_i is amount of substitute components of the component i;

N istotal components within the part family of the component i.

By using a basic mathematical model, the factor of substitution f_{si} decreases at a rate r_i proportionally to the number of components n_i existing within the part family. If f_{si} is the factor of substitution of a component i, then f_{si} varies at a rate $\Delta f_{si} = r_i f_{si}$ as much as the number of components n_i increases or decreases; in other words, for every unit that increases the value n_i in the system, f_{si} takes a proportional value to this change. Hence

$$\Delta f_{si} = \left(-r_i f_{si}\right) \Delta n_i. \tag{11}$$

In differential equation form,

$$\frac{df_{si}}{dn_i} = -r_i f_{si} = \left[\frac{-n_i}{\left(\left(\sum_{i=1}^{c} N_i - 1\right)/C\right)}\right] f_{si}. \tag{12}$$

For any value of r_i, the solution of the differential equation is presented in next expression:

$$f_{si} = e^{-n_i^2/2[(\sum_{i=1}^{c} N_i - 1)/C]}. \tag{13}$$

Figure 3 shows some patterns of the factor of substitution under different sizes of part families. In this figure we can observe that, in a scenario with absence of substitute components ($n_i = 0$), the factor of substitution takes a maximum value ($f_{si} = 1$), and while increasing the value of n_i, the value of f_{si} approximates to zero.

2.2.2. Integration of the Proposed Model. Expressions (8) and (9) determine the safety stock levels for the components of a modular products system with commonality and under an aggregate inventory. However, these levels can be reduced including the factor of substitution in expression (8) as follows:

$$\mathrm{SS}_i = e^{-n_i^2/2[(\sum_{i=1}^{c} N_i - 1)/C]} k \sqrt{\sum_{j=1}^{n}\sum_{l=1}^{m} a_{ij} b_{jl} \sigma_l^2 + 2\sum_{j=1}^{n}\sum_{l=1}^{m-1}\sum_{z=2}^{m} a_{ij}^2 b_{jl} b_{jz} \rho_{lz} \sigma_l \sigma_z}\sqrt{L_i}. \tag{14}$$

When demands are independent, expression (14) is simplified as follows:

$$\mathrm{SS}_i = e^{-n_i^2/2[(\sum_{i=1}^{c} N_i - 1)/C]} k \sqrt{\sum_{j=1}^{n}\sum_{l=1}^{m} a_{ij} b_{jl} \sigma_l^2}\sqrt{L_i}. \tag{15}$$

Expressions (14) and (15) are the result of joining the component commonality with the GT philosophy for reducing the safety stock levels. We can see that when f_{si} takes its maximum value, expression (14) becomes expression (8); while increasing the value by n_i, the safety stock SS_i is reduced.

The basic principle of the proposed model consists in reducing safety stock levels in modular production systems through an exponential smoothing. This reduction is in function of the degree of commonality and of the amount of components N_i and n_i in the part families. The reduction is given due to the possibility of sharing cyclical and safety stocks between substitute components. Thus, this strategy allows eliminating the negative effect in case of stock-outs.

To evaluate the proposed model, Section 3 presents two applications based on simulation regarding the operation of two different modular products systems.

3. Application and Results

The proposed model is evaluated through two applications based on the simulation of three years of operation of two modular products systems, where each system has its own structure and its own degree of component commonality. The

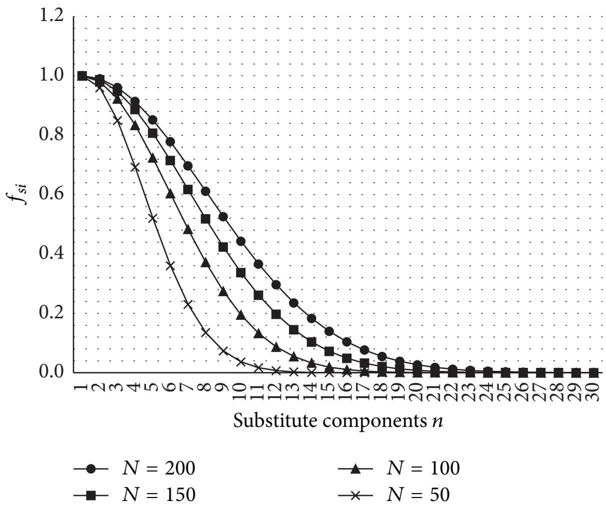


FIGURE 3: Functions for the factor of substitution.

analysis of each application makes the comparison of performance between safety stocks calculated for two scenarios: (1) under the only presence of component commonality and (2) with the presence of component commonality and the factor of substitution from GT philosophy.

The simulations have been developed using C++ language, where after generating demands for end products, the safety stocks, reorder points, initial and final inventories, components used, and stock-outs for each component are calculated. The results for each scenario in both applications have been derived from thirty simulation runs. Figure 4 shows the general simulation process.

To make the applications simple, we suppose the following conditions held:

(1) A continuous review (Q, R) policy is used to determine the safety stock levels.

(2) There is one period of lead-time for first application.

(3) There are two periods of lead-time for second application.

(4) In each period simulated, demand for end products l follows a normal distribution, with mean μ_l and standard deviation σ_l.

(5) For each case, it assumes aggregate inventories for production.

(6) The CSL is 90% ($k = 1.28$).

(7) There is a buffer of enough substitute components to meet the demand in case of stock-outs.

(8) The substitution of components does not affect or change the shape, function, costs, and physical and mechanical properties of the end product.

(9) Each component analyzed belongs to a different part family.

3.1. Application One. This application simulates and analyzes two modular products (EP1 and EP2) of an enterprise that offers a high variety of different modular products to its customers. To manufacture all its products, the enterprise applies GT philosophy to arrange its components in part families. The two products analyzed are assembled from 3 modules and 4 components as shown in Figure 5. The structure of these two products has a degree of commonality of 1.7.

We suppose that the demands of these two end products are independent and normally distributed with means $\mu_{\text{EP1}} = 700$ and $\mu_{\text{EP2}} = 1100$, standard deviations $\sigma_{\text{EP1}} = 80$ and $\sigma_{\text{EP2}} = 120$. Table 1 shows the initial inventories and order quantities used for the two scenarios analyzed.

TABLE 1: Initial inventories and quantity orders.

c_i	1	2	3	4
I. Initial	10000	9500	10500	9000
Q_i	7000	8000	7000	4000

Case 1 (safety stocks with commonality). Based on the structure of Figure 4 and considering that the system handles aggregation in inventories with only component commonality, the safety stock for each component is determined by applying expression (9). Table 2 shows the calculated values for safety stocks and reorder points.

TABLE 2: Safety stock levels and reorder points.

c_i	1	2	3	4
SS_i	185	212	185	154
ROP_i	1985	2712	1985	1254

The results of the thirty simulation runs for this case are shown in Table 3. This table shows that five stock-outs occurred in five simulation runs, generating a stock-out average equal to 1. The average inventories for each component also are showed.

Case 2 (safety stocks with commonality and factor of substitution). In this case, we suppose that each component i of the two modular products analyzed belongs to a part family, the experiment assumes that each part family has its own total number of components N_i with n_i substitute components for the component i, and each substitute component has a large buffer to meet any demand. Table 4 shows the details with respect to the composition of the part families of each component i of the system analyzed.

For an organization, obtaining the data in Table 4 is not a difficult task; they can be obtained through the construction of part families and identifying the substitute components for each member of the families. Once this information is structured, it can be used to calculate the safety stock levels for each component.

Given the information in Table 4, safety stock for each component of the system is determined using the expression (15), which considers the aggregation in inventories, existence of component commonality, independent demands, and the

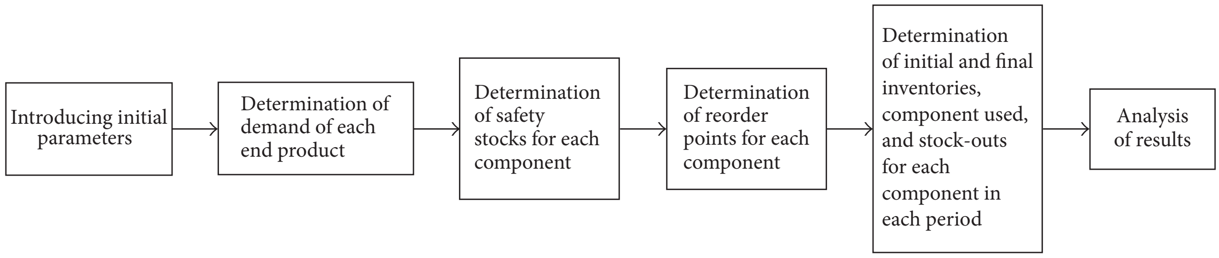
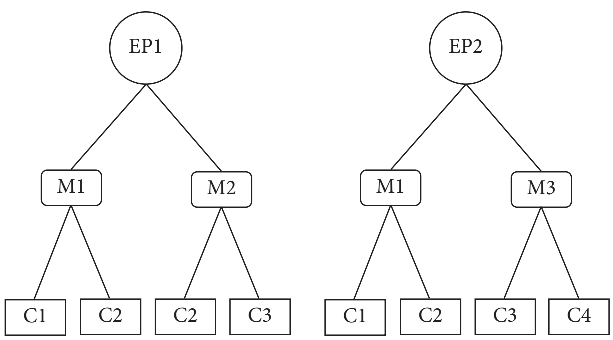


FIGURE 4: Simulation process.

TABLE 3: Results of the simulation: Case 1.

Stock-outs			Average inventories			
Amount of stock-outs	Runs with stock-outs	Average of stock-outs	$c1$	$c2$	$c3$	$c4$
5	5	1	5563	6847	5804	3701



$$a_{ij} = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{bmatrix} \qquad b_{jl} = \begin{bmatrix} 1 & 1 \\ 1 & 0 \\ 0 & 1 \end{bmatrix}$$

FIGURE 5: A system of two modular products and its matrices of composition.

TABLE 4: Part families composition.

c_i	1	2	3	4
N_i	25	30	45	60
n_i	3	6	4	6

TABLE 5: Safety stock levels and reorder points.

c_i	1	2	3	4
SS_i	166	135	152	98
ROP_i	1966	2635	1952	1198

factor of substitution. Table 5 shows the calculated values for safety stocks and reorder points.

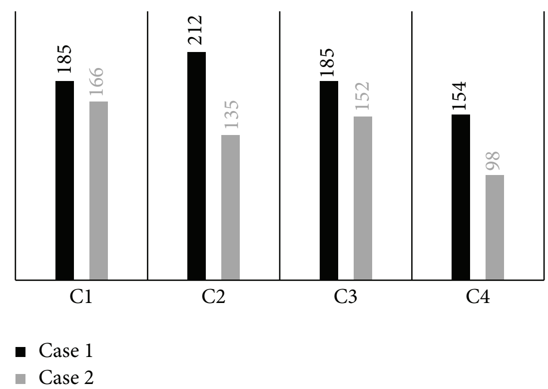


FIGURE 6: Safety stock levels for each component in both scenarios.

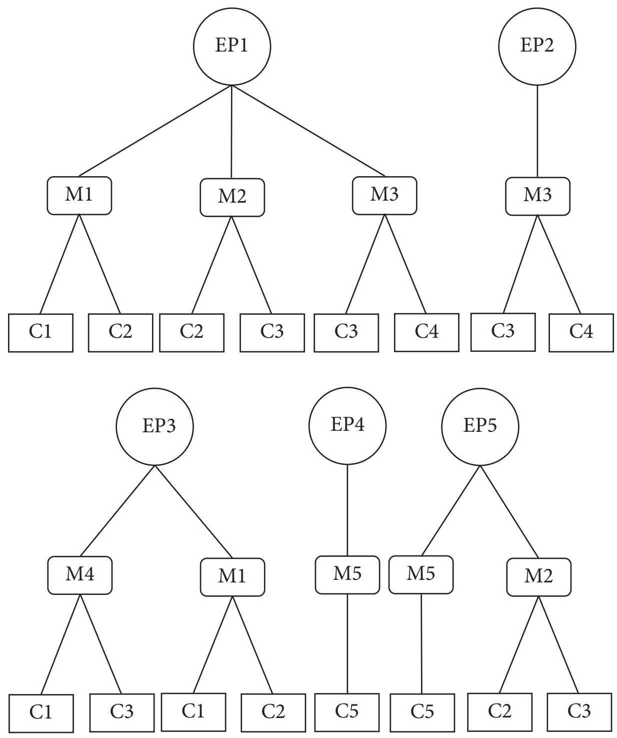
The results of the thirty simulation runs for this case are shown in Table 6. This table shows that eight stock-outs occurred in six simulation runs, generating a stock-out average equal to 1.3. The average inventories for each component also are showed.

3.1.1. A Performance Comparison between the Two Cases. Tables 3 and 6 show the results of each case; these tables show that there are a greater number of stock-outs and lower average inventories in Case 2 as a result of reducing safety stock levels. However, the experiment involves the possibility of using substitute components to meet this demand, while stock-outs in Case 1 become in shortage costs. Figure 6 shows the difference between safety stock levels calculated in each case for each component in the system. An example of one simulation run for both cases is shown in Table 7.

3.2. Application Two. Similar to the previous application, this application analyzes and simulates a system of modular products composed of five end products EP1, EP2,. . ., EP5, which are assembled from five modules and five components as shown in Figure 7. The structure has a degree of commonality

Table 6: Results of the simulation: Case 2.

Stock-outs			Average inventories			
Amount of stock-outs	Runs with stock-outs	Average of stock-outs	$c1$	$c2$	$c3$	$c4$
8	6	1.3	5542	6795	5785	3648



$$a_{ij} = \begin{bmatrix} 1 & 0 & 0 & 1 & 0 \\ 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad b_{jl} = \begin{bmatrix} 1 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 \\ 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 1 \end{bmatrix}$$

Figure 7: A system of five modular products and its matrices of composition.

of 2.5. The system uses the ATO strategy to meet the needs of its customers.

For this modular products system, we suppose that the demands of the end products are dependent. Table 8 shows the initial inventories and the order quantities of each component of the system, whereas Table 9 shows the means of the demands, the standard deviations, and the correlation coefficients of the end products. The information of both Tables 8 and 9 are used for the two cases analyzed.

Case 1 (safety stocks with commonality). In an environment where there are dependent demands between end products, determining safety stocks of each component of the system is performed by applying expression (8). Table 10 shows the calculated values for safety stocks as well as reorder points for each component.

The results of the thirty simulation runs for this case are shown in Table 11. This table shows that eight stock-outs occurred in eight simulation runs, generating a stock-out average equal to 1. The average inventories for each component also are showed.

Case 2 (safety stocks with commonality and factor of substitution). Similar to Case 2 of the application 1, each component i of the modular products system belongs to a part family. Each part family has its own total number of components N_i with a number n_i of substitute components by the component i, and each substitute component has a large buffer to meet any demand. Table 12 shows the details regarding the composition of the part families of each component i of the system analyzed.

For this case, the safety stocks are calculated using expression (14), because this expression considers the existence of aggregation in inventories, commonality, dependent demands, and factor of substitution. Table 13 shows the calculated values of the safety stocks and reorder points for each component of the system.

The results of the thirty simulation runs for this case are shown in Table 14. This table shows that forty-four stock-outs occurred in twenty-six simulation runs, generating a stock-out average equal to 1.7. The average inventories for each component also are showed.

3.2.1. A Performance Comparison between the Two Cases. Tables 11 and 14 show the results of each case; these tables show that there are a greater number of stock-outs and lower average inventories in Case 2 as a result of reducing safety stock levels. Similar to that in application one, the experiment involves the possibility of using substitute components to meet this demand, while stock-outs in Case 1 become in shortage costs. Figure 8 shows the difference between safety stock levels calculated in each case for each component in the system. An example of one simulation run for both cases is shown in Table 15.

4. Discussion

Currently, uncertainty in demand and variability in consumer behavior hinder decision-making concerning the determination of the optimal safety stock levels. As a result, an organization requires a sufficient level of these inventories to ensure a high CSL. Greater safety stock levels represent higher costs. Of course, safety stocks are not the only factor that can negatively affect the CSL; there are other factors that also affect it directly, such as product quality, after-sales

Table 7: Application 1: demands, components used, and initial and final inventories.

Period (month)	Demands		Case 1												Case 2											
			Initial inventory				Components used				Final inventory				Initial inventory				Components used				Final inventory			
	FP1	FP2	c1	c2	c3	c4	c1	c2	c3	c4	c1	c2	c3	c4	c1	c2	c3	c4	c1	c2	c3	c4	c1	c2	c3	c4
1	724	1062	10000	9500	10500	9000	1786	2510	1786	1062	8214	6990	8714	7938	10000	9500	10500	9000	1786	2510	1786	1062	8214	6990	8714	7938
2	772	1076	8214	6990	8714	7938	1848	2620	1848	1076	6366	4370	6866	6862	8214	6990	8714	7938	1848	2620	1848	1076	6366	4370	6866	6862
3	800	1197	6366	4370	6866	6862	1997	2797	1997	1197	4369	1573	4869	5665	6366	4370	6866	6862	1997	2797	1997	1197	4369	1573	4869	5665
4	740	1062	4369	9573	4869	5665	1802	2542	1802	1062	2567	7031	3067	4603	4369	9573	4869	5665	1802	2542	1802	1062	2567	7031	3067	4603
5	728	1189	2567	7031	3067	4603	1917	2645	1917	1189	650	4386	1150	3414	2567	7031	3067	4603	1917	2645	1917	1189	650	4386	1150	3414
6	770	1142	7650	4386	8150	3414	1912	2682	1912	1142	5738	1704	6238	2272	7650	4386	8150	3414	1912	2682	1912	1142	5738	1704	6238	2272
7	718	1012	5738	9704	6238	2272	1730	2448	1730	1012	4008	7256	4508	1260	5738	9704	6238	2272	1730	2448	1730	1012	4008	7256	4508	1260
8	737	1289	4008	7256	4508	1260	2026	2763	2026	1289	1982	4493	2482	**0**	4008	7256	4508	1260	2026	2763	2026	1289	1982	4493	2482	**0**
9	794	1220	8982	4493	2482	4000	2014	2808	2014	1220	6968	1685	468	2780	1982	4493	2482	4000	2014	2808	2014	1220	**0**	1685	468	2780
10	683	1014	6968	9685	7468	2780	1697	2380	1697	1014	5271	7305	5771	1766	7000	9685	7468	2780	1697	2380	1697	1014	5303	7305	5771	1766
11	630	1292	5271	7305	5771	1766	1922	2552	1922	1292	3349	4753	3849	474	5303	7305	5771	1766	1922	2552	1922	1292	3381	4753	3849	474
12	673	1281	3349	4753	3849	4474	1954	2627	1954	1281	1395	2126	1895	3193	3381	4753	3849	4474	1954	2627	1954	1281	1427	2126	1895	3193
13	585	1017	8395	10126	8895	3193	1602	2187	1602	1017	6793	7939	7293	2176	8427	10126	8895	3193	1602	2187	1602	1017	6825	7939	7293	2176
14	671	1090	6793	7939	7293	2176	1761	2432	1761	1090	5032	5507	5532	1086	6825	7939	7293	2176	1761	2432	1761	1090	5064	5507	5532	1086
15	677	1186	5032	5507	5532	5086	1863	2540	1863	1186	3169	2967	3669	3900	5064	5507	5532	5086	1863	2540	1863	1186	3201	2967	3669	3900
16	691	1117	3169	2967	3669	3900	1808	2499	1808	1117	1361	468	1861	2783	3201	2967	3669	3900	1808	2499	1808	1117	1393	468	1861	2783
17	614	1093	8361	8468	8861	2783	1707	2321	1707	1093	6654	6147	7154	1690	8393	8468	8861	2783	1707	2321	1707	1093	6686	6147	7154	1690
18	543	1123	6654	6147	7154	1690	1666	2209	1666	1123	4988	3938	5488	567	6686	6147	7154	1690	1666	2209	1666	1123	5020	3938	5488	567
19	626	981	4988	3938	5488	4567	1607	2233	1607	981	3381	1705	3881	3586	5020	3938	5488	4567	1607	2233	1607	981	3413	1705	3881	3586
20	610	1288	3381	9705	3881	3586	1898	2508	1898	1288	1483	7197	1983	2298	3413	9705	3881	3586	1898	2508	1898	1288	1515	7197	1983	2298
21	691	1135	8483	7197	8983	2298	1826	2517	1826	1135	6657	4680	7157	1163	8515	7197	1983	2298	1826	2517	1826	1135	6689	4680	157	1163
22	773	1103	6657	4680	7157	5163	1876	2649	1876	1103	4781	2031	5281	4060	6689	4680	7157	5163	1876	2649	1876	1103	4813	2031	5281	4060
23	616	1230	4781	10031	5281	4060	1846	2462	1846	1230	2935	7569	3435	2830	4813	10031	5281	4060	1846	2462	1846	1230	2967	7569	3435	2830
24	631	1006	2935	7569	3435	2830	1637	2268	1637	1006	1298	5301	1798	1824	2967	7569	3435	2830	1637	2268	1637	1006	1330	5301	1798	1824
25	705	972	8298	5301	8798	1824	1677	2382	1677	972	6621	2919	7121	852	8330	5301	8798	1824	1677	2382	1677	972	6653	2919	7121	852
26	664	1207	6621	2919	7121	4852	1871	2535	1871	1207	4750	384	5250	3645	6653	2919	7121	4852	1871	2535	1871	1207	4782	384	5250	3645
27	729	1116	4750	8384	5250	3645	1845	2574	1845	1116	2905	5810	3405	2529	4782	8384	5250	3645	1845	2574	1845	1116	2937	5810	3405	2529
28	772	1181	2905	5810	3405	2529	1953	2725	1953	1181	952	3085	1452	1348	2937	5810	3405	2529	1953	2725	1953	1181	984	3085	1452	1348
29	582	1032	7952	3085	8452	1348	1614	2196	1614	1032	6338	889	6838	316	7984	3085	8452	1348	1614	2196	1614	1032	6370	889	6838	316
30	766	1105	6338	8889	6838	4316	1871	2637	1871	1105	4467	6252	4967	3211	6370	8889	6838	4316	1871	2637	1871	1105	4499	6252	4967	3211
31	622	1120	4467	6252	4967	3211	1742	2364	1742	1120	2725	3888	3225	2091	4499	6252	4967	3211	1742	2364	1742	1120	2757	3888	3225	2091
32	705	1255	2725	3888	3225	2091	1960	2665	1960	1255	765	1223	1265	836	2757	3888	3225	2091	1960	2665	1960	1255	797	1223	1265	836
33	679	1024	7765	9223	8265	4836	1703	2382	1703	1024	6062	6841	6562	3812	7797	9223	8265	4836	1703	2382	1703	1024	6094	6841	6562	3812
34	709	1059	6062	6841	6562	3812	1768	2477	1768	1059	4294	4364	4794	2753	6094	6841	6562	3812	1768	2477	1768	1059	4326	4364	4794	2753
35	728	1156	4294	4364	4794	2753	1884	2612	1884	1156	2410	1752	2910	1597	4326	4364	4794	2753	1884	2612	1884	1156	2442	1752	2910	1597
36	671	1217	2410	9752	2910	1597	1888	2559	1888	1217	522	7193	1022	380	2442	9752	2910	1597	1888	2559	1888	1217	554	7193	1022	380

Table 8: Initial inventories and quantity orders.

c_i	1	2	3	4	5
I. Initial	10000	10000	10000	10000	10000
Q_i	6000	12000	14000	4000	4000

Table 9: Correlation coefficients, means of demands, and standard deviations.

ρ_{lz}	EP1	EP2	EP3	EP4	EP5
EP1	—	0.72	0.61	0.75	0.8
EP2	0.72	—	0.55	0.66	0.91
EP3	0.61	0.55	—	0.32	0.53
EP4	0.75	0.66	0.32	—	0.44
EP5	0.8	0.91	0.53	0.44	—
μ_i	550	450	650	600	450
σ_i	80	75	95	105	75

Table 10: Safety stocks and reorder points.

c_i	1	2	3	4	5
SS_i	333	390	411	261	278
ROP_i	4033	4790	5711	2261	2378

Table 11: Results of the simulation; Case 1.

Stock-outs			Average inventories				
Amount of stock-outs	Runs with stock-outs	Average of stock-outs	$c1$	$c2$	$c3$	$c4$	$c5$
8	8	1	5375	8452	10024	3951	3978

Table 12: Part families composition.

c_i	1	2	3	4	5
N_i	9	15	18	9	13
n_i	4	7	5	5	6

Table 13: Safety stocks and reorder points.

c_i	1	2	3	4	5
SS_i	176	55	152	97	66
ROP_i	3876	4455	5452	2097	2166

Table 14: Results of the simulation: Case 2.

Stock-outs			Average inventories				
Amount of stock-outs	Runs with stock-outs	Average of stock-outs	$c1$	$c2$	$c3$	$c4$	$c5$
44	26	1.7	5239	8169	9728	3821	3820

services, and production capacity. Integrating all these factors to ensure a high CSL is an important area for research.

The proposed model in this paper solves the problem of reducing safety stock levels without affecting CSL in organizations that employ modular production as a strategy to offer a wide variety of products. The model suggests that the safety stock level for a component belonging to a modular products system can be reduced through exploiting the benefits of the aggregation of inventories, standardization of components, the degree of commonality, and the GT

Table 15: Application 2: demands, components used, and initial and final inventories.

Period (month)	Case 1														
	Initial inventory					Components used					Final inventory				
	c1	c2	c3	c4	c5	c1	c2	c3	c4	c5	c1	c2	c3	c4	c5
1	10000	10000	10000	10000	10000	2033	2471	2809	973	879	7967	7529	7191	9027	9121
2	7967	7529	7191	9027	9121	1419	1850	2293	940	967	6548	5679	4898	8087	8154
3	6548	5679	4898	8087	8154	1746	2201	2656	1053	1063	4802	3478	2242	7034	7091
4	4802	3478	16242	7034	7091	1964	2240	2611	961	1054	2838	1238	13631	6073	6037
5	2838	13238	13631	6073	6037	1925	2371	2826	998	1262	913	10867	10805	5075	4775
6	6913	10867	10805	5075	4775	1934	2003	2387	812	977	4979	8864	8418	4263	3798
7	4979	8864	8418	4263	3798	1586	1681	2113	850	712	3393	7183	6305	3413	3086
8	3393	7183	6305	3413	3086	1905	2175	2682	1014	1133	1488	5008	3623	2399	1953
9	7488	5008	3623	2399	1953	1715	2114	2586	1035	1197	5773	2894	1037	1364	756
10	5773	2894	15037	1364	4756	2267	2601	3022	1068	1158	3506	293	12015	296	3598
11	3506	12293	12015	4296	3598	1603	1874	2324	857	1075	1903	10419	9691	3439	2523
12	7903	10419	9691	3439	2523	1842	2152	2830	1192	1251	6061	8267	6861	2247	1272
13	6061	8267	6861	2247	1272	1959	2069	2522	916	968	4102	6198	4339	1331	304
14	4102	6198	4339	5331	4304	2029	2330	2795	1032	958	2073	3868	1544	4299	3346
15	2073	3868	15544	4299	3346	2286	2408	2838	1042	855	0	1460	12706	3257	2491
16	6000	13460	12706	3257	2491	1746	2087	2486	965	960	4254	11373	10220	2292	1531
17	4254	11373	10220	2292	1531	1774	2141	2603	972	1123	2480	9232	7617	1320	408
18	2480	9232	7617	1320	4408	1838	1929	2468	933	891	642	7303	5149	387	3517
19	6642	7303	5149	4387	3517	2027	2359	2731	1017	881	4615	4944	2418	3370	2636
20	4615	4944	16418	3370	2636	1981	2506	2942	1101	1065	2634	2438	13476	2269	1571
21	2634	2438	13476	2269	1571	1335	1524	1884	733	945	1299	914	11592	1536	626
22	7299	12914	11592	1536	4626	1287	1834	2219	838	1121	6012	11080	9373	698	3505
23	6012	11080	9373	4698	3505	1917	2149	2528	938	973	4095	8931	6845	3760	2532
24	4095	8931	6845	3760	2532	1925	2210	2694	1003	1236	2170	6721	4151	2757	1296
25	2170	6721	4151	2757	1296	1931	2323	2924	1214	979	239	4398	1227	1543	317
26	6239	4398	15227	1543	4317	1667	2046	2401	854	1015	4572	2352	12826	689	3302
27	4572	14352	12826	4689	3302	2232	2543	2991	1108	1029	2340	11809	9835	3581	2273
28	2340	11809	9835	3581	2273	2146	2447	2942	1115	1002	194	9362	6893	2466	1271
29	6194	9362	6893	2466	5271	1813	2394	2879	1110	1290	4381	6968	4014	1356	3981
30	4381	6968	4014	1356	3981	2314	2622	2892	938	1081	2067	4346	1122	418	2900
31	2067	4346	15122	4418	2900	2049	2326	2745	976	847	18	2020	12377	3442	2053
32	6018	14020	12377	3442	2053	1898	2179	2551	932	887	4120	11841	9826	2510	1166
33	4120	11841	9826	2510	5166	1890	2326	2802	1068	997	2230	9515	7024	1442	4169
34	2230	9515	7024	1442	4169	1831	2137	2583	1031	865	399	7378	4441	411	3304
35	6399	7378	4441	4411	3304	1932	2145	2735	1078	1060	4467	5233	1706	3333	2244
36	4467	5233	15706	3333	2244	1435	1874	2223	786	1039	3032	3359	13483	2547	1205

Period (month)	Case 2														
	Initial inventory					Components used					Final inventory				
	c1	c2	c3	c4	c5	c1	c2	c3	c4	c5	c1	c2	c3	c4	c5
1	10000	10000	10000	10000	10000	2033	2471	2809	973	879	7967	7529	7191	9027	9121
2	7967	7529	7191	9027	9121	1419	1850	2293	940	967	6548	5679	4898	8087	8154
3	6548	5679	4898	8087	8154	1746	2201	2656	1053	1063	4802	3478	2242	7034	7091
4	4802	3478	16242	7034	7091	1964	2240	2611	961	1054	2838	1238	13631	6073	6037
5	2838	13238	13631	6073	6037	1925	2371	2826	998	1262	913	10867	10805	5075	4775
6	6913	10867	10805	5075	4775	1934	2003	2387	812	977	4979	8864	8418	4263	3798
7	4979	8864	8418	4263	3798	1586	1681	2113	850	712	3393	7183	6305	3413	3086
8	3393	7183	6305	3413	3086	1905	2175	2682	1014	1133	1488	5008	3623	2399	1953
9	7488	5008	3623	2399	1953	1715	2114	2586	1035	1197	5773	2894	1037	1364	756
10	5773	2894	15037	1364	4756	2267	2601	3022	1068	1158	3506	293	12015	296	3598
11	3506	12293	12015	4296	3598	1603	1874	2324	857	1075	1903	10419	9691	3439	2523
12	7903	10419	9691	3439	2523	1842	2152	2830	1192	1251	6061	8267	6861	2247	1272
13	6061	8267	6861	2247	1272	1959	2069	2522	916	968	4102	6198	4339	1331	304
14	4102	6198	4339	1331	4304	2029	2330	2795	1032	958	2073	3868	1544	299	3346
15	2073	3868	15544	4299	3346	2286	2408	2838	1042	855	0	1460	12706	3257	2491
16	6000	13460	12706	3257	2491	1746	2087	2486	965	960	4254	11373	10220	2292	1531
17	4254	11373	10220	2292	1531	1774	2141	2603	972	1123	2480	9232	7617	1320	408
18	2480	9232	7617	1320	4408	1838	1929	2468	933	891	642	7303	5149	387	3517
19	6642	7303	5149	4387	3517	2027	2359	2731	1017	881	4615	4944	2418	3370	2636
20	4615	4944	16418	3370	2636	1981	2506	2942	1101	1065	2634	2438	13476	2269	1571
21	2634	2438	13476	2269	1571	1335	1524	1884	733	945	1299	914	11592	1536	626
22	7299	12914	11592	1536	4626	1287	1834	2219	838	1121	6012	11080	9373	698	3505
23	6012	11080	9373	4698	3505	1917	2149	2528	938	973	4095	8931	6845	3760	2532
24	4095	8931	6845	3760	2532	1925	2210	2694	1003	1236	2170	6721	4151	2757	1296
25	2170	6721	4151	2757	1296	1931	2323	2924	1214	979	239	4398	1227	1543	317
26	6239	4398	15227	1543	4317	1667	2046	2401	854	1015	4572	2352	12826	689	3302
27	4572	14352	12826	4689	3302	2232	2543	2991	1108	1029	2340	11809	9835	3581	2273
28	2340	11809	9835	3581	2273	2146	2447	2942	1115	1002	194	9362	6893	2466	1271
29	6194	9362	6893	2466	1271	1813	2394	2879	1110	1290	4381	6968	4014	1356	0
30	4381	6968	4014	1356	4000	2314	2622	2892	938	1081	2067	4346	1122	418	2919
31	2067	4346	15122	4418	2919	2049	2326	2745	976	847	18	2020	12377	3442	2072
32	6018	14020	12377	3442	2072	1898	2179	2551	932	887	4120	11841	9826	2510	1185
33	4120	11841	9826	2510	5185	1890	2326	2802	1068	997	2230	9515	7024	1442	4188
34	2230	9515	7024	1442	4188	1831	2137	2583	1031	865	399	7378	4441	411	3323
35	6399	7378	4441	4411	3323	1932	2145	2735	1078	1060	4467	5233	1706	3333	2263
36	4467	5233	15706	3333	2263	1435	1874	2223	786	1039	3032	3359	13483	2547	1224

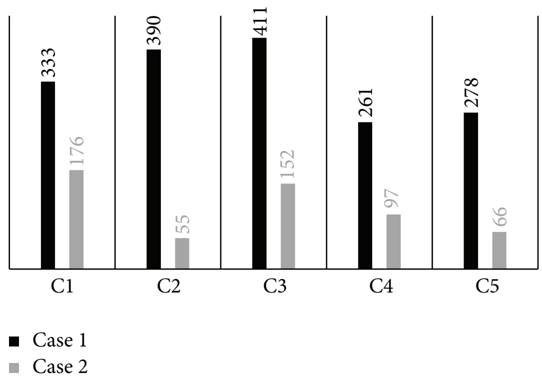


Figure 8: Safety stock levels for each component in both scenarios.

philosophy. The model assumes that the negative effect of increasing the amount of stock-outs can be eliminated when using substitute components to meet demands.

The model facilitates basic economies of substitution, such as costs reduction and inventory reduction as well as reduction in system complexity. For best performance, the model requires a high degree of integration between all areas of the organization, because that forces organizations to adopt the best strategies to achieve a proper standardization and to define an efficient methodology for the construction of part families.

5. Conclusions and Suggestions for Future Research

In this paper, we explored and quantified the positive effect of linking component commonality and GT philosophy on safety stock levels for organizations that employ modular production. Specifically, we achieved two objectives: (1) we showed an efficient way of reducing safety stock levels, and (2) we expanded knowledge regarding the positive relationship between component commonality and the GT philosophy.

The main contribution of this paper is the development of an efficient model for reducing safety stocks levels in modular production systems by linking component commonality with GT philosophy, thus creating a factor of substitution for components with great physical similarities. The factor of substitution constitutes an extension to the basic theory of quantitative models used for determining safety stock levels in organizations employing modular production. The model is a good option for companies whose holding costs are bigger than their shortage costs.

It is important to mention that, traditionally, researchers have developed mathematical models to try to determine the optimal safety stock levels for different strategies of production. They assumed that the demand that exists within the elapsed time period between when an order is made and when it is received follows a normal distribution. However, some studies have shown that the normal distribution is not the best representation of the demand behavior during a waiting time, but for ease of operation, a model that assumes a normal distribution represents the basis for other applications with higher requirements.

The proposed model is compared with the traditional method through a simulation study for two modular products systems with different degrees of commonality, where, for each component in both systems, we calculated the safety stocks, reorder points, initial and final inventories, and the usability of components. The result shows a reduction in safety stock levels allowing a high CSL.

For future research, the model can be tested using components belonging to the same part family and these can be substituted between them; also the model can be adjusted to different demand distributions to evaluate the performance. It is possible to supplement it with a study assessing the impact on total costs under different scenarios and different operational strategies. Finally, the model can be extended to products of more than three levels of complexity.

Competing Interests

The authors declare that they have no competing interests.

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