

An Application of a Cost Minimization Model in Determining Safety Stock Level and Location

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Abstract

In recent decades, the lean methodology and the development of its principles and concepts have widely been applied in supply chain management. One of the most important strategies of being lean is having efficient inventory within the whole supply chain. Managing inventory efficiently requires appropriate management of safety stock in order to compensate the weakness of the supply chain for product availability. A nonlinear cost minimization safety stock model with the objective of minimizing the total logistics cost is developed in this paper. This model is also applied to a real-world case company which is a manufacturer. The model results in optimum levels and locations of safety stock within the company's supply chain in order to minimize total logistics costs.

Index terms— cost, lean, optimization, safety stock, supply chain.

1 Introduction

Today's competitive environment, applying the lean paradigm has been extended to the field of supply chain management. Taylor (1999), Adamides et al. (2008), Ainuma & Tawara (2006), Lamming (1996), Crino et al. (2007), Wu & Wee (2009) researched on lean supply chain. Naylor (1999), Qi et al. (2007), Mason-Jones et al. (2000) compared lean paradigm with other methodologies in supply chain management. Contributors of a supply chain, no matter to which industry they belong, aim to follow a lean philosophy to make their business processes more and more efficient in order to survive on the market. Manufacturers are one of these contributors and inventory plays a paramount role in their efforts to become lean. Chun Wu (2003), Wu (2009), Cullen & Towill (2001) studied on the application of lean manufacturing. There are different inventory drivers such as level of supply chain collaboration and visibility, forecast accuracy, order pattern, and safety stock policy, among others. Therefore, proper management of inventory and consequently safety stock as one of its drivers has become critical objective towards achieving leanness. In this paper, we propose a safety stock cost minimization model in a manufacturing case company that is attempting to become lean by managing the inventory across its supply chain efficiently, and towards this goal, efficient levels and locations of safety stock becomes more and more significant as a prerequisite condition.

An optimization model of safety stock can be built on different objectives. Minimizing cost, maximizing service level, and aggregate considerations are examples of such objectives (Silver, 1998). Optimal determination approaches based on cost and service level objectives are more appropriate for practical applications (Inderfurth, 1991). One of the vital goals of the enterprise is to maximize earnings under certain investment conditions (Long et al., 2009). On the other hand, as reducing costs of materials, equipment, and labor is difficult at best in today's competitive market, enterprises are more interested in targeting logistics costs in this regard (Long et al., 2009). In this paper, minimization of logistics costs is selected as the basis of the determination of optimum safety stock. Logistics costs are mainly related to procurement and supply, manufacturing process, and after sales service. Thus, holding and shortage costs are selected as representations of logistics costs in the optimization model. Indeed, product availability is a critical measure for the performance of logistics and supply chain (Coyle

44 et al., 2009). Any obstacles at any node and level of supply chain can result in unavailability of products to
45 their customers. There are different issues that cause disruptions and unavailability of products in the supply
46 chain, as for example variability, whether in demand or lead time; quality issues; or internal and external issues
47 such as low delivery performances, improper scheduling, inadequate product capacity, poor maintenance, among
48 others. Figure ?? 1 is a schematic of a supply chain with its nodes such as different tiers of suppliers, producer,
49 assembly, distributors, and customer. Any actions taken by any member of the chain can affect the profitability
50 of the others. Therefore, companies have great interest in having better coordination among the contributors of
51 their supply chain (Silver, 1998). Safety stock is essential to compensate for the weakness of the supply chain
52 for part availability and this factor has been considered in the selected optimization model. In this paper, we
53 apply a safety stock cost minimization model in a case company which is a manufacturer. In the next section,
54 we provide a review of the literature. In Section 3, we describe the case company. In Section 4, we introduce the
55 model, followed by the model formulation in Section 5. Results are then presented in the next section, followed
56 by validation. We then provide a discussion of the results and their implication, and then conclude with some
57 suggestions for avenues of future research.

58 2 II.

59 3 Literature Review

60 According to the literature, there are different approaches and methods for determining safety stock under
61 different situations. Some different methods for computing safety stock in the Just In Time (JIT) environments
62 are presented by Natarajan &Goyal (1994). These methods deal with objectives related to service level, expected
63 number of stock outs, tradeoff between stocking out and carrying extra buffer, minimization of total cost comprises
64 of set-up, holding, and shortage costs. Efficient level of inventory increases the inventory turnover in companies.
65 Reducing the level of inventory helps to increase the turns according to its definition. One of the approaches
66 towards reduction of inventory especially in Just In Time (JIT) environments is reducing lot sizes. On the
67 other hand, smaller lot sizes will lead to uncertainties and consequently stock outs (Natarajan &Goyal, 1994).
68 Therefore, safety stock is really needed to protect against these kinds of uncertainties. Minner (1997) uses dynamic
69 programming algorithms to find the optimal combinations of coverage times with the target of minimizing the
70 average holding costs in serial, divergent, and convergent inventory systems. In this paper, it is assumed that
71 customer demand is normally distributed and correlations between demands are permitted. One of the outcomes
72 of this paper is that concentrating safety stocks at the first and final stages would be optimal for a serial system
73 with a high enough service level.

74 A linear programming model with the objective of establishing a trade-off among plan changes, carrying, and
75 shortage costs under resource constraints for a multi-item production system is presented by Kanyalkar & Adil
76 (2009). Plan changes cost is related to the instabilities occur under rolling schedule. These instabilities in the
77 chain affect costs such as setup and expediting costs and they also affect material plans like shortage or excess
78 of components (Kanyalkar & Adil, 2009). Jung et al. (2008) present a linear programming formulation which
79 includes the control variables of safety stock with the purpose of minimization of the total supply chain's inventory
80 while meeting the target of the service level. This model incorporates the nonlinear performance functions, the
81 interdependence between the service level at upstream and downstream stages of supply chain and also the safety
82 capacity constraint. A section also provided for linearization of the nonlinear functions of the model. Some of
83 the assumptions applied in this model are normally distributed demand, zero lead time at the warehouse, and
84 constant production capacity. In addition, it is assumed that raw material and transportation means in any size
85 are always available.

86 A dynamic model of the safety stock by assuming a Vendor Managed Inventory (VMI) system is presented by
87 Yuan Li &Jian Li (2009). Under VMI system, the uncertainties related to the efficiency of the supplier disappear
88 and the model considers only the variability sourced by demand.

89 Patel & Rodrigues (2010) present the dynamics of the model of optimizing safety stock for small-scale aluminum
90 utensil manufacturing industry. This model takes into account factors of demand, production rate, delay, and
91 waste time. Indeed, this paper concentrates on the bullwhip effect in a manufacturing supply chain and tries
92 to reduce it by increasing safety stock. Zhao et al. (2001) use a simulation approach to evaluate alternative
93 methods of determining the level of safety stock based on historical forecasting errors in multilevel MRP systems.
94 In addition, the relation between the safety stock multiplier and different system performance measures such as
95 total cost, service level, and schedule instability in different methods analyzed and results also provided. Badinelli
96 (1986) is about combining stock out cost and holding costs functions towards determining the optimal safety stock.
97 It also presents a technique for estimating the stock out with a decision maker's disvalue function.

98 An approximation model for safety stock in a two echelon distribution system is provided by Desmet et al.
99 (2010). This model tries to incorporate the variance of the retailers and the central warehouse in the replenishment
100 lead time. It also takes into account the variance of the service time of orders at the warehouse as it has significant
101 effect on the system's lead time variance. Inderfurth (1991) represents a safety stock optimization model in multi-
102 stage problems with divergent structure and provides a dynamic programming algorithm for solving that. The
103 analysis for the impact of the correlation of demands on safety stock allocation has also provided in this paper.
104 This model does not include inter-stage shortage costs by assuming of having a certain capacity of slack resources

105 for operating flexibility. Inderfurth (1995) is the continuation of his previous work in 1991. He extended his study
106 to a case that demand is not only cross-product but also cross-time correlated. Cross-time correlation of demand
107 yields a tendency to keep safety stock at the end-item level, while cross product correlation provides a tendency
108 for holding buffer more in upstream stages. One of the results of this study is that increasing the correlation
109 in both products and time makes the safety stock policy to be more expensive. This research also shows that
110 not taking into account demand correlation may result in incorrect sizing and positioning of safety stock in
111 multi-stage manufacturing systems. Neglecting this may also lead to missed cost reduction opportunities.

112 A nonlinear integer optimization model with the objective of minimization of the total setup and inventory
113 holding costs by considering service level constraint has been provided by Carlson & Yano (1986). The only
114 variability that is incorporated into the model is related to demand. In addition, it is assumed that there are no
115 capacity constraints. The model suggests having safety stock at those stages with high setup or disruption costs.

116 An optimization model with the purpose of minimizing the total holding and shortage costs is presented
117 by Aleotti Maia & Qassim (1998). Then, an analytical solution provided for finding the preferable case by
118 comparing inventory and opportunity costs. It is concluded that holding inventory at the intermediate levels
119 is not economical if it is solely used for reduction of the frequency of stock out. The model from this paper
120 is expanded for this study and applied in a real-world case company. The reason for this selection is that the
121 objective of this model is the same as the objective of the case company which is minimization of the cost.
122 Determination of the optimal level and location of safety stock in a supply chain with different stages and
123 stochastic environment is a very complex task; therefore, most of the models and approaches provided in this
124 regard have applied certain assumptions in their own cases to make it simpler. Some of these approaches are
125 applicable for only a specific inventory system, some of them limit the distribution of demand, and some of them
126 exclude the suppliers' variability. In this paper, we present a general model with the objective of logistics costs
127 minimization by considering both internal and external variability and taking into account of part availability
128 factor which is very important in the chain.

129 4 III.

130 5 Case Study

131 The company under study, which we will hereinafter refer to as ABC for the purpose of confidentiality, is a
132 manufacturer in the aerospace industry. The company is characterized by high demand variability and long lead
133 time, among others. ABC is a multi-stage manufacturer. Tiers of suppliers, procurement, manufacturing, final
134 assembly, and customers (internal and external) are different nodes of the ABC's supply chain. The downstream
135 nodes are the upstream nodes' customers, and the replenishment lead time of customer nodes is the order waiting
136 time provided by their upstream nodes. In addition, ABC has a generally structured multi-stage system and there
137 is no restriction with respect to the number of predecessors and successors of any node. Such multistage systems
138 focus considerable attention on setting and positioning safety stock. ABC has two different manufacturing plants
139 (MFs). The procurement department of the company is responsible for procuring the raw materials or semi-
140 finished parts through suppliers to manufacturing plants or even supplying parts from one manufacturing plant
141 to another (inter plants transfers). Indeed, the word "supplier" in the model could be the representative of the
142 external supplier or internal manufacturing entity. It should be noted that procurement's location can be different
143 from manufacturing ones. Finished parts from manufacturing entities have two internal customers that pull their
144 outputs; they are Assembly (ASSY) and Aftermarket (AFM). These two latter entities are the last stages of the
145 internal chain of the company just before the end customer. There are also some external supplied finished parts
146 required for Assembly and Aftermarket that the procurement department is again in charge of supplying them.
147 The Assembly entity has different finished product families with their own specifications. Therefore, if availability
148 of parts (right parts at right time) can be assured for the internal customers, on-time delivery performance to
149 the end customer will be assured as well. This availability should be guaranteed through safety stock, but the
150 optimum safety stock level and location should also minimize logistics costs.

151 6 IV.

152 7 Model Description

153 The optimization model is presented through different possible value streams of each finished product family
154 of the company and developed using lingo optimization software to result in the optimum level of safety stock
155 with its optimum location in the stream. Value stream is the aggregation of all actions needed to bring a specific
156 product through problem-solving task, information management task, and physical transformation task (Womack
157 and Jones, 2003). Value stream mapping as a tool of lean is a method to depict material and information flow
158 throughout whole the chain for both value added and non-value added processes. Value stream is used to give
159 the visibility of the whole supply chain from end to end for each specific part. By applying the model through
160 different value streams, it will not only result in the optimal level of the safety stock but also in the optimal
161 location of it in the supply chain (raw material safety stock, semifinished part safety stock, or finished part safety
162 stock). Each of the possible value streams of the case company can have different combinations of the chain's
163 contributors before the end customer. In order to limit the number of stages and for simplification, only the

last two stages of those value streams that have more than two nodes before the internal customer stage are selected. Therefore, all the previous stages and their connections are being excluded and their performances are being captured only through the input of the latest second stage. The other reason for this limitation is the difficulty in defining the shortage costs in upstream stages of the chain due to lack of visibility and control. Furthermore, the objective of the model is cost minimization, and the upstream stages' contributions towards cost are significantly less than the downstream stages, thus this simplifying assumption should have a negligible effect on overall results. Although, there is a sample (Value Stream 4) presented in "Computational Results" section that goes beyond this limitation just to show the applicability of the model for the whole chain from end to end point.

Shortage cost, overage cost, and delivery performances (percentage of product availability) are the inputs of the model. Different combinations of raw material (semi-finished part) and finished part are considered as indices in the model based on the selected value streams.

V.

8 Model Formulation

For all value streams, the notations of the model are as follows: K_i is the summation of the availability percentage of raw material/semi-finished part for manufacturing through procurement based on the absolute suppliers' performances (P_i) and the availability percentage of procurement's safety stock for that part (x_i/q_i). Indeed, procurement can deliver whatever quantities they received on time through suppliers plus their safety stock to the manufacturing. K_p is the summation of the availability percentage of the finished part which is dependent on the manufacturing performance (P_p) and also their previous stages' performances (K_i) and the availability percentage of manufacturing's safety stock for that part (x_p/q_p). Likewise, manufacturing can deliver whatever quantities of finished parts they can produce on time which is also dependent on the deliveries of their previous stages in the chain plus their own safety stock quantities to their customers (ASSY and AFM). The related formulas of K_i and K_p are as (1) and (2):

$$(2) q \times K_p = \sum_i q_i \times K_i + P_p + x_p/q_p$$

In the cases that the finished part is directly procured through the external supplier for the customers, K_p formula will be equal to (1). P_i and P_p are calculated as average numbers based on historical data from the last year. A report called the First Filled Rate (FFR) is used for calculation of these parameters. This report is used to represent the availability of the right part at the time that is required. The FFR result takes into account the total on hand stock in its calculation which does include safety stock as well. It should be noted that P_i and P_p should be the absolute delivery performance of supplier and manufacturing without the contribution of the safety stock that may be used during last year. Therefore, the safety stock has been excluded from the FFR report for this purpose. In addition, when there are two stages in the selected value stream, the FFR report also includes the contribution of the last second stage's performance in its results for calculating the last stage's performance which is manufacturing. Therefore, this must also be excluded. Indeed, P_p is the manufacturing performance without taking into account the stock out of raw materials (Aleotti Maia & Qassim, 1998). Hence, to calculate the required absolute value of P_p from FFR, three other parameters should be defined. First one is K'_p which is the exact number extracted through FFR, the other one is P'_p which is the FFR's result excluding safety stock contribution. And the third one is K'_i which is the historical previous stage's delivery performance; by dividing this by P'_p the absolute manufacturing performance is measured ($P_p = P'_p / K'_i$). Indeed, there is no direct report for tracking absolute manufacturing performance in the case company. Table 1 is a snapshot of a sample FFR and presents the formulas used to eliminate the safety stock from its calculation. As shown through the table, in the 12th week of 2010, the FFR report gives 100% ($K'_p = 100\%$) as the delivery performance of manufacturing to its customer because it takes into account the 300 pieces of safety stock for meeting the past and current requirements; however, safety stock must be excluded through this calculation and P'_p becomes 18%. The next step for calculating the absolute manufacturing performance would be the elimination of the effect of the previous stage's performance (K'_i).

About the calculation of P_i in FFR, it should be noted that if the supplier delivers a part on time with the right quality, but defects occur during transportation from procurement to manufacturing or customer, although the delivery performance of the supplier is 100%, P_i will be 0% since the part is not available for use. Therefore, P_i can also be called "part availability" instead of supplier delivery performance.

It is worth mentioning here that ABC has three different strategies for managing its inventory. It applies a two-bin kanban system for the parts with low costs. The company is moving towards excellence and applying a pull system for managing the inventory of those parts that have high cost with high volume; but this system is not applicable for all parts due to the complexity and lack of required conditions such as having suppliers with delivery performance of higher than 80% and with a supermarket of finished goods, having parts with a robust process and steady volume, among others. Therefore, its inventory strategy for the rest of the parts with high cost and low volume is MRP system. Based on this, a safety stock strategy is really required for this latter category of parts. For calculating q_i and q_p , we need to understand the risk period. Risk period consists of a review period and replenishment lead time (Tempelmeier, 2006). The review period is the basis on which the company updates its data. As a result, if a company reviews its data once a week, its review period would be

one week. Of course this review period has an effect on the duration that the company should wait to receive its order through the supplier. In the case company of this paper the data are updated daily; therefore, there is no need for defining the review period. Consequently for parts managed by the MRP system, quantities within the replenishment lead time have found as the most appropriate definition for q_i and q_p to result in the proper level of safety stock for the company through the model. In essence, if changes happen in demand within this period (replenishment lead time), we cannot count on the suppliers' support 100% of the time. Safety stock is required for coverage of this variability. The first step for their calculation would be identifying the planned order quantity of each specific part (raw/semi or finished part) per week according to its planning parameters which it itself is related to ordering policies. Some of the examples of planning parameters in this regard are Lot for Lot, Weekly Batch, 2 Weeks Batch, and Fixed Order Quantity, among others. The second step would be the calculation of the average weekly forecast demand of that specific part for the next year. After that, the division of the planned order quantity and average weekly demand would result in the replenishment lead time in weeks. When changes happen in the supply chain such as changes in the demand or capacity ration, entrance of new competitors, introduction of a new product, or retirement of a matured one, the safety stock required for the supply chain must be re-evaluated (Jung et al., 2008). ABC has decided to run the model and update it every quarter, therefore, the weekly demand of the next quarter would be merged based on the calculated replenishment lead time. And finally, the maximum quantity of this combination will be selected as q_i / q_p in order to allow the safety stock strategy to support the worst case.

Table ?? : First fill rate report sample One of the advantages of this method of calculating q_i and q_p is making the market variability involved by taking into account of the forecast demand. It should be mentioned that the planned order quantity for a manufacturing part should always be calculated through its demand only in the plant in which it is being manufactured because the part will be replenished based on the ordering policy in that plant. On the other hand, in the case that a raw material has more than one customer (MF and AFM), calculation of q_i required by manufacturing through weekly demand seen in procurement (entity that receives part through supplier) is not correct because procurement sees the demand of both customers mix. Therefore, the respective q_i must be calculated through the part's parameters (planned order and weekly demand) all in the manufacturing plant that it is going to be used.

9 Shortage costs (costs of safety stock violation)

have different definitions for raw materials (semi-finished parts) and finished parts as they are located in different stages within the chain and their shortages have different effects on the system. The shortage cost of the raw material (semi-finished part) is the summation of the expediting cost on the supplier, expediting cost on transportation, and overtime of the manufacturing section. On the other hand, shortage of the finished part which is required by Assembly, causes disruptions and stock not pulled for all the other parts related to that finished part and also its finished product in different locations of the supply chain. In addition, shortage of the finished part causes the finished assembled product to be held up unreleased. Therefore, the shortage cost is defined as follows: during last year*0.1)/365 Coefficient of 10% in the above formula is the annual interest rate that company could receive by putting this amount of money in the bank, although the company has this as inventory buckets instead of cash right now.

The cost of shortage of the finished part required by Aftermarket is defined as the profit that the company will lose by not having the part ready to deliver on time to the customer, which is the direct cost. Besides that, there are many intangible effects of this shortage that are called indirect costs and are difficult to gauge accurately (Graves et al., 1993). One of them is loss of customers' goodwill that may turn them to other competitors in the future. On the other hand, at the time of shortage of a specific part, the Aftermarket department may rent out another more expensive part instead of the required one to the customer until it arrives. Therefore, the shortage cost of these parts is defined as four times of the standard cost (Std.Cost) of the finished part.

The cost of overage is defined as the interest that the company is losing by holding inventory instead of having it in cash. Hence, it is the multiplication of standard cost of the part and the annual interest rate (10%).

As can be seen through the formulas and definitions, a period of one year has been selected for historical data collection. As the factors (such as shortage cost and delivery performances) that are gathered within this time frame are critical to make an appropriate decision about the level and location of safety stock, one year has been selected in order to have a sufficient window view.

Some samples of value streams associated with their models' formulas are presented below.

Value stream 1 shown in Figure ??5 consists of one raw material/semi-finished part used to make one finished part which has two customers, ASSY and AFM. The corresponding objective function and constraints are presented by (3).

$$\text{Min } C_q q + C_C C + C_P K + P K_i i + p u$$

$$\text{Subject To } K_i K + P_i i + u K + p u + K + P + K + p + u = ? + ? + ? + ? =$$

$$+ ? \times ? = ? ? ? = ? \times =$$

If for this case, there were two different kinds of finished parts but again in demand with both customers, then there should be a summation on both indices of finished part (p) and customer (u) in the objective function:

$$\text{Min } C_q q + C_C C + C_P K + P_i i + i i + s i o i + i q + C_K p + s p u + p u + C_K$$

$$\text{Subject To } K_i K + P_i i + u p + K + p + u + K + P + K + p + u = ? + ? + ? + ? = + ? \times ? =$$

$$= ? ? ? = ? \times =$$

288 In value stream 2 which is shown in Figure ?? 6, two raw materials/semi-finished parts are used to make one
 289 finished part which has two customers, ASSY and AFM. The corresponding model is also presented by (5).Figure
 290 6 : Value stream 2 2 2 (1) () 1 1 2 (1) 1 2 2 (()) 1 1 : 1, 1, 2 , 1, 2 1, 1, 2 2 , 1,2 (5)

$$291 \quad 1 \text{Min} C q q C C P K P i i i s i o i i i i q C K p u s p u p u u q C K P K p u p u i o p u p u i \text{ SubjectTo } i K i i K P$$

$$292 \quad i i u K p u u K K P i p u p u i = ? + ? ? ? = = + ? ? = + ? ? ? = = ? = ? = ? = ? = ? =$$

293 As before, if there were two different finished parts for the same situation, the model would be changed as (6):
 294 2 2 (1) () 1 1 2 2 (1) 1 1 2 2 2 (()) 1 1 1 : 1, 1, 2 , 1,2 MinC q q C C P K P i i i s i o i i i i q C K p u s p u p u
 295 p u q C k K P p u p u o p u i p u p u i \text{ SubjectTo } i K i i K P i i = ? + ? ? ? = = + ? ? ? = = + ? ? ? ? = = =
 296 ? = ? = 1, ,1, 2 2 , , 1, 2 (6)

$$297 \quad 1 p u K p u p u K P K p u p u i i ? = ? = ? =$$

298 As can be seen through the constraints of the model, the company's objective is to have 100% delivery
 299 performances. Therefore, the upper boundaries of both stages are assigned to 1 in order to not to allow the
 300 model to impose a shortage to the system. Of course, these upper bounds could be less than 1 based on the
 301 service level goals in different cases. By this definition of the model, costs factors would be the indicators for the
 302 location of the safety stock and its level would be identified based on the boundaries of the delivery performances.
 303 This optimization model will be linear if there is only one raw material/semi-finished part and optimum point
 304 with minimum cost will happen only in one of the four boundaries. Based on this, we assume the optimization
 305 model as (7) with only one customer for finished part:(1) () (1) (())

$$306 \quad : 1 1 (7) \text{Min} C q q C C P K P i i i s i o i i i q q C C K K P K p u p u p u i s p u o p u p u \text{ SubjectTo } K i K P i i$$

$$307 \quad K p u K P K p u p u i = ? + ? + ? + ? \times ? ? ? ? \times$$

308 Varying the location of the safety stock based on the optimum point in two sample cases of the linear model in
 309 (7) are shown with the following feasible regions in Figures.7and8. In addition, Table 2 presents the comparison
 310 between the costs in each of the cases and also the recommended location of the model for the safety stock. In
 311 this comparison, it is assumed that q i and q p are equal. In order to make the results of the model more effective
 312 for the company, one of the most problematic finished product families of the Assembly was selected, and value
 313 streams of its finished parts that are going to be assembled were reviewed with the model. As each of the selected
 314 final product families could have 100 different value streams in the case company, it was decided to apply the
 315 optimization model only for those value streams that end with finished parts that were consistently in shortage
 316 report during last year in order to limit samples. Value streams of these pacer parts vary. Some of them could
 317 have only the supplier stage before the assembly and some others could be very long. As discussed before, these
 318 long value streams were limited by taking into account only parts of level 1 and 2 of its finished product's bill of
 319 materials (BOM).

320 10 VI.

321 11 Computational Results

322 Results of the model applied to some value stream samples of one finished product family in the company are
 323 presented in Table 3. This table includes input factors to the model such as delivery performances (P i ,P p),
 324 parts quantities (q i , q p), costs (C s , C o) along with parameters required to calculate them (K' i , P' p
 325 , K' p , standard cost) for each value stream. This table also presents the old and new safety stock levels and
 326 total costs (for those cases that all required data were available)to compare previous situation with new one. All
 327 historical data presented in this

328 12 a) Value Stream 1

329 Shortage costs of ASSY and AFM (customers) are the first two highest costs; therefore, the model has targeted
 330 them at first and recommended that the delivery performances in those entities be increased to 100% by keeping
 331 safety stock for the finished parts. ASSY and AFM can count on receiving their required demand on time for
 332 0.61% and 0.30% respectively; thus, they need to compensate the 0.39% and 0.70 % of unavailability of partsby
 333 asking manufacturing to keep safety stock.

334 Then, the third and fourth highest costs are the overage costs of the same entities. Hence, the model suggests
 335 keeping some level of safety stock in the raw material (semi-finished part) level as well to lower the level of finished
 336 parts' safety stocks. It is shown that procurement can count on on-time delivery performance of supplier(s) for
 337 0.57% and they have to reimburse the remaining 0.43% by having safety stock. As in this case, safety stock has
 338 been increased in both levels of supplier and manufacturing, of course before applying the recommendations, the
 339 capacity of both should be checked in order to be aligned with the new level of demand and input respectively.

340 13 b) Value Stream 2

341 According to the priority of the costs, shortage should be removed for the Assembly entity by keeping safety
 342 stock for its required finished part. In this case, the manufacturing performance is zero; therefore, having safety
 343 stock for the rawmaterials' level in case of improving the input ration to this entity will not make any changes.
 344 Consequently, there is no choice but to pay for the holding cost for the finished part, although this holding cost
 345 is the second highest cost. On the other hand, as soon as manufacturing performance increases even slightly, the

346 level of safety stock required for the finished part will decrease by recommending holding some safety stock for
347 raw materials.

348 **14 c) Value Stream 3**

349 Again the highest cost is the shortage cost of the finished part and an action required to reduce this cost by making
350 K_p (delivery performance) 100%. As the manufacturing performance is 100% ($P_p = 1$) and based on the formula
351 of $K_p = P_p \times K_i$, the only way to make K_p equal to 1 is by making K_i equal to 1. Therefore, having safety
352 stock for raw material is recommended by the model for this purpose. In sum, in this case, the manufacturing
353 entity has produced whatever they received from procurement; therefore, to improve their delivery performance,
354 the input amount should be improved. Of course, for this kind of change, the capacity of manufacturing should
355 be checked in order to be aligned with its input.

356 **15 d) Value Stream 4**

357 In this case, the highest cost is related to the shortage of finished part required for Aftermarket; hence, safety
358 stock should be kept for this customer. Then, the biggest loss would happen if the company cannot deliver the
359 required demand of ASSY; As manufacturing's performance in response to Assembly's demand is 100% and it
360 can produce whatever it receives from procurement, delivery performance to ASSY will be improved only by
361 increasing input of the raw material to manufacturing. To make a decision about the value of K_i , the model
362 will hit the third highest cost which is the raw material's shortage cost. The selected value for K_i will also affect
363 the level of required safety stock for Aftermarket.

364 **16 e) Value Stream 5**

365 Apparently, it is understood that there is no need for safety stock for Aftermarket as its demand for the next
366 quarter is zero. But, it should be noted that as the manufacturing performance for this customer is zero, safety
367 stock should be considered as soon as demand occurs. On the other hand, for the purpose of cost reduction,
368 delivery performance to Assembly should become 100%. As the manufacturing performance in response to this
369 customer is also zero, the full quantity of the finished part within the replenishment lead time should be kept
370 as safety stock. By improving manufacturing's performance up to 50%, the level of safety stock required to be
371 kept in finished part will be lowered but still there would not be any recommendation for keeping safety stock for
372 raw material. But, as soon as manufacturing's performance increases by more than 50%, the model will suggest
373 starting keeping safety stock in the raw material stage as well and balancing it to minimize the total cost.

374 **17 f) Value Stream 6**

375 Based on the investigation done for this case, it is known that raw material has quality problems most of the
376 times. With this background, the result of the model does make sense: to keep safety stock in that level of the
377 chain.

378 **18 g) Value Stream 7**

379 The model suggests balancing the level of safety stock by keeping it in both raw material and finished part levels
380 and ensuring the on-time delivery to the customer, Assembly.

381 **19 h) Value Stream 8**

382 This value stream includes one raw material and one finished part with only one customer, Assembly, just as
383 in Value Stream 7. As shown previously, safety stock was kept at both levels; but now the model is suggesting
384 keeping safety stock for the finished part only. The reason is that manufacturing performance is almost zero and
385 improving its input will never help to provide on time delivery to Assembly. On the other hand, holding cost
386 of the raw material is really greater than its shortage cost; so, it is not beneficial even for lowering the level of
387 finished part's safety stock.

388 **20 i) Value Stream 9**

389 This sample shows one of the class A finished parts required for Assembly for the selected product family. This
390 finished part has three semi-finished parts (level 2 in finished product's BOM which are L, N, and S in Table 3).
391 "L" is an in-house part and is manufactured in ABC. Furthermore, the manufacturing plant requires raw material
392 (T) to produce this part which is procured through the supplier. Part T is in level 3 in the BOM. Therefore, this
393 sample goes far beyond the limitation of levels 1 and 2, and shows that the model is applicable for all stages of
394 the value streams as long as the input data of the model are provided.

395 Manufacturing, receives the two other semifinished parts (N and S) required for producing the finished part
396 directly through suppliers. Figures 9 and 10 present the respective value stream and BOM. Assume that there
397 is a bottleneck in the first value stream in Figure ?? 9 as the manufacturer does not have the capacity for the
398 requested new level of demand. Then the other two value streams can make their delivery performances 100% by

399 keeping safety stock, although the finished product cannot be cleared yet due to the pacer part of the first value
400 stream (if there is no safety stock kept for the finished product). In this situation, there may be some complaints
401 that safety stock must not be kept in the other value streams either since in the end, the company will pay for
402 the holding costs while the finished product cannot be released. The response to this complaint is that if the first
403 value stream comes out of the pacer situation, then another one will become the pacer due to not having safety
404 stock. In essence, bottleneck always moves. Therefore, for this case, it makes sense to keep safety stock only for
405 two of the value streams although the delivery performance of cost of the finished part based on its formula (C
406 $op \times K p - (P p \times K 1 \times K 2 \times K 3)$) will be decreased.

407 This last value stream (value stream 4), can be a representative case to illustrate the error and especially in
408 this case, the overestimating of safety stock result in the analysis of parts in isolation and not within the chain.
409 If, ALNS was being considered separately and apart of its chain, system may allocate some level of safety stock
410 for that due to the $K' p$ which is 85%. But, when this part is analyzed within its chain, it is understood that
411 the reason for no availability of the finished part is not due to the last stage performance but it is due to the low
412 delivery performances of the semi-finished parts. Therefore, keeping safety stock in the last stage only increases
413 the holding cost of the system. VII.

414 21 Validation

415 In this section, historical data on a raw material part will be used for analysis and compared to the results of the
416 model.

417 As illustrated in Figure ?? 11, there were periods in the last 5 months during which the company was in
418 shortage and had negative stock. There was no safety stock assigned to the part during these periods. On the
419 other hand, the stock situation became better starting in week 14 by allocating 600 units of safety stock. Thus
420 the theoretical safety stock was 0 and 600 for this part during the last five months. The same analysis in the
421 same period has been done for $P i$ and $K' i$ as shown in Figures.12 and 13 the finished part will not be 100% due
422 to the low performance of the value stream with the bottleneck. On the other hand, by improving the delivery
423 performances even only for two value streams out of three, holding It can be seen that the weakness of part
424 availability in weeks 13, 14, and 15 had been compensated by safety stock; although this weakness could not be
425 remunerated previously as there was no safety stock. Therefore, it is concluded that by this amount of availability
426 for this part, safety stock is essential to guarantee on-time delivery to manufacturing.

427 The optimization model was then run for the raw material's value stream. The result of the model was 394
428 pieces for the raw material's safety stock; but of course this level is based on the next quarter ratio of demand.
429 Indeed, the lower level of safety stock recommended through the model is related to the maximum quantity of
430 this part that will be required in the next three months based on the forecast. And this maximum number is
431 being considered in the model to decide the level of safety stock to guarantee the worst case. On the other hand,
432 it is shown through Figure ?? 13 that by keeping 600 pieces of safety stock, the level of stock is going to be
433 increased and this is not a desired case as holding cost is associated with this increase; therefore, lowering the
434 level of safety stock does make sense.

435 Figures.14 and 15 show the historical data of three factors, FFR (%), safety stock fulfill rate (SS FR%), and
436 number of parts with quality issues (QN in pieces) for three different parts. The messages of these charts are
437 provided as well. These messages were aligned with the safety stock model's results obtained for the respective
438 parts.

439 22 Discussion and Implications

440 The recommendations of the model are according to the current situation of the system. Of course as soon as
441 the company takes action towards improving its system for parts availability within the chain, the results of the
442 model for level and location of required safety stock will be adjusted accordingly. The managerial guidelines that
443 are provided in this section can be used in any kind of manufacturing systems.

444 Re-sourcing of the suppliers would be a solution for their low delivery performances and quality problems.
445 Increasing the capacity of manufacturing and improving its quality would be a solution for low availability
446 percentage at semi-finished and finished parts level.

447 On the other hand, in the cases that the company requires keeping some level of safety stock due to the bad
448 performance of vendors (low delivery performance, low quality), it is recommended that a VMI system be applied
449 to have safety stock at the vendors' place.

450 The existing FFR report in the case company for the Aftermarket entity is based on their forecast demand
451 instead of their firm orders; therefore, the model is not capturing the accurate delivery performance record for
452 them. By deciding the level of safety stock based on the forecast demand, we will put safety stock on top of the
453 safety stock because forecast demand is itself a kind of buffer stock. To solve this problem, it is recommended
454 that ABC design an FFR report specifically for Aftermarket in order to capture the performances in response to
455 only firm orders.

456 There may be some parts that are dual sourced and there is a quota arrangement between different suppliers,
457 but the FFR report being used in the case company does not include the vendor field in its results. Therefore,
458 it is recommended that the supplier field in the FFR report be considered as well to allow the company to

459 recognize their delivery performances separately and consequently be able to make decisions about re-sourcing
460 more accurately.

461 One of the other factors other than delivery performance or service level of the suppliers in making decisions
462 in the dual source cases is the waiting time for receiving the late parts. Indeed, the company as a customer will
463 select the supplier with the lower waiting time among the ones with the same service level. One way of tracking
464 the waiting time of the supplier is through the calculation of the period within the replenishment lead time in
465 that the company had negative stocks; but it is subject to keeping stock of each supplier separately to be able
466 to relate its negative period to the corresponding supplier. Now consider a case that the supplier of a specific
467 required raw material has the delivery performance of 50%, demand is one piece per week, its replenishment lead
468 time is 10 weeks, and its waiting time is 2 weeks. Assume that the worst case for its q_i for the next quarter is
469 10 pieces. And again assume that it is the case that the model suggests keeping safety stock for the remaining
470 50% of the time that the supplier is late, which is equal to 5 pieces. This level of safety stock is equivalent to 5
471 weeks of demand, although the company will receive its late demand after 2 weeks according to the waiting time
472 of the supplier. Therefore, the company does really need safety stock of 2 weeks instead of 5 weeks. Hence, no
473 matter if it is a dual source case or not, it can be concluded that waiting time is also an important factor for
474 determining the optimum safety stock.

475 If there is safety stock for the finished assembled product or it is scheduled for build ahead, sizing the required
476 safety stock within the chain should be done by taking into account of these factors as well. One way to get them
477 involved is by converting them to the weeks of demand for each stage and comparing them with the suggested
478 amount of safety stock (like the method suggested for waiting time). But the time lag between the time that
479 we put safety stock for the finished product (or build ahead) and the time that we will have it should also be
480 considered; otherwise, reducing the safety stock within this period by will put the system in a shortage situation.

481 For some cases where unavailability of a part is solely related to the low delivery performances and not to
482 quality issues, safety lead time can be applied instead of safety stock.

483 Delivery performances of some parts in their last stage are very low due to different engineering issues such
484 as changing the layout and design consistently. Therefore, recommendation of the model to have safety stock for
485 these parts will make sense only if the cost of reverse engineering of these parts is less than their shortage cost.

486 If the model suggests increasing the level of safety stock for a specific stage, the company will receive it by
487 the end of the total lead time of the chain related to that part. Therefore, if the company adds the extra pieces
488 of safety stock to its demand, it will allow all purchase orders to be expedited although this extra amount is not
489 the actual demand and it is required for safety stock. Hence, the company must inform the suppliers that it needs
490 this portion of demand for their next lead time. On the other hand, it is really important to take into account
491 the lead time of the whole chain, otherwise, it will put them in a shortage situation. As a result, knowing the
492 existence of this time lag makes the selection of the periods for calculating q_i and q_p more accurate. It should be
493 noted that after selecting this appropriate period, standard cost of the parts should also be updated accordingly.

494 The q_i for those parts that are strategic ones should be validated with the responsible value stream managers.
495 Indeed, quantities of this kind of parts could be really greater than the number which is result in through the
496 mentioned definition for them. There are different indicators that make a part strategic such as the critical parts
497 that are single sourced, or the parts that have limited suppliers or the parts with the resourcing strategy. For
498 example, there could be a single sourced critical part which is received in a batch and based on the experience it
499 is known that if one part of this batch has a quality issue, there is a high possibility that the entire batch needs
500 to be scrapped. Therefore, by having correct level of safety stock for this part, the company can survive and save
501 the supplier's lead time.

502 **23 IX.**

503 **24 Conclusions**

504 This research extends the work of Aleotti Maia and Qassim (1998). They proposed a nonlinear safety stock
505 optimization model for a system with n suppliers, one manufacturer and one customer with the objective of total
506 inventory cost minimization. In this study we extended the model to be applicable to the whole supply chain of
507 a generally structured multi-stage manufacturing system. Proper required index, parameters, and variables have
508 been introduced and added more flexibility to the model implementation. In addition, the possibility of stock out
509 for all materials at any stage of supply chain (raw material, semi-finished part or finished part) has been taken
510 into account in the that the material (raw material or semi-finished part) required by manufacturing is always
511 available. This consideration makes the model more realistic. In this research, the safety stock optimization
512 model is provided with the objective function of total logistic costs minimization to result in the optimal level
513 and location of it across the supply chain. The constraints of the model provided for the boundaries of the delivery
514 performances of each stage of the supply chain. Then, we applied the optimization model in a practical realworld
515 problem with different possible value streams. We accurately defined the inputs of the model such as shortage
516 and overage costs and also quantities of the parts. Lingo 11.0 was used to solve the non-linear optimization
517 model.

518 The weakness of the supply chain must be compensated with safety stock, while it is optimized to meet the
519 desired objective of the business. It has been shown in this paper that in optimizing the safety stock based on a

520 cost minimization objective, not only its level but also its location in the supply chain is important. Indeed, by
 521 keeping safety stock in upstream stages, the company will save in holding costs. On the other hand, by keeping
 522 safety stock in downstream stages, it will save lead time. Therefore, these two options must be traded off towards
 523 optimizing safety stock location for minimizing the total logistics costs.

524 Through this procedure, the company can improve its profitability and also become a superior competitor
 525 with its chain.

526 The first contribution of this paper is developing a nonlinear optimization safety stock model applicable for
 527 the whole supply chain. Thus, the applications are not limited to specific stages or levels of the chain. The
 528 second contribution of this study is applying the proposed safety stock optimization model to a realworld case
 529 company. Through this contribution, it has been shown that analysis of any part in isolation and not within the
 530 chain will result in errors (overestimating or underestimating) in safety stock calculation. It also proved that in
 531 optimizing the safety stock, not only its level but also its location within the supply chain is really critical.

532 The optimization model developed in this paper can be adjusted according to the requirements of different
 533 value streams of any supply chain. Therefore, it is applicable to any kind of manufacturing system with the goal
 534 of creating flow in their supply chain and reducing logistic costs by applying lean principles.

535 If a part is procured through more than one supplier, the current model tracks their performance with only
 536 one average number representative of all of them. In future work, the model may be extended simultaneously by
 537 increasing the accessibility of the other required input data to decide on the level of safety stock foreach of these
 538 suppliers separately.

539 Due to the inaccessibility of the required data, the model is currently limited to the last two stages before
 540 the customer in the chain. Again, by enhancing the visibility and control of the upstream stages in the chain,
 541 the model can be applied for each specific part from its starting point until the end of the chain. Furthermore,
 542 by increasing the accessibility of the data, the cost of shortage of raw material/semi-finished part can be more
 543 accurate by adding the re-sequencing cost of manufacturing.

544 The cost of shortage of the finished part required by Assembly can be more precise by making the average
 545 days of shortage weighted based on the frequency of its occurrence (increasing or decreasing trend of shortage).

546 One of the avenues for future work for this research would be taking into account the factors of waiting time for
 547 receiving the late parts, safety stock for the finished assembled product, and build ahead in making the decision
 548 for the safety stock.

549 Sensitivity analysis would be helpful for this model. This kind of analysis will support the system for taking
 550 appropriate action towards improving the system. For example, it will help to find out that improving delivery
 551 performance even with a slight amount will make a big difference in the level of required safety stock and
 552 consequently saving costs for the system.

553 In order to have a high level view of safety stock kept across the chain, this model can be applied to the
 554 aggregate level of stages and entities involved in the chain instead of applying it to the part level. Indeed, q_i and
 555 q_p will be the total demand of the downstream stage in a specific period seen by its upstream stage (kits of parts
 556 instead of one part). Delivery performances will be delivery performance of each stage to its downstream stage
 557 in respond to its whole demand. The parts that were historically pacers with the maximum number of shortages
 558 within the total demand of each stage will be selected as the representatives for calculating the shortage and
 559 overage costs of the stages for determining the location of safety stock.

560 25 X.

561 26 Appendix

562 Now, assume a case that there are two different finished parts manufactured in the same plant and they require
 563 a common raw material. Model formulation and value stream for this case would be as (8) $q_i = q_p + q_i \times q_p = ?$
 564 $q_i \times q_p = ?$

565 Procurement sees the summation of demands for both finished parts through manufacturing at once and
 566 not separately. Therefore, mathematical proof of (8) is provided to make sure that the used formulation is
 567 accurate. Indeed, it is shown that manufacturing plant absorbs the input ration of the raw material based on its
 568 performance for each finished part: ^{1 2}

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Figure 1: Figure 1 :

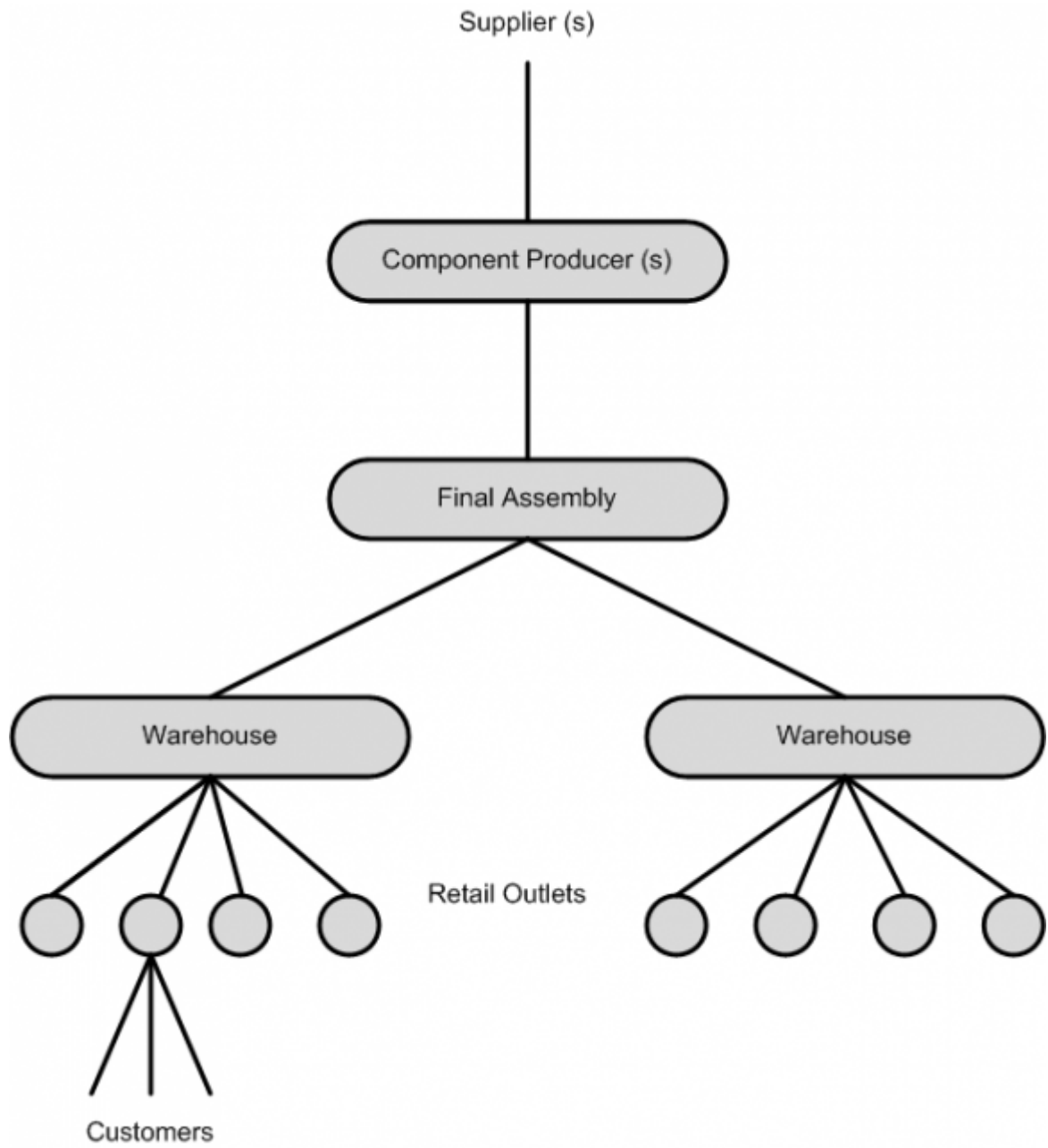
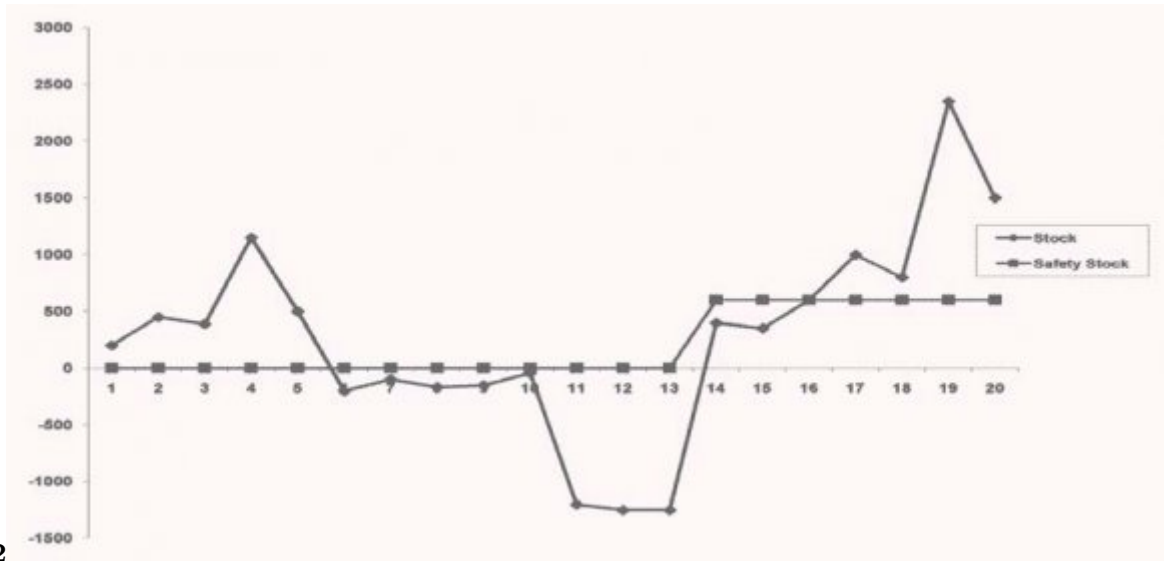
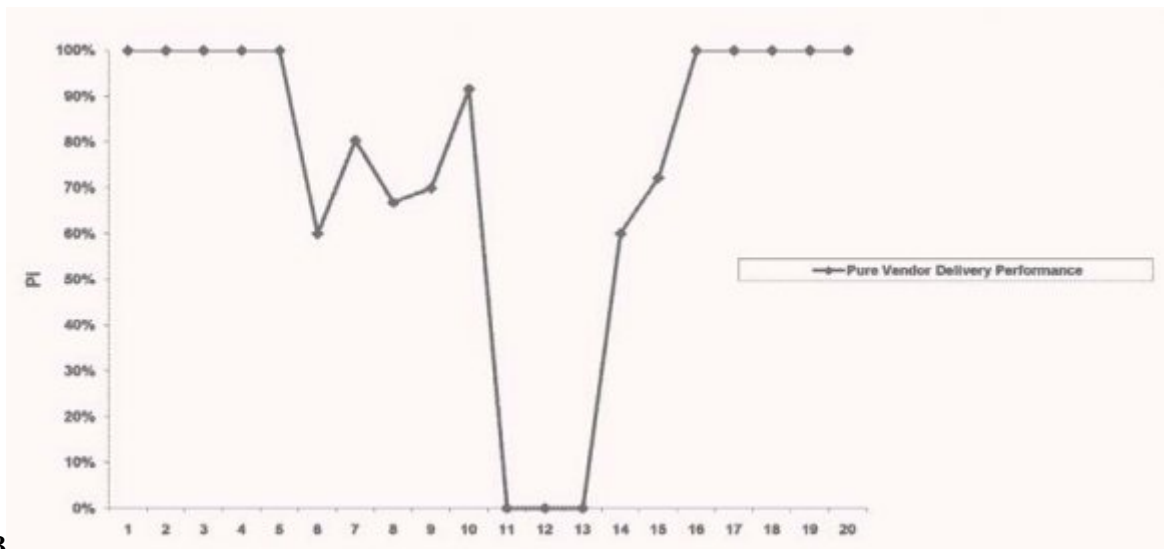


Figure 2:



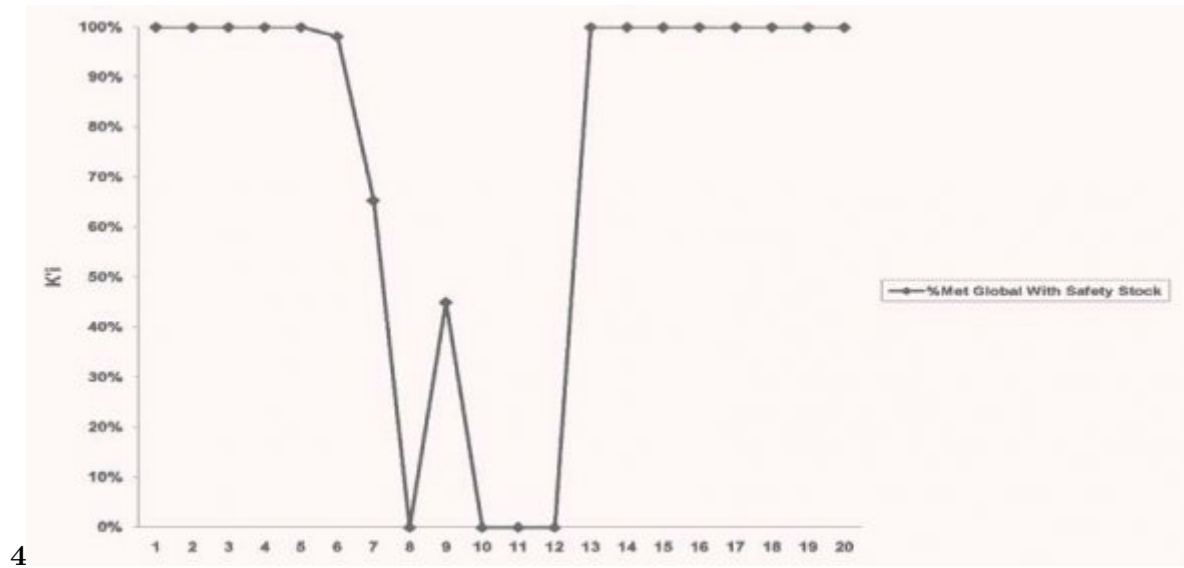
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Figure 3: Figure 2 :



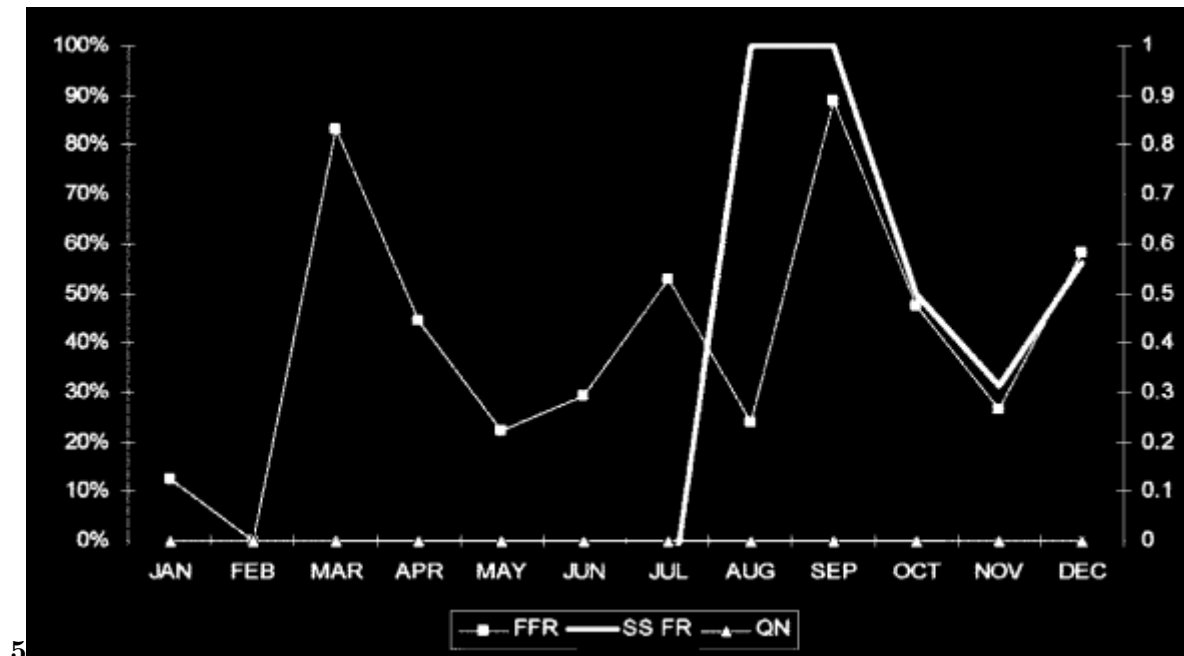
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Figure 4: Figure 3 :



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Figure 5: Figure 4 :



5

Figure 6: Figure 5 :

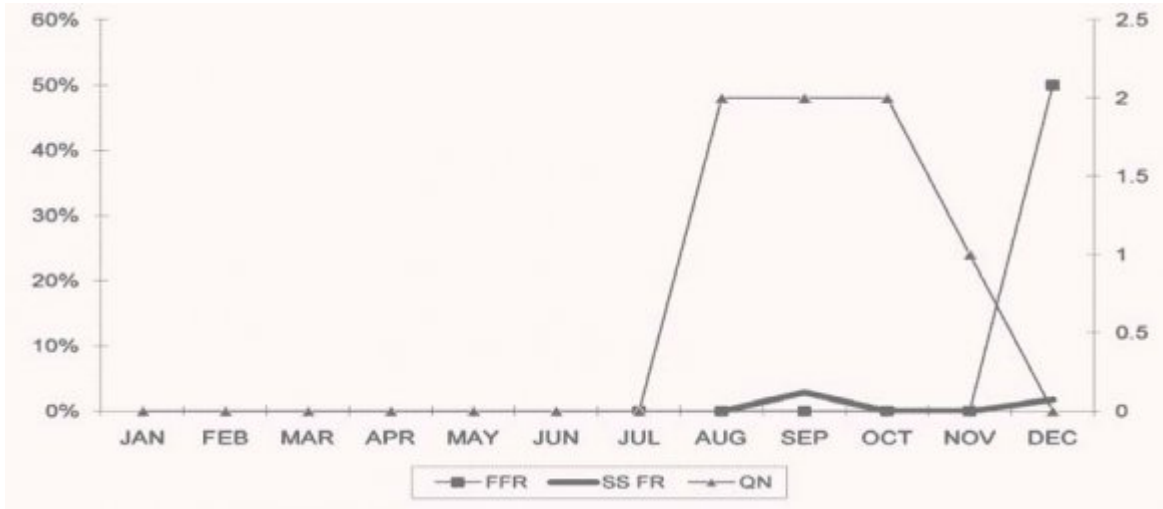


Figure 7:

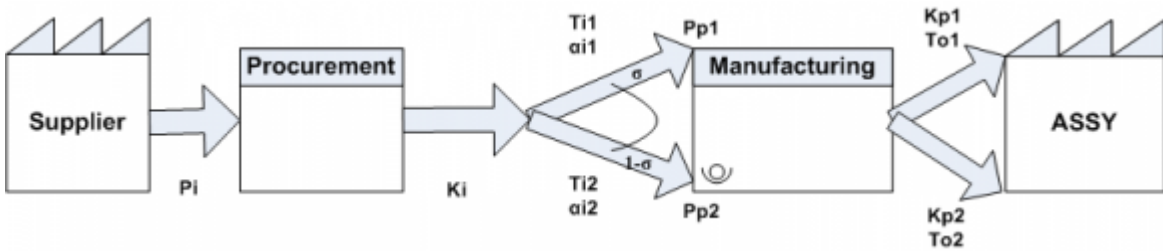


Figure 8: An

Pi Ki Pp Kp
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Figure 9: External Supplier Procurement Xi Manufacturing Pi Ki Xp Pp Customer Kp
 Manufacturing Procurement Xi Manufacturing Xp Customer

2

Case	Costs Comparison	Safety Stock for Raw Material	Safety Stock for Finished Part
1	$Cop > Csp > Csi > Cos$	Yes	No
2	$Cop > Coi > Csp > Csi$	No	No

Figure 10: Table 2 :

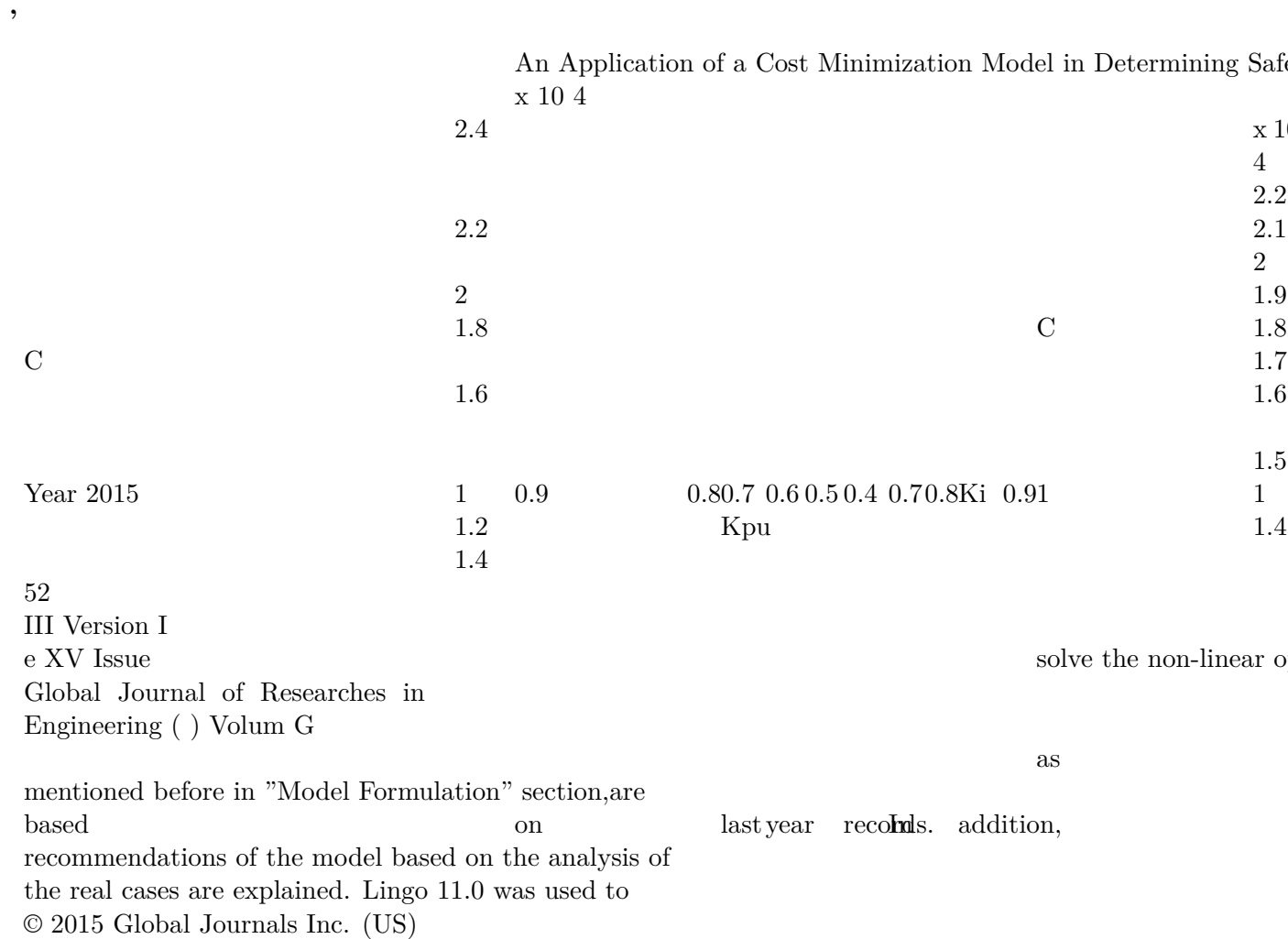


Figure 11: table ,

3

Figure 12: Table 3 :

$$\begin{aligned}
\text{Min} C = & \sum_{i=1}^n C_i x_i + P_i \left(\sum_{i=1}^n x_i - K \right) \\
& + \frac{1}{2} \sum_{i=1}^n C_i x_i^2 + \frac{1}{2} \sum_{i=1}^n C_i x_i^2 \\
\text{Subject To} & : \\
K_i & \leq x_i \leq K_i \\
K_{P_i} & \leq x_i \leq K_{P_i} \\
K_{pu} & \leq x_i \leq K_{pu} \\
K & \leq \sum_{i=1}^n x_i \leq K
\end{aligned} \tag{8}$$

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Figure 13:

-
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