

# Spare parts inventory control: a literature review

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## Abstract

Spare parts inventory are needed for maintenance and repair of final products, vehicles, industrial machines and equipments, frequently requiring high investments and significantly affecting customer satisfaction. Inventory management is complex due to the large number of different items and low demands. This article presents a literature review on single location spare parts inventory control, embracing both demand forecasting techniques and inventory control decisions on the different life cycle stages. Overall, the literature review identified the following research opportunities on inventory management: criteria to decide to stock or not an item, how much to order in the first and the last batch, demand forecasting and inventory control models integration and case studies on real applications.

## Keywords

Inventory control. Spare parts. Lumpy demand.

## 1. Introduction

Spare parts inventories are different from other types of inventories in companies. Cohen and Lee (1990), Cohen, Zheng and Agrawal (1997), Muckstadt (2004), Kumar (2005) and Rego (2006) have pointed out some important factors in the management of these inventories:

- Customers have rising expectations concerning quality of associated products and services. The occurrence of failure is already a concern and the delay in repairing due to lack of spare parts worsens clients' negative perception;
- Some items have high demand (parts with great wearing and those related to preventive maintenance), but the great majority has intermittent demand and;
- The increasing complexity of products and the life cycles reduction generate an increase on the amount of active codes and risk of obsolescence.

Initially, it is important to distinguish disposable parts from repairable ones. Spare parts are extremely expensive in some segments, and their repair (instead of discard) is feasible; damaged units can be replaced either by new units or by repaired ones. In this case,

the inventory control models should also consider the costs and repair time. Sherbrooke (2004) discusses the case of repairable parts.

Another dimension of the inventory control is associated with the existence of a single or multiple locations inventories (KENNEDY; PATTERSON; FREDENDALL, 2002). This article focuses on the literature related to the management of spare parts inventory in a single location.

The article begins with specific forecasting methods for intermittent demand. Demand forecasting is used to estimate the inventory control parameters and, in some cases, also to decide how much to order at the replenishment time.

Then, some methods for item classification are revised in order to set up the inventory control regarding the type of control, service level and related costs. The aspects usually considered in these classifications comprise value, criticality, demand, and the product's phase in the life cycle.

The life cycle of spare parts is associated with the life cycle of the final products which use them (FORTUIN; MARTIN, 1999). Their demand is affected

by several factors: size and age of the “population” of final products (sales, running fleet, installed base, etc.); maintenance characteristics of these products (preventive, corrective, etc.); and characteristics of the parts and their defects (wear, accident, aging, etc.). Fortuin (1980) divides the life cycle of parts in three phases: initial, normal or repetitive and final. Throughout these phases, different decisions have to be taken:

- To hold inventory or not: demands which are very low in the beginning of the life cycle (as well as in the end) lead the manager to question whether parts should be stored or not. For many items, the demand is so low that the decision of not storing, meeting the demand circumstantially after its occurrence may be the best decision;
- Initial orders: uncertainty about the demand growth hampers the planning of the initial orders;
- Inventory control: upon deciding that the part needs to be stored, a inventory replenishment routine is necessary, considering different goals (costs and/or service level) and demand behavior (trends and seasonality) and;
- Final orders: high production and maintenance costs of the productive processes associated with low demands and expected lifespan of products lead companies to interrupt the production of parts at a given time. In some cases, the last production batch is increased to provide additional spare parts final inventory.

These different decisions in each phase of the life cycle of parts are addressed in the following sections of this article.

## 2. Demand forecasting

Most spare parts present intermittent demand, that is, occur at given moments followed by long and variable periods without demand. Intermittent demands are particularly difficult to predict and shortage may result in extremely high costs (HUA et al., 2007).

According to Love (1979), demand forecasts are absolutely necessary for the inventory levels planning. Although forecasts are subject to errors, the knowledge of these errors enables the definition of the necessary safety stocks. Makridakis, Wheelwright and Hyndman (1998) constitute a classical reference in demand forecasting. A review of the past 50 years of the demand forecasting literature on inventory management can be found in Syntetos, Boylan e Disney (2009).

One point that is not often discussed in the literature is the choice of the time bucket that characterizes the demands. Of course, the shortest the

time bucket, the more demand seems intermittent. Comparative studies performed by Eaves and Kingsman (2004) and by Teunter and Duncan (2009) make use of monthly data; Ghobbar and Friend (2003) analysis are based on weekly data; and Gutierrez, Solis and Mukhopadhyay (2008), on daily demands.

A more accurate approach for intermittent demands was developed by Kreyer et al. (2005) to compute the mean and variance of demand during the lead-time. In their approach, known as Single Demand Approach (SDA), as opposed to the more traditional Periodic Demand Approach (PDA) with time buckets, three random variables are used: amounts demanded during the lead-time, time intervals between demand occurrences, and the lead-time itself.

Several other authors have addressed intermittent (“lumpy”) demand forecasting of spare parts, among them: Croston (1972), Syntetos and Boylan (2001), Ghobbar and Friend (2003), Eaves and Kingsman (2004), Willemain, Smart and Schwarz (2004), Regattieri et al. (2005), Hua et al. (2007), Gutierrez, Solis and Mukhopadhyay (2008), Gomez (2008), Teunter and Duncan (2009).

The pioneer work by Croston (1972) demonstrates that the use of classical methods of exponential smoothing on intermittent demand items generates high forecasting errors and, as a consequence, unnecessarily high safety inventories. Croston (1972) proposes an alternative method which separates the estimation of intervals between demands of the amounts demanded in each occurrence. Johnston and Boylan (1996) compared forecasting made through exponential smoothing to the ones made through Croston’s method, and concluded that the latter is superior when the average interval between demands is greater than 1.25 time periods (time bucket). Syntetos and Boylan (2001) pointed out a bias in the original Croston’s model and proposed a correction that gave rise to the SBA (Syntetos-Boylan Approximation) model.

Ghobbar and Friend (2003) compared 13 forecasting techniques to aircraft parts demand and proved the superiority of the techniques: weighted moving average, double exponential smoothing (Holt), and Croston’s method. Similar results were presented by Regattieri et al. (2005). Eaves and Kingsman (2004) evaluated spare parts demand forecasting techniques in the case of British air-force (RAF), including SBA and Croston’s method, and demonstrated the superiority of the SBA method to a certain service level.

Willemain, Smart and Schwarz (2004) developed forecasting models for intermittent demands, using the bootstrapping technique to assess the demand distribution during lead-time, considering

autocorrelation and introducing small demand variations to the original series (jittering). Comparing the new model to Croston's method and exponential smoothing, they concluded that the first provides better results, especially for small historical series. Hua et al. (2007) used bootstrapping together with regression analysis in demand forecasting of parts in the petrochemical industry and showed the advantages of the proposed model.

Gutierrez, Solis and Mukhopadhyay (2008) presented a forecasting model based on neural networks which proved to be superior to the exponential smoothing, SBA and Croston's methods. Li and Kuo (2008) developed the Enhanced Fuzzy Neural Network (EFNN) method, which uses the fuzzy logic, in connection with the Analytical Hierarchical Process (AHP) and genetic algorithms. Li and Kuo (2008) showed that the model provides better results using 14 series of 12 months.

Gomez (2008) analyzed 24 time series classified as strong intermittent (criterion of BOYLAN; SYNTETOS; KARAKOSTAS, 2008), using auto adjustment techniques over the classical forecasting models (Simple Smoothing, Croston's and SBA) and an original model based on Kalman's Filter. For this sample, the model with Kalman's Filter presented smaller Mean Absolute Percentage Error (MAPE) in 21 of the series; while the auto adjusted SBA model was better in 3.

Teunter and Duncan (2009) compared the following methods: Moving Average, Simple Exponential Smoothing, Croston's, SBA, and bootstrapping. Initially, the inadequacy of the traditional forecasting error measures (MAD, MSE, MAPE) was discussed and the adoption of measures based on the service and inventory level was recommended. The study realized with 5,000 spare parts for British air-force (RAF) proved the superiority of Croston's, SBA and bootstrapping techniques. The authors propose adjustments in the demand forecasting during the lead-time, so that orders are triggered when there is demand, obtaining better results than the original ones.

Most of the cited works are comparative studies through simulation which consider only demand forecasting. It is noteworthy that the study of demand precedes and orientates the definition of inventory control models (FOOTE, 1995).

It is important to remark that, even in "reactive" models (SANTORO; FREIRE, 2008) which do not directly use demand forecasting to decide how much to order each time, require medium-term demand forecasts for the definition of their parameters. Such estimates should be revised as new historical data come up and how often this should be done is still a little explored matter.

Babai et al. (2009) presented a dynamic inventory control model (review of the model parameters at each time interval) based on forecasting and compared its performance with a traditional static model. The results obtained show similarity at service levels and superiority in storage costs, when the dynamic procedure is used.

The classification of parts for effective inventory control will be discussed in the next section. Characteristics of the demand and its predictability are among the several classification criteria.

### 3. Classification of spare parts

According to Huiskonen (2001) and Boylan, Syntetos and Karakostas (2008), the items classification is an essential part of the inventory management systems, in order to: i) determine the adequate level of managerial attention; ii) allow the choice of demand forecasting and inventory control methods; and iii) establish different performance goals at the inventory turnover and service levels between categories. However, most of the surveyed works use the classification of parts only to choose the demand forecasting model instead of the inventory control method.

The organizations which keep inventory of spare parts commonly classify these items through different criteria, setting different service levels for each category (SYNTETOS; KEYES; BABAI, 2009). It is recommended that spare parts of the industrial maintenance to be classified according to criticality in the categories: Vital, Essential, and Desirable - VED (GAJPAL; GANESH; RAJENDRAN, 1994), whereas consumer goods are usually classified in Pareto's graphs in the categories ABC - high, medium and low values (SILVER; PYKE; PETERSON, 1998).

Williams (1984) proposed the partition of the demand variance during lead-time into three components: variability in the interval between demands, in the amount demanded per order, and in the replenishment lead-time. From preset sections, items are divided in three categories: intermittent, slow moving and smooth.

Botter and Fortuin (2000), Sharaf and Helmy (2001) and Suryadi (2003) have applied the AHP method for the VED categorization of items to decide holding or not the items in stock (Section 4). Braglia, Grassi and Montanari (2004) applied the AHP method together with Reliability Centered Maintenance (RCM) in order to classify industrial spare parts and decide between different storage policies.

Zhang, Hoop and Supatgiat (2001) developed a model for the minimization of parts inventories subject to average service level and replenishment frequency constrains. The solution is obtained through a modified ABC classification. For each item  $i$ , the value  $[D_i / (c_p \cdot L_p)]$  is computed, where  $D_i$  represents the average annual demand of the item  $i$ ;  $c_p$  its unit cost, and  $L_p$  the average lead-time. This classification enables the simplification of the proposed optimization model with the adoption of service levels per category, instead of varying it item by item. In their case study, they obtained over 30% reduction of inventory costs with the proposed policy.

Eaves and Kingsman (2004) resumed Williams' model (1984), reclassifying spare parts in five categories (Table 1): smooth, irregular, slow moving, slightly intermittent and highly intermittent. Nevertheless, the adopted classification criteria are arbitrary, hindering the generalization of results. They analyzed the inventory levels of a continuous review policy based on forecasting gathered through five distinct models (SBA, Croston's, simple exponential smoothing, moving average and last year average), and the SBA model was consistently superior to the others (generating lower average inventory levels).

Syntetos, Boylan and Croston (2005) classified items in four quadrants, considering two axes: average interval between demands ( $p$ ) and the square of the variation coefficient of variation of the demand ( $CV^2$ ). The division points along the axes ( $p = 1.25$  and  $CV^2 = 0.49$ ) were theoretically established and proven in tests with 3,000 demand series of auto-parts. The article compares three forecasting methods (simple exponential smoothing, Croston's and SBA) and recommends the use of Croston's method for quadrant I ( $p < 1.25$  and  $CV^2 < 0.49$ ) and the use of the SBA method for the others.

Boylan, Syntetos and Karakostas (2008) showed an application of the method above in a software enterprise. The parts are classified in:

- i) highly intermittent ( $p > 1.25$  and  $CV^2 > 0.49$ );
- ii) slightly intermittent ( $p > 1.25$  and  $CV^2 < 0.49$ );
- and iii) non-intermittent ( $p < 1.25$ ). Considering a policy of continuous review, two forecasting methods (SBA and moving average) and one service level minimum, the results obtained by simulation point out smaller inventories with the SBA method for the slightly intermittent category. But, in the highly intermittent category, none of the studied policies have reached the minimum service level.

The following sections discuss inventory control models for each phase of life cycle of parts.

#### 4. Decision to stock or not to stock

One alternative for the reduction of spare parts inventory levels is the critical revision of the need to maintain or not each one of the items active. Models developed under the premise that all items must be stored should be reconsidered. Is it worth bearing the costs of storage, even for only one unit, or would it be better to acquire the item under demand? This section discusses the question of whether or not to stock a given item.

Silver, Pyke and Petterson (1998) approached the specific problem of whether or not to stock, citing Johnson (1962), Popp (1965), Croston (1974), Shorrock (1978), and Tavares and Almeida (1983). Johnson (1962) proposes two criteria: one to start storing an item currently purchased upon demand, and another to stop stocking an item purchased to stock. Popp (1965) compared the costs of the alternatives to currently purchased upon demand (zero inventories), purchased to stock, and hybrid strategies. The model disregards the costs to add the item to management system; treats demand as continuous; and considers storage and order costs constant for the three strategies. Shorrock (1978) proposed an operational decision model based on the formulation proposed by Popp (1965).

Croston (1974) elaborated a similar criterion in periodic review systems with maximum inventory, negligible lead-time, maximum of one demand occurrence for each revision interval, and normal distribution of the amount demanded by occurrence.

Tavares and Almeida (1983) considered the case of demand following Poisson distribution and inventory options of zero or one. The model evaluates these options through the comparison of their costs: for inventory of "one", it considers regular costs of holding and ordering; for "zero" inventory, it eliminates the

Table 1. Classification proposed by Eaves and Kingsman (2004).

Frequency	Variability of		Category
	Amount	Lead-time	
Low	Low		Smooth
	High		Irregular
High	Low		Slow moving
	High	Low	Slightly intermittent
		High	Highly intermittent

holding costs and increases the ordering cost because it comprises emergency purchases (they will occur only when there is already one order on hold). The option for “zero” inventory will take place when the average demand of the item is greater than a lower bound demand calculated by the specific formulation.

Olthof and Dekker (1994 apud TRIMP et al., 2004) presented a storage decision rule for spare parts where at least one unit should be kept in inventory if its unit annual holding cost is greater than the expected annual shortage cost (emergency purchase and penalties for downtime).

Silver, Pyke and Petterson (1998) modified the original model by Popp (1965) to consider the existence of the cost to include the item in the inventory control system. Alternative formulations for decision in two conditions are obtained: i) keeping other Popp’s premises; and ii) changing the premises of similar costs for regular and emergency orders.

Botter and Fortuin (2000) applied the AHP method in a case study performed in the electronic industry. The study uses the VED classification of criticality of items together with a demand classification (high, medium or low) to take or not the decision to store the item. The AHP methodology was also adopted by Suryadi (2003) in a similar decision model applied to the inventory of maintenance pieces at the petrochemical industry.

In a multiple case study in the Brazilian automotive dealers, Rego (2006) reported the use of different empirical criteria for storage decision:

- Store only the parts which have had demand in all 3 past months;
- Store only the parts which have had demand in 4 of the 6 past months;
- Assign decreasing weights to the past six months (6, 5, 4, 3, 2 and 1). For each item, it is performed the weighted sum for the months that had demand, in the past six months. If this sum is smaller or equals 6 points, the item should not be stored and vice-versa and;
- Compute the weighted frequency (FMP) of the item for the month  $i$  ( $FMP_i = 0.9 * FMP_{i-1} + 1.2 * X$ ), where:  $X = 1$  if there was demand in the previous month, otherwise  $X = 0$ . By this formula, the FMP ranges from 0 to 12, being storable items if  $FMP > 1.60$ .

There have not been found more recent references about decision criteria of to stock or not an item. In some models, stocking or not may be implicit considered in the formulation by properly setting its parameters. For example, in the continuous review model, the decision of not stocking is achieved setting order point equals to zero and lot sizes of one.

## 5. Initial orders

When new products are launched on the market, spare parts managers may decide to anticipate the occurrence of demand, creating an initial inventory of parts, or let the demand occur and, only then, trigger the orders. Even though errors in the initial order may be corrected in future orders, it is difficult to set the initial order due to lack of historical demand. Often, in the automobile industry, this initial inventory is arbitrarily determined by the product manufacturer (REGO, 2006).

Walker (1996) elaborated graphs to aid the initial purchase decision for repairable items, based on a limited amount of products in the market and under the assumption that the time between failures is exponentially distributed. Such premise is quite restrictive, since it does not consider the different rates of failure of spare parts during its life cycle, namely, the phases of early mortality (when the failure rate is decreasing) and further aging of components (when the failure rate is increasing).

Haneveld and Teunter (1997) dealt with storage strategies for slow moving and high cost parts based on the concept of remaining lifetime ( $V$ ), which determines when not to store (order only upon demand) is the best alternative. If remaining lifetime is longer than “ $V$ ”, the optimal solution is to keep one unit in inventory. They then developed a formulation which optimizes the amount for sizing the initial order of parts ( $n$ ). The model is a case where the decision to store or not to store is a result of the inventory control policy itself, also involving the matter of the initial order, in this case, supposedly made at a lower cost, because it is made simultaneously to the order of the equipment that will use the spare part.

Pères and Grenouilleau (2002) developed a model for dimensioning the initial order of spare parts for the International Space Station project, aiming to minimize the probability of delaying any maintenance operation subject to budget limitations.

Syntetos, Keyes and Babai (2009) proposed an additional category of items  $D$ , in the ABC classification, composed of the critical parts of just launched products, defined subjectively, which should be kept in inventory and in this category for the first six months of their “lifetime”.

Once the matter of the initial order has been discussed, we will consider hereafter the normal or repetitive phase of spare parts life cycle. The relevant aspect to be studied in the next section is the inventory control; basically answering the questions of when and how much to replace of each part.



## 6. Inventory control

This section is subdivided in two: the first part deals with the classic inventory models, while the second approaches the specific models for intermittent demand.

### 6.1 *Classic models*

The inventory models for products with high and independent demand is a consolidated area in operations management. From the original work by Harris (1913) on Economic Order Quantity (EOQ), different inventory models have been developed; including the following classic models:

- Continuous Review (R, Q): in this model the inventory is continuously monitored and, when the level reached the order point "R" a lot size of "Q" (economic order quantity) is placed;
- Periodic Review (T, S): in this case, orders are placed in fixed interval of time "T", in an amount to replace the inventory position to the maximum inventory level "S" and;
- Base Stock (B): here, at each withdrawal from inventory, an order of the same amount is made for replacing the baseline, keeping the inventory position (inventory on hand plus open orders) constant and equal to "B".

The first two are basic models for inventory control of high and stationary demand items. In the continuous review the amount replenished is constant and the time interval is variable. On the other hand, in periodic review the time interval is fixed and the amount replenished is variable.

While continuous and periodic review models are used for items with high demand, the base stock is more suitable for item with low demand, including the case of most spare parts. When the base stock is applied to items with very low demand, the replenishment orders will usually be scattered orders from a single piece.

Love (1979), Silver, Pyke and Petterson (1998), Muckstadt (2004), Sherbrooke (2004) and Hopp and Spearman (2008) are a few references which approach the vast theme of inventory control. Specific models for intermittent demands for spare parts with low demand are discussed in the following section.

### 6.2 *Spare parts models*

Williams (1982) discussed inventory control models for items with intermittent demand and proposed a model similar to (R, Q), considering variable interval between demands according to a Gamma distribution

and that at most one demand may occur during the lead-time. In a later article, Williams (1984) expanded the previous formulation to slow moving items and smooth demand.

Popovic (1987) developed a periodic review model in which the maximum inventory are determined based on a demand distribution estimated a priori and adjusted a posteriori using Bayesian inference with accumulated historical information. Initially, the demand rate ( $\lambda$ ) is considered constant and, then, an alternative model is presented for time varying demand rate, given by  $\Lambda(t) = (k + 1)\lambda t^k$ .

Similarly, Aronis et al. (2004) made use of the Bayesian model to forecast the demands and determine the single parameter "B" of a base stock model for spare parts. Estimates and failure history of similar items are used a priori to fit the proper distribution of the demand and then the levels of required inventories (base level) are calculated.

Schultz (1987) developed an inventory model from the base stock, including demand forecasting, analogous to the models developed by Croston (1974). Different from the standard base stock model which considers the placement of orders as soon as a withdrawal occurs, Schultz' model shows that there is a potential gain in postponing the orders and it develops a formulation for this ideal delay.

Petrovic et al. (1990) claims that the decisions in the spare parts management need to consider subjective aspects in addition to the traditional data for costs, lead times and demand. They developed an expert system to manage inventory with the premise that the distribution of the time between failures of a component follows the exponential distribution (therefore did not consider the cases of early mortality and aging/wearing). Users estimate the failure rates of components (or classify them in a subjective scale) and then answer questions about reparability, repair time, cost and criticality level of components. After inputting and processing data, the user gets the list of recommended lot sizes and the total expected inventory cost. There is no comparison of results with other policies.

Dekker, Kleijn and De Rooij (1998) developed a model with different processing for demands named as critical and non-critical. Adopting a deterministic lead-time and demand with Poisson distribution, formulas were presented to set the parameters of a lot by lot replacement policy (at each demand, an order of the same amount is made), where part of the inventory is "reserved" only for the supply of critical demands.

Jin and Liao (2009) developed a formulation for the continuous review system (R, Q) where the spare

parts supplies the maintenance demand from a growing set of products, minimizing the costs of purchase, storage, failure, and revision of control parameters at each time interval. The model assumes that the intervals between failures follow an exponential distribution (constant failure rate). Liao et al. (2008) developed a similar model, with the assumption that the set of products grows at a constant rate and the interval between failures follows Weibull distribution (therefore comprising a wide range of failure models).

Lonardo et al. (2008) present a method for the determination of the desired levels of spare parts inventories, minimizing only the storage costs subject to constraints of minimum service level and assuming a normal distribution for demand. The proposed model is solved by probabilistic linear programming where the set of feasible solutions is generated by Monte Carlo simulation. The application of the model in a set of 2,704 industrial items indicates an inventory cost reduction of 15% over the actual inventory costs for the same service level.

Gomes and Wanke (2008) formulated a heuristic to obtain the parameters in  $(s, S)$  model ("s" denotes the order point) using Markov chains and steady state probability distributions for inventory positions, assuming costs of holding, ordering and shortage, and also assuming Poisson demand. Using the heuristic to solve a set of instances, the costs achieved were, in average, only 2.65% above the optimum solution obtained through simulations.

Silva (2009) compared results from simulations made with 338 maintenance parts of a steel plant, based on a seven-year demand time series. The demand forecasting method adopted followed the bootstrapping model by Willemain, Smart and Schwarz (2004). The average and variance of the demand distribution during the lead-time were obtained according to the SDA approach by Krever et al. (2005), using Laplace, Gamma, Poisson and Normal distributions. The inventory policy adopted was the continuous replacement and its parameters were obtained by the minimization of total costs. The results showed the superiority of the Laplace distribution against the others, even against the Normal distribution previously considered by the company, gathering significant inventory cost reduction and improvement in the service level.

## 7. Obsolescence and final orders

The shutdown of the production of a certain product causes the life cycle of the spare parts exclusive

of this product to enter a decreasing phase and brings up important questions to managers: for how long should the spare parts inventory be replaced? How much should be ordered in a last batch? After the last order (or even before), given a certain excessive amount of stored parts, how much should be scrapped in face of decreasing demands?

At the limit, not to stock may be the most economical alternative to the manager, and the models discussed in section 4 are applicable here, too. Yet, some legal aspects can superimpose the economic criteria in this decision-making. In Brazil, the Laws of Consumer Protection (CDC-Código de Defesa do Consumidor) (BRASIL, 1990) require manufacturers (and traders) to supply spare parts during the lifespan of the product, one concept not very well defined.

Fortuin (1980) argued that even when the failure rates and the set of final products are known, it is still difficult to anticipate the demand, because other factors influence it:

- Consumers prefer to acquire new products instead of servicing the defective ones;
- Consumers prefer not to repair the products because the defect may be of little importance; and
- Non-original parts may be used in the repair of the products.

Two articles by Rosenfield (1989, 1992) address the question of disposal of excess inventory. Rosenfield develops a series of models to determine when and how much to dispose of the surplus considering uncertain demands, obsolescence and perishability. The models consider the potential value of the inventory sales minus the expected costs of storage against possible regained values (*salvage value*) in the instant liquidation. Good references on this topic are listed in the article by Rosenfield (1989).

Several authors approach the problem of final orders: Fortuin (1980), Silver, Pyke and Petterson (1998), Teunter and Fortuin (1998, 1999), Hill, Omar and Smith (1999), and Teunter and Haneveld (2002).

Fortuin (1980) developed a model to determine the size of the final orders of a given spare part to be discontinued. The model assumes a remaining lifetime given in number of years and normal and independent annual demands. The goal is to reach the service level stated at the lowest expected cost of obsolescence (demand smaller than the amount stored) and shortage (demand greater than the amount stored).

Silver, Pyke and Petterson (1998) discussed how large the final order should be in face of the decreasing uncertain demands and argued that the costs involved (excess inventory vs. shortage cost) are difficult to

balance. Alternatively, they set a minimum desired service level to be reached by the final order. The model is based on the estimates of demand during the remaining life cycle and its standard deviation.

Teunter and Fortuin (1998, 1999) reported, in two papers, a theoretical improvement after the application of the inventory model for spare parts at Philips, in its service headquarters located in Eindhoven, the Netherlands. This center supplies parts during the service period, being this period established for each brand of product. The service period, in general, largely exceeds the production period and a final order must be made for the last replacement, which occurs simultaneously to the closing of the production period. The final order should (with high probability) be enough for all the remaining service period.

The developed formulation balances the costs of parts shortage (leading to the substitution of the complete product by a new one or to the offer of discounts to the costumers) and the costs for producing/purchasing and storing these parts. The authors apply stochastic dynamic programming to achieve the optimal solution and also present a simplified version that provides near optimal solutions.

Besides the final order, Teunter and Fortuin's (1999) discussed the matter of how much to withdraw from the spare parts inventory surplus each month during the service period.

Hill, Omar and Smith (1999) dealt with the situation where new orders of spare parts can be launched and the decision involves minimizing the costs of ordering and inventory holding, shortage and obsolescence, during the remaining service period. When the inventory level reaches zero (or close to zero), it must decide whether a new order should be placed (and how much) or it is better to cope with the possible shortage. The model assumes Poisson process with decreasing rates over the time and presents a solution method based on probabilistic dynamic programming.

Teunter and Haneveld (2002) also address inventory control of spare parts in the terminal phase (interval between stopping production of the equipment which uses the part and the end of the maintenance

contracts). The modeling considers the inexistence of order costs, but includes a price increase of the parts in case the orders are made after the equipment production is stopped. The purpose is to minimize costs (not discounted) of replacement, inventory maintenance, delays and discard (of non-used parts at the end of the life cycle). The policy starts out with an order to reach the desired service level (S) and new orders are can be placed considering a decreasing series of values for (S) for future intervals within the planning horizon.

## 8. Conclusions

This article presents a literature review on inventory management of spare parts at single location, seeking to characterize the state-of-the-art and identify gaps which may guide future works. Initially, we would like to highlight the lack of publications by Brazilian authors on this theme, as verified in the bibliographical survey. Also, there is a clear gap in the comparison of different criteria for the decision of stock or not to stock in more representative data settings.

The classification of items in categories is an important tool to prioritize managerial efforts and define the parameters for inventory control. In most case studies in the literature, the classification of parts is highlighted, though usually applied only for the choice of the forecasting model. With the current *software* & *hardware* resources, it is possible to classify items dynamically, to enhance inventory control.

The choice of the inventory control model for each given spare part is a critical activity into the general process of inventories management with multiple items. The dynamic classification of items according to its stage in the life cycle should help managers in the choice and calibration of models for each item. In this context, the term "model" is applied not only to procedures of inventory control, but also to the decisions on initial orders, final orders and disposal, including the demand forecasting methods.

In order to classify the items, in addition to the measures of criticality and uncertainty of demands (average interval between demands, mean and variation of amount demanded, etc.), the evaluation of the current life cycle phase of the part should be included. Table 2 shows a suggested classification based on this dimension.

The initial orders are necessary for items in class "1" which has short time series to demand forecast. Very few scientific papers address this issue. The combination of the demand forecasting techniques with the reliability studies (accelerated life and prototypes testing) is a promising field still unexplored.

Table 2. Classification of spare parts based on life cycle.

Class	Life cycle phase
1 - New	Parts in production for less than 6 months
2 - Active	Parts in production for more than 6 months
3 - Orphan	Parts in production only for replacement
4 - Terminal	Parts out of production with remaining inventory
5 - Inactive	Parts out of production without inventory



The future demand assessment is needed in classes “1” to “4”. In this field, some recent developments (neural networks, Kalman filters) still have to be extensively tested so that they can be compared to more traditional methods in spare parts control (SBA, Bootstrapping). In this case, it is recommended the use of measures of inventory performance, in addition to forecasting errors.

The choice of the inventory control model for each part can be applied only to classes “1” to “3”. Efforts have been undertaken in the development of complex models which are specific for the management of spare parts, and, in some cases, based on assumptions that restrict the practical application. Comparative studies between different models on great mass of data are of high relevance from the theoretical and practical point of view.

The decision on the final order occurs in the transition between classes “3” and “4”. Policies of excess inventory disposal can be applied to classes “2” to “4”. Support models to these decisions are also little explored. Models developed with less restrictive premises and tested on real database should result in important contribution to the subject.

Finally, the case studies on the applications of models and techniques for inventory control in real companies (where the matters of managerial understanding, complexity and efforts become evident), contribute to the reduction of gaps between theory and practice. Examples of this type of study can be found in Cohen et al. (1990), Botter and Fortuin (2000), Srijbosch, Heuts and Schoot (2000), Trimp et al. (2004), Levén and Segerstedt (2004), Wanke (2005), Porras and Dekker (2008), Wagner and Lindemann (2008), Syntetos, Keyes and Babai (2009) and Silva (2009).

Case studies, beyond providing opportunities for decision models testing, allow discussing aspects of the implementation of inventory control systems (management and information technology) itself, which are of great importance for the practical application of academic knowledge.

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