Cash Supply Chains
Cash Management Optimization in Commercial Bank Branches
Miguel Sampaio Tavares
Department of Engineering and Management, Instituto Superior Técnico

Abstract
Throughout the cash supply chain only one product is moved, cash itself, in a two-way flow. Cash management implies significant costs of transportation, handling and sorting, as well as high opportunity costs related with the inventory levels, due to cash's great liquidity. In this work, the process of cash inventory management was analyzed in the optics of a commercial bank branches. A multi-period optimization model is developed to support the decision making in cash management and planning. Based on the costs involved, the current inventory and the foreseen demand, the model minimizes the total costs by determining the periods and amounts involved for the collections and supplies of cash. Cash daily demand is composed by over-the-counter (OTC) deposits, OTC withdrawals and Automatic Teller Machine (ATM) withdrawals. For each of them, demand was forecasted, with several linear regression models being tried. For none of the 8 branches analyzed, the models applied explained a high proportion of the demand for its three components. ATM payments forecast models were the ones with better performance. The optimization model was applied to the selected branches with results obtained for a period of two months. Given the forecast poor performance, the optimization model assumes perfect information on future demand. The application of the optimization model provided a 34,6% to 61% reduction in total costs when compared with the costs incurred by each branch without optimization, which constitutes a significant potential for improvement. The sensitivity analysis presented suggests that the total cost is highly sensitive to the opportunity costs for the capital in inventory.

Keywords – Cash supply chain; Demand forecast; Inventory management; Linear Programming; Optimization

1 Introduction
Even though cards and electronic transactions and other new payment instruments are experiencing a significant growth, physical money, i.e. coins and paper currency, continues to be of great importance in the economy, namely in Portugal, being the payment instrument with the largest number of transactions and still growing in volume and value. Thus, bank branches have an important role within commercial banks’ distribution channels, always looking to meet demand. Transportation, handling and opportunity cost of capital are the main costs that come along with cash management at branches. In financial institutions cash is the only product moving along the supply chain, composing two-way flows.

The problem addressed by this research arose in the management of a leading Portuguese commercial bank, with the main goal of providing a decision support tool for the process of cash inventory management in branches, seeking to reduce its costs while providing the required service level. A multi-period optimization model was developed to determine the optimal periods and amounts involved for the collections and supplies of cash at each branch. To forecast the demand, multiple linear regression models were developed.

The rest of this paper is organized as follows. In Section 2, literature review is presented. Section 3 presents an overview of the case study. In Section 4, the method used for demand forecast is described, as well as the results of the multivariate linear regression models. Section 5 includes the optimization model, with its conceptual description and mathematical formulation. Results are discussed in Section 6. Section 7 includes the main conclusions and future work prospects.

2 Literature review
In the following, we reviewed the available literature regarding cash supply chain management, particularly papers concerning optimization and demand forecasting. Literature regarding cash supply chain optimization is scarce and most of the articles on
optimization and forecasting focus exclusively on ATM networks.

2.1 General overview

Hatzakis et al. (2010) provide an overview of the state of the art in research on operations in financial services, including inventory and cash management, namely cash inventory management under deterministic and stochastic demand and cash supply chains. Rajamani et al. (2006) present a conceptual framework to analyze the elements present in the US cash supply chain (which has similarities with the European cash supply chain) presenting it as a closed-loop supply chain and describing the cash flows along the system. No particular model is presented. Mehrrota et al. (2010) address the problem of adopting efficient recirculation policies adopted by the US financial system. A mixed-integer programming model was developed to access each policy’s performance, based on a theoretical ratio of payments/receipts.

2.2 Demand forecast

Good inventory management tools require accurate forecasting systems, as the forecasting of the demand is an input to for the optimization model (Brentnall et al., 2010). All the following articles focus on ATM demand, differing from branch demand as ATM just allow withdrawals while branches allow withdrawals and deposits and can still have available adjacent ATM equipment.

In the context of a time series forecasting competition (www.neural-forecasting-competition.com/NN5), based on daily cash withdrawals amounts from 111 ATMs in the UK over a period of 2 years, several researchers built time series and neural network models. Teddy and Ng (2011) employed a local learning model, based on an associative memory neural network. Wichard (2011) proposed a hybrid model combining a seasonal for a 7-day cycle, a nearest trajectory model and a neural network model. Coyle et al. (2010) proposed a self-organizing fuzzy neural network with a multi-step-ahead prediction. Andrawis et al. (2011) combined by simple average a linear model, a Gaussian process regression and a neural network model, with a step-by-step approach. Venkatesh, et. al (2014) worked on the same time series, out of the competition, employing a clustering model, having groups of ATMs with similar day-of-the-week demand patterns, followed forecasting through one of four different neural network models. The effectiveness of this approach would depend on the possibility of having cluster-level replenishment plans.

Out of this competition dataset, other papers were reviewed. Wagner (2010a) analyzed forecasting accuracy under information sharing, considering co-variability between different ATM daily demand series, inter-temporal correlation and spatial correlation, as well as calendar effects, through the application of a vector time series model and an ARIMA model. The main goal was determining the overall performance and the potential of joint forecasting for individual inventory planning. Brentnall et al. (2010) provided predictive sequential comparisons between linear models, autoregressive models, structural time series models and Markov-switching models, concluding that Markov-switching models are preferred as they produce density forecasts instead of point forecasts, which can be useful. The authors also refer that the approach chosen for forecasting should be independent from the inventory management method and that different methods and models should be tested as different methods and models may suit better different ATM demand series.

2.3 Optimization

The following articles focus on ATM or branch inventory management for cash and its optimization.

Simulis et al. (2007) applied simulated annealing for optimizing an ATM network. Previously, the authors forecasted demand using neural network models. Castro (2009) developed stochastic programming models and mixed integer linear programming models for optimizing an ATM network in Spain, assuming a given uncertain money demand and identifying the importance of different cost elements.

Osorio and Toro (2012) developed a multi-period mixed-integer linear programming model in order to find optimal decisions related with cash inventory along a network of bank branches in Colombia. Transfers between branches were allowed. Maximum and minimum inventory levels were defined iteratively for each period. Previously, the demand was forecasted applying neural networks.

Cardona and Moreno (2012) presented a two-step model for reducing cash management costs in a single branch, forecasting demand using ARMA models and neural networks models and using this data in a linear programming model they developed. Authors refer the propagation of the forecasting models through the optimization model, leading to possible violations in some constraints.

Also related with the topic, Wagner (2010b) and Wagner (2010c) worked on optimizing ATM networks by combining cash inventory management with vehicle routing.

3 Case study

All operations with banknotes and coins, from their production to their destruction, constitute the cash life cycle. Different entities are responsible for those operations, seeking to regulate the supply and demand of cash in a rational an efficient way. The main stages of cash life cycle are production, distribution, circulation, recirculation, sorting and destruction (Banco de Portugal, 2013).

Production. Within the euro area, the European Central Bank (EBC) and the different national central banks are jointly responsible for the printing of euro banknotes, being each banknote denomination allocated to different national central banks following ECB decisions. Coin production can be realized by any national central bank and is also coordinated by the ECB.
Distribution. The newly produced cash is kept in the national central bank, or exported to other national central banks until it is issued. The cash already issued is distributed by commercial banks, through their branches and ATM network. These credit institutions supply themselves at the national central bank, hiring cash-in-transit companies (CIT) to execute those operations. Most of the cash withdrawal and deposit operations at the national central bank, as well as supply and collection operations at the branches and ATM network are executed by the CITs. Each CIT has centralized facilities for cash holding and sorting. Credit institutions hold inventory there in order to meet the needs along their cash distribution network. In the same way, excess cash at the branches and ATMs may be collected to the CIT facility and the excess here to the national central bank.

Circulation. This stage accounts for all the cash transactions between individuals and businesses within the society.

Recirculation. Cash deposited at commercial banks undergo a sorting and checking process at the branch. The unfit cash (old cash without physical quality for circulation) is sorted, being kept in inventory until the next CIT visit. Authenticity is also checked in each deposit. At a second stage these processes are also executed at the CIT facility. The fit cash is then available for circulation.

Sorting and Destruction. At the national central bank sorting and checking operations are executed once more, by sophisticated sorting machines. Damaged and counterfeit cash is destroyed.

The commercial banks role in the cash life cycle takes place mainly at the distribution and recirculation stages. Cash transportation and sorting imply significant costs concerning branches’ inventory management, as well as high opportunity costs related with holding cash in inventory. In every branch, the bank seeks to meet the public cash demand, composed by OTC withdrawals and deposits and ATM withdrawals. Hence, the flow of cash constitutes a two-way flow. This specific product can be presented in different denominations (e.g. €10 bill and €2 coin), but the amount composing each transaction may consist of different denominations. When the inventory is low, in order to meet demand, the branch manager may order a supply from a CIT under contract. Also, when there is excess of cash in balance, a CIT collection can be provided. As already referred, some of the cash deposited at the branch does not present enough quality for withdrawals, being kept in inventory. When a CIT visit takes place, the unfit cash is collected along with the excess of fit cash.

As mentioned above, regarding the branches’ cash management process in study, there are transportation costs, sorting/handling costs and opportunity costs of capital. The transportation cost is fixed per journey, as contractually agreed between the bank and the CIT, not depending on the branch location or on other branches’ orders. Handling costs relate to the sorting of all the collected cash by the CIT at its facility. This cost depends on the number of banknotes/coins of each currency denomination. Additionally, there is an opportunity cost of capital regarding the amount of cash held in inventory, as holding cash may be considered as an alternative to a bank investment.

4 Demand forecast

As noted previously, cash demand in a branch may consist in OTC deposits and withdrawals and ATM withdrawals. For each of these three parts of demand, forecasting is needed. The data was selected from historical observations, in 8 branches, of two time periods from August to December in two consecutive years, consisting in approximately two hundred observations for each branch. Daily data only consists in working days’ observations. The ATM demand during branch shut downs (the ATM is always available) is considered on the working day after. As in the data available cash demand is not broken into denominations, the whole work presented assumes this aggregation.

Two common methodologies for cash daily demand forecasting present in the literature review are time series analysis and neural networks. This work does not consider those methodologies since the collected data consists in short time series, those time series have lags due to irregular closing periods (e.g. bank holydays) and are not continuous (data is broken into two periods). Also, we wanted to identify possible explanations for demand variation.

Multiple regression has been applied to forecast demand. In this approach, the variation in a dependent (or response) variable is related with several different independent (or explanatory) variables. The present model building follows an approach based on Kutner et al. (2004). For this author, a good model is one that uses a small number of meaningful explanatory variables to predict a relatively large proportion of the variability in the response variable.

The following variables were considered the multiple linear regression models’ building. Most of the variables were considered as qualitative variables (or as factors). Period, year, month, day of the month, day of the week, post-holiday day, number of closure days before the given period. Several different models were tested when deciding on variables to include, as well as interactions between them. The measure to select the best fitting model (for each demand element at each branch), was the adjusted $R^2 (R^2_{adj})$ criterion, also known as coefficient of determination. This criterion provides the proportion of variability in the dependent variable that is explained by the model.

The best models’ performances in the chosen criterion are presented in Table 1. In none of the branches studied, the three parts of demand forecasted are explained in a high proportion by the selected models. Variability in “ATM withdrawals” was the part of demand with higher proportion explained by the models, as its $R^2_{adj}$ assumed values between 0.73 and 0.80 for 6 of the 8 branches under analysis. Counter demand forecasting effectiveness was far below. For the models built for the dependent variable “OTC withdrawals”, $R^2_{adj}$
assumes figures of 0.06 to 0.22. For variability in “OTC deposits” $R^2_{adj}$ was found between 0.29 and 0.45 for 6 of the branches under analysis.

Table 1 – Adjusted $R^2$ criterion for the best multiple linear regression models in each demand element, per branch.

<table>
<thead>
<tr>
<th>Branch ID</th>
<th>OTC deposits</th>
<th>OTC withdrawals</th>
<th>ATM withdrawals</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R^2_{adj}$</td>
<td>$R^2_{adj}$</td>
<td>$R^2_{adj}$</td>
</tr>
<tr>
<td>ID_1</td>
<td>0.726</td>
<td>0.1627</td>
<td>0.7649</td>
</tr>
<tr>
<td>ID_2</td>
<td>0.4282</td>
<td>0.1302</td>
<td>0.7895</td>
</tr>
<tr>
<td>ID_3</td>
<td>0.3334</td>
<td>0.07479</td>
<td>0.7608</td>
</tr>
<tr>
<td>ID_4</td>
<td>0.3383</td>
<td>0.1597</td>
<td>0.4574</td>
</tr>
<tr>
<td>ID_6</td>
<td>0.318</td>
<td>0.06478</td>
<td>0.7289</td>
</tr>
<tr>
<td>ID_8</td>
<td>0.1287</td>
<td>0.2152</td>
<td>0.7978</td>
</tr>
<tr>
<td>ID_9</td>
<td>0.2905</td>
<td>0.1273</td>
<td>0.7276</td>
</tr>
<tr>
<td>ID_10</td>
<td>0.3958</td>
<td>0.06075</td>
<td>0.5991</td>
</tr>
</tbody>
</table>

The values obtained in this measure of performance were not considered to be reliable enough in order to test the model with a different data sample and later to use the models forecasting results as input in the optimization model.

5 Mathematical model

5.1 Description of the mathematical model

The mathematical model applied to the case study is a multi-period linear programming model developed to provide optimal decisions concerning cash inventory management by a commercial bank branch, in particular the planning of cash collections and supplies.

Cash inventories must always meet demand. Cash demand is composed by out-flows, namely OTC and ATM withdrawals, and inflows, over-the-counter deposits. Part of the deposits consist of cash no longer suitable for circulation (unfit cash), being those units unavailable for withdrawals.

Cash collections and supplies are provided by a CIT company. The transportation cost is fixed per journey. There is also a cost for handling the collected cash, proportional to the total amount of cash collected. In every journey, the totality of unfit cash is collected. The cash supplied, consists of fit cash only. By the end of a working day an order may be placed, being the transfer effective on the next period’s morning. Nevertheless, at the end of a period the cash balance must be enough to meet the next day’s demand. There is also a fixed minimum level for the cash balance. There are no backorders and the CIT is always available to supply the branch.

Moreover, there is an opportunity cost concerning holding cash inventory. Regarding this aspect, the amount of cash (fit and unfit) in inventory at the end of each period and the number of days until the next working day are taken in account, as well as the rate for the opportunity cost of capital.

The cash flows do not include cash denomination, only reflecting the value transferred. Counter and ATM demand have been considered together.

Regarding the time scale, a daily scale is considered. Only working days are treated as periods.

Based on the costs involved, the current inventory and the foreseen demand, the model minimizes the total costs by determining the optimal periods and amounts involved for the collections and supplies of cash.

The decisions about flows are done on a daily basis, for a given time horizon. It then follows that the model must be applied at the end of each period, updating the parameters, namely the new starting inventory and the revised demand forecast for the new periods considered.

The problem can be summarized as follows. Given the data provided, determine the defined variables so that the total cost regarding the branch’s cash management is minimized. Given: the starting inventory of cash, fit and unfit; the length of the time horizon considered; the number of days from each period to the following; the minimum fit cash inventory allowed; the proportion of unfit cash per deposit; the transportation cost per CIT trip; the handling cost per euro collected; the opportunity cost per euro per day. Determine: The amount of cash collected and supplied by the CIT for each period. Strictly related to these flows is the planned inventory for each period.

5.2 Model formulation

The multi-period linear programming model is presented as follows.

Sets and Indices

$I = \{1, \ldots, i, \ldots, h\}$ is the discrete set of periods representing the time horizon from 1 to $h$, being each period represented by the index $i$.

Parameters

$s_0$ – Fit cash starting inventory, in €;

$s_0^u$ – Unfit cash starting inventory, in €;

$h$ – Time horizon length, in periods;

$p_i$ – Foreseen withdrawals, in €, for period $i$, $i \in I$;

$r_i$ – Foreseen deposits, in €, for period $i$, $i \in I$;

$n_i$ – Number of days between period $i$ and period $i+1$, $i \in I$;

$u$ – Transportation cost per CIT journey, in €;

$k$ – Handling cost per euro collected, in €;

$c$ – Opportunity cost of capital, in €, per euro in balance, per day;

$d$ – Proportion of unfit cash in deposits;

$q$ – Minimum fit cash inventory allowed at the end of each period;

$M$ – Auxiliary parameter representing a very large number.

Variables

All variables are non-negative. The last variable is binary.

$s_i$ – Fit cash balance, in €, at the end of period $i$, $i \in I$;

$s_i^u$ – Unfit cash balance, in €, at the end of period $i$, $i \in I$;
Given the characteristics of the problem and according to the above sets, indices, parameters and variables, the problem is formulated as follows.

Objective function

\[
\min Z = \sum_{i \in I} \left( u \, w_i + k \, (y_1 + \bar{y}_1) + c \, n_i (s_i + \bar{s}_i) \right)
\]  

Subject to:

Fit cash flow balance
\[
s_i = s_0 + (1 - d) \, r_i - p_i + x_i - y_i \quad (\forall i \in I; i \neq i_1) \tag{2}
\]

Unfit cash flow balance
\[
\bar{s}_i = \bar{s}_0 + d \, r_i - \bar{y}_i \quad (\forall i \in I; i \neq i_1) \tag{4}
\]

Unfit cash collection
\[
\bar{s}_0 - \bar{y}_{i_1} \leq M(1 - w_{i_1}) \tag{6}
\]
\[
\bar{y}_{i_1} \leq \bar{s}_0 \tag{7}
\]
\[
\bar{s}_{i-1} - \bar{y}_i \leq M(1 - w_i), \forall i \in I; i \neq i_1 \tag{8}
\]
\[
\bar{y}_i \leq \bar{s}_{i-1}, \forall i \in I; i \neq i_1 \tag{9}
\]

Minimum inventory level for fit cash
\[
s_i \geq p_{i+1} - (1 - d) \, r_{i+1}, \forall i \in I \tag{10}
\]
\[
s_i \geq q, \forall i \in I \tag{11}
\]

Other auxiliary equations
\[
x_i \leq M \, w_i, \forall i \in I \tag{12}
\]
\[
y_i \leq M \, w_i, \forall i \in I \tag{13}
\]
\[
\bar{y}_i \leq M \, w_i, \forall i \in I \tag{14}
\]

The objective function [1] of the model is to minimize the total costs of cash inventory management incurred by the branch within the \( h \) periods considered. This function includes transportation costs of CIT moves to the branch (first term), handling costs of collected cash (second term) and opportunity costs of capital regarding holding inventory.

Constraints [2] and [3] ensure the balance of fit cash in the branch as the summation of the balance of fit cash in the previous day and the flows of fit cash in the considered period (inflows are the amount of fit cash of client deposits and the CIT supplies, outflows are the totality of client withdrawals and the amount of fit cash collected by the CIT). Equation [2] regards the first period of the given time horizon, equation [3] account for the remaining periods.

Constraints [4] and [5] ensure the balance of unfit cash in the branch as the summation of the balance of unfit cash in the previous day and the flows of unfit cash in the considered period (inflows are the amount of unfit cash of client deposits, outflows are the amount of unfit cash collected by the CIT). Equation [4] regards the first period of the given time horizon, equation [5] account for the remaining periods.

Constraint [10] guarantees that the balance of fit cash at the end of each period is able to meet the next period’s demand. Constraint [11] guarantees that the
The multi-period optimization model presented in the previous section was used on the 8 branches under analysis. The model is applied sequentially in a step-by-step approach, meaning that a run was executed setting sequentially each day as the starting period of the multi-period model. After each run, the model parameters are updated, as the set of periods starts now on the second period of previous run. The starting inventory is updated based on the previous run’s solution and demand is updated as well, since the set of periods is deferred in one observation.

The time horizon considered was 20 periods. Results were obtained from 40 to 43 runs on each branch. The first 10 periods were not considered in the results in order to the initial inventory adjustments not to bias the results. From the remaining runs, only the first period of each run was considered in the results analysis.

As the obtained demand forecast was not considered reliable enough, the model was employed assuming perfect information on future demand. Thus the following results presented represent the maximum potential for improvement, as forecasts are always wrong.

In the following results presentation, costs are distinguished into the three main cost elements that compose the total cash management cost for each branch in the period considered: Transportation cost, proportional to the number of CIT trips to the branch; Handling costs, proportional to the amount of cash collected; and Capital costs, proportional to the sum of the daily cash balances (fit and unfit), therefore it is also proportional to the average cash inventory in the considered period of time.

The figures presented in this section represent only one of the branches under analysis (ID_2), as an illustrative example.

6.1 Comparison between optimized and non-optimized scenarios

The results obtained from the optimization model application (Optimized Base Scenario) were compared with the costs each branch incurred from the registered historical inventory decisions (Non-Optimized Base Scenario) given the cost parameters defined for the model (considered the baseline assumptions).

In the non-optimized scenario, capital cost composed the majority of the total cost of the 8 branches considered, representing more than 80% of total cost in 7 of the branches.

The optimization model provided a cost reduction in every branch, as presented in Table 2. This improvement is highly significant, as the total cost has been reduced by 34.6% to 61%.

The main cost element being reduced was the cost of capital, which also represents the cost with highest weight. This cost was the cost element with greater contribution to total cost in 6 out of 8 branches for the optimized scenario.

Transportation cost increase in 7 branches indicates that a higher number of collections/supplies performed by the CIT are compensated, to a certain extent, by the decrease in inventory levels.

There is no clear trend on handling costs change. As when a CIT visit occurs all unfit cash is collected, if a branch followed this rule it would only reduce handling cost by reducing the amount of fit cash collected.

Table 2 – Percent change in total cost and in each cost element due to optimization.

<table>
<thead>
<tr>
<th>Branch</th>
<th>Percentage change of costs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Transportation</td>
</tr>
<tr>
<td>ID_1</td>
<td>-22%</td>
</tr>
<tr>
<td>ID_2</td>
<td>295%</td>
</tr>
<tr>
<td>ID_3</td>
<td>124%</td>
</tr>
<tr>
<td>ID_4</td>
<td>65%</td>
</tr>
<tr>
<td>ID_6</td>
<td>49%</td>
</tr>
<tr>
<td>ID_8</td>
<td>73%</td>
</tr>
<tr>
<td>ID_9</td>
<td>125%</td>
</tr>
<tr>
<td>ID_10</td>
<td>50%</td>
</tr>
</tbody>
</table>

Figure 1 illustrates the comparison between both scenarios for one of the branches. The scale the presented values assume is based on the total cost for the non-optimized scenario, which assumes a cost of 100.

6.2 Sensitivity analysis

Sensitivity analysis was performed to evaluate the impact in total cost and on optimal decisions due to changes in relevant parameters.
The performed analysis uses the Optimal Base Scenario as comparative scenario (this base scenario always assumes a value of 100).

**Transportation cost per CIT trip**

Since the transportation cost per CIT trip is contractually agreed between the Bank and the CIT, it is under no expected uncertainty. Nevertheless it is directly linked with one of the cost drivers.

This parameter was analyzed for variations of ± 10% and ± 20%.

For a 20% variation of the parameter, total cost increased at most 6.8% for positive variations and decreased at most 7.5% for negative variations. For a 10% variation, the maximum impact on total cost was +3.6% for positive variations and -4.2% for negative variations.

The decrease in cost per CIT journey may lead to an increase on journey frequency. Analysis shows this increase in number of trips always lead to a reduction of inventory levels (observed in capital costs). The reduced variation in capital and total costs along the analyzed branches suggests this parameter variation has low impact on transportation timing and frequency.

Figure 2 illustrates the sensitive analysis for the optimal solutions in one branch, where the above observations also apply.

**Handling cost**

Similarly to the cost per CIT trip, the handling cost per unit results from a contract and so it is under no expected uncertainty. As it is directly related with the total sorting/handling cost, a sensitivity analysis was performed.

The parameter was submitted to variations of ± 20% and ± 40%.

For a 40% variation of the parameter, the maximum impact on total cost was +17.3% for positive variations and -19.2% for negative variations. For a 20% variation, the maximum impact on total cost was +8.8% for positive variations and -8.8% for negative variations. In 4 out of the 8 branches, for either a ± 20% or ± 40% parameter variation, total cost percent change was under ± 5%.

As previously mentioned, when a CIT visit occurs all unfit cash is collected, if a branch follows this rule it only reduced handling cost by reducing the amount of fit cash collected. This fact reveals the low impact this parameter variation has on the decisions suggested by the model, besides the direct impact on costs.

Figure 3 illustrates the sensitive analysis on the handling cost for the optimal solutions in one branch.

**Opportunity cost of capital**

This parameter is the one under greater uncertainty, as it depends on the financial market and on the Bank’s performance. Furthermore this value determination is not simple and is very inaccurate.

For each branch, different scenarios were analyzed assuming different annual percentage rates (APR). The rates and equivalent daily cost per euro are displayed in Table 3.

Table 3 – Opportunity cost of capital for the different scenarios.

<table>
<thead>
<tr>
<th>Annual percentage rate (effective)</th>
<th>1%</th>
<th>3%</th>
<th>5%</th>
<th>7.5%</th>
<th>10%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal daily rate</td>
<td>0.00272%</td>
<td>0.00890%</td>
<td>0.01336%</td>
<td>0.019813%</td>
<td>0.0262116%</td>
</tr>
<tr>
<td>Cost per day per euro in balance</td>
<td>0.0000</td>
<td>0.0006</td>
<td>0.0009</td>
<td>0.00013</td>
<td>0.00019</td>
</tr>
</tbody>
</table>

Results are compared with the base scenario, which assumes a 3% APR and total cost value of 100. For a 1% APR the optimized total cost assumes values between 45 and 73, depending on the branch. A 5% APR induces total costs from 121 to 145. With 7.5% APR total cost assumes values from 147 to 192. With a 10% APR total cost values are found between 169 and 234.

The high impact on total cost is not only driven by variations on total costs but also by transportation costs, as higher opportunity costs of capital lead to an effort in
decreasing inventory levels, which is only possible by increasing the number of CIT visits. This behavior is visible in the illustrative example of one of the branches, in Figure 4.

Given the significant impact the opportunity cost of capital has on the results obtained by the optimization model, an assessment on the importance of knowing the real opportunity cost of capital was performed. This analysis consists of a comparison in total costs of deciding according to the given 3% APR as opportunity cost of capital, even if it does not translate the real opportunity cost of capital (Fixed Solution), with deciding based on the real opportunity cost of capital (Adaptable Solution). This analysis is provided for one of the branches in Figure 5.

Table 4 shows the increase in total cost, per branch, of assuming a 3% APR instead of the (possible) real APR for cash inventory. As observed, branches may incur significant increase in cost. Negative values presented in the table do not translate actual cost reductions. As we only consider the first period of each model’s run and each run has a time horizon of 20 periods, the last 19 runs included in their time horizon periods out of the 2 month time for result analysis. This apparent reduction in cost is due to handling more collected cash in the periods considered in the results. However, sooner or later the CTI will visit the branch, so in the long run those extra costs would arise. In a continuous process the model with adjusted parameters always induces greater cost reductions in the long run.

Minimum fit cash balance

As this parameter is defined by the Bank, it is not subject to uncertainty. However, it has an impact on service level, so it may be reviewed.

Parameter variations of ± 33% were tested and compared with the base scenario (€30,000). A reduction of €10,000 in the minimum allowed fit cash inventory level is translated into a total cost reduction from 3% to 14%. An increase in the same amount has a positive impact on the total cost between 6% and 14%. Analysis shows this parameter only impacts inventory levels. Thus, changing this parameter will not alter the timing and quantities involved in supplies/collections, only affecting the inventory levels. This analysis is provided for one of the branches in Figure 6.
7 Conclusions

This paper studied the cash supply chain with increased focus on cash inventory management at a commercial bank branch level.

A multi-period linear programming optimization model was developed to support the decision making in cash management and planning, minimizing the cost associated with this by determining the periods and amounts involved for the collections and supplies of cash.

Prior to optimization, several linear regression models were built to forecast branch demand, which is composed by OTC deposits, OTC withdrawals and ATM withdrawals. The results obtained by these models were not considered reliable enough to be integrated as input data in the optimization model, as in none of the branches under analysis the variability in the different elements of demand was simultaneously explained in a sufficient proportion. However, as the developed forecasting models only used calendar related variables there is space for improvement by testing other relevant variables of different type of data and by testing other suggested methods applied by other authors, such as neural network models and time series analysis. For these purposes longer time series of data are required.

The application of the optimization model, assuming perfect information on future demand, provided a 34.6% to 61% reduction in total costs when compared with the costs incurred by each branch without optimization, which constitutes a significant potential for improvement. The sensitivity analysis performed stressed the importance of the opportunity cost of capital (translated by the annual percent rate) associated with cash inventory levels and its impact on total costs, as well as on transportation decisions.

The work performed can be considered a first step in building a robust inventory management tool to support the decision making on cash management at commercial bank branches. For this development, further improvements should be accounted for. As already remarked, better forecasting methods and models should be developed, which require longer demand time series in order to do so. As splitting the demand time series into different banknote/coin denominations would imply a significant increase in models and a more than likely decrease in demand forecasting quality, aggregated demand should continue to be used. Therefore, branch managers are stills needed in this decision making process in order to define each order composition per denomination. Another piece of improvement is the definition of the minimum inventory levels per branch, or accounting for stockout costs and its probability according to inventory levels and forecasting performance. It would also be interesting to model the counter and ATM flows, as they are separated in the real system and have some timing restrictions when considering transfers between these elements. Finally, a wider system may be considered, including the whole branch network as well as the CIT facilities in order to plan inventory in an integrated and global way, improving the Bank’s inventory level at the CIT according to branches’ demand needs and eventually test other alternatives in this cash distribution channel.

8 References


