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Brazilian Strategy for Managing the Risk of Foreign Exchange Rate Exposure During a Crisis*

Antonio Francisco A. Silva Jr.**

Abstract

Even in a floating foreign exchange rate regime, monetary authorities sometimes intervene in the currency market due to liquidity demand and foreign exchange crises. Typically, central banks intervene using foreign currency trades and/or by changing domestic interest rates. We discuss this framework in the context of an optimal impulse stochastic control model. The control and performance equations include interventions with swap operations in the domestic market, since the Central Bank of Brazil also uses these operations. We evaluate risk management strategies for central bank interventions in case of crisis based on the model. We conclude that the Brazilian risk management strategy of increasing holdings of international reserves and decreasing short foreign exchange rate exposure in domestic public debt after 2004 gave the country more flexibility to manage foreign exchange rate risk in 2008 and to avoid higher interest rates to attract international capital as was necessary in previous crises.

Keywords ou Palavras-chave: foreign exchange rate, intervention, central bank

JEL Classification ou Classificação JEL: C51, C52, C61, E58, F31

* The views expressed here do not necessarily represent the view of the Central Bank of Brazil.

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1- Introduction

The 1970s witnessed a change in the international monetary system from a regime of pegged exchange rates, which had prevailed since the Bretton Woods Conference. During the 1970s exchange rates fluctuated widely (Frenkel, 1981). Research into exchange rates tries to explain their behavior in response to several mechanisms using structural and equilibrium models, purchasing power parity, covered and uncovered interest rate parity, the monetary approach and the portfolio balance approach among others. For a detailed review of foreign exchange rate literature since the 1970's see Taylor (1995). Meese and Rogoff (1983) introduced an inflection point into this subject as they support the idea that a random walk model is the best alternative for exchange rate behavior modeling. It is difficult to beat the random walk exchange rate forecast because the relationship between the nominal exchange rate and the fundamental underlying macroeconomic conditions may be inherently non-linear (Kilian and Taylor, 2003).

According to Turnovsky and Grinols (1996) an extensive literature analyzing optimal exchange rate intervention evolved during the 1980's. This literature contributed to the debate over fixed versus flexible rates and the authors argued that the existing models suffered from several limitations since underlying assumptions were usually some variant of the static IS-LM model or based on a mean-variance framework. However, the authors stated that the optimal exchange rate regime, attained by an optimal monetary intervention rule, would be critically dependent upon the nature, the sources and the relative sizes of the stochastic disturbance affecting the economy which would not be covered by the standard literature.

New approaches to exchange rate modeling emerged and estimation of parameters and stochastic calculus became important subjects (Krugman and Miller, 1992). In this context, a target zone exchange rate model emerged in the 1980s and it was formalized by Krugman (1991). Flood and Garber (1991) defined the target zone as a non-linear compromise between fixed exchange rates and freely floating exchange rates. According to Krugman (1991) a target zone differs from a fixed rate regime in allowing a fairly wide range of variation for the exchange rate around a reference rate[1]. So, some exchange rate flexibility is allowed and interventions in the exchange rate are

[1] This range is commonly called an exchange rate band.

more an occasional problem than a continuous preoccupation. Svensson (1992) discusses the exchange rate band as a way to monetary independence in spite of fixed exchange rates. However, target zone literature assumes that the band and intervention policies are exogenously given (Jeanblanc-Picqué, 1993).

In fact there is a huge debate on the efficacy of foreign exchange rate intervention but even in a floating exchange rate regime, central banks usually intervene in the foreign exchange rate[2]. One kind of intervention is the purchase or sale of foreign currency. If a central bank purchases foreign currency, it is expected that there will be domestic currency depreciation. Furthermore, it would expand the domestic money supply unless it is offset by the sale of domestic bonds[3]. This type of intervention will increase international reserves. There are studies suggesting that sterilized interventions rarely work, as Flood and Marion (2002) stated. Since there is uncertainty about the link between exchange rates and economic fundamentals, interventions may send signals which tend to confirm coordinating agents' expectations, inducing them to converge on a particular model of the economy and pick a value for the exchange rate that is similar to that targeted by the monetary authority. Evidence for the effectiveness of official intervention is unclear, although some recent studies do suggest a significant link between interventions and the foreign exchange rate[4]. Indeed, after the meeting of G-5 economic leaders in 1985 led to the Plaza Accord, intervention in the markets for major exchange rates has been regular and, at times, heavy (Taylor, 1995).

According to Cadenillas and Zapatero (2000), the use of impulse control theory to model exchange rate behavior began with Jeanblanc-Picqué (1993). Her model works with a stochastic process for the exchange rate and in order to keep it within a given band the monetary authority uses impulse control methods, i.e. interventions in the foreign exchange market. There is a cost associated with each intervention and this cost is minimized. This cost has two components: a fixed cost plus a cost proportional to the size of intervention. Since there is a fixed cost, the optimal policy is not an infinite

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[2] For an analysis of the rationale of interventions see Dominguez and Frankel (1993a,b) and Taylor (1995).

[3] Non-sterilized intervention occurs when the effects of foreign exchange market intervention on the money supply are not neutralized.

[4] Karunaratne (1996), for instance, postulates an optimal control model to test the proposition of ineffectiveness of the Reserve Bank of Australia (RBA) intervention. It used multi-cointegration techniques to test whether the stochastic process of RBA intervention exhibits long-run equilibrium relations and the test results supported the effectiveness of interventions.

number of interventions. Jeanblanc-Picqué proves the existence of an optimal policy based on an impulse control method. Optimal impulse control problems have only appeared in the literature recently. Aubin (2000) discusses quasi-variational inequalities as a viable approach to solve optimal impulse control problems and emphasizes that this approach was developed in the 1970's.

This paper discusses a model for optimal exchange rate intervention based on the impulse control theory. We use an impulse stochastic control problem to analyze Brazilian risk management strategy for managing the risk of foreign exchange rate exposure in recent years. In the impulse stochastic control problem there is an equation that describes the control function and another that describes the cost function. Then, based on the previous estimation and calibration of these equations, we discuss risk management strategies for the Central Bank of Brazil and we evaluate Brazilian risk management strategy in the 2008 international financial crisis.

2- The Impulse Stochastic Control Problem

Mundaca and Oksendal (1998), hereinafter MO, describe an optimal intervention policy for central banks in order to stabilize the exchange rate. Their paper differs from that of Jeanblanc-Picqué (1993) in the sense that it allows for two types of control, namely discrete time foreign exchange interventions with foreign currency trades, and continuous exchange rate control with domestic interest rates. Another difference is that the exchange rate band is not exogenous, but is a result of the solution of the optimal stochastic intervention control problem.

Optimal central bank intervention in the foreign exchange market is also studied in Cadenillas and Zapatero (1999, 2000), hereinafter CZ. Their first paper uses only impulse control, as in Jeanblanc-Picqué (1993). Their second paper uses classical (continuous control with interest rate) and impulse (using international reserves) stochastic control, as in MO. Both CZ papers consider the exchange rate to be a geometric Brownian motion rather than a pure Brownian motion and that the costs of interventions by purchasing foreign currency are lower than the costs of selling it, which in some cases may be closer to reality for emerging economies, since purchasing foreign currency increases international reserves. Furthermore, they give numerical examples and evaluate the model based on those examples. Unfortunately, those numerical examples are for didactic purposes only and do not reflect any real economy.

The above literature on optimal intervention control of foreign exchange rates is based on the target zone model. It assumes that the monetary authority intervenes in order to keep the exchange rate within a band. However, as pointed out by MO the currency band is not necessarily credible and may be exposed to speculative attacks. Speculative attacks are not rare in emerging economies and central banks often use domestic interest rates and international reserves to defend against them. In this paper we use the MO model with a geometric Brownian motion as in the CZ papers. A geometric Brownian motion allows us to simulate speculative attacks and to check the behavior of the model in reaction to a disturbance function since we may include a drift.

Here we consider that in exchange rate crisis events, the monetary authority may use two kinds of controls. The first one is a continuous control using the interest rate (r_s) and the second one is an impulse control with interventions in the foreign exchange market and domestic bond market and/or swaps (ξ's). Hereinafter, impulse control based on foreign currency trading is also called spot intervention. We also consider that the central bank puts into effect impulse control through purchases or sales of domestic currency bonds or swaps that pay foreign exchange rate fluctuations, hereinafter called swap or bond interventions[5]. We define the exchange rate Y_t as domestic currency units per unit of foreign currency at time t, and we assume that Y is a stochastic process given by:

$$Y_t = y + \int_0^t p \cdot ds - \int_0^t b \cdot r_s ds + \sigma B_t - a_1 \sum_{j:\theta_j \leq t} \xi_{1,j} - a_2 \sum_{j:\theta_j \leq t} \xi_{2,j} \quad (1)$$

where,

Y_t is the exchange rate stochastic process starting at y;

p is the exogenous economic pressure on the exchange rate;

$b.r_s$ is the influence of interest rate (r_s) on the exchange rate. Here interest rate corresponds to the difference between domestic and foreign interest rates;

σ is a positive constant;

B_t is the Brownian motion;

[5] The Central Bank of Brazil for instance has been using swap operations since 2002 and these operations are a kind of non deliverable forward.

$a_1.\xi_1$ is the influence of interventions on the exchange rate of buying ($\xi<0$) or selling ($\xi>0$) a total amount ξ of foreign currency;

$a_2.\xi_2$ is the influence of interventions on the exchange rate of buying ($\xi<0$) or selling ($\xi>0$) a total amount ξ of swaps between foreign exchange rates and interest rates in local currency, and bonds in domestic currency that pay foreign exchange rate changes.

s is an instant of time.

Exogenous economic pressure on the exchange rate p and additional impulse control ξ_2 are introduced as modifications to the model given in MO. For optimal control it is necessary to establish a cost function which is to be minimized and the equation below defines this function:

$$J^w(s,y) = E^{(s,y)}\left[\int_s^T e^{-\rho t}\left(k(Y_t - m)^2 + \beta\left(r_t - \bar{r}\right)^2\right)dt + \sum_{i=1}^{2}\sum_{j:\theta_j \le T} e^{-\rho\theta_j}\left(c_i + \lambda_i \xi_{ij}^2\right)\right] \qquad (2)$$

where, ρ is the discount rate, m is an implicit (not revealed) target value for exchange rate, $\bar{r}$ is a reference value for the interest rate[6] and $k, \beta, \lambda_1, \lambda_2, c_1, c_2$ are the cost function parameters. We assume that the system starts at the state $x=(s,y)$. $T \le \infty$ is a given (fixed) future time and $E^{(s,y)}$ is the expectation with respect to the probability law of Y_t..

The model was used to analyze Brazilian foreign exchange market features in the floating regime period, with a specific cost function, where the size of interventions have a quadratic effect, rather than a linear one as in the CZ and MO examples. Furthermore, an additional kind of exchange rate intervention was included in the model: domestic bonds and swaps settled in domestic currency. The Central Bank of Brazil uses this kind of intervention as a complementary tool to defend against foreign exchange rate speculative attacks. The solution of the optimal impulse stochastic control problem is presented in Appendix I. This model is discussed in Silva Junior, Cajueiro and Yoneyama (2004) and in Silva Junior (2005).

[6] We consider this reference rate to be equal to zero, as a simplification attained by axis translation.

3. Simulation of Risk Management Strategies

Brazil has had a floating foreign exchange rate regime since January 1999, although the central bank has intervened in the domestic dollar market due to liquidity demand and foreign exchange crises. Since January 1999 there have been four periods of foreign exchange rate stress. The first one occurred in January 1999 itself and it caused a change from a fixed to a floating foreign exchange rate regime. The second one was due to Argentinian crisis in 2001, the third one occurred before the Brazilian presidential elections in 2002 and the last one was due to the international financial crisis in 2008. Table 1 shows BRL depreciation in the four periods.

Table 1 – BRL depreciation against USD

Period		Min	Max	Change
31/12/98	30/03/99	1.207	2.164	79.3%
31/10/00	28/09/01	1.909	2.801	46.7%
01/03/02	28/02/03	2.271	3.955	74.2%
02/06/08	16/11/09	1.559	2.500	60.4%

As discussed above one way to intervene in the foreign exchange rate is the use of interest rates since this influences the flow of foreign capital. The use of interest rates to control the exchange rate is a kind of continuous control, or classical stochastic control. Higher domestic interest rates induce foreign capital inflows attracted by better yields. On the other hand, they will constrain economic growth and increase domestic debt. In fact, interest rates are often used to control inflation, i.e. as monetary policy, rather than foreign exchange rate control. Nevertheless, in periods of speculative currency attacks, interest rates may be used to avoid severe currency depreciation in emerging market economies.

Typically many central banks in emerging market economies also intervene in the foreign exchange rate by using foreign currency trades. Thus, international reserves are used as insurance against crises since they may be used to smooth foreign exchange rate changes.

The Central Bank of Brazil also intervenes in the domestic market with swap operations. This means that if the demand from non-financial firms for foreign currency is high, they may agree to a swap operation for hedging purposes settled in the domestic currency with a financial firm. In this case the non-financial firm receives the gains or accepts the losses arising from foreign exchange rate fluctuations and pays interest (see figure 1). The Central Bank may also sell foreign currency (international reserves) in the spot market. Alternatively, if non-financial firms are concerned by the high inflow of foreign currency and the appreciation of the domestic currency, they may agree to swap operations for hedging purposes, transferring the gains or losses arising from foreign exchange rate fluctuations to financial firms and receiving interest (figure 2). The Central Bank may also buy foreign currency in the spot market which will increase holdings of international reserves. The financial sector cannot absorb all of the market risk and the Central Bank of Brazil plays the role of the hedge supplier, as shown in figures 1 and 2 (swap operations between the central bank and financial companies).

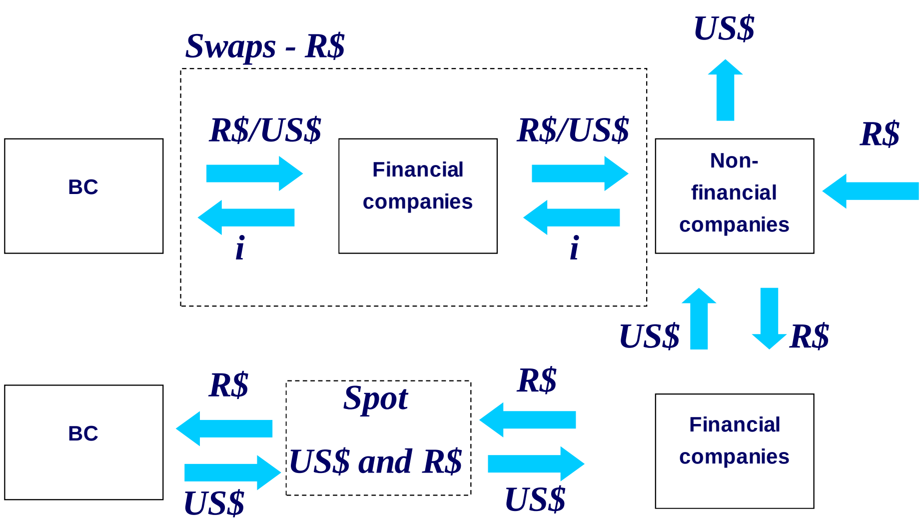

Figure 1 – Swaps operations of the Central Bank of Brazil (Central Bank is short foreign exchange rate)

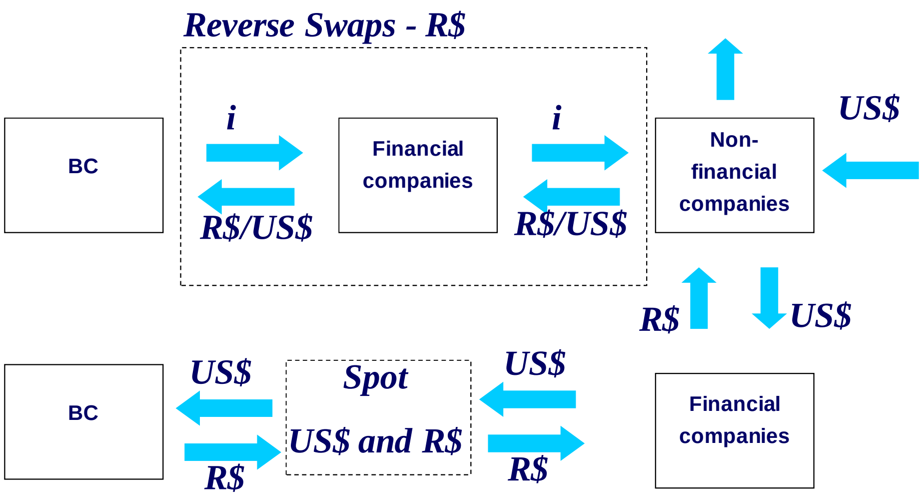

Figure 2 – Swaps operations of the Central Bank of Brazil (Central Bank is long foreign exchange rate)

To simulate the model from equations (1) and (2) we need to identify the parameters of equation (1) and to calibrate the parameters of equation (2). Silva Junior, Cajueiro and Yoneyama (2004) and Silva Junior (2005) did that based on the period that includes the crises of 1999, 2001 and 2002. An econometric approach was used to estimate the parameters of equation (1). Notice that it is also necessary to specify parameters in equation (2). The choice of c_i and λ_i must take into account the relative effects of k and β on the cost function and these specifications depend upon monetary policy choices. The estimated parameters of equation (1) are based on the following equation for the floating regime period of February 1999 to April 2004 using daily data:

$$\Delta y_t = a_0 + b \cdot r_{t-1} + a_1 \cdot \xi_{1,t-1} + a_2 \cdot \xi_{2,t-1} + \varepsilon_t \qquad (3)$$

PTAX data published by the Central Bank of Brazil were used for exchange rates (y). Interest rate differentials (r) are calculated using Selic rates (domestic interest rates) and three months US Treasury Bill rates (foreign interest rates). The volumes of interventions with foreign currency (ξ_1) and interventions with bonds and/or swaps (ξ_2) were estimated using international reserves data and public announcements.

GARCH, EGARCH and TGARCH models were tested and EGARCH(2,1) was considered the best based on Akaike and Schwarz criteria. Results are shown in the table 2. The coefficients all correspond to expectations, i.e. foreign currency (spot) and bond sales and increasing interest rates have negative impacts on the foreign exchange rate (domestic currency appreciation). Nevertheless, coefficients for bonds and swaps operations were not statistically significant at a 95% confidence level, but did show statistical significance at a 90% confidence level.

Table 2 - Estimated results for equation (3)

	Constant	Interv. Spot	Interv. Bonds	Interst rate dif.
Coefficients	0.0020	-0.0045	-0.0025	-0.0110
p-values	0.001	0.020	0.091	0.008

Source: Silva Junior, Cajueiro and Yoneyama (2004)

Since the impacts of exchange rate interventions have been estimated, it is necessary to specify the parameters of the cost function. These parameters reflect the weights that central bank considers for exchange rate deviations from an "implicit target", and the costs of each kind of intervention, as discussed earlier. In fact it is not easy to specify these parameters and they reflect a more general policy for international reserves management, domestic debt structure, monetary policy etc.

Silva Junior, Cajueiro and Yoneyama (2004) specified the costs parameters for simulation purposes taking into account Brazil's exchange rate volatility, interest rates, estimated intervention using reserves, bonds, swaps and the estimated parameters of table 2. Furthermore, as in table 1, they run simulations including an exchange rate drift of 0.01, five times the normal rate (0.002), considering this number to be typical in periods of exchange rate devaluation pressure.

Now, we are going to evaluate the policy of accumulating international reserves and reducing foreign exchange rate short exposure on the domestic debt. The Brazilian government has applied this strategy since 2004. The international environment of high demand for commodities and goods and high international liquidity made the implementation of this strategy possible since Brazil has accumulated a large current account surplus. The parameters for drift (0.01) and volatility (0.045) used in table 1 of this paper are the same as those observed during the international crisis in 2008. We then calibrated the cost function in order to evaluate how higher international reserves and low short foreign exchange rate exposure helped the country during the crisis. The parameters of equation (2) for a base case were:

$k=0.1; \qquad \beta=0.0005; \qquad \rho=0.000595$

$c_1=1.25E\text{-}5; \quad c_2=1.25E\text{-}5; \quad \lambda_1=6E\text{-}5; \qquad \lambda_2=6E\text{-}5$

Based on the identification and calibration above we simulated some scenarios. The aim of this paper is to evaluate the behavior of the model and to discuss the strategies for risk management of foreign exchange rate adopted by the Brazilian government. The results of a simulation for the base case are presented in the first row of table 3. For simulation purposes, it is considered that the implicit exchange rate target during the crisis in 2008 was R$/US$ 2.0. So, in the base case we have a continuous intervention using the SELIC interest rate equal to 15.1%, a daily spot intervention equal to US$ 565 million and a daily swap intervention of US$ 314 million when the foreign exchange rate reaches R$/US$ 2.151.

Table 3 – Simulation of Risk Management Strategies

k	*beta*	*lam1*	*lam2*	SELIC	*Qsi1*	*Qsi2*	PTAX	Case
x 102	x 104	x 105	x 105					
5	5.5	6	6	15.1	565	314	2.151	Base
1	5.5	6	6	15.1	564	313	2.248	Flexibility with PTAX
5	5.5	4	6	12.8	719	267	2.144	High Lev Int Reserves
5	5.5	8	6	16.7	470	348	2.156	Low Lev Int Reserves
5	5.5	6	4	14.2	533	445	2.148	Low FX in the Debt
5	5.5	6	8	15.5	582	242	2.152	High FX in the Debt
5	5.5	8	8	17.4	489	271	2.158	Low Int Reserves High FX in the Debt
5	5.5	4	4	12.3	691	384	2.142	High Int Reserves Low FX in the Debt

The second simulation supposes that we have more flexibility with the PTAX (we reduce the *k* coefficient of the cost function) and the model suggests that we should intervene only if the PTAX reaches a higher value of R$/US$ 2.248. In the third simulation we assume that the country has a higher volume of international reserves (we reduce the λ_1 coefficient in the cost function). Note that in this case we intervene more in the spot market and may use a lower interest rate (continuous intervention) and less swaps. Otherwise, as we can see in the fourth simulation with less international reserves available to the country, burdens are higher in terms of interest rates and swaps. The fifth simulation supposes that there is more flexibility in using swaps since the domestic public debt is not too short on PTAX (we reduce the λ_2 coefficient in the cost function). It is also possible to intervene with lower interest rates and in this case with lower international reserves. The sixth simulation shows the opposite of the fifth. In the seventh simulation with higher λ_1 and λ_2 coefficients the country needs to intervene with higher interest rates and we can see the opposite in the last simulation. Note that the interest rate difference between the last two simulations is 5%. This means that with a high level of international reserves and low short (or even long) foreign exchange rate exposure of the public debt, the intense use of interest rates in a financial crisis may be avoided.

Figures 3 and 4 highlight the fact that holding international reserves and having long foreign exchange rate exposure with swaps operations allows the central bank to be more parsimonious in using interest rates during crisis events. For an emerging market economy this is an important issue. Indeed, Silva Junior, Cajueiro and Yoneyama (2004) and Silva Junior (2005) discussed the optimal impulse stochastic control strategy and argued that the government's strategy should be to accumulate higher levels of international reserves and/or not to have a short position in swaps at times when there is no stress in the market[7]. This strategy would allow the country to avoid the intensive use of interest rates during financial crises. In the brief simulation example shown in table 2, the estimation and calibration of the model suggest that the benefit of having flexibility with international reserves and swaps would avoid a 5% increase in interest rates when compared with a low flexibility scenario.

[7] It is worth mentioning that the government strategy did in fact seem to go in that direction.

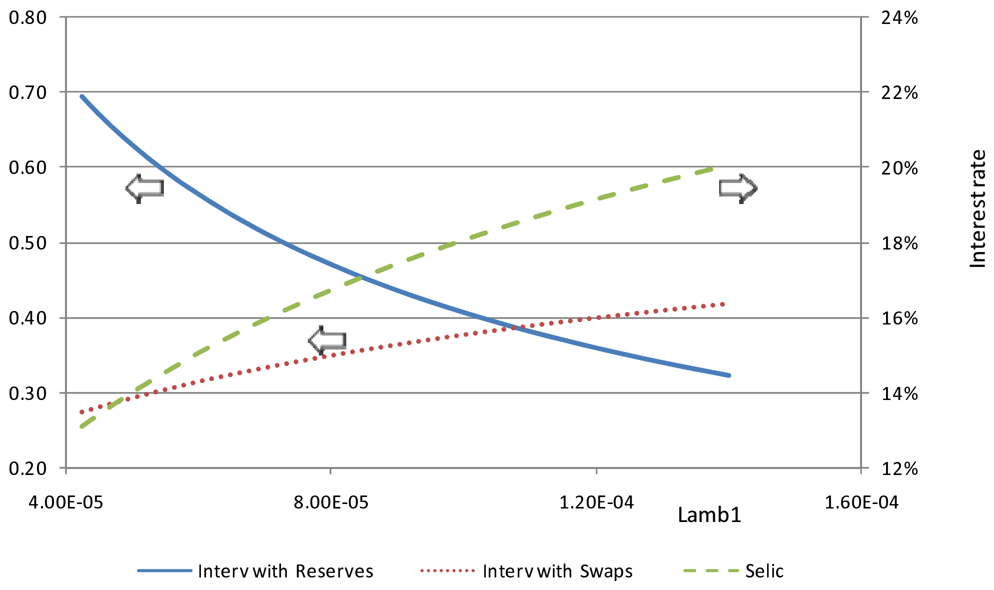

Figure 3 – Daily interventions as a function of λ_1

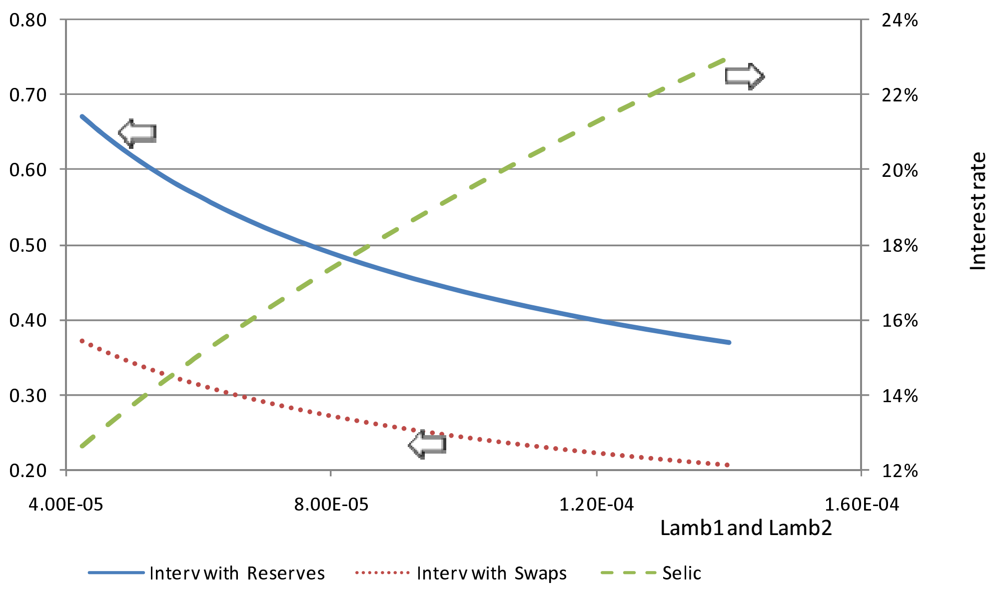

Figure 4 – Daily interventions as a function of λ_1 and λ_2

4. Brazilian Risk Management Strategy

Based on this model, the central bank may intervene in the market using interest rates, foreign reserves or swaps. It is considered here that these interventions will only be made in financial crisis to smooth the foreign exchange rate variations which may disrupt the country's economy. This is an important remark in terms of the objectives of this paper since in a period when there is no financial stress, interest rates are used only for monetary policy purposes[8].

Remember also that an increase in interest rates to attract international capital and to avoid domestic currency depreciation has a fiscal cost and may impact economic activity and decrease GDP growth. On the other hand, holding international reserves has a carry cost since domestic interest rates are higher than the interest rates of highly rated government bonds in which most of the reserves are invested. The literature regarding adequacy of holdings of international reserves therefore generally addresses two aspects of determining their optimal level. The first is related to the carry costs. The second aspect is related to the benefits of holding international reserves since they work as a self insurance mechanism to avoid crisis. Higher levels of international reserves may reduce the impact of a crisis on GDP growth and may reduce the cost of borrowing money abroad. With a low level of reserves carry costs are lower but borrowing costs abroad are higher and the country's exposure to a financial crisis likewise.

In fact, a long foreign exchange rate position in swaps operations also has a carry cost for the country since a long foreign exchange rate position with swaps works in the same way as holding international reserves. Note that one interesting feature of swaps operations is the possibility to have a short foreign exchange rate position. This allows the country to use these operations as a substitute for international reserves. Nevertheless, having a short exchange rate position with swaps or bonds may increase the short exchange rate exposure of the domestic debt. For instance, consider a scenario of low holdings of international reserves. In the event of a crisis the central bank could intervene by taking short foreign exchange rate positions in swaps operations. But the central bank cannot do this indefinitely since domestic debt structure may be affected and the participants in the financial market would be concerned about the country's ability to pay its domestic debt in a scenario of speculative attacks which may devaluate the domestic currency and even increase the domestic debt[9]. A long foreign exchange rate exposure works in the opposite direction during a crisis. A devaluation of the domestic currency in a crisis makes a positive impact by reducing the sovereign net domestic debt.

[8] In the case of Brazil interest rates are used in the inflation targeting program.

[9] In the period that includes the contagion from the Argentinian crisis (2001) and the stress with the 2002 elections there was a high level of short foreign exchange rate exposure of the domestic debt in Brazil.

Let's now evaluate Brazilian risk management strategy for foreign exchange rate exposure after 2004 and discuss how the country managed the occurrence of the international crisis in 2008. Figure 5 shows the R$/US$ exchange rate and the appreciation of the real after 2004 is very clear. The appreciation of the real was a consequence of several factors such as the boom in commodity prices and liquidity in the international markets. This economic environment made the Brazilian strategy to increase holdings of international reserves possible, and in 2006 this trend was accelerated. Figure 6 shows Brazilian holdings of international reserves. This trend to increase holdings of international reserves was not specific to Brazil. Several emerging market economies did the same, although the motivations may have been different from one country to another. Some countries, for instance, try to manage the foreign exchange rate for trade purposes. It does not seem to be the case in Brazil since the foreign exchange rate regime is floating and figure 5 makes it clear that there is no target level or even a band for the foreign exchange rate. Furthermore, it is important to note how severe the 2008 crisis was for the foreign exchange rate, since it varies between 1.56 and 2.5.

Figure 5 – R$/US$ Exchange Rate

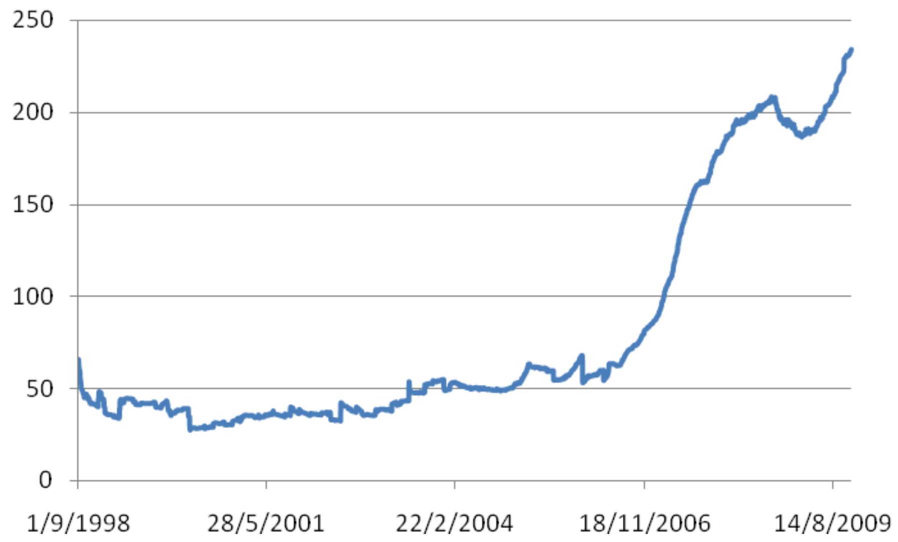

Figure 6 – Holdings of International Reserves (US$ billions)

In figure 7 we can see that the short exposure of the foreign exchange rate with swaps was reduced after 2003 and the government reverted to a long position in foreign exchange rate exposure that amounted to US$ 22 billion by September 2008[10]. As a result of interventions the short exposure of the foreign exchange rate reached US$ 12 billion i.e. an intervention of US$ 34 billion with swaps operations.

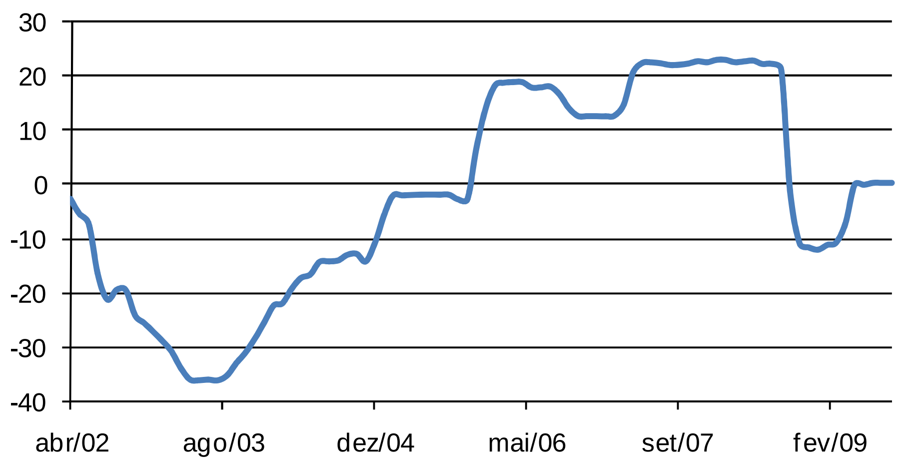

Figure 7 – Swaps position (US$ billions)

[10] Short exposure is represented in the figure with a negative sign and long exposure is represented with a positive sign.

Figure 8 shows the behavior of the domestic interest rate in Brazil. In the period of the 2008 crisis it was not necessary to increase the interest rate in Brazil dramatically. In fact there was a prior tendency to increase interest rates as part of a tightening of monetary policy due to inflation figures. The high level of international reserves and the flexibility available due to swap positions allowed the central bank to avoid intervening in the market with high interest rates to attract foreign currency as was necessary in previous crises.

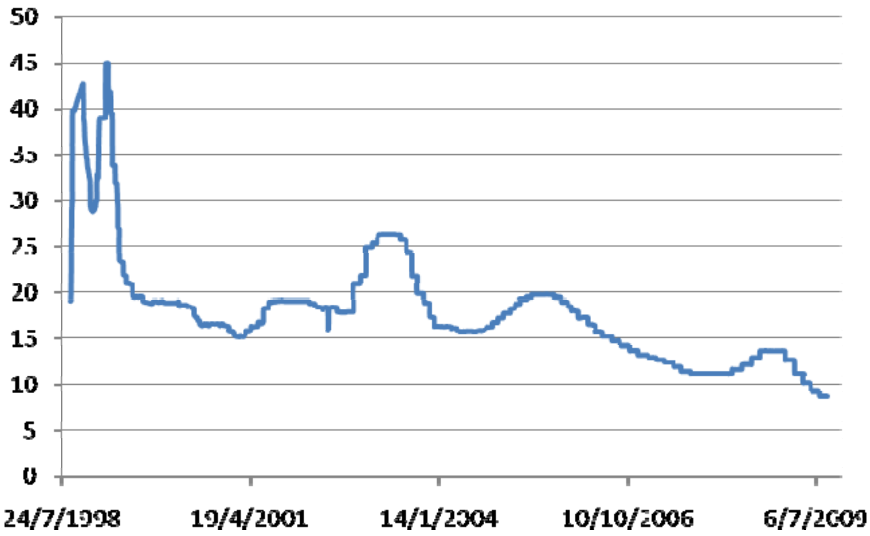

Figure 8 – Domestic interest rate in Brazil (%)

In table 4 we compare the interventions of the Central Bank of Brazil in three periods of crisis[11]. In 2002, the central bank intervened with higher interest rates compared to the year of 2001. Silva Junior, Cajueiro and Yoneyama (2004) and Silva Junior (2005) argued that the short exposure of the public debt to the foreign exchange rate was too high in 2002 and there was serious concern regarding public debt solvency. This was evidence that the impulse stochastic control model fits the central bank's behavior during a crisis. In 2008, the government strategy of increasing international reserves and reducing short exposure of the foreign exchange rate in the public debt allowed the central bank to operate its monetary policy without major concern about increasing interest rates. In other words, interventions with international reserves and

[11] Figures for the 2001 and 2002 periods were extracted from Silva Junior, Cajueiro and Yoneyama (2004).

swaps were higher in 2008 than in 2001 and 2002, and interventions with interest rates were lower which is in the direction indicated by the model[12].

Table 4 – Central Bank of Brazil interventions during financial crises

	2001	2002	2008
Interventions with international reserves(US$ bi)	8.2	7.4	12
Interventions with swaps or bonds (US$ bi)	3.7	1.7	34
Interest rate differential (%)	16.35	18.07	13.5

The model discussed above is consistent with the Central Bank of Brazil's behavior during crises. This model sheds light on the discussion about the carrying costs of international reserves for a country. Domestic interest rates are paid on domestic debt and in the case of Brazil domestic public debt was around R$ 1.4 trillion in 2009. So, if we consider that international reserves may help to prevent higher domestic interest rates we should discount the benefit of lower domestic debt costs from the carry costs of reserves. Of course we have to consider all the other benefits such as avoiding GDP losses, the lower costs of external debt etc.

5. Conclusions

In this paper we take a previous paper on the optimal impulse stochastic control problem for exchange rates, and discuss the Brazilian government's strategy of increasing holdings of international reserves and reducing or eliminating short exposure to the foreign exchange rate of its public debt.

Based on observation of the contagion from the Argentinian crisis in 2001, the stress associated with the presidential election in 2002, and the spillover from the international crisis of 2008, we show that the model fits the Central Bank of Brazil's reaction in a financial crisis. So, based on the model, higher intervention flexibility with international reserves and with swap operations allows the central bank to intervene less with interest rates during financial crises.

[12]Stone, Walker and Yasui (2009) discuss other measures adopted by the Central Bank of Brazil like auctions of credit lines to help compensate for the loss of dollar export credit lines for Brazilian companies, the program to lend dollars against dollar denominated collateral and the announcement of a swap line with the Fed among other measures.

It is worth to analyzing the interactions among the variables i.e. the interactions among the interest rate, international reserves and swaps. The simulations presented in this paper make it clear that, in the optimal intervention model for the risk management of foreign exchange rate exposure during a crisis; higher holdings of international reserves may avoid the need for higher interest rates. Simulations also make it clear that the use of swaps allows more flexibility in monetary policy operations in the event of a crisis. It may also reduce the need for higher interest rates and holdings of international reserves.

Thus, it is important to highlight that the risk management decision of the government to increase international reserves and to reduce short foreign exchange rate exposure from 2004 to 2008 made it possible for the Central Bank of Brazil to manage the financial turmoil of 2008 without a dramatic increase in the interest rate.

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Appendix I – The Optimal Impulse Stochastic Control Model

We consider that during exchange rate crisis events, the monetary authority may use two kinds of control. The first is a continuous control using the interest rate (r_s) and the second is an impulse control using interventions in the foreign exchange and domestic bond markets (ξ's). Hereinafter, impulse control based on foreign currency trading is also called spot intervention. This is widely applied by central banks around the world, as discussed above. We also consider that the central bank effects impulse control by purchasing or selling domestic currency bonds and swaps[13]. This model is solved in Silva Junior, Cajueiro and Yoneyama (2004) and Silva Junior (2005).

Consider Ω a given set, F a σ-algebra on Ω, and P a probability measure on the measurable space (Ω,F). Consider also the probability space (Ω,F,P) with a filtration F_t generated by a one dimensional Brownian motion that represents uncertainty in the economy. Thus, exchange rate is a random variable, i.e. a function mapping Ω in **R**. We define the exchange rate Y_t as domestic currency units per unit of foreign currency at time t, and we assume that Y is an adapted stochastic process given by:

$$Y_t = y + \int_0^t p \cdot ds - \int_0^t b \cdot r_s ds + \sigma B_t - a_1 \sum_{j:\theta_j \le t} \xi_{1,j} - a_2 \sum_{j:\theta_j \le t} \xi_{2,j} \qquad (1)$$

where,

- Y_t is the exchange rate stochastic process starting at y;
- p is the exogenous economic pressure on the exchange rate;
- $b.r_s$ is the influence of interest rate (r_s) on the exchange rate. Here interest rate corresponds to the difference between domestic and foreign interest rates;
- σ is a positive constant;
- B_t is the Brownian motion;
- $a_1.\xi_1$ is the influence of interventions in the exchange rate of buying ($\xi<0$) or selling ($\xi>0$) a total amount ξ of foreign currency;
- $a_2.\xi_2$ is the influence of interventions in the exchange rate of buying ($\xi<0$) or selling ($\xi>0$) a total amount ξ of swaps between foreign exchange rate and interest rates

[13] The Central Bank of Brazil uses this kind of intervention.

in local currency, and bonds in domestic currency that pay foreign exchange rate changes.

The exogenous economic pressure on the exchange rate p and the additional impulse control ξ_2 are introduced here as modifications to the model given in MO. For optimal control it is necessary to establish a performance function to be minimized and equation (2) defines this function:

$$J^w(s,y) = E^{(s,y)}\left[\int_s^T e^{-\rho t}\left(k(Y_t - m)^2 + \beta\left(r_t - \bar{r}\right)^2\right)dt + \sum_{i=1}^{2}\sum_{j:\theta_j \le T} e^{-\rho\theta_j}\left(c_i + \lambda_i \xi_{ij}^2\right)\right] \qquad (2)$$

where ρ is the discount rate, m is a target value for the exchange rate, $\bar{r}$ is a reference value for the interest rate[14] and $k, \beta, \lambda_1, \lambda_2, c_1, c_2$ are performance parameters. $T \leq \infty$ is a given (fixed) future time and E^y is the expectation with respect to the probability law of Y_t. We assume that the system starts at the state $x=(s,y)$.

Unlike MO we use a quadratic loss function for spot interventions. So, we assume that larger interventions have a higher weight in the performance function than that assumed by MO and CZ.

Let U denote the set of continuous controls $u:\boldsymbol{R}^n \to U$. The set of continuous controls U comprises the interest rate $r=(r_t)_{t\in\boldsymbol{R}}$. Suppose that in a given state the monetary authority decides to intervene and give the system an impulse control $\xi \in Z \subset \boldsymbol{R}^l$, where Z is a given set of admissible impulse values. The aim is to find a set of combined controls (r_t, ξ_t) in equation (1) that minimizes the performance function of equation (2). This combined control comprises the continuous control and the impulse control. The solution of this system is attained with quasivariational Hamilton-Jacobi-Bellman (HJB) inequalities.

The impulse control is applied at discrete times θ_j with selected amounts ξ_{1j} and ξ_{2j} of interventions in foreign exchange and bond markets respectively. V denotes the set of all impulse controls. The sequence $\upsilon=(\theta_1, \theta_2, \ldots, \theta_N; \xi_{11}, \xi_{12}, \ldots \xi_{1N}; \xi_{21}, \xi_{22}, \ldots \xi_{2N})$ is called the impulse control. The combined stochastic control is the set $W=U x V$,

[14] We consider this reference rate to be equal to zero, as a simplification attained by axis translation.

which comprises stochastic (continuous) control and impulse control. Considering only the continuous control, the following process:

$$X_t = X_t^{(r)} = \begin{bmatrix} s+t \\ Y_t^{(r)} \end{bmatrix}; t \geq 0; X_0 = \begin{bmatrix} s \\ y \end{bmatrix} = x \tag{3}$$

is an Ito diffusion. The probability law of $X_t^{(w)}$ is $Q^{x,w}$. It is possible to associate a second order partial differential operator L to this diffusion. The connection between L and Y_t is that L is the generator of the process X in $C_0^2(\boldsymbol{R}^2)$, the space of twice continuously differentiable functions on $\boldsymbol{R}^2$ with compact support, with the following partial differential operator:

$$L^r(s,y) = L^{r(s,y)} f(s,y) = \frac{\partial f}{\partial s} - (br_s - p)\frac{\partial f}{\partial y} + \frac{1}{2}\sigma^2 \frac{\partial^2 f}{\partial y^2} \tag{4}$$

which is defined for all functions $f{:}\boldsymbol{R}^2 \to \boldsymbol{R}$ for which the derivatives involved exist at $x=(s,y)$.

In this case, continuous control describes a Markov control, since functions $f_u=-b.r_s$ and the "crisis function" $f_c=p$ in equation (1) do not depend on the start point $x=(s,y)$. The values we chose at time t for these functions depend only on the state of the system at this time[15]. The aim is to find the optimal control since:

$$\Lambda(x) = \inf_{w \in W} J^w(x) \tag{5}$$

In this paper we use different functions from MO's example since we include a drift p and quadratic cost functions for interventions. We point out that $p\text{-}b.r_s$ is a Lipschitz continuous function and the performance function always has the same sign and is locally bounded away from zero as required by Brekke and Oksendal (1997) [16].

Let H denote the space of all measurable functions $h{:}\ \boldsymbol{R}^2 \to \boldsymbol{R}$. Thus, we define the intervention operator (or switching operator) $M : H \to H$ by:

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[15] See Oksendal (1995).

[16] Brekke and Oksendal (1997) present a verification theorem for combined stochastic control and impulse control, and Mundaca and Oksendal (1998) use this result.

$$M\,h(s,y)=\inf_{\xi\in Z}\left\{h(s,y+\gamma(\xi))+L(\xi)e^{-\rho s}\right\} \tag{6}$$

for all $h\in H$, and $x\in \boldsymbol{R}$. Using MO Theorem 1 it can be stated that there exists a continuous function $\phi:\boldsymbol{R}^2\rightarrow[0,\infty)$ with the following properties:

$$\phi \text{ is stochastically } C^2 \text{ with respect to } X_t^{(r)} \text{ for all } r:\boldsymbol{R}^2\rightarrow\boldsymbol{R} \tag{7}$$

$$\phi \leq M\phi \text{ on } \boldsymbol{R}^2 \tag{8}$$

$$L^r\phi(s,y)+e^{-\rho s}\left(k(y-m)^2+\beta(r)^2\right)\geq 0 \tag{9}$$

for almost all (s,y) with respect to the Green measure for $X_t(r)$, for all $r=r(s,y)$: $\boldsymbol{R}^2\rightarrow \boldsymbol{R}$. Thus, according to MO:

$$\phi(x)\leq J^{w}(x) \textit{ for all } w\in W \tag{10}$$

They also suppose that in addition to Eqs. (7)-(9), there exists a function $\hat{r}$: $\boldsymbol{R}^2\rightarrow \boldsymbol{R}$ such that the minimal value zero on the left hand side of Eq. (9) is attained, i.e.

$$L^{\hat{r}(s,y)}\phi(s,y)+e^{-\rho s}\left(k(y-m)^2+\beta r^2\right)=0 \tag{11}$$

for all $(s,y)\in D$, where

$$D:=\{x;\phi(x)<M\phi(x)\} \tag{12}$$

Define the impulse control $\hat{\upsilon}$ as follows:

$$\hat{\theta}_{k+1}=\inf\left\{t>\hat{\theta}_k\,;X_t^{(k)}\notin D\right\};\ \text{k=0,1,2,…and } \hat{\theta}_0=0 \tag{13}$$

where $X_t^{(k)}$ is the result of applying the control

$$\left(\hat{r}_t,\left(\hat{\theta}_1,\ldots,\hat{\theta}_k,\infty;\hat{\xi}_{11},\hat{\xi}_{12},\ldots,\hat{\xi}_{1k},\ldots;\hat{\xi}_{21},\hat{\xi}_{22},\ldots,\hat{\xi}_{2k},\ldots\right)\right)$$

to X_t, and

$$\hat{\xi}_{k+1} = R_\phi\left(X^{(k)}_{\hat{\theta}^-_{k+1}}\right);\ k=0,1,2,\ldots \tag{14}$$

where

$$X_{\theta^-_{k+1}} = \lim_{t\uparrow\theta_k} X_t \tag{15}$$

Put $\hat{w} = \left(\hat{u},\hat{\upsilon}\right)$ and suppose that

$$\lim_{k\to\infty} \hat{\theta}_k = \infty \text{ almost surely } Q^{x,\hat{w}} \text{ for all } x\in\boldsymbol{R} \tag{16}$$

and that

$$\lim_{k\to\infty} E^x\left[\phi\left(X^{\left(\hat{w}\right)}_{\theta^-_{k+1}}\right)\right] = 0\text{, for all } x\in\boldsymbol{R} \tag{17}$$

Thus, according to Brekke and Oksendal (1996):

$$\phi(x) = \Lambda(x) \tag{18}$$

and the optimal combined stochastic control is $w^* = \hat{w} \in W$.

The above result is known as a quasi-variational inequality (QVI) solution for a classical-impulse control problem. A function ϕ satisfies the QVI for the classical-impulse stochastic control problem if equations (8), (9) and (11) hold. In Perthame (1984a) we may find a version of the dynamic programming principle for the classical-impulse stochastic control problem and its Theorem 2 is a result related to Brekke and Oksendal (1997), although it is insufficient for this application. Perthame (1984b) studied the existence and uniqueness of a similar QVI. Cadenillas and Zapatero (2000) also present a version of the dynamic programming principle for their application.

The solution ϕ of the QVI separates two regions. The continuum region is defined by equation (12), where no intervention in the foreign exchange market (impulse control) should be made while X_t is in D. When X_t reaches the boundary of D, see equation (13), we apply an intervention and X_t returns to D.

We use the above QVI result to find the final solution for our problem. So, considering $m=0$ as a simplification attained by axis translation, and using the partial differential operator definition from equation (4) in equation (9):

$$\frac{\partial \phi}{\partial s} - (b\alpha - p)\frac{\partial \phi}{\partial y} + \frac{1}{2}\sigma^2 \frac{\partial^2 \phi}{\partial y^2} + e^{-\rho s}\left(ky^2 + \beta\alpha^2\right) \geq 0 \qquad (19)$$

for almost all $y \in \boldsymbol{R}$ and every $\alpha \in U = \boldsymbol{R}$. The minimum of function:

$$g(\alpha) \equiv -b\alpha \frac{\partial \phi}{\partial y} + \beta\alpha^2 e^{-\rho s} \qquad (20)$$

is attained with:

$$\alpha = \frac{b}{2\beta}\frac{\partial \phi}{\partial y} e^{\rho s} \qquad (21)$$

This value of α is a candidate for the optimal control using interest rates. Substituting this value α in equation (19), the left side must be equal to zero in region D (the region where no impulse control is applied) and so:

$$\frac{\partial \phi}{\partial s} - \frac{b^2}{4\beta}\left(\frac{\partial \phi}{\partial y}\right)^2 e^{\rho s} + p\frac{\partial \phi}{\partial y} + \frac{1}{2}\sigma^2 \frac{\partial^2 \phi}{\partial y^2} + e^{-\rho s} k y^2 = 0 \qquad (22)$$

As a candidate for the minimum of $\Lambda(s,y)$ the following function is used:

$$\phi(s, y) = e^{-\rho s}\psi(y) \qquad (23)$$

for a suited function Ψ (to be determined). Consider also that $D=\boldsymbol{R}x(-\eta,\eta)$, by symmetry, for a suited value of $\eta \in (0,\infty)$. The interval $(-\eta,\eta)$ is interpreted as a band of admissible values for the foreign exchange rate, where there are no interventions by central bank in the foreign exchange rate market. Applying equation (23) to equation (22) the following result is attained:

$$\frac{\partial^2\psi}{\partial y^2} + A\frac{\partial\psi}{\partial y} - B\left(\frac{\partial\psi}{\partial y}\right)^2 - C\psi(y) = -E(y) \tag{24}$$

where

$$A = \frac{2p}{\sigma^2}, \quad B = \frac{b^2}{2\beta\sigma^2}, \quad C = \frac{2\rho}{\sigma^2}, \quad E(y) = \frac{2ky^2}{\sigma^2} \tag{25}$$

Considering only the case where *y>0*, the solution of equation (24) is:

$$f''(y) - Af'(y) - B(f'(y))^2 - Cf(y) = -E(y) \tag{26}$$

$$f(0) = z; \quad f'(0) = 0; \quad 0 \le \mathrm{y} \le \mathrm{T} \tag{27}$$

For a given $z>0$, $f(y) = f_z(y)$ is the solution of the above system. Consider that there is a $z>0$ with at least two different values of $y \in (0,T)$, $y_1<y_2<T$, where:

$$f_z'(y_1) = f_z'(y_2) = Q(a^*, \lambda^*) \tag{28}$$

The two smallest positive numbers with this property are chosen and a^* and λ^* are the vectors of *a's* and *λ's* coefficients of equations (1) and (2). The exchange rate trigger level for intervention is chosen as $\eta = y_2$ and as the candidate for the value function Ψ in the interval $[0, \eta]$ it is chosen:

$$\psi(y) = f_z(y); \quad 0 \le y \le \eta \tag{29}$$

The key point here is the determination of function $Q(a^*, \lambda^*)$, since it establishes the connection between continuous and impulse control. Thus, according to MO the next step is to consider a switching operator defined by:

$$M\phi(y) = \inf_\xi \left\{\phi(s, y - a_1\xi_1 - a_2\xi_2) + \left((c_1 + \lambda_1\xi_1^2) + (c_2 + \lambda_2\xi_2^2)\right)e^{-\rho s} \right\} \tag{30}$$

or, since $\phi(s,y)=\psi(y)e^{-\rho s}$:

$$M\psi(y)=\inf_{\xi}\left\{\psi(y-a_1\xi_1-a_2\xi_2)+\left(c_1+\lambda_1\xi_1^2\right)+\left(c_2+\lambda_2\xi_2^2\right)\right\} \tag{31}$$

Minimization of equation (32) gives the *inf* of equation (31):

$$h(\xi)=\psi(y-a_1\xi_1-a_2\xi_2)+\left(c_1+\lambda_1\xi_1^2\right)+\left(c_2+\lambda_2\xi_2^2\right) \tag{32}$$

First order condition gives in the point defined by $\hat{\xi}=\hat{\xi}(y)$ the minimum of the equation (32):

$$\frac{\partial h}{\partial\hat{\xi}_1}=\frac{\partial\psi}{\partial y}\frac{\partial y}{\partial\hat{\xi}_1}+2\lambda_1\hat{\xi}_1=0 \text{ and } \frac{\partial h}{\partial\hat{\xi}_2}=\frac{\partial\psi}{\partial y}\frac{\partial y}{\partial\hat{\xi}_2}+2\lambda_2\hat{\xi}_2=0$$

thus:

$$\psi'\left(y-a_1\hat{\xi}_1-a_2\hat{\xi}_2\right)=\frac{2\lambda_1\hat{\xi}_1}{a_1}=\frac{2\lambda_2\hat{\xi}_2}{a_2}=Q\left(a^*,\lambda^*\right) \tag{33}$$

From equations (23) and (29) it can be stated that function *Ψ(y)* defines a candidate for the minimal performance function. Thus, equations (28) and (33) are the connection between continuous and impulse controls, then

$$y_1=y-\sum_{i=1}^{2}a_i\hat{\xi}_i \tag{34}$$

If $y=\eta$ (the trigger level) and since

$\psi(y)=M\psi(y)$ for $y\geq\eta$

we have:

$$\psi(y)=\psi\left(y+a_1\hat{\xi}_1+a_2\hat{\xi}_2\right)+\sum_{i=1}^{2}\left(c_i+\lambda_i\hat{\xi}_i^2\right) \tag{35}$$

This means that the monetary authority intervenes continuously using interest rates when ϕ is strictly smaller than $M\phi$ and the monetary authority intervenes discontinuously (buying or selling reserves, bonds and swaps) whenever $\phi = M\phi$. The size of intervention is the solution to the optimization problem. The system of equations has six unknown variables: z, α, y_1, y_2, ξ_1 and ξ_2. There is no analytical solution to this combined control problem as solution of the ordinary differential equation (26) is numerical.

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