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Exploring Carry Trade and Exchange Rate toward Sustainable Financial Resources: An application of the Artificial Intelligence UKF Method

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Abstract: This paper constructs a heterogeneous agent model for the foreign exchange market that is based on the law of supply and demand and includes carry trade, central bank intervention, and macroeconomic fundamentals. With the artificial intelligence method of the unscented Kalman filter, this paper investigates carry traders' expectation formation and risk aversion and the impact of their activities on the movement of the Chinese yuan exchange rate and on the efficiency of central bank intervention. The findings demonstrate that carry traders' activities are partially responsible for fluctuations in the Chinese yuan exchange rate; carry traders behave with obvious risk aversion; their activities tend to weaken the ability of the central bank to intervene in China's foreign exchange market; and the volatility of the Chinese yuan exchange rate and the weight of carry traders are negatively related. Based on these empirical results, specific suggestions for exploring sustainable financial resources are provided.

Keywords: Chinese yuan exchange rate; carry trade; unscented Kalman filter

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1. Introduction

Since the concept of the triple bottom line to address sustainability issues by balancing the aspects of the economy, environment and society, proposed in [1], increasing numbers of countries and firms have explored the use of sustainable resources to achieve sustainability goals. However, it is noted that most countries and firms are underinvesting in environmental and social aspects due to insufficient economic resources, among which financial resources are an important part [2]. If institutions or firms enable the generation of sufficient financial resources, they can assist firms in pursuing sustainability without suffering from the limitations of the economy.

The managed floating exchange rate system of the Chinese yuan, which was established in 1994, has been largely improved since the foreign exchange reform on 11 August 2015. The current system determining the Chinese yuan exchange rate is more market-oriented and transparent. With the constant improvement in the marketization of the exchange rate, the Chinese yuan has attracted much attention among academics and practitioners [3]. The law of supply and demand is not the only determinant of the Chinese yuan exchange rate; the activities of heterogeneous traders in the exchange rate market are playing an increasingly important role. Especially since the international financial crisis in 2007 and the major developed economies beginning to operate a quantitative easing policy, the global monetary system has had the characteristics of low interest rates and high liquidity. The Chinese yuan, which appreciates unilaterally and has low volatility, has become the world's most attractive carry trade currency [4], leading to the entry of hot money into China for arbitrage with the carry trade strategy, and the cross-border capital flow has become increasingly volatile in China [5,6]. Therefore, carry trade in China's foreign exchange market is a current problem and deserves more attention.

Heterogeneous traders with heterogeneous beliefs in the foreign exchange market have long been recognized by the literature [7]. Early heterogeneous agent models were established with only two types of heterogeneous traders, i.e., fundamentalists and chartists, and did not provide sufficient interpretation of exchange rate formation and other puzzles, such as the forward premium puzzle in the foreign exchange market [8]. Later, carry trade, as one kind of trading strategy and one kind of heterogeneous belief, was introduced into the heterogeneous agent model used in many studies. Carry traders' activities have been proven to have a significant and increasing influence on the exchange rate [9]. Studies have examined various characteristics of carry traders' activities in the foreign exchange market, such as the ability to explain the forward premium and currency funds, factors determining carry traders' profits, the linkage between carry trade risk premia and customer order flow, and the potential asymmetric dependence between carry trade and currency return [10–12]. Meanwhile, the heterogeneous agent model for carry traders explains the forward premium puzzle, exchange rate disconnects, deviation of the market-determined exchange rate from the fundamental value, and the microstructure of the foreign exchange market [13–15].

However, the law of supply and demand is seldom valued in the related literature concerning heterogeneous agent models. Also ignored are the central bank's activities and the influence of changing exchange rate policies in the foreign exchange market, such as the adjustment of carry traders' activities based on the changing exchange rate policy and its impact on the implementation of central bank intervention. In fact, the central bank, as one of the main participants in the foreign exchange market, adjusts the supply and demand of foreign exchange market funds by purchasing or selling currencies directly in the foreign exchange market to maintain the exchange rate at a certain level or within a certain range [16]. The central bank and the traders compose the supply and demand in the foreign exchange market and are of great importance to the formation of exchange rates. After the foreign exchange reform on August 11, 2015, Chinese yuan exchange rate fluctuations became more strongly determined by the supply and demand in China's foreign exchange market [17]. The effect of carry traders' behaviors on the movement of the Chinese yuan exchange rate and the efficiency of the foreign exchange intervention of the Chinese central bank after the reform, as well as the potential sustainable financial resources in China's foreign exchange market, are therefore worth exploring. Discussion of these issues is expected to provide theoretical suggestions to relevant government departments in China and participants in the foreign exchange market.

Therefore, this paper contributes to the existing literature along the following lines. First, based on the heterogeneous agent literature, a heterogeneous agent model that considers carry trade observations and the law of supply and demand in the foreign exchange market is constructed for exchange rate determination. Second, carry traders' expectations and risk aversion and the impact of their activities on the efficiency of central bank intervention are highlighted in this theoretical model. Heterogeneous traders are also allowed to switch among all three forecasting rules according to the past performance of the Chinese yuan exchange rate. Third, this paper discusses the adjustment of carry traders' activities due to changing foreign exchange reform and the influence of this adjustment on the effect of central bank intervention. Fourth, this paper analyzes the exploration of sustainable financial resources in the foreign exchange market in terms of the interaction between carry traders' behavior and exchange rate formation. In summary, by offering a modified heterogeneous agent model, this paper provides a better explanation of the exchange rate formation mechanism and carry traders' activities in the foreign exchange market.

The remainder of the paper is organized as follows. Section 2 first reviews the literature on sustainability and heterogeneous beliefs, provides a definition of sustainable financial resources and addresses the research gaps. Section 3 develops a heterogeneous agent model including fundamentalists, chartists, and carry traders under the consideration of central bank intervention. Section 4 outlines the unscented Kalman filter (UKF) method, which is used for empirical analysis in this paper. Section 5 describes the data and reports the empirical results generated by the model. Section 6 discusses the implications of the present study. Finally, Section 7 concludes the article.

2. Literature Review

2.1. Sustainable Financial Resources

'Sustainable financial resources' is never properly defined. In this section, we attempt to provide a reasonable definition. To this end, the analysis starts from the definition of sustainability. Sustainability or sustainable development is a vast concept that has hundreds of definitions. Following the publication of the UN-sponsored World Commission on Environment and Development report Our Common Future, it has been discussed during the last decades. According to WCED, sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are all in harmony and enhance both current and future potential to meet human needs and aspirations [18]. Despite its acclaimed vagueness and ambiguity, the WCED definition of sustainable development has been highly instrumental in developing a "global view" with respect to our planet's future [19–21]. For many in the field, sustainability is defined through the following interconnected domains or pillars: environment, economic, and social [22]. However, sustainability is not only "being green" or "maintenance forever" [23]. In general, sustainability is more focused on increasing the quality of life with respect to environmental, social, and economic considerations both in the present and for future generations, and it can be regarded as a type of stability or a system state characterized by some quantity that remains invariant [24,25].

In recent decades, the term 'sustainability' has been expanded in different domains. In the economic domain, sustainability provides a guiding framework for defining, creating, and managing wealth [24]. For example, a sustainable economy is defined as one in which resources are not used up faster than nature renews them. It also marks a thriving climate for business that balances environmental, social, and economic vitality, issued by Oregon Environmental Council in 2010; "Sustainable Micro-enterprise", which is from the context of self-sustainability, is defined as financial institutions or firms' long-term ability to meet goals and requires private profitability, including a return on equity, net of subsidy, that exceeds the private opportunity cost of resources through financial markets [26,27]; and "corporate sustainability", which is the code for long-term corporate success with the consideration of multiple dimensions [24,28]. In conclusion, 'sustainable' is defined in this paper from the perspective of 'meeting business needs in the long term'.

According to the concepts related to sustainability mentioned above, exploring sustainable resources is undoubtedly covered in the concept of sustainable development. Meanwhile, sustainable resources are supposed to meet human needs and aspirations, and sustainable financial resources should meet the needs and aspirations of the business in the long term. To give a specified definition of sustainable financial resources, we then focus on the definition of financial resources. In most of the literature, "financial resources" have been discussed without a specified definition. However, from the analysis of these papers, "sources of funding for investment" plays a key role [29–33]. One definition of financial resources was proposed as follows: it is the resources—including financial institutions, capital markets, and owner's equity—from which enterprises obtain the funds they need to finance their investments, capital, and current activities [34]. Although providing funds plays a key role in these analyses, it cannot be the only function for financial resources, and being able to meet or help to meet the needs for funding is more important here. Accordingly, this paper suggests the following definition of sustainable financial resources: they are stable resources that could meet or help meet the institutions' and firms' need for funding to finance their investments, capital and current activities in the long term.

Although a large amount of literature has studied financial resources from different angles, including their features and implications on multiple aspects of business, the sustainability of financial resources is seldom mentioned. Meanwhile, discussions about financial resources focus more on the capital market and pay little attention to the foreign exchange market and its connection to sustainable financial resources, which is complicated but worth studying.

2.2. Heterogeneous Agents

The existence of heterogeneous traders and the deviation of their expectations from rational expectations have long been explored by extensive literature dating back to a heterogeneous agent model with two types of agents, fundamentalists and chartists, introduced in [7]. According to them, fundamentalists compare the market-determined exchange rate with the fundamental rate to forecast the future movement of the exchange rate, while chartists forecast the future movement of the exchange rate by calculating the last change in the market-determined exchange rate. Similar results are also drawn by [35,36]. Later, the strategy switching of heterogeneous traders was noted in the literature on heterogeneous agent models. According to the typical switching mechanism with heterogeneous beliefs, traders adjust investment strategies according to the efficiency of recent strategies [37,38]. A similar model emphasizing nonlinear dynamics in the exchange rate is introduced by [39], which was later developed by [40–42]. Among the first to estimate a fully dynamic heterogeneous agent model with survey data, it is confirmed in [43] that the expectations of investors can be dynamic with three forecasting rules and that investors switch between these forecasting rules depending on their past performance. These heterogeneous agent models with nonlinear switching mechanisms have an absolute advantage in describing exchange rate dynamics and explaining volatility clustering, the heavy tail property, and disconnect puzzles, which are not covered by the linear model [44–46].

However, as the existing heterogeneous agent models consider only two types of traders, they fail to provide convincing explanations for the forward premium puzzle. Therefore, carry traders' activities should be introduced into dynamic models of the exchange rate for further research. Carry trade, which is a popular trading strategy among currency investors, is designed to exploit deviations from uncovered interest parity (UIP). If UIP holds, the interest rate differential of two countries is offset, on average, by the expected change in the exchange rate. In a carry trade, an investor borrows currencies of low interest and then buys and invests in high-yielding currencies. Although the exact size of carry trade flow is uncertain, the results reported in the literature have suggested that the influence of carry traders on the exchange rate is large and increasing [9,47].

Characteristics related to different aspects of carry traders' activities in the foreign exchange market have been considered in many studies [48–50]. Based on investment styles, including carry trade, it is shown that carry trade is one of the most important factors that can explain most of the index of returns on professionally managed currency funds [51,52]. The carry trade strategy also represents the magnitude of the forward premium, and the reduction in the profits of carry traders with increasing investment size causes the forward premium anomaly to disappear [10]. Carry trade returns, which have been proven to have long-range dependence in developed markets, can be explained mostly by the risk factors related to the foreign exchange market and have predictive power with other contemporaneous drivers, such as interest rate differentials and foreign exchange rate volatility [53–56]. By comparing a portfolio based on expectations with trend and carry trade portfolios, it is found that carry trade strategies become less profitable with low interest rate differentials and note that the time-varying characteristic of monetary policy affects expectations [57]. The investigations show that currency carry trade risk premia and the linkage between carry trade risk premia and customer order flow could explain most of the term structure of exchange rate predictability [12]. Consistent with the literature on nonlinear exchange rate models, the excess returns with carry trading strategies, along with the potential asymmetric dependence between the carry trade and currency return, have been found in the foreign exchange market [58–60]. Studies on carry trade are key to understanding currency excess returns, especially for emerging currencies [61,62]. Furthermore, it is argued that the carry-to-risk ratio considering credit default swaps could help the central bank understand the attractiveness of the carry trade strategy and operate effective policies to restrict the activities of carry traders [63]. With an endogenous regime switching model, it is found that carry trades are profitable in a regime with low exchange rate volatility and unprofitable during economic downturns [64].

In the research concerning carry trade strategies and the foreign exchange market, the heterogeneous agent model with three types of agents is presented and applied. A heterogeneous agent model was introduced with carry traders as a third group of investors, and it is noted that the weights of the three types of traders adjust over time [13]. Another model with carry traders, fundamentalists, and chartists is proposed and the interactions between chartists and carry traders are part of the explanation of the forward premium puzzle has been demonstrated in [8], which contradicts the results in [10]. In line with the heterogeneous agent model developed in [8], a private data set was used to study the returns of carry trade strategies for emerging and developed markets, and it is found that carry trade strategies are not significant regressors for the Mexican peso during the Great Recession [54]. It is noted that the heterogeneous agent model with carry traders helps explain the puzzles of carry trading profits and exchange rate disconnects, as well as the microstructure of the market in terms of aspects such as the interactions between heterogeneous agents [14]. However, the uncertainty related to economic policy and the subsequent adjustment of exchange rate expectations, which should also be included in the heterogeneous agent model, are rarely considered [65]. Based on the assumption of three types of heterogeneous beliefs, it is found that there are multiple heterogeneous equilibria in China's foreign exchange market and that carry traders' activities are responsible for the deviation of the market-determined Chinese yuan exchange rate from its fundamental level [15]. With an empirical heterogeneous agent model, two trading strategies are designed considering carry trade and momentum signals and they prove that these new strategies are a good hedge with desirable diversification merits [66].

These empirical studies on heterogeneous beliefs, which challenge the traditional rational agent framework, confirm the good performance of heterogeneous agent models in describing, explain and forecast foreign exchange market dynamics and show that they are fit for studying issues associated with the market microstructure [67,68]. The performance of carry trades in the foreign exchange market has always been an important question of the heterogeneous trader model, and the literature has studied the characteristics of carry traders and the effect of their activities on the foreign exchange market from various aspects. However, the heterogeneous agent model does not consider the law of supply and demand in a foreign exchange market with a floating exchange rate system and central bank intervention or the adjustment of carry traders' activities based on the changing exchange rate policy and the resulting impact on the implementation of central bank intervention.

2.3. Research Gaps

In a floating exchange rate system, the exchange rate is determined according to the law of supply and demand. The activities of all the participants in the foreign exchange market compose the supply or demand of domestic or foreign currencies [69]. The central bank, as the maker and executor of monetary policy, is also one of the main participants in the foreign exchange market. The main purpose of the central bank participation in the foreign exchange market is maintaining exchange rate stability and rationally adjusting the international reserves. By purchasing or selling currencies directly in the foreign exchange market, the supply and demand of foreign exchange market funds can be adjusted to maintain the exchange rate at a certain level or within a certain range [70]. In a floating exchange rate system, the free trade of heterogeneous traders in the foreign exchange market may cause the market-determined exchange rate to be overvalued or undervalued for a long time, which has a negative impact on the economy. In this situation, the central bank will purchase or sell domestic currency in the foreign exchange market to maintain the exchange rate of the domestic currency [16]. For traders with heterogeneous beliefs and the central bank that regulates the market, their transactions in the foreign exchange market are part of the supply and demand in the foreign exchange market [69]. Therefore, on the basis of the law of supply and demand, the interaction between the central bank and heterogeneous traders in the foreign exchange market cannot be ignored. In this paper, the market-clearing exchange rate is computed within the law of supply and demand, and central bank intervention is included in the model. The model constructed in this paper provides a better illustration of the activities of heterogeneous traders and the central bank and of the impact of the interaction of their activities on the formation of the exchange rate.

The existing heterogeneous agent models, which consider the behaviors of fundamentals, chartists, and carry traders, tend to ignore the interaction between the behaviors of various market participants, especially carry traders, exchange rate policies, and the central bank. In fact, the interest rate, which is an important indicator carry traders consider when choosing trading strategies, is the main tool central banks use to regulate financial markets and the supply and demand of domestic currencies [71]. Therefore, carry traders' activities will affect the currencies the central bank sells and purchases in the foreign exchange market to a certain extent. In other words, the carry trade strategy will have an impact on the effectiveness of central bank intervention, especially in China's foreign exchange market with its managed floating exchange rate system in a state of continuous improvement [72]. With a model of exchange rate determination considering heterogeneous traders, this paper analyzes the influence of carry traders' activities on central bank intervention. The results show that the trading behavior of carry traders has weakened the effect of central bank intervention on the formation of the exchange rate.

To maintain the stability of the domestic foreign exchange market, the central bank implements some relevant macro policies, such as restrictions on the volume or the mechanism of currency trading, as well as the quotation of the benchmark exchange rate [73]. The monetary policy uncertainty causes the adjustment of carry trade excess returns, which is highly related to the interest rate and macro policies [49]. The adjustment of carry trading strategies will have an influence on the formation of the exchange rate and central bank intervention. This paper emphasizes the impact of the exchange rate policies related to an important foreign exchange rate reform on traders' behavior in the foreign exchange market and conducts a detailed analysis with the samples before and after the implementation of the exchange rate policies. The results prove that the implementation of exchange rate policies related to an important foreign exchange rate reform has a significant impact on the weight and risk aversion of carry traders.

Furthermore, since the foreign exchange market is one of the most important financial markets, exploration of sustainable financial resources from the foreign exchange market is also an important issue. The literature focuses on the sources of funding in domestic currency for institutions and firms, ignoring the important relationship of foreign currency assets and the foreign exchange market. With trading strategies highly related to exchange rate policies, carry traders' activities and their association with exchange rate formation have an important impact on the potential financial resources in the foreign exchange market. Based on the empirical results of the exchange rate determination model, the financial resources associated with the foreign exchange market and their sustainable character are first analyzed in this paper.

3. Theoretical Model

In this section, a nonlinear empirical model of the Chinese yuan exchange rate is outlined to identify the behaviors of heterogeneous agents. Assume that there are three types of heterogeneous agents in China's foreign exchange market: fundamentalists, chartists, and carry traders. Expectation formation and risk preference differ for each type of agent. Traders will adjust their expectations according to the profit in the last period, which means that the weights attributed by heterogeneous agents change over time. Additionally, the Chinese yuan exchange rate is assumed to be determined by the interaction of supply and demand in China's foreign exchange market, which is also due to the further development of the exchange rate formation system after August 11, 2015.

3.1. Hypothesis and Derivation of the Model

The model starts with the expectation formation of the three types of agents mentioned previously. The first forecasting rule is the fundamentalist rule. Fundamentalists forecast the exchange rate according to the belief that the market-determined exchange rate will return to its fundamental value. When using this rule, agents expect the exchange rate to converge to the UIP fundamental rate; therefore, they calculate the difference between the market-determined rate and the fundamental rate in the last period to forecast the movement of the exchange rate in the next period

$$\widetilde{E}_t^f(s_{t+1}) = s_{t-1} + \alpha_f\left(s_{t-1}^* - s_{t-1}\right), \tag{1}$$

where $\widetilde{E}_t^f(s_{t+1})$ is the exchange rate expected by fundamentalists at time t+1 given the information available at time t, which includes $s_0, s_1, \ldots, s_{t-1}, s_0^*, s_1^*, \ldots, s_{t-1}^*$. It is assumed that agents do not know the values of s_t and s_t^* and forecast the exchange rate at the beginning of period t. This assumption can also be found in [42]. s_{t-1} is the spot exchange rate at time t-1, s_{t-1}^* presents the fundamental exchange rate at time t-1, and α_f is a parameter describing the speed at which the agents using a fundamentalist rule expect the spot exchange rate to return to its fundamental value. Empirical results suggest that α_f is a small positive value, and this paper follows the literature to assume that $0 < \alpha_f < 1$ [7,42,74].

Assuming that the fundamental exchange rate s_t^* is given by UIP, the change in the log of the exchange rate is determined by the interest rate differential [75],

$$\Delta\log(s_t^*) = \beta\left(r_{t-1}^d - r_{t-1}^f\right) + \xi_t, \tag{2}$$

where $\Delta\log(s_t^*)$ is the difference of the logistic value of the fundamental rate at time t and t-1; r_t^f presents the foreign risk-free interest rate, and r_t^d is the domestic risk-free interest rate; the parameter β presents the importance of the interest rate differential in forecasting the fundamental exchange rate and is supposed to be smaller than 1; and ξ_t is a parameter of white noise. For convenience, we rewrite Equation (2) and have

$$s_t^* = e^{log(s_{t-1}^*)+\beta(r_{t-1}^d - r_{t-1}^f)+\xi_t}, \tag{3}$$

The second forecasting rule is a chartist rule. With this rule, agents expect that the exchange rate in the next period will follow the same pattern as it did in the previous period. Chartists calculate the last change in the exchange rate to forecast the exchange rate in the next period

$$\widetilde{E}_t^c(s_{t+1}) = s_{t-1} + \alpha_c(s_{t-1} - s_{t-2}) \tag{4}$$

where $\widetilde{E}_t^c(s_{t+1})$ is the exchange rate expected by the chartists at time *t*+1 given the information available at time t, and s_{t-2} is the spot exchange rate at time t-2. The parameter α_c is the degree of extrapolation; a positive α_c reflects the trending forecast, and a negative α_c implies mean-reverting expectations. Following [8] and [42], α_c is assumed to be a positive value and smaller than 1.

The last forecasting rule is carry trade. Carry traders expect that the exchange rate will change in a direction opposite the UIP. If the domestic interest rate is greater than the foreign interest rate, the domestic currency will depreciate under the UIP theory, and carry traders will borrow the currency with a lower interest rate and obtain profit from investing the currency with a higher interest rate. Therefore, carry traders use the interest rate differential to forecast the exchange rate in the next period, as in the equation

$$\widetilde{E}_t^i(s_{t+1}) = s_{t-1} + \alpha_i\left(r_{t-1}^f - r_{t-1}^d\right) \tag{5}$$

where $\widetilde{E}_t^i(s_{t+1})$ is the exchange rate expected by the chartists at time $t+1$ given the information available at time t, r_{t-1}^f is the risk-free interest rate in a foreign country during the last period, and r_{t-1}^d is the risk-free interest rate in the domestic country during the last period. As mentioned above, it is assumed that carry traders forecast the exchange rate at the beginning of period t and have no information about the contemporaneous exchange rate s_t or interest rates r_t^f and r_t^d. The parameter α_i reflects the degree to which carry traders expect the interest rate differential to have an impact on the exchange rate. Positive α_i reflects the expectations formed by carry traders, while negative α_i reflects the expectations based on the UIP. Assume that $0 < \alpha_i < 1$ similar to the suggestions in [8] and [76].

In this paper, it is assumed that only Chinese yuan and U.S. dollars are traded in China's foreign exchange market. Since over 90% of the transactions in China's foreign exchange market are between Chinese yuan and U.S. dollars, this assumption is legitimate. Assume that a typical trader in China's foreign exchange market has a disposable position of P_t^j at time t, where j represents three types of heterogeneous agents and $j = f, c, i$. Traders invest I_t^j in foreign currency with a foreign interest rate of r_t^f and invest the remaining position $P_t^j - s_t I_t^j$ in domestic currency with a domestic interest rate of r_t^d. s_t is the direct quote of the Chinese yuan, and all other values are measured in Chinese yuan. After investing for one period, the trader's disposable position will be P_{t+1}^j at $t+1$. Then, we have

$$P_{t+1}^j = \left(1 + r_t^f\right) s_{t+1} I_t^j + \left(1 + r_t^d\right)\left(P_t^j - s_t I_t^j\right). \tag{6}$$

The position of P_t^j will be determined according to the principle of expected utility maximization. Following the suggestions in [39], assume that the expected utility of P_{t+1}^j is positively related to the expected value of the position at time t and negatively related to the conditional variance generated by investing the position of P_{t+1}^j, which will be defined later. Therefore, the expected utility of P_{t+1}^j for the three types of traders would be

$$U_t^j\left(P_{t+1}^j\right) = \widetilde{E}_t^j\left(P_{t+1}^j\right) - \frac{1}{2}\mu_j \sigma_t^j\left(P_{t+1}^j\right), \tag{7}$$

where $U_t^j(P_{t+1}^j)$ is the expected utility of P_{t+1}^j, $\widetilde{E}_t^j(P_{t+1}^j)$ is the expected value of P_{t+1}^j at time t, μ_j presents the trader's risk aversion, $\sigma_t^j(P_{t+1}^j)$ is the conditional variance of P_{t+1}^j. Substituting Equation (6) into Equation (7), we have

$$U_t^j(P_{t+1}^j) = \left(1 + r_t^f\right)\widetilde{E}_t^j(s_{t+1}) I_t^j + \left(1 + r_t^d\right)\left(P_t^j - s_t I_t^j\right) - \frac{1}{2}\mu_j\left[\left(1 + r_t^f\right) I_t^j\right]^2 \sigma_t^j(s_{t+1}) \tag{8}$$

Then, the first derivative of $U_t^j(P_{t+1}^j)$ is

$$\frac{\partial U_t^j\left(P_{t+1}^j\right)}{\partial P_t^j} = (1 + r_t^f)\widetilde{E}_t^j(s_{t+1}) - s_t\left(1 + r_t^d\right) - \mu_j\left(1 + r_t^f\right)^2 I_t^j \sigma_t^j(s_{t+1}). \tag{9}$$

Let it be zero; then, we have the optimal amount of the position to invest in foreign currency for each type of trader at time t

$$I_t^j = \frac{\left(1 + r_t^f\right)\widetilde{E}_t^j(s_{t+1}) - \left(1 + r_t^d\right) s_t}{\mu_j\left(1 + r_t^f\right)^2 \sigma_t^j(s_{t+1})}, \tag{10}$$

where $\sigma_t^j(s_{t+1})$ is the conditional variance of s_{t+1} and presents the risk of s_{t+1}. In [39], $\sigma_t^j(s_{t+1})$ is defined as the weighted average of the squared forecasting errors made by heterogeneous traders. It is argued that agents have very short memory and the forecasting errors made in the latest period are the most important [8]. Therefore, we follow it to give the definition of $\sigma_t^j(s_{t+1})$,

$$\sigma_t^j(s_{t+1}) = \left[\widetilde{E}_{t-2}^j(s_{t-1}) - s_{t-1}\right]^2 \tag{11}$$

A larger deviation degree represents a greater risk.

3.2. Switching Mechanism for Agents

The next step is to introduce the possibility for agents to switch their forecasting rules of the exchange rate, which is based on discrete choice theory and called fitness learning, assuming that agents evaluate forecasting rules by computing the past risk-adjusted rates of return with these rules [77]. If one of the forecasting rules is more or less profitable than the others, then the traders will adjust (increase or reduce) the weight of the forecasting rule used currently [42]. In this paper, the weights are modified in the following based on the literature [8,42]. For j = f, t,

$$\omega_t^j = \begin{cases} \frac{e^{\delta\widetilde{\pi}_{t-1}^j}}{e^{\delta\widetilde{\pi}_{t-1}^f}+e^{\delta\widetilde{\pi}_{t-1}^c}+e^{\delta\widetilde{\pi}_{t-1}^i}} & if\left|r_t^d-r_t^f\right|>\tau \\ \frac{e^{\delta\widetilde{\pi}_{t-1}^j}}{e^{\delta\widetilde{\pi}_{t-1}^f}+e^{\delta\widetilde{\pi}_{t-1}^c}} & if\left|r_t^d-r_t^f\right|\leq\tau \end{cases} \quad (12)$$

and for j = i,

$$\omega_t^j = \begin{cases} \frac{e^{\delta\widetilde{\pi}_{t-1}^j}}{e^{\delta\widetilde{\pi}_{t-1}^f}+e^{\delta\widetilde{\pi}_{t-1}^c}+e^{\delta\widetilde{\pi}_{t-1}^i}} & if\left|r_t^d-r_t^f\right|>\tau \\ 0 & if\left|r_t^d-r_t^f\right|\leq\tau \end{cases} \quad (13)$$

where ω_t^f, ω_t^c, and ω_t^i are the weights given to the forecasting rules of fundamentalists, chartists, and carry traders, respectively.

The weights depend on whether the absolute value of interest rate differential $\left|r_t^d-r_t^f\right|$ is greater than the threshold τ, which should be a positive but small value. Following [8], τ is set at a value of 0.03 in this paper. τ measures the implementation costs and is similar to transaction costs. Higher implementation costs lead to higher volatility and risk, so carry traders will not be active in the market [78]. Only if the carry trade strategy is expected to be profitable will it be implemented, and then the weights of different types of forecasting rules would be the upper parts of Equations (12) and (13). If $\left|r_t^d-r_t^f\right|$ is lower than the threshold τ, then the carry trade strategy will not yield substantial profit, and carry traders will disappear from the market. The weights are mainly formed by δ and $\widetilde{\pi}_{t-1}^j$. The parameter δ represents the intensity with which agents switch the weights of forecasting rules, and δ should be a positive value. However, if δ goes to infinity, all agents shift to the best forecasting rule and make the optimal decisions. Therefore, under the limited assumption of rational expectation, δ is not supposed to be a large positive value. $\widetilde{\pi}_{t-1}^j$ is the risk-adjusted profit at time t-1 for each type of forecasting rule. This profit is also based on the assumption mentioned above that agents forecast the exchange rate at the beginning of period t, and they do not know the contemporaneous profit at that time. Since traders will take the risk into account when estimating the profit with each forecasting rule, $\widetilde{\pi}_t^j$ is defined as

$$\widetilde{\pi}_t^j = \pi_t^j - \mu_j\, \sigma_t^j(s_{t+1}), \quad (14)$$

where $j = f, c, i$; π_t^j is the investment profit of time $t-1$ realized at the beginning of period t.

To simplify the analysis, the investment profit of one-unit currency is considered for only one period; then, we have

$$\pi_t^j = \left[\left(1+r_t^f\right)s_t - \left(1+r_t^d\right)s_{t-1}\right]sgn\left[\widetilde{E}_{t-1}^j(\Delta s_t) + r_t^f\widetilde{E}_{t-1}^j(s_t) - r_t^d s_{t-1}\right] \quad (15)$$

where $sgn(x) = \begin{cases} 1 for\ x>0 \\ -1 for\ x<0 \\ 0 for\ x=0 \end{cases}$. The first part of Equation (15) presents the investment profit based on the movement of the exchange rate, and $sgn\left[\widetilde{E}_{t-1}^j(\Delta s_t) + r_t^f\widetilde{E}_{t-1}^j(s_t) - r_t^d s_{t-1}\right]$ indicates whether the forecasted changing direction of the exchange rate is the same as the market-determined changing direction.

3.3. Model Solution

In this section, the market-clearing exchange rate in the foreign exchange market is determined to close the model. For each heterogeneous forecasting rule, traders demand a certain amount of foreign currency based on the expected utility of investment, in which traders' heterogeneous expectations and behaviors are all included. Then, the total demand for foreign currency in the foreign exchange market will be the weighted sum of the demand with each heterogeneous rule. Therefore, the total demand of foreign currency at time t is

$$D_t = \sum \omega_t^j\left(\widetilde{\pi}_t^j\right) I_t^j\left(\widetilde{E}_t^j\right), \quad (16)$$

where $j = f, c, i$; D_t is the total demand of foreign currency in the foreign exchange market at time t. From Equation (16), we find that D_t depends on ω_t^j, I_t^j, and $\widetilde{E}_t^j$, which presents the expectations of heterogeneous traders.

The supply of foreign currency is mainly composed of the amount of foreign currency supplied by the central bank for intervention and the domestic trade surplus. Then, we have

$$C_t = \zeta_1 T_t + \zeta_2 V_t, \quad (17)$$

where C_t is the total supply of foreign currency in the foreign exchange market at time t, T_t is a measure of the domestic trade balance, and V_t is the amount of foreign currency that the central bank purchases or sells for intervention in the foreign exchange market. A positive T_t indicates a positive current account balance, and the domestic currency tends to appreciate, and vice versa. When the central bank purchases foreign currency, V_t is negative, and the domestic currency tends to depreciate, and vice versa. The parameters ζ_1 and ζ_2 represent the influence of the central bank intervention and domestic trade balance on the foreign exchange market, and they should be positive.

Equations (16) and (17) are combined to solve the market-clearing exchange rate, which is

$$s_t = \frac{\left(1 + r_t^f\right)}{\left(1 + r_t^d\right)} * \frac{\sum_{j=f,c,i}\left[\frac{\widetilde{E}_t^i(s_{t+1})\omega_t^j}{\mu_j\left(1+r_t^f\right)\sigma_t^j(s_{t+1})} - \zeta_1 T_t - \zeta_2 V_t\right]}{\sum_{j=f,c,i}\left[\frac{\omega_t^j}{\mu_j\left(1+r_t^f\right)\sigma_t^j(s_{t+1})}\right]} + \eta_t, \quad (18)$$

where s_t is the market-clearing exchange rate of the Chinese yuan at time t; and η_t is a parameter of white noise. Equation (18) indicates that the market-clearing exchange rate is mainly determined by some microeconomic factors, such as heterogeneous expectations and risk aversion of different agents, and some macroeconomic factors, such as the interest rate in domestic and foreign countries and central bank intervention. Additionally, the lags of the actual exchange rate and the fundamental exchange rate play an important role in the exchange rate determination. This completes the theoretical model of this paper.

4. Methodology

To study the performance of carry traders in China's foreign exchange market and its impact on the efficiency of central bank intervention, all the parameters in Equation (18) are estimated, including $\alpha_f, \alpha_c, \alpha_i, \delta, \beta, \mu_f, \mu_c, \mu_i, \zeta_1, \zeta_2$. However, the estimation of nonlinear models is always challenging, and the estimation of Equation (18) is particularly challenging given that the fundamental value of the Chinese yuan exchange rate—one of the variables in Equation (18)—is unobservable. In this case, it is not a good idea to estimate the parameters in our model with common empirical methods. In this paper, the artificial intelligence method of the unscented Kalman filter (UKF), which is a novel development in the field of nonlinear system estimation, will be used for the empirical analysis.

The UKF method, proposed by [79], is an extension model of the Kalman filter (KF) and a typical nonlinear filter algorithm. The UKF has been widely used in unilinear control systems, especially in the field of target tracking [80–82]. Similar to the KF method, the UKF requires a state function and a measurement function for the target. A state model describes the state of transition and is used for prediction. A measurement model describes the relationship between the state variable and the measurement variable. Based on the measurements of observable signals in the nonlinear system, the aim of the UKF is to produce several sampling points with the covariance of the current state and propagate these sampling points through an unscented transform to obtain a more accurate estimation of the mean and covariance of the measurement variable. This method avoids the need to calculate the Jacobian matrix and thus greatly improves the accuracy of nonlinear system estimation.

In this paper, the empirical model is constructed to track the formation and movement of the exchange rate. The actual value of the exchange rate is a measurement value, which is observable. The fundamental exchange rate, which is measured based on macroeconomic fundamentals, is a state value of the exchange rate and unobservable. The model in this paper has the characteristics of a nonlinear system: the fundamental exchange rate and the market-determined exchange rate can be considered a state variable and a measurement variable, respectively. Meanwhile, Equations (18) and (3) can be taken as a measurement model and a state model, respectively. Therefore, the UKF method is suitable for estimating the model in this paper.

4.1. Introduction of the UKF

The basic approach of the UKF is similar to the random samples of a specific distribution function in Monte Carlo simulations. The unscented transformation (UT), which is founded on the intuition that it is easier to approximate a probability distribution than it is to approximate a nonlinear function or transformation, is used in the UKF for nonlinear system estimation [83]. As mentioned above, the UKF method is used in a nonlinear system with a state function and a measurement function. First, a set of sigma points for the state variable will be constructed with given mean and covariance, and then each sigma point will be substituted into the nonlinear measurement function to construct the transformed sigma points and estimate the transformed mean and covariance. The approach is specified as follows.

Initially, the state function and measurement function with vector form variables are established. The two equations are

$$y_t \triangleq h(x_t, u_t, n_t) \tag{19}$$

$$x_t \triangleq g(x_{t-1}, u_t, v_t) \tag{20}$$

where y_t is the noisy observation of the system; x_t is the system state; n_t is the observation noise; v_t is the process noise; and u_t is the input. Assume that n_t and v_t are normally distributed with a mean R and a variance Q, respectively. Combining the state variable, observation noise variable and process noise variable into a matrix form yield.

$$x_t^a \triangleq \left(x_t^T, v_t^T, n_t^T\right)^T \tag{21}$$

Then, initialize the mean matrix $\overline{x}_0^a$ and covariance matrix P_0^a of the fundamental exchange rate x_t at the initial point

$$\overline{x}_0^a \triangleq \left(\overline{x}_0^T, \overline{v}_0^T, \overline{n}_0^T\right)^T, P_0^a \triangleq \begin{bmatrix} P_{\overline{x}_0} 0 0 \\ 0 P_{v_0} 0 \\ 0 0 P_{n_0} \end{bmatrix}, \tag{22}$$

where $\overline{x}_0 = E[x_0]$, $P_{\overline{x}_0} = \mathrm{E}[(x_0 - \overline{x}_0)(x_0 - \overline{x}_0)^T)]$. Then, the dimension of x_t^a is

$$n_a = n_x + n_v + n_n \tag{23}$$

With this dimension, $2n_a + 1$ sigma points are constructed based on the initial mean and variance matrices

$$\chi^a_{i,t-\mathbf{1}/t-\mathbf{1}} \triangleq \begin{cases} \bar{x}_0, & i = 0, \\ \bar{x}_0 + \varphi\sqrt{P_{\bar{x}_0}}, & i = 1, \ldots, n_a, \\ \bar{x}_0 - \varphi\sqrt{P_{\bar{x}_0}}, & i = n_a + 1, \ldots, 2n_a, \end{cases} \quad (24)$$

where φ is a scale parameter

$$\varphi = \sqrt{n_a + \lambda}, \lambda = \alpha^2(n_a + \kappa) - n_a. \quad (25)$$

Normally, the parameter of κ is a positive value to ensure the semipositive definiteness of the covariance matrix. The parameter α limits the size of the $2n_a$ sigma point distribution, and it is not supposed to be large.

Transform the sigma points $\chi^a_{i,t-\mathbf{1}/t-\mathbf{1}}$ through the state function in Equation (20) to the sigma points $\dot{\chi}^a_{i,t/t-\mathbf{1}}$ and obtain

$$\dot{\chi}^a_{i,t/t-\mathbf{1}} = g\left(\chi^a_{i,t-\mathbf{1}/t-\mathbf{1}}, u_t, v_t\right), \quad (26)$$

where $i = 1, \ldots n_a, n_a + 1, \ldots, 2n_a$. For the transformed sigma points $\dot{\chi}^a_{i,t/t-\mathbf{1}}$, calculate their weighted mean value and covariance value,

$$\bar{x}_{t/t-1} = \sum\nolimits_{i=0}^{2n_a} \omega_i^m \dot{\chi}^a_{i,t/t-\mathbf{1}}, \quad (27)$$

$$P_{\bar{x}_{t/t-1}} = \sum\nolimits_{i=0}^{2n_a} \omega_i^c \left\{ \left[\dot{\chi}^a_{i,t/t-\mathbf{1}} - \bar{x}_{t/t-1}\right] \times \left[\dot{\chi}^a_{i,t/t-\mathbf{1}} - \bar{x}_{t/t-1}\right]^T \right\} + \mathbf{Q}, \quad (28)$$

where $\bar{x}_{t/t-1}$ is the mean and $P_{\bar{x}_{t/t-1}}$ is the variance of $\dot{\chi}^a_{i,t/t-\mathbf{1}}$. The weights ω_i^m and ω_i^c are defined as

$$\omega_0^m = \frac{\lambda}{n_a + \lambda}, \quad (29)$$

$$\omega_0^c = \frac{\lambda}{n_a + \lambda} + \left(1 - \alpha^2 + \beta\right), \quad (30)$$

$$\omega_0^m = \omega_0^c = \frac{1}{2(n_a + \lambda)}, \ i = 1, \ldots, \quad (31)$$

The parameter β is a nonnegative value used to incorporate knowledge of the higher order moments of the distribution. Normally, the optimal value of β is 2 for a Gaussian prior [84]. With $\bar{x}_{t/t-1}$ and $P_{\bar{x}_{t/t-1}}$, the weighted sigma points are

$$\chi^a_{i,t-\mathbf{1}/t-\mathbf{1}} \triangleq \begin{cases} \bar{x}_{t/t-1} & i = 0, \\ \bar{x}_{t/t-1} + \varphi\sqrt{P_{\bar{x}_{t/t-1}}}, & i = 1, \ldots, n_a, \\ \bar{x}_{t/t-1} - \varphi\sqrt{P_{\bar{x}_{t/t-1}}}, & i = n_a + 1, \ldots, 2n_a, \end{cases} \quad (32)$$

Transform the sigma points of $\chi^a_{i,t/t-\mathbf{1}}$ through the measurement function of Equation (19),

$$\mathbf{Y}_{i,t/t-\mathbf{1}} = h\left(\chi^a_{i,t/t-\mathbf{1}}, u_t, n_t\right), \quad (33)$$

where $i = 1, \ldots n_a, n_a + 1, \ldots, 2n_a$. Then, calculate the mean and covariance of the measurement vector $\mathbf{Y}_{i,t/t-\mathbf{1}}$,

$$\bar{y}_{t/t-1} = \sum\nolimits_{i=0}^{2n_a} \omega_i^m \mathbf{Y}_{i,t/t-\mathbf{1}}, \quad (34)$$

$$P_{\bar{y}_{t/t-1}} = \sum\nolimits_{i=0}^{2n_a} \omega_i^c \left\{ \left[\mathbf{Y}_{i,t/t-\mathbf{1}} - \bar{y}_t\right] \times \left[\mathbf{Y}_{i,t/t-\mathbf{1}} - \bar{y}_t\right]^T \right\} + \mathbf{R}, \quad (35)$$

where $\overline{y}_{t/t-1}$ is the mean and $P_{\overline{y}_{t/t-1}}$ is the covariance of $\overline{y}_{t/t-1}$. Furthermore, calculate the covariance of the station vector and the measurement vector,

$$P_{x_t y_t} = \sum_{i=0}^{2n_a} \omega_i^c \left\{ \left[X_{i,t/t-1}^a - \overline{x}_{t/t-1}^a \right] \times \left[\mathbf{Y}_{i,t/t-\mathbf{1}} - \overline{y}_t \right]^T \right\}, \tag{36}$$

where $P_{x_t y_t}$ is the covariance. Then, the Kalman gain is defined as

$$K_t = P_{x_t y_t} P_{\overline{y}_{t/t-1}}^{-1}, \tag{37}$$

where K_t is the Kalman gain, which is used to update the state estimates from measurements of the system. With this Kalman gain, the updated UKF estimate and its covariance are given by

$$\overline{x}_{t/t} = \overline{x}_{t/t-1} + K_t \left(y_t - \overline{y}_{t/t-1} \right), \tag{38}$$

$$P_{\overline{x}_{t/t}} = P_{\overline{x}_{t/t-1}} - K_t P_{\overline{y}_{t/t-1}} K_t^T \tag{39}$$

Finally, the conditional distribution of x_t is obtained. With this distribution, the maximum log-likelihood principle is used for estimating the optimal values of all the parameters in the nonlinear system.

4.2. Procedures

This part outlines the procedures followed in this paper to perform empirical analysis with the UKF method. First, to simplify the model, rewrite Equations (39) and (40) into

$$s_t \triangleq h\left(s_{t-1}, s_{t-2}, s_{t-3}, s_{t-4}, s_{t-5}, s_{t-6}, s_{t-1}^*, s_{t-3}^*, s_{t-5}^*, r_t^f, r_{t-2}^f, r_t^d, r_{t-2}^d, T_t, V_t, \eta_t \right), \tag{40}$$

and

$$s_t^* \triangleq g\left(s_{t-1}^*, r_{t-1}^d, r_{t-1}^f, \xi_t \right). \tag{41}$$

Equations (40) and (41) are taken as a measurement model and a state model, respectively. Second, initialize the mean and variance in the fundamental exchange rate of the Chinese yuan to construct sigma points of the fundamental exchange rate with the state model. Third, use unscented transformation on these sigma points to map them into sigma points of the measurement variable. Fourth, calculate the covariance of the fundamental exchange rate vector and the measured exchange rate vector to obtain the Kalman gain for updating the sigma points of the fundamental exchange rate in the next cycle. Finally, find the maximum log-likelihood in each cycle to obtain the optimal values for the parameters in our model.

5. Results

5.1. Data Description

The data for estimation is monthly data from July 2005 through August 2018. All data used are sourced from the WIND database. The currency data are the monthly middle rate of the Chinese yuan quoted against the U.S. dollar. Take the one-month bond yield in the Chinese interbank bond market as the risk-free return of Chinese yuan assets and the one-month treasury rate as the risk-free return of U.S. dollar assets. The change in foreign exchange reserves held by the People's Bank of China is used for the measurement of the central bank intervention policy. The current account balance is calculated as the domestic trade balance. In addition to conducting empirical analysis with the whole sample, this paper studies the results with two subsamples, one from July 2005 to July 2015 and the other from August 2015 to August 2018.

Table 1 reports the descriptive statistics of the data. Table 1 shows the statistical values of the whole sample (group A), the subsample before August 2015 (group B), and the subsample after the foreign exchange reform in August 2015 (group C). The mean of the Chinese yuan exchange rate is close to 6.8 for the whole sample period. The average rate of the subsample from July 2005 to July 2015 is slightly higher, while that for the subsample after the reform in 2015 is close to 6.6. This result indicates the appreciation of the Chinese yuan after the reform. The full sample of the Chinese yuan exchange rate exhibits higher skewness and kurtosis. The foreign interest rate has a lower mean and higher kurtosis than the domestic interest rate. The monthly mean of the foreign interest rate is close to zero, which indicates the expansionary monetary policy in the United States. The change in the foreign exchange rate after the reform in 2015 is much less than that before the reform. This finding indicates that the Chinese central bank did reduce its intervention in China's foreign exchange market. The current account balance gradually increases after the foreign exchange reform in 2015, and its kurtosis is higher than that before the reform.

Table 1. Descriptive statistics.

	Mean	St. dev.	Max	Min	Skewness	Kurtosis
Group A: July 2005–August 2018						
Chinese yuan rate	6.777	0.594	8.222	6.104	1.004	2.955
Foreign interest rate	0.011	0.017	0.052	0.000	1.405	3.429
Domestic interest rate	0.035	0.014	0.078	0.010	0.232	2.794
Change in foreign exchange reserves	151.819	414.936	1125.960	−1079.220	−0.442	3.748
Current account balance	248.246	165.834	612.862	−320.020	−0.007	3.545
Group B: July 2005–July 2015						
Chinese yuan rate	6.830	0.661	8.222	6.104	0.736	2.213
Foreign interest rate	0.012	0.019	0.052	0.000	1.143	2.548
Domestic interest rate	0.035	0.015	0.078	0.010	0.316	2.597
Change in foreign exchange reserves	243.003	386.851	1125.960	−928.040	−0.370	3.644
Current account balance	207.009	144.523	604.621	−320.020	0.033	4.983
Group C: August 2015–August 2018						
Chinese yuan rate	6.603	0.198	6.918	6.298	0.059	1.785
Foreign interest rate	0.007	0.006	0.019	0.000	0.666	2.155
Domestic interest rate	0.038	0.009	0.057	0.027	0.382	1.877
Change in foreign exchange reserves	−146.377	364.251	240.340	−1079.220	−1.284	3.825
Current account balance	383.103	160.950	612.862	−109.390	−1.168	5.176

5.2. Model Estimation and Testing

To avoid the local maximization of log-likelihood values, all initial values of the parameters to be estimated are randomly generated within a reasonable range, and the optimal parameter set is found through the estimated value of 100,000 times. Table 2 lists the parameter settings used in the estimation.

Table 2. Parameter selection of the model.

Parameter	Value	Explanation
α_f	(0, 1)	Speed of mean reversion
α_c	(0, 1)	Extrapolation parameter of the chartists
α_i	(0, 1)	Importance of the interest rate differential in forecasting the exchange rate
δ	(1, 10)	Intensity of choice parameter
β	(0.1, 1)	Importance of the interest rate differential in forecasting the fundamental exchange rate
μ_f	(0, 6)	Coefficient of risk aversion for fundamentalists
μ_c	(0, 6)	Coefficient of risk aversion for chartists
μ_i	(0, 6)	Coefficient of risk aversion for carry traders
ζ_1	(2, 20)	Coefficient of foreign exchange intervention
ζ_2	(2, 20)	Coefficient of domestic trade balance

Following the data set in [42], the speeds of mean reversion of fundamentalists α_f, chartists α_c, and carry traders α_i are chosen in the open interval (0,1), so all three strategies are attractive, and none of them dominates the foreign exchange market. The intensity of choice parameter δ is set to be a value no more than 10, following the suggestions in [8]. The parameter β is chosen between 0.1 and 1. The risk aversion parameters μ_f, μ_c, and μ_i are set to be values not exceeding 6. The coefficients of foreign exchange intervention ζ_1 and domestic trade balance ζ_2 are set to no more than 10, according to the regression results in [44]. The values of all these parameters will be chosen randomly from the corresponding interval each time. Table 3 shows the estimation results. The Taylor inequality coefficient is used to test the model fit and ranges from 0 to 1, where a smaller value indicates better fit. Additionally, a stationarity test is performed on the fitted residuals of the model. If the residual is stationary, then the estimation results of the model are reasonable. In Table 3, all three coefficients of Taylor's inequality are smaller than 0.3, which indicates that the model fits well in China's foreign exchange market. Residual-based augmented Dickey–Fuller (ADF) statistics show that the unit root hypothesis is rejected at the 1% significance level for the residual sequence. That is, the residual sequence of the model constructed in this paper is stable, and the estimation results of the parameters in the model are reasonable.

Table 3. Estimation results.

	Group A: July 2005–August 2018	**Group B: July 2005–July 2015**	**Group C: August 2015–August 2018**
α_f	0.414 *	0.097 *	0.472 *
α_c	0.863 *	0.873 *	0.698 *
α_i	0.892 *	0.484 *	0.505 *
δ	7.443 **	10.000 ***	7.782 *
β	0.812 ***	0.925 ***	0.843 ***
μ_f	3.350 *	5.240 *	1.198 *
μ_c	0.122 *	0.102 *	0.115 *
μ_i	2.954 *	2.248 *	2.720 *
ζ_1	2.433 **	2.984 **	2.278 **
ζ_2	2.780 **	2.284 **	2.132 **
Log-likelihood value	−166.339	−73.412	−64.333
Taylor's inequality	0.248	0.080	0.290
Residual-based ADF statistic	−6.376 ***	−2.653 ***	−2.970 ***

Notes: The table above presents coefficient estimates from estimating Equation (16). Significance is listed as ***, **, and * for significance at the 1%, 5%, and 10% level, respectively.

The results in Table 3 show that fundamentalists, chartists and carry traders do exist in China's foreign exchange market, and these traders have heterogeneous expectations regarding the Chinese yuan exchange rate. Meanwhile, all related parameters are significant at the 10% significance level, indicating that the optimal values of these parameters obtained by the log-likelihood maximization method are reasonable. The values shown in the second column of Table 3 are the estimation results for the full sample. Fundamentalists expect that the Chinese yuan exchange rate will gradually return to its fundamental value with a speed of 0.414. Chartists expect that the Chinese yuan exchange rate will follow its previous behavior with a parameter of 0.863. The estimated value of parameter α_i is 0.892, which indicates that carry traders believe the interest rate differential of China and the United States is of great importance in the formation of the Chinese yuan exchange rate. The values shown in the second and third columns of Table 3 are estimation results for the sample from July 2005 to July 2015 and from August 2015 to August 2018, respectively. These results indicate that the forecasting rules are changing over time. After the foreign exchange reform in 2015, the speed at which the Chinese yuan exchange rate moves to its fundamental value greatly increases from 0.097 to 0.472, but the parameter for the Chinese yuan exchange rate following its previous behavior significantly decreases from 0.873 to 0.698. Regarding the carry trade rule, the parameter for the Chinese yuan exchange rate deviating from the interest rate differential of China and the United States increases from 0.484 to 0.505.

The risk aversion values of the three types of traders are also reported. Based on the full sample, the risk aversion value is 3.350 for fundamentalists, 0.122 for chartists, and 2.954 for carry traders. This result indicates the stronger risk aversion of fundamentalists; in particular, the risk aversion value of fundamentalists is greater than 5.2 in the subsample before the exchange reform of 2015. That is, fundamentalists are sensitive to market shifts and exhibit the characteristic of strong risk aversion. Chartists show a preference for risk or risk neutrality, with a risk aversion value of approximately 0.1. The risk aversion of carry traders is in a middle position among the three types of traders. The risk aversion values of carry traders estimated with the samples before and after the reform of 2015 are below 2.8. According to the forecasting rules mentioned above, the fundamentalists and carry traders expect that the Chinese yuan exchange rate will return to its fundamental value, or the interest rate differential of China and the United States. If the actual exchange rate deviates far from its fundamental value or the interest rate differential, then fundamentalists and carry traders will not have a strong incentive to adopt a reverse strategy, and this is the most likely reason for their higher risk aversion. As to the chartists, if the market declines, then they will expect the Chinese yuan exchange rate to follow its previous behavior for a while and will have the incentive to adopt the reverse strategy in the market. Therefore, they do not exhibit obvious risk aversion.

The intensity of the estimated choice parameter δ is 7.443, 10, and 0.782 for the full sample and the subsamples before and after the foreign exchange reform of 2015, respectively. These results indicate that the related policy of the foreign exchange reform has reduced the intensity of choice in the switching mechanism. Regarding the parameter β in the function of the fundamental exchange rate, the estimated value is 0.812 for the full sample, 0.925 for the sample before the reform, and 0.843 for the sample after the reform. These results show that the fundamentalists have to some extent adjusted to the interest rate parity when they forecast the exchange rate, but the degree of adjustment is not obvious. The results also show that the importance of the interest rate differential in fundamentalists' forecast of the exchange rate declines after the reform.

Now, we consider the impact of central bank intervention on the formation of the Chinese yuan exchange rate. The coefficient of foreign exchange intervention is 2.433 for the full sample, a value much smaller than that found in [44], which is 8.27. The coefficient decreases from 2.987 to 2.278 after the reform, indicating that the impact of central bank intervention on the Chinese yuan exchange rate declines notably after the foreign exchange reform. This result is consistent with the goal of the foreign exchange reform policy in August 2015. The coefficient of the domestic trade balance for the full sample is 2.78, which is close to the value of 3.04 estimated in [44]. The impact coefficient of the domestic trade balance on the formation of the Chinese yuan exchange rate falls from 2.284 to 2.132 after the foreign exchange reform. The empirical results based on the model we construct in this paper fully reflect the economic reality in China.

To analyze the impact of the carry traders' activities on the effectiveness of central bank intervention, the model with only fundamentalists and chartists is further studied in this paper. All the results are shown in Table 4. Tables 3 and 4 show that the coefficient of foreign exchange intervention ζ_1 estimated with the sample before the reform is 2.214, which is lower than the value of 2.984 estimated in the model with carry traders. This finding indicates that the central bank's foreign exchange intervention is more effective with the existence of carry traders before the foreign exchange reform. However, for the sample after the foreign exchange reform in 2015, the coefficient of foreign exchange intervention estimated in our model is 3.051, which is obviously higher than the value of 2.278 estimated in the model without carry traders. That is, carry traders' behaviors, including the prediction of the Chinese yuan exchange rate and the purchase and selling of currencies, weaken the power of the Chinese central bank to intervene in the formation of the Chinese yuan exchange rate. Furthermore, China's foreign exchange market tends to be a market with liberalized transactions driven by market supply and demand, and the Chinese yuan exchange rate is close to the market equilibrium rate.

Table 4. Estimation results of the model without carry traders.

	Group A: July 2005–August 2018	Group B: July 2005–July 2015	Group C: August 2015–August 2018
α_f	0.919 *	0.011 *	0.793 *
α_c	0.892 *	0.661 *	0.912 *
δ	4.085 *	8.329 *	7.210 *
β	0.855 ***	0.848 ***	0.993 ***
μ_f	5.326 *	3.031 *	2.842 *
μ_c	0.106 *	0.115 *	0.103 *
ζ_1	2.006 **	2.219 **	3.051 **
ζ_2	2.962 **	2.087 **	3.952 **
Log-likelihood value	−142.666	−59.600	−70.416
Taylor's inequality	0.155	0.228	0.060
Residual-based ADF statistic	−5.024 ***	−3.126 ***	−4.990 ***

Notes: In Section 3, a model is built with three types of forecasting rules. If it is assumed that there are no carry traders in the foreign exchange market, and the model can be modified to a two-agent model, which is similar to the model in [44]. The table above presents the coefficient estimates from estimating the two-agent model without carry traders. Significance is listed as ***, **, and * for significance at the 1%, 5%, or 10% level, respectively.

5.3. Other Results and Analysis

With the parameters listed in Table 3, the relevant variables in the model can be calculated for further analysis. We focus on the relationship between the weight of carry traders and the interest rate differential; this paper is mostly concerned with the movements of the Chinese yuan exchange rate forecasted by carry traders. Additionally, the relationship between the weight of carry traders and the volatility of the Chinese yuan exchange rate is analyzed.

Figure 1 shows the weight of carry traders and the interest rate differential. The axis on the left side of Figure 2 represents the weight of carry traders, and the right axis represents the interest rate differential between China and the United States. The interest rate differential begins to decrease from the year 2005 and is close to zero during the initial stage of the global financial crisis in 2007. Then, the interest rate differential becomes negative. This finding indicates that the Federal Reserve Bank operates the expansionary monetary policy continuously, and the benchmark interest rate of the United States is lower than that of China following the international financial crisis. The interest rate gap between the United States and China is expanding until the end of 2015. In December 2015, the benchmark interest rate of the United States begins to increase, and the interest rate gap starts to shrink. Meanwhile, the weight of carry traders in China's foreign exchange market is stable before the end of 2015. That is, carry traders take the interest rate differential as the most important factor related to the formation of the Chinese yuan exchange rate. During the period from August 2015 to August 2018, the interest rate differential is approximately −0.03, but the weight of carry traders is frequently changing. This phenomenon explains the significant impact of policies related to foreign exchange reform on the expectation formation of carry traders.

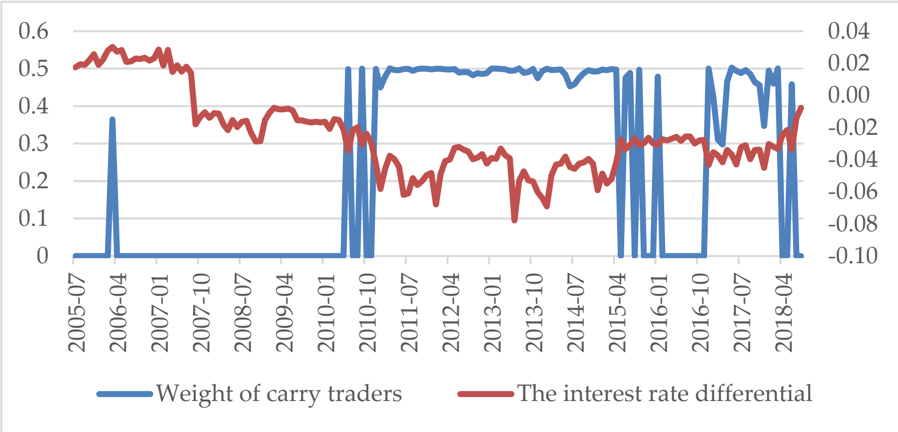

Figure 1. Weight of carry traders and the interest rate differential.

Figure 2. Actual movement of the Chinese yuan exchange rate and the change expected by carry traders.

The movement of the Chinese yuan exchange rate forecasted by carry traders for the full sample is shown in Figure 2. The trend of the actual movement of the Chinese yuan exchange rate is also plotted as a comparison. Comparison of the trend of the Chinese yuan exchange rate movements forecasted by carry traders with the trend of the actual movement of the Chinese yuan exchange rate shows that carry traders expect the Chinese yuan exchange rate to be less volatile than it actually is. According to the forecasting rules discussed above, carry traders believe that the movement of the Chinese yuan exchange rate is a certain multiple value of the domestic and foreign interest rate differential. After the initial stage of the international financial crisis, the interest rate differential of China and the United States continues to be negative and falls, and the movement of the Chinese yuan exchange rate forecasted by carry traders is negative. Thus, carry traders make judgments based on the interest rate differential and believe that the Chinese yuan should appreciate after the financial crisis. After the foreign exchange reform in August 2015, carry traders still expect the appreciation of the Chinese yuan, but the magnitude of appreciation forecasted is lower than that forecasted during the period before the foreign exchange reform. Therefore, carry traders are uncertain about the direction of the Chinese yuan exchange rate after the reform; they take a wait-and-see approach and even expect the Chinese yuan to depreciate to a certain extent. Actually, the Chinese yuan exchange rate does show frequent fluctuations and depreciates in most cases after the foreign exchange reform in August 2015.

According to the above analysis, carry traders require an incentive to enter the foreign exchange market. It is normally the case that carry traders' activity is negatively related to the volatility of foreign exchange rates. A strong negative relationship between foreign exchange market volatility and the carry trade strategy is found in [85] and [8]. In this paper, the relationship between the volatility of the Chinese yuan exchange rate and the weight of carry traders ω_t^j in Equation (11) is also studied. Figure 3 shows the scatter plot of the volatility of the Chinese yuan exchange rate and the weight of carry traders. After the reform, there is a significant increase in Chinese yuan exchange rate volatility, which can also be found in Figure 2 in our paper. Therefore, we do not use the same proportional scales in Figure 3, as the real trends in the scatter plots would not be shown clearly. The figure on the left is based on the volatility of the Chinese yuan exchange rate and the weight of carry traders in the sample from July 2005 to July 2015, and the right figure is based on the volatility of the Chinese yuan exchange rate and the weight of carry traders in the sample from August 2015 to August 2018. The dotted line is the trend line. Figure 3 shows the negative relationship between the volatility of the Chinese yuan exchange rate and the weight of carry traders during the two periods, especially during the period from August 2015 to August 2018. Thus, after the foreign exchange reform in August 2015, China's foreign exchange market clearly shows the characteristics of a market under the floating exchange rate system, and the market for the Chinese yuan is gradually becoming more mature with the law of supply and demand.

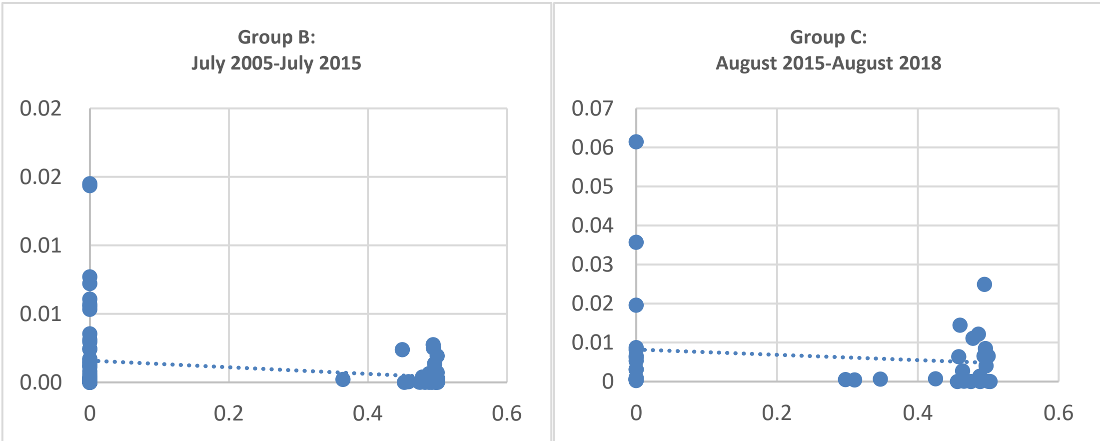

Figure 3. Scatter plot of the volatility of the Chinese yuan exchange rate and the weight of carry traders.

To test the robustness of the negative relationship between the volatility of the Chinese yuan exchange rate and the weight of carry traders, we calculate the correlation coefficients of the Chinese yuan exchange rate volatility and the weight of carry traders for the two sample periods—which are −0.127 and −0.257, respectively—which also supports our results.

6. Implications

6.1. Theoretical Implications

The foreign exchange market is a worldwide network and the largest financial market in the world that enables the exchanges of currencies around the globe. The main functions of the foreign exchange market are conversion of one currency to another, securing short-term credit and hedging foreign exchange risks. Participants in the foreign exchange market can be categorized into five major groups: commercial banks, foreign exchange brokers, the central bank, multinational corporations (MNCs), and individuals and small businesses. Although most of the volume of the transactions is represented by interbank transactions, transactions between banks and their nonbank customers is a large amount. This study analyzes the direct and indirect relationship between the foreign exchange market and financial resources from these features. First, transfer of funds (foreign currency) from one country to another is the basic and the most visible function of the foreign exchange market for the settlement of payments. Regardless of whether firms or institutions are considered, it is inevitable that they will change currencies or ask foreign exchange brokers to change currencies during the course of normal business activities, including investment and payment. Among them, commercial banks, who serve their bank customers as retail clients that conduct foreign commerce or make international investments in financial assets that require foreign exchange, are the major participants in the foreign exchange market. Second, the foreign exchange (forex) provides a short-term credit to importers to facilitate the smooth flow of goods and services from country to country, and an importer can use credit to finance foreign purchases. Other firms that are unable to obtain this credit can transfer currencies in the forex market so that they can invest in different currencies or hedge the risk or transfer the risk of their assets in domestic currencies, etc. Even small businesses can use the foreign exchange market to facilitate the execution of commercial or investment transactions and hedge the foreign exchange risk. Third, hedging risk—an important function provided by the foreign exchange market—is an essential feature that is of great importance in institutions' or firms' investment. Foreign currency positions can be added or reduced to adjust the composition of investments or avoid financial risks, especially foreign exchange risks. Actually, risks of foreign exposure are not only faced by those firms or institutions that directly make financial transactions in foreign currency denominations but are also faced by other firms that are indirectly related to the foreign currency and, as such, are exposed to foreign currency risk during business operations.

Based on the discussion above, it can be concluded that the foreign exchange market plays an important and essential role in financial resources, and this is closely related to the functions of the foreign exchange market. Therefore, only a foreign exchange market with a stable transaction environment and complete functions can provide sustainable resources for institutions or firms. With the continuous advancement of the Chinese yuan exchange rate reform policy, the Chinese yuan exchange rate system has gradually become a completely floating exchange rate system. Trading is becoming more transparent, transactions are more active, and the trading environment in China's foreign exchange market is becoming more stable. However, the results in both the full sample and the subsamples show that under the influence of carry traders' activities, and the impact of carry traders' activities on the formation of the Chinese yuan exchange rate, the ability of the central bank to intervene in the foreign exchange market is weakened. Furthermore, these findings indicate that it is not easy for the central bank to manage the fluctuations caused by carry traders' activities in China's foreign exchange market and to maintain the stable development of the market, which is obviously harmful to the stability of financial resources in China's foreign exchange market. Therefore, exploring sustainable financial resources associated with carry traders' activities is of great importance for China's foreign exchange market.

In this context, the following problems related to sustainable financial resources in the market could be expected. (1) Speculative activities will be motivated in the international financial market, and noise trading may dominate the foreign exchange market. The carry trade strategy is a common currency speculation strategy used by many hedge fund managers and institutional traders. Investors using the carry trade expose themselves to currency risk and are rewarded by positive returns over time. Carry traders' activities will promote the narrowing of the interest rate differential, and accordingly, the risk of international lending by financial institutions or enterprises will be relatively high. (2) In a floating exchange rate system, exchange rate fluctuations are large and frequent, and exchange rate risk will be relatively high. Meanwhile, carry traders' activities have a significant impact on exchange rate fluctuations and exchange rate risk. Therefore, enterprises must consider the risk of exchange rate fluctuation when importing or exporting commodities. At the same time, due to the changing exchange rates, commodity prices may change very quickly. The resulting high cost of raw materials and management will cause certain obstacles to the operation of financial institutions and enterprises. (3) With the frequent fluctuations in the exchange rate, the foreign exchange market will become more volatile. Especially after the foreign exchange reform in August 2015, carry traders have become more sensitive to the changes in the interest rate differential and have a higher risk aversion to risks in the foreign exchange market. Meanwhile, carry traders' behavior in the foreign exchange market weakens the impact of central bank intervention on the formation of the exchange rate. Therefore, for the central bank to maintain the sustainable stability of the financial markets in China, especially China's foreign exchange market, it is necessary to pay attention to the impact of carry traders' behavior.

6.2. Managerial Implications

Based on the abovementioned problems related to the exploration of sustainable financial resources in the foreign exchange market, this paper proposes strategies to help institutions, firms, and central banks obtain or maintain sustainable financial resources in China's foreign exchange market.

First, although the People's Bank of China has consistently promoted the foreign exchange rate reform policy in accordance with the three principles of initiative, controllability, and gradualism since 1994, there are drawbacks to the managed floating exchange rate system that cannot be ignored. To maintain the stability of the foreign exchange market function, the central bank needs to consider the indirect impact of interest rate policies on the foreign exchange market by accounting for carry traders' activities when formulating exchange rate policies. The offshore lending rate and short-selling cost could be adjusted to reduce the motivation for arbitrage and indirectly manage exchange rate fluctuations. Additionally, the central bank must pay close attention to the changing order flows of traders with heterogeneous beliefs in the foreign exchange market.

Second, the impact of carry traders' activities on the formation of the exchange rate and the return of currency assets cannot be ignored. To obtain ongoing liquidity, as well as asset returns, enterprises should pay attention to the behavior of carry traders and the interaction between carry traders and noise traders. Since carry trade strategies are based on the interest rate differential, enterprises and financial institutions should make use of interest rate swaps or other interest rate derivatives when conducting a transaction to avoid foreign exchange risk and the exchange rate fluctuations that may be caused by carry traders' activities.

Third, short-term contracts would be helpful to reduce organizational costs and maintain the long-term stable development of enterprises and financial institutions. Especially for export companies receiving foreign currencies, it is necessary for contract makers to take the changing interest rate and exchange rate risk into account when specifying contract terms. Additionally, the foreign currency collection should be completed in advance, and foreign exchange derivatives can be used to help avoid the risk of the asset systems, especially for small businesses.

7. Conclusions

This study introduces a heterogeneous agent model that includes carry traders in addition to fundamentalists and chartists for foreign exchange rate determination, with the consideration of the law of supply and demand and central bank intervention. With the UKF artificial intelligence method, this paper empirically analyzes the Chinese yuan exchange rate formation, the weight and risk aversion of carry traders, the impact of carry traders' activities on the formation of the Chinese yuan exchange rate, the effectiveness of central bank intervention in China's foreign exchange market, and the relationship between the impact of carry traders' activities and the exploration of sustainable financial resources in China's foreign exchange market.

This paper contributes to the existing literature in several ways. First, the carry trade observation and the law of supply and demand are considered in the heterogeneous agent model constructed in this paper. Second, carry traders' expectations and risk aversion and the impact of their activities on the efficiency of central bank intervention are considered in the theoretical model. Third, the adjustment of carry traders' activities due to the changing foreign exchange reform and the influence of this adjustment on the effect of central bank intervention are discussed. Fourth, this paper analyzes the exploration of sustainable financial resources in the foreign exchange market considering the interaction between carry traders' behavior and exchange rate formation. In summary, based on the modified heterogeneous agent model presented, the results in this paper offer a better explanation of exchange rate formation and carry traders' activities in the foreign exchange market. Furthermore, the empirical analysis of the carry trades' activities provides theoretical guidance for exploring sustainable financial resources for institutions and firms in China's foreign exchange market.

Based on the above research and analysis, this paper draws the following conclusions. First, carry trade is partly responsible for determining the Chinese yuan exchange rate. Although carry traders' activities do not dominate China's foreign exchange market, they explain basically half of the expectation of traders in the market, especially after the foreign exchange reform in August 2015. Second, risk aversion differs across trader types. Carry traders behave with obvious risk aversion, but their aversion to risk is weaker than that of fundamentalists; chartists show a preference for risk or risk neutrality. Third, the impact of central bank intervention on the formation of the Chinese yuan exchange rate is examined, as well as the influence of carry trader activities on this impact. The results show that the impact of foreign exchange intervention on China's foreign exchange market declines notably after the reform, which is consistent with the goal of the foreign exchange reform policy in August 2015. Carry traders' activities weaken the power of Chinese central bank intervention in the formation of the Chinese yuan exchange rate. Fourth, the foreign exchange reform policy is found to have significant influence on the expectation formation of carry traders. In addition, the relationship between the volatility of the Chinese yuan exchange rate and the weight of carry traders turns out to be negative, especially during the period after the foreign exchange reform in August 2015. Finally, the dominance of carry traders' activities in China's foreign exchange market would deter the market from providing sustainable financial resources for institutions and firms.

However, the model constructed in the paper does not describe the characteristics of heterogeneous agents' behavior very well. Without considering the ambiguity of individuals' utility and the ambiguity of subjective probability, the expected utility theory used to analyze the optimal position of the foreign currency does not well describe the risk decision of the agents. In addition, the parameters of the risk attitudes of heterogeneous agents—which are supposed to be time-varying with the accumulation of wealth, heterogeneous expectations and decisions, and changing returns from investment—are assumed to be constant. Overall, the characteristics of traders with heterogeneous beliefs in the foreign exchange market are worth further examination.

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