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AN ARTIFICIAL STOCK MARKET IN A SYSTEM DYNAMICS APPROACH

Davide Provenzano
Ph.D. Student in Financial Mathematics, University of Palermo, Italy
MPhil Student in System Dynamics, University of Bergen, Norway
Via Ammiraglio Rizzo n°53, 90142 Palermo, Italy
Cellular: +39.091.3337514136
Fax: +39.091.426781
davidepro@yahoo.com
sd125@ifi.uib.no

Abstract.

In order to model the stock market behavior and characterize asset price and wealth dynamics arising form interactions of heterogeneous agents, this paper studies the price dynamics induced by two of the most commonly used financial trading strategies. It shows how these strategies amplify noise, and cause phenomena such as excess and cluster volatility.

Since this kind of study starts from the analysis of trading strategies, it follows the bottom-up approach that is typical of agent-based financial markets. Investors' trading rules are modeled, more or less, as the strategies used in the real world.

In closing, some of the questions centred on market stability will be discussed. No attempt has been made to make forecasts, which are not trivial for this kind of models.

To model market behavior and trading strategies, system dynamics methodology has been used.

Key words: Share price, financial markets, bottom-up approach, professional traders, fundamental market price, trend followers, system dynamics.

Introduction.

Share price fluctuations have always interested financial economists but, since the Wall Street crisis of 1929 and the "stock market crash" of the 19th October 1987, there has been having a revival of interest for this kind of issues.

Actually, the general question of market stability and price formulation is especially acute in finance since these markets, more than others, have price providing information and balancing supply and demand.

Recently, a lot of structural asset pricing models have been introduced, emphasizing the role of heterogeneous beliefs in financial markets, with different groups of traders having different expectations about future prices; they explain market instability and complicated dynamic, including periodic cycles and chaos, as a result of their different opinions and beliefs.

Most of these agent-based models are composed of two typical agent types. The first type believes that the stock price is determined by the fundamental market value of the share, the second one, instead, may predict the future price using simple trading rules, extrapolation of trend and patterns observed in past prices.

These are of course only a few of the strategies used in real markets. But they are known to be widely used and understanding their influence on price provides a starting point for other behavioral models.

This paper analyses a stock market functioning in which traders are characterized by bounded rationality, heterogeneous behavior and bounded financial resources.

To sum up the major results, I show that:

1. arbitrage by the first type of traders, called professional traders in this paper, tends to stabilize the stock price and tends to lead it toward the fundamental price;
2. the positive feedback trading of the second type of traders, called trend followers in this paper, tends to cause the instability of speculative dynamics;
3. the different combination of arbitrage and positive-feedback strategies generates various pattern of speculative price.

Context.

This way of studying stock price fluctuations is typical of agent-based financial market (the bottom up approach) which is a tool for exploring behaviors in financial market that are far from traditional notions of equilibrium. Research from several disciplines including economics, computer science, physics and psychology, are contributing to this very active field. It represents one of the most interdisciplinary areas of study operating today.

In this domain, the artificial stock market is a new but growing field of study and some purposes of this research have been well documented by Blake LeBaron[1]. It allows us to observe what traders are actually thinking and doing, and to put emphasis on their interactions through the price system.

Problem and purpose

Typical financial market issues are:

- What does the traders actually believe? Does she believe in the efficient market hypothesis?
- What exactly is the forecasting model (or the trading strategy) employed by the trader?
- Why are stock markets so volatile?
- How sophisticated is the trader? Will she get more and more sophisticated as time goes on?
- What explain the volatility of foreign exchange market?
- Why do countries undergo currency crises?

[1] Blake LeBaron (Graduate School of International Economics and Finance, Brandeis University) maintains a Web site on Agent-Based Computational Finance (ACF) which is an application of agent-based computational methods to finance and financial markets.

In this paper, the first three questions will be discussed and the characteristic patterns of speculative prices (speculative dynamics and chaos) will be shown as generated by trading between different strategies of different investors categories. In particular, this paper is directed to describe, understand and explain how professionals' and trend followers' strategies determine share price oscillations. Therefore, it deals with a very controversial issue in the financial literature following early 1980's and still absolutely topical, namely, the convergence of the share price toward a value that is possible to assume as the market fundamental value of the share. Under the efficient market hypothesis, indeed, price should instantly and correctly adjust to the market value of the share, but the repeated stock market crises, more or less severe, prove that this hypothesis may not take place on all occasions.

The fourth question is left as a future challenge whereas the last two are out of its purpose.

Two are the major components of the market in this paper: traders and their interaction. Traders' part also includes their speculative strategy since agents will be characterized with well defined dynamic trading rules modeled more or less as strategies used in the real world.

To model the market behavior, system dynamics methodology is used.

The system dynamics approach.

In this paper system dynamics is used to describe, understand and explain how professionals' and trend followers' strategies determine share price oscillations.

In this domain, the system dynamics approach represents a valid alternative to pure mathematical models since it allows explaining the behavior of stock price without incurring in all the technicalities typical of mathematical formulations.

Causal loop and stock and flow diagrams also give a visible description and explanation of the relationship between the variables of the system enlarging the model understanding also to those who don't have a mathematical background.

Moreover, system dynamics allows testing different alternative gaining knowledge about the actual behavior of the system studied and filling the gap between understanding the structure and understanding the behavior.

Conceptual model, verbal description with feedback loop diagrams.

In this section the conceptual model will be described into details with particular attention to the trading strategies and price dynamics they generate.

Starting from the analysis of the market, the model assumptions are:

- all firms are represented by an imaginary company whom share capital is divided in N shares;
- no dividends are paid;
- there is a single asset (measured in unit of shares) that can be converted to money viewed as a risk free asset paying interest;
- the number of shares is conserved; every time an agent buys a share another agent loses that share. Thus, the sum of all agents' position is constant;
- the number of traders is the same as the number of shares, so when an equilibrium position is reached in the market each trader holds a share;

- each trader decide his strategy in the market comparing the number of desired shares with the number of held shares;
- each trader spends a certain time to conform to her goal;
- the number of desired shares for each trader is fixed by her trading strategy formalized by the differential equation:

$$\frac{dx_i(t)}{dt} = u_i(x_i(t),\ p(t),\ \frac{dp(t)}{dt}) \qquad \text{with} \quad i=1, 2, 3,....., n$$

where :

t is time;
$x_i(t)$ is the number of shares held by the i^{th} category of speculators at time t;
$p(t)$ is the stock price at time t;
$u_i(\cdot)$ represents the trading activity of the i^{th} category of speculators;

- the total number of traders is split in two categories even though it can be split to the extent it equals the number of traders;
- $\sum_{i=1}^{n} x_i(t) = N$, namely, all the shares are subscripted; in the particular case of two category of traders, the formula becomes $x(t)+y(t)=N;$
- the initial money per capita is 1000 currency units;
- the interest rate is 1%;
- since there are only two categories of investors, two are the speculative decisions considered;
- synchronous trading are assumed.

Regarding the trading strategies, the most common approach to describe them is based on their information inputs. Following this approach, we can distinguish between value strategies, also called fundamental strategies, for one hand, and trend following strategies to the other hand.

Value or fundamental strategies are based on external information leading to a subjective assessment of the long term fundamental value of the share also called fundamental price. These strategies use external value signals as inputs and take a positive (long) position when the asset is underpriced and, if the asset becomes even more underpriced, the position either stays the same or gets larger. Similarly if the mispricing is positive they take a negative (short) position.

In this paper these investors are called *Professional Traders*; negative-feedback traders or fundamentalists are other names that is possible to find in the literature for these speculators. These investors are also called reflective traders by J.M.Keynes (1936) and information traders by F.Black (1986).

Starting from the opinion that their perceived value may not be fully reflected in the current stock price, those traders think future prices will move toward their perceived value. Therefore they believe in the efficient market hypothesis, namely, shares have a fundamental value and sooner or later the stock price will converge toward it.

Comparing their subjective assessment of the fundamental value with the stock price, they attempt to make profits buying when the stock price is below the fundamental value and selling when the stock price is above the fundamental value of the share.

Following the Black hypothesis, in this paper the professional traders' strategy considers also the slope of the function describing the stock price behavior. Therefore, the total quantity of shares professional traders desire next time step takes care if the price is increasing or decreasing. Thus, the more the stock price is far from its reference value the more aggressive they are. This hypothesis has had confirmation in the Day e Huang model (1990) as well.

To make the model closer to reality it has been assumed that, although all professional traders know the reference value of the share, they decide to become active in the market in different moments when the stock price lies in a definite non-trading interval. Therefore, all professional traders won't become active in the market unless the stock price exceeds this non-trading interval.

It doesn't matter how the reference value is assessed, namely, how these traders form their opinion about it because, in this project, results are independent of the method of valuation.

The second decision rule considered in this project depends only on the price history, namely, orders are positively correlated with recent price changes.

A lot of very common financial decisions can be described as positive-feedback trading strategies. For instance, these strategies can result from portfolio selections grounded on extrapolative expectations, from "stop-loss" orders that boost sells when prices are falling, from portfolio assurance strategies or from a trend following.

This strategy is used by one of the most labeled category of traders: positive-feedback traders (DeLong et al.(1990)), noise traders (DeLong et al.(1991)), sheep (Day e Huang (1990)), bandwagon traders (Taisei Kaizoji (1998)), chartists, etc are only a few of the names that is possible to find in the literature for these investors. To give my contribution to this list of names, I will refer to them as *Trend Followers*.

Trend Followers don't have all the information they need to assess the fundamental value of the share or they don't believe that this value exists. They accept past price as inputs and invest based on the belief that prices changes have inertia. Therefore, they take a positive (long) position if prices have recently been going up, and a negative (short) position if they have recently been going down. For these traders, the quantity of desired shares is the result of the product between the trend effect times the quantity of shares they would have in the equilibrium situation (Reference Number of Share per Trader).

Trend followers amplify noise and induce trends in price, namely, if the stock price is increasing their buying activity push it up even more.

For both traders, decision are hold as long as the situation that justify it is present in the market; so this paper deals with order-based strategies instead of positions-based orders. As a result of their interaction, the dynamical properties of speculative price depend both of trend followers' strategy and arbitrage by professional traders. The mechanism is, more or less, as follows: if a substantial mispricing develops by chance, value investors became active. Their trading strategies shrink the mispricing, with a corresponding change in price. This cause trend followers to become active; their trading sustains the trend and causes the mispricing to cross through zero. This continues until the mispricing became large, but with

the opposite sign, and the process repeats itself. Therefore, for the stock market, the possibility to reach an equilibrium position, where the share price is equal to the fundamental value, depends on which of the two strategies is dominant, the dominance depending, in this project, by the number of traders in the respective category and the time they take to conform to their goal.

Professional traders' strategy forms a negative-feedback loop. Whenever stock price increases, the fundamental value/stock price ratio decreases, professional traders' desired shares decreases and the gap with the held shares decreases as well. If the stock price is above the fundamental value of the share, professional traders desire a quantity of shares less than their held shares, the gap is negative and its decreasing causes an increase in the professional traders' supply. The more professional traders' supply increases, the more stock price decreases and the loop is closed. This is the negative Balancing Trading feedback loop B1 in Figure 1.

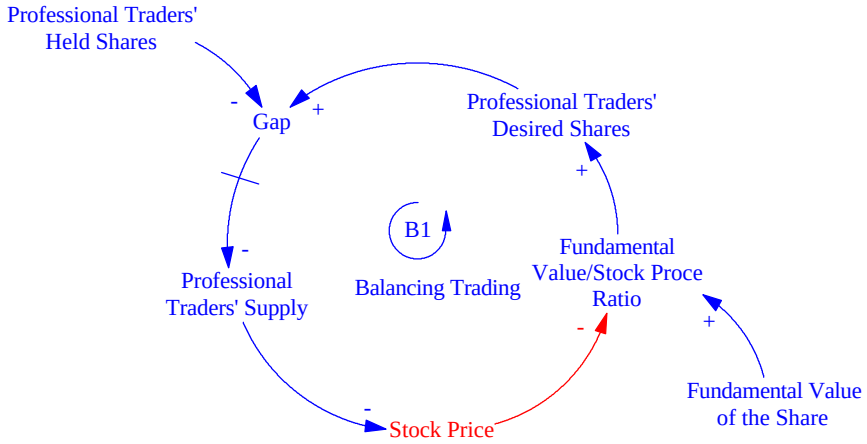

Figure 1: Balancing loop when the price is increasing and is above the fundamental value of the share.

In the opposite situation, a decrease in the stock price below the fundamental value of the share causes an increase in the professional traders' demand. As the Figure 2 shows, the feedback loop is still a balancing one.

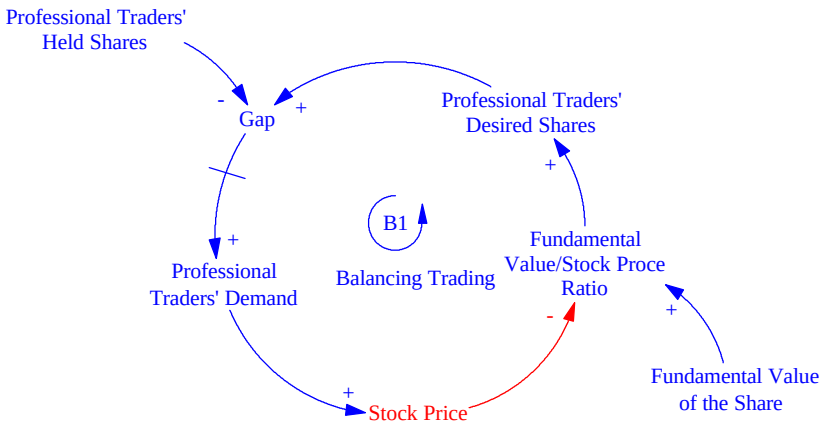

Figure 2: Balancing loop when the stock price is decreasing and is below the fundamental value of the share.

Trend followers' trading strategy forms, instead, a positive feedback loop. When the stock price increases, after a certain delay, trend followers perceive that the stock price trend is positive and, according to their strategy, their desired quantity of shares increases. The resulting increase in the gap causes an increase in the stock price forming the positive Reinforcing Trading feedback loop R1 in Figure 3

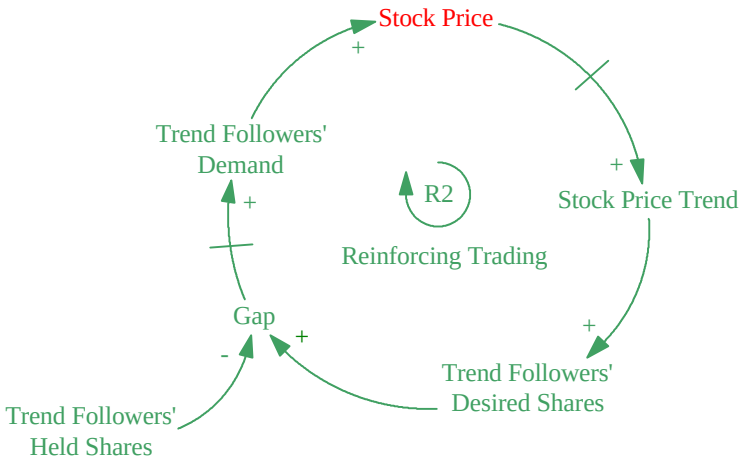

Figure 3: Reinforcing loop when the stock price is increasing.

When the stock price decreases the positive feedback loop is shown in Figure 4

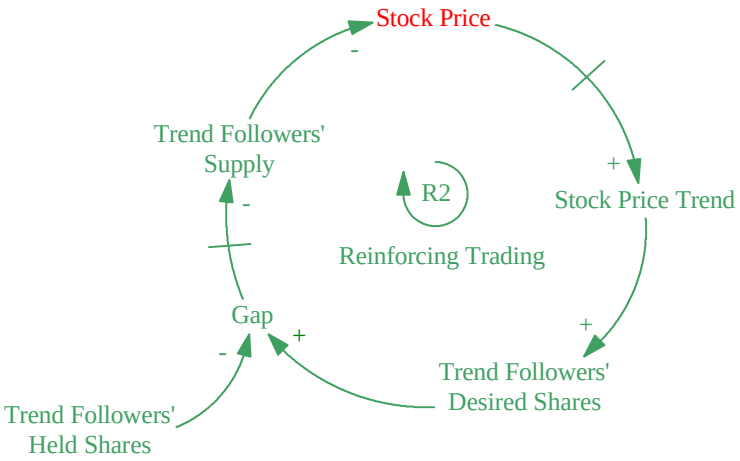

Figure 4: Reinforcing loop when the stock price is decreasing.

In real stock markets the fundamental value of the share is not a constant but varies over time a as consequence of several factor as, for instance, mergers, a firm's decision to make new investments or to improve the net operational income increasing the investment productivity, etc. To represent the situation of a floating fundamental value of the share over time, the economic theory by which stock prices track value is followed. In this way, a little fraction of the stock price is due to the market value of the company and, as a consequence, Professional Traders adjust, with a certain delay, their estimation of the fundamental value of the share over time. The complete causal loop diagram is sketched in figure 5.

Formal model based on stock and flow diagrams.

The verbal description of the model made with causal loop diagrams has emphasized the feedback structure of the system. In this section the stock and flow diagram will be presented to show how the system dynamic model has been built.

The stock and flow structure of professional traders is shown in figure 6. The whole population of professional traders is split in two groups: active professional traders and inactive professional traders. Such a distinction is necessary because, although they have the same decision-making rule, only a few professional traders react to the difference between the stock price and the fundamental value of the share when the stock price varies inside the non-trading interval. Over a certain threshold all the professional traders are active. The variable Ratio of Inactive P T defines the rate of inactive professional traders by a function whose graph is shown in figure 7. If the Non Trading Ratio is equal to 0, all the professional traders are active. Of course, trading activity depends only by active professional traders.

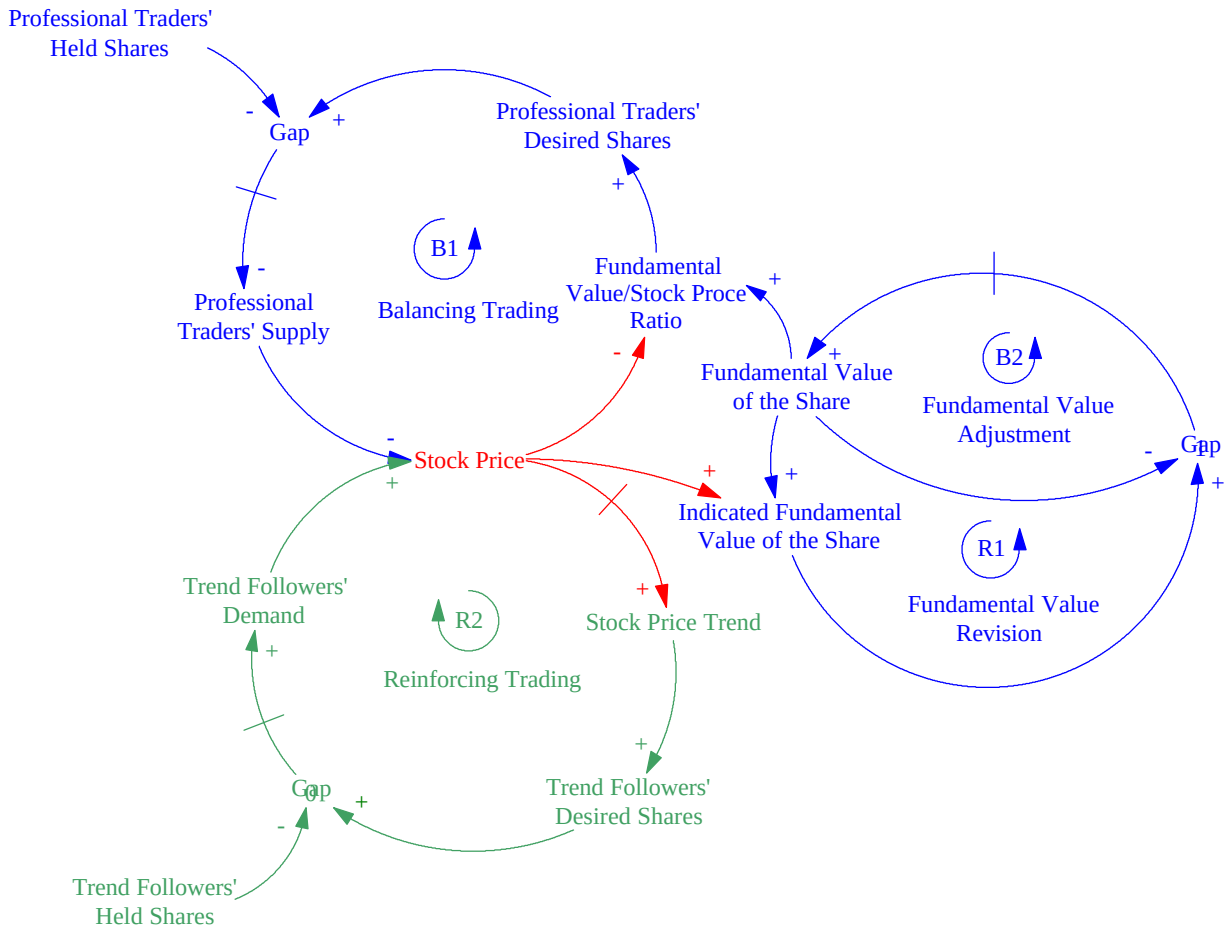

Figure 5: Causal loop diagram of the whole stock market.

The variable Active P T Desired Shares holds the decision making rule by which active professional traders quantify the number of shares they desire. The decision-making rule is expressed by the following formula:

$$f\left(p(t), dp(t)/dt\right) = \left[\frac{F}{p(t)} - \frac{e}{F}\frac{dp(t)}{dt}\right]$$

where:

p(t) is the stock price at time t;

$\frac{dp(t)}{dt}$ is the first derivative of the stock price;

ε is the reactivity coefficient to the stock price variation;

F is the fundamental value of the share.

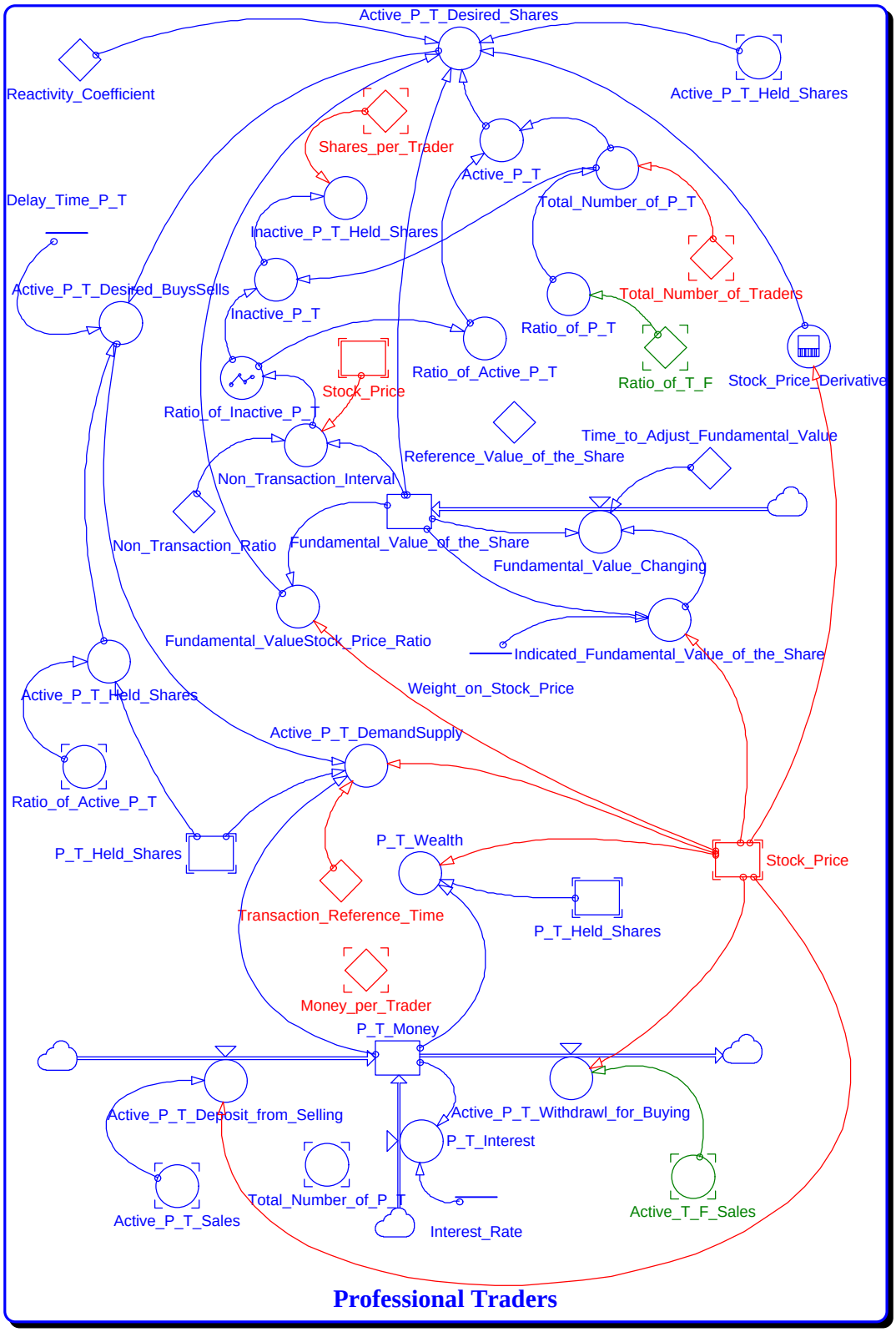

Figure 6: Professional traders' stock and flow structure.

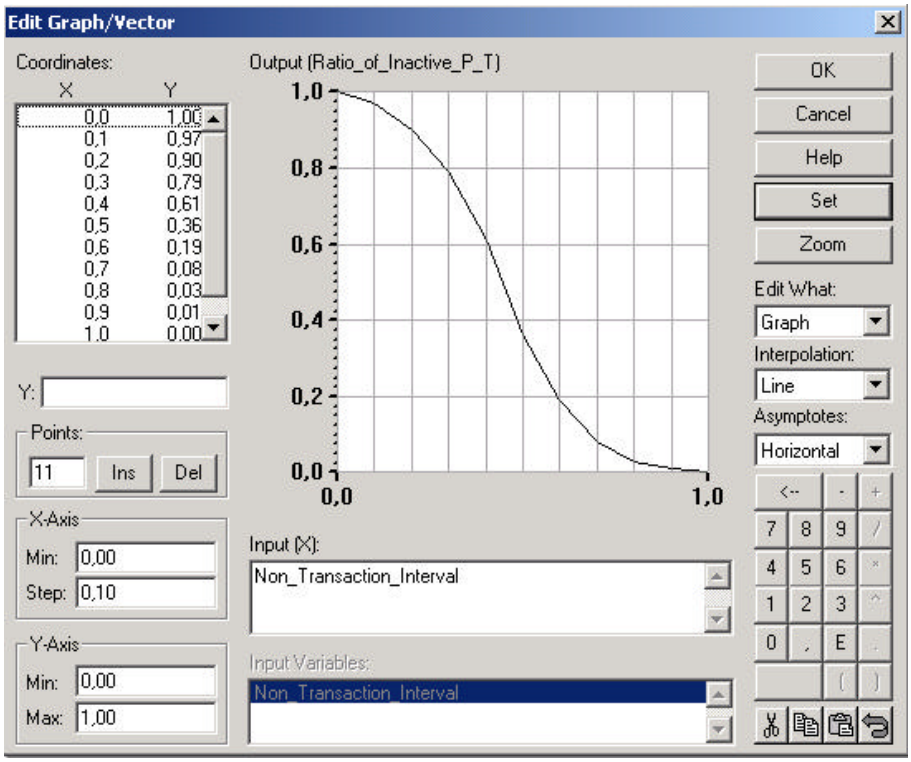

Figure 7: Distribution of professional traders inside the non transaction interval.

Concerning the fundamental value of the share, a variant of the floating goals structure it is used to represent the variation of its estimated value over time produced by the stock price oscillations. With a delay of 21 days (about a trading month), the fundamental value is updated to the indicated value of the share.

The total quantity of money in the variable Active P T Money is a financial constraint for the buying activity of these speculators.

The stock and flow structure of trend followers investors is sketched in figure 8a and figure 8b. Figure 8a show the stock and flow structure needed to model the trend followers' expectation formation. Using the TREND function, the trend followers' trading strategy is modeled easily. It also allows taking into account the time request for traders to collect and analyze data, and to react to changes in the growth rate of stock price. The basic structure for trend extrapolation is represented two times: the first one to extrapolate the long run trend and the second one to extrapolate the short run trend.

The long run trend is the anchor point for the trend extrapolation and covers a time horizon for reference conditions of 125 trading days (six months). The time horizon for the reference conditions in the short run trend is, instead, of 62 trading days (three months). Considered the extreme volatility of stock market and to give more importance to the short run trend, the weight on the long run trend is fixed at 30%.

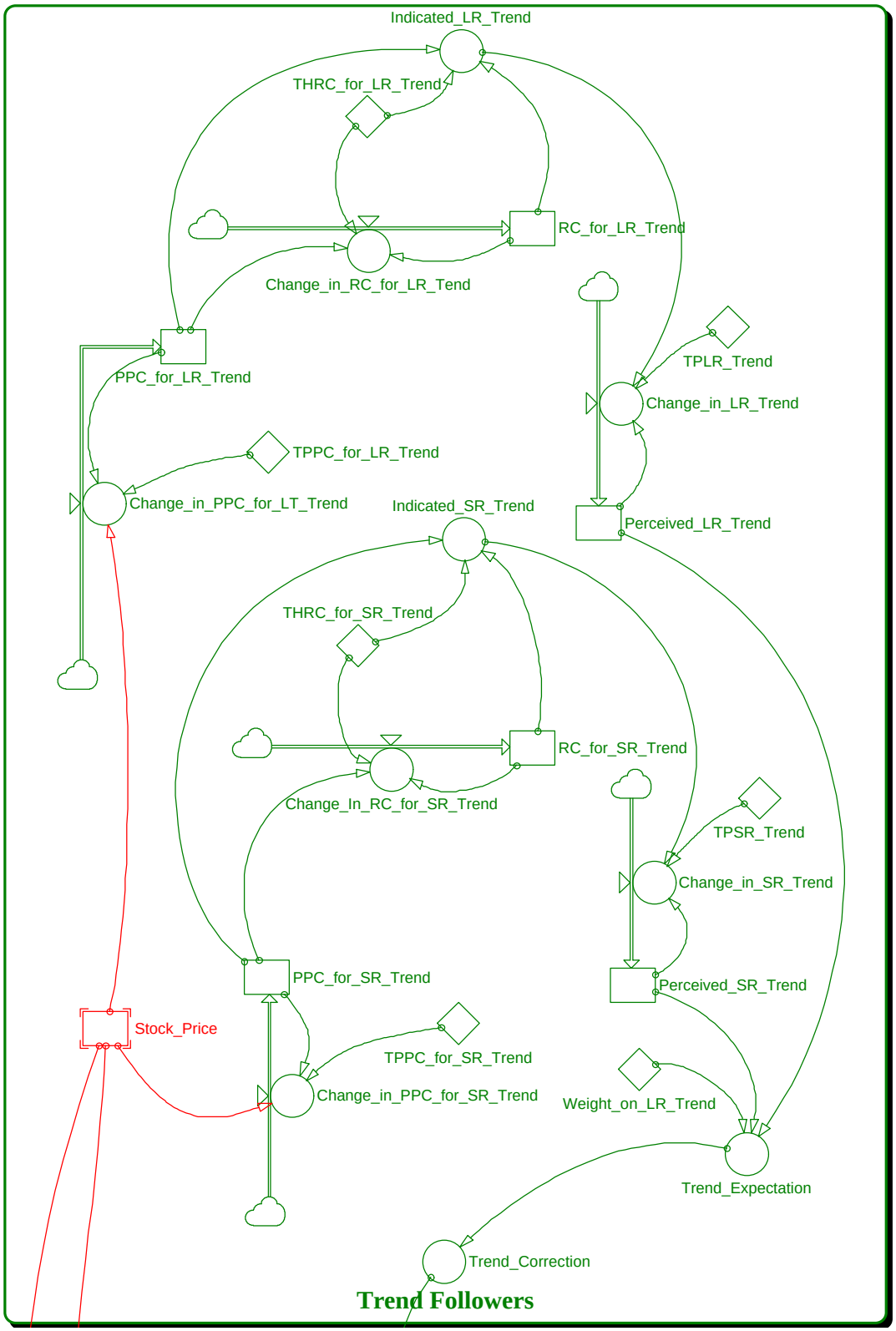

Figure 8a: Trend followers' stock and flow structure.

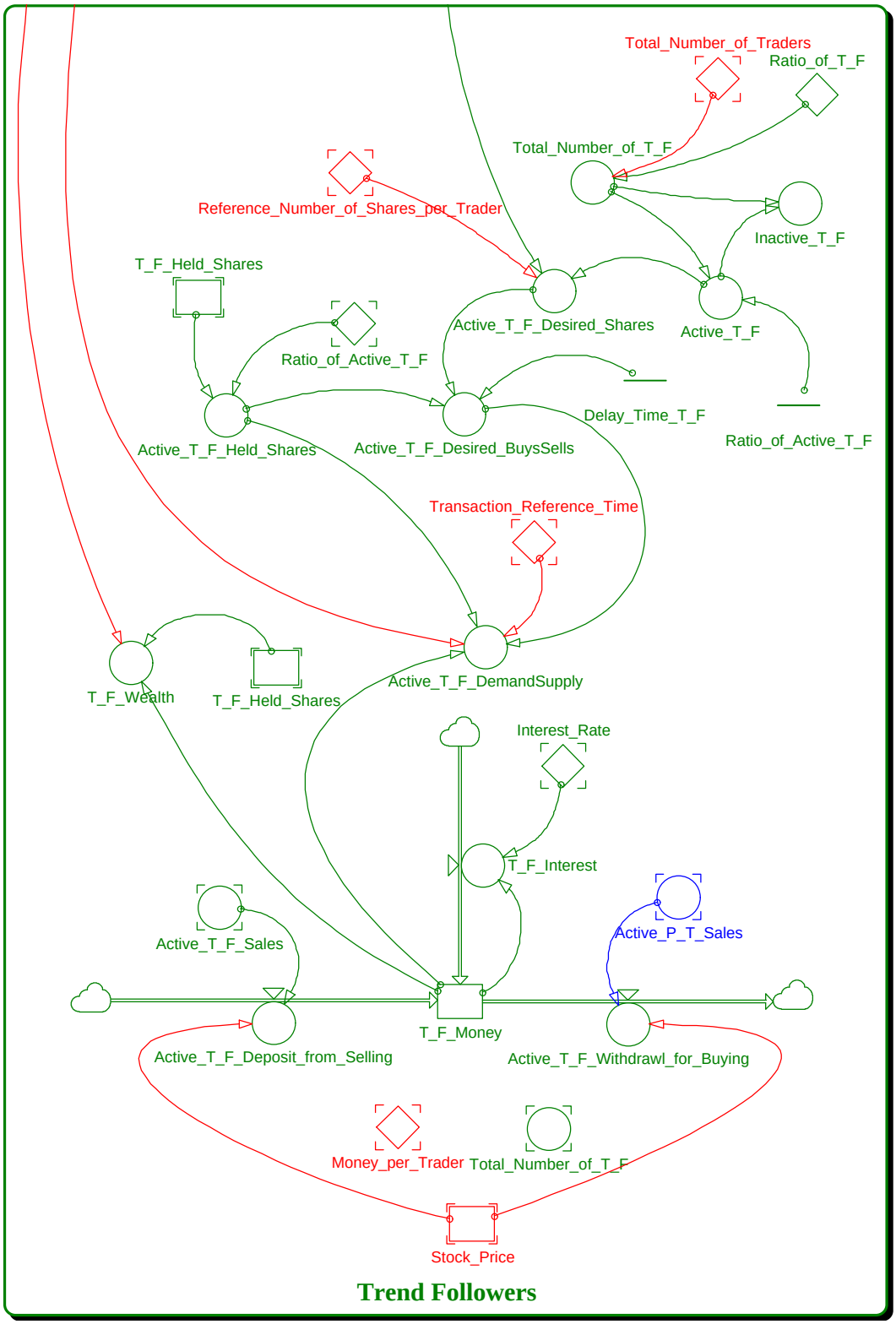

Figure 8b: Trend followers' stock and flow structure.

Also for this group of investors the distinction between active and inactive is modeled in the stock and flow structure even though all trend followers are supposed to be active.

The stock market stock and flow structure is sketched in figure 9. In the bottom part of the structure it is possible to recognize the trading ring where transactions only take place between active investors.

Simulations.

To study the stock price behavior in different situations of trend followers' ratio a few simulations are made in this section. These simulations take a time horizon of 1000 trading days, namely, four years considering that one trading year is made of about 250 days. All these simulations start with a situation of stock price below the fundamental value, but this initial hypothesis can be modified without loss of generality for the model.

Figure 10 (Sim0) shows the market equilibrium when the stock price equals the fundamental price. If the stock price equals the fundamental value of the share, professional traders don't trade and the stock price doesn't undergo any initial modification, no trend is induced into stock price and, therefore, trend followers don't exchange as well.

To reproduce the main results of financial theory on stock price oscillations caused by different trading strategies, the first 6 simulations are made without considering the effect of the non-transaction ratio.

Figure 11 (Sim1) shows the stock price behavior when the rate of trend followers is small (0.20). The other figures show the same behavior when the trend followers' ratio is 0.5 (Sim2), 0.8 (Sim3), 0.87 (Sim4), 0.873 (Sim5), 0.875 (Sim6) respectively.

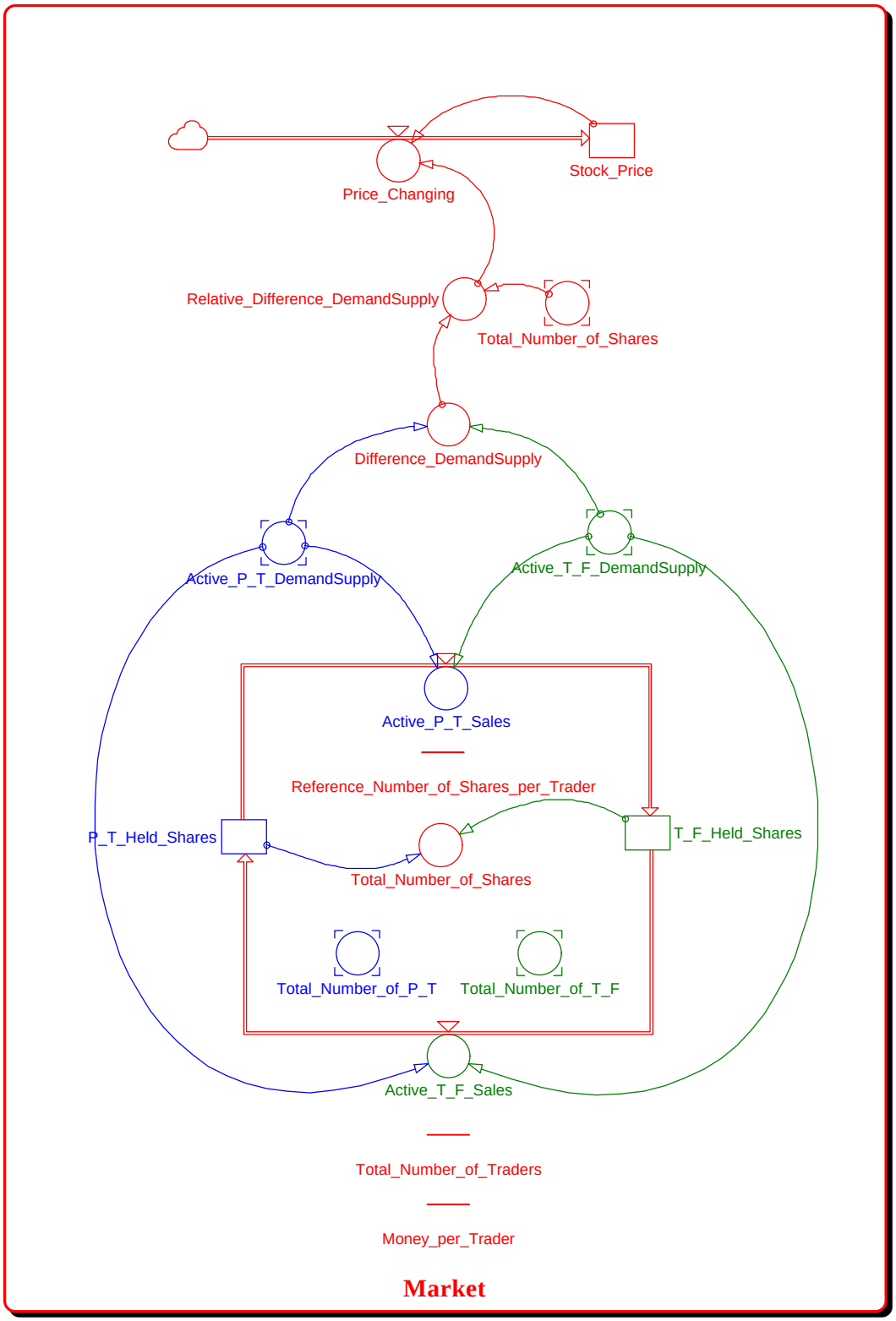

Figure 9: Stock market stock and flow structure.

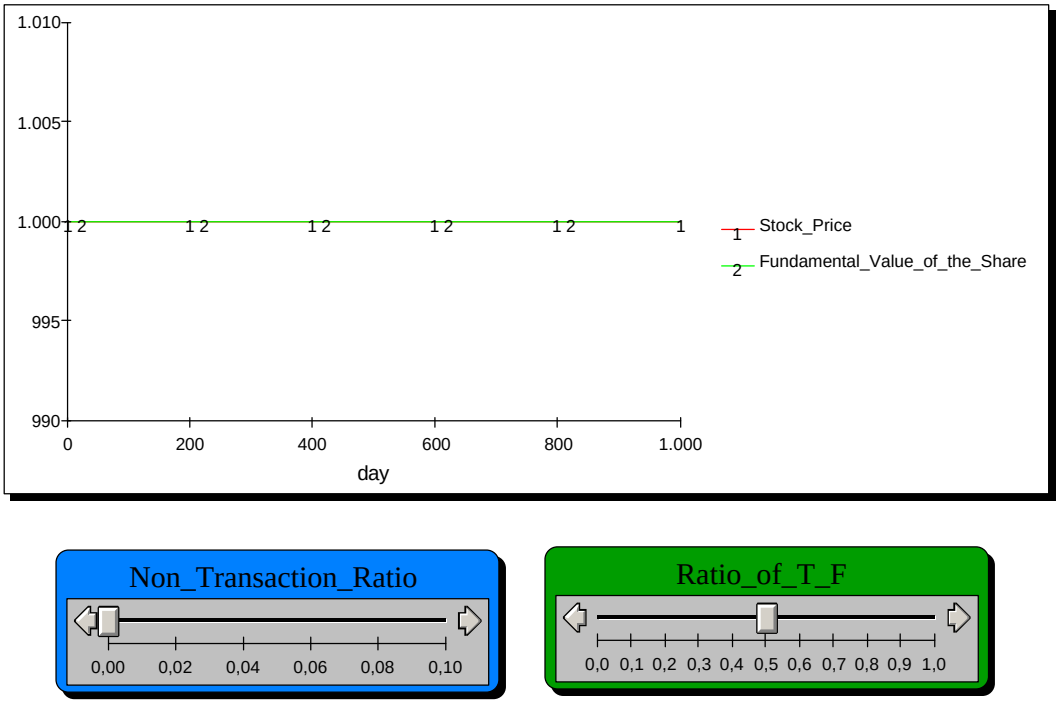

Figure 10: Stock market equilibrium when the stock price equals the fundamental value of the share (Sim0).

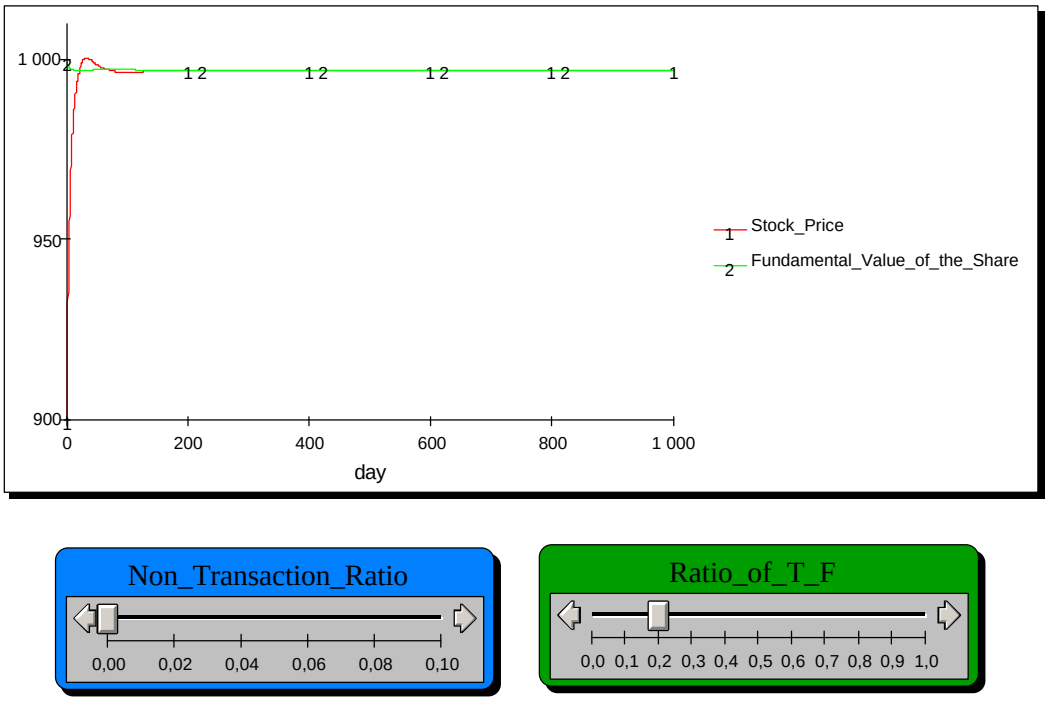

Figure 11: Stock price behavior when the rate of trend followers is 20% (Sim1).

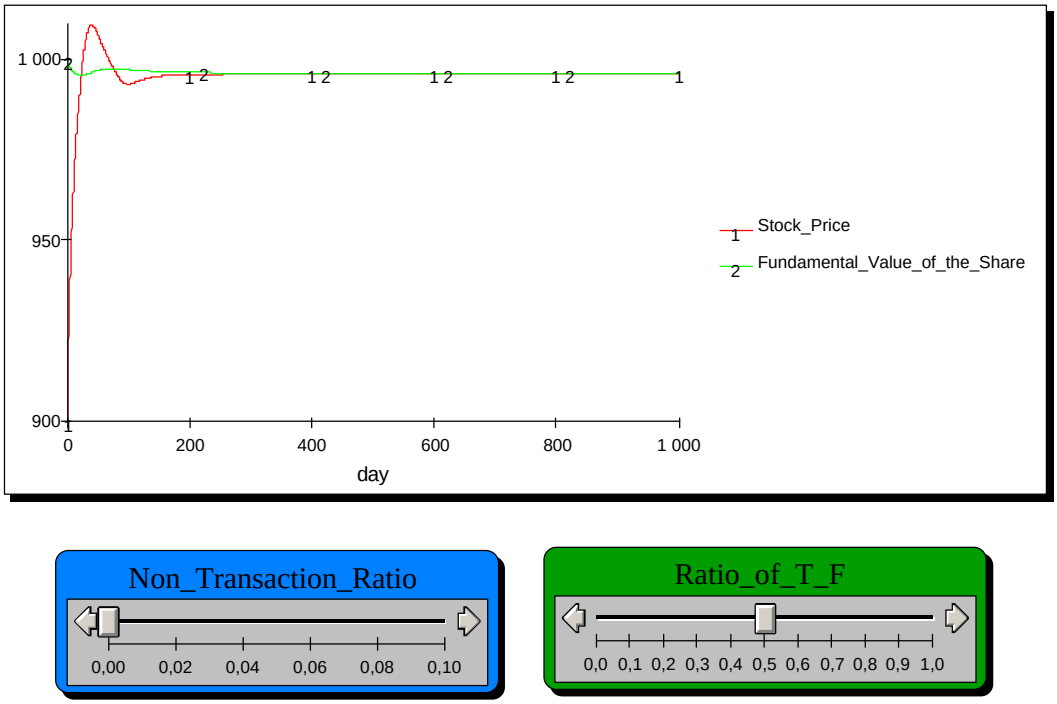

Figure 12: Stock price behavior when the rate of trend followers is 50% (Sim2).

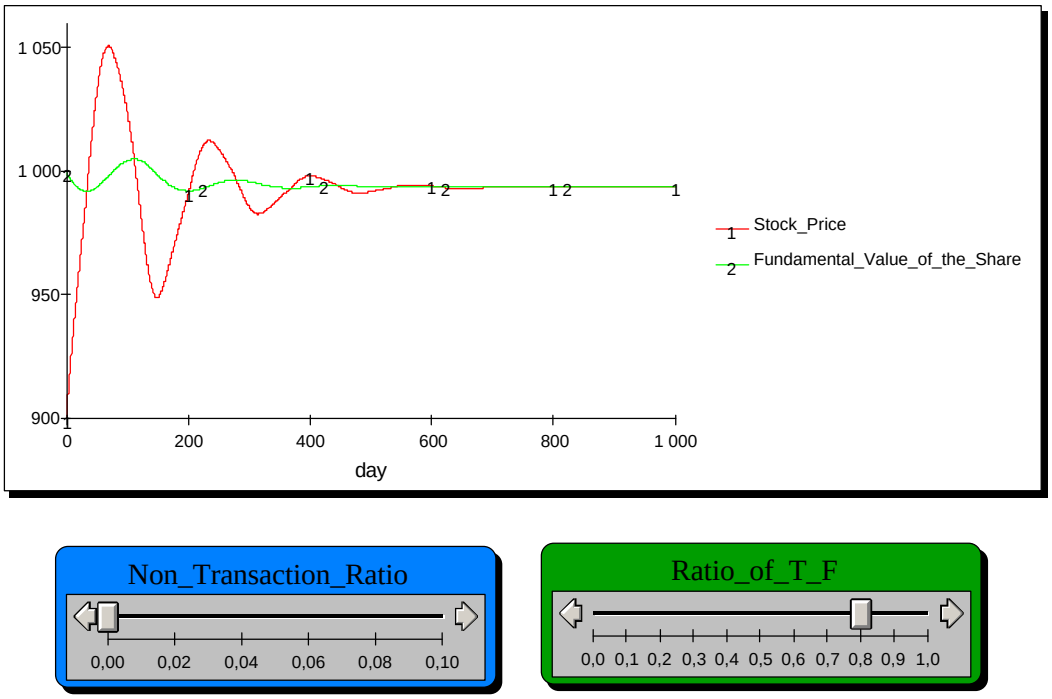

Figure 13: Stock price behavior when the rate of trend followers is 80% (Sim3).

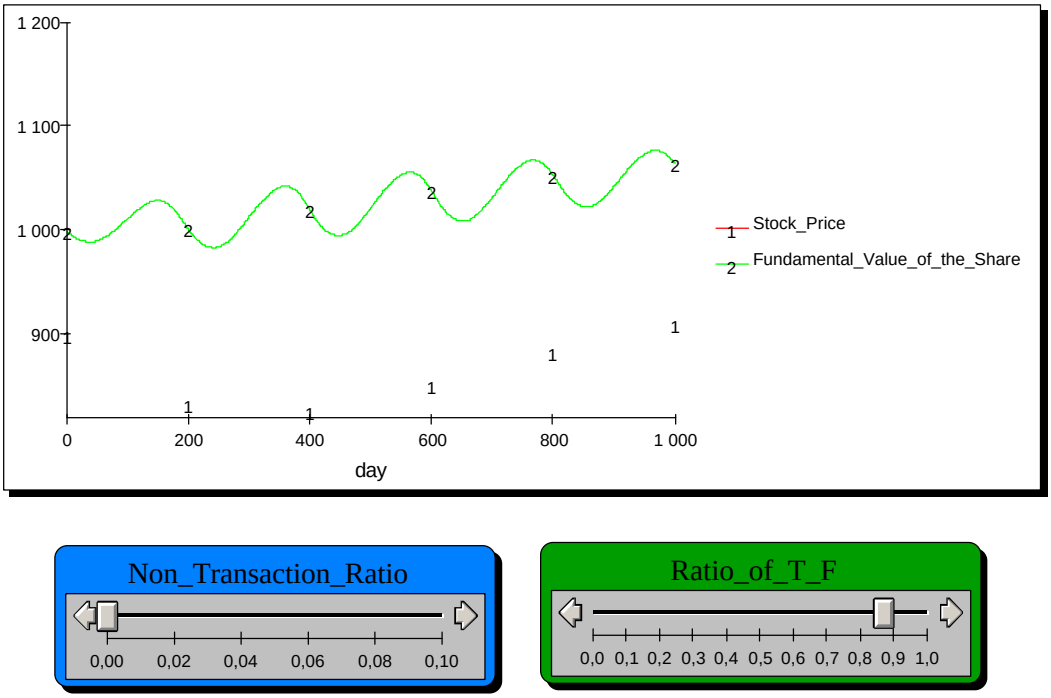

Figure 14: Stock price behavior when the rate of trend followers is 87% (Sim4).

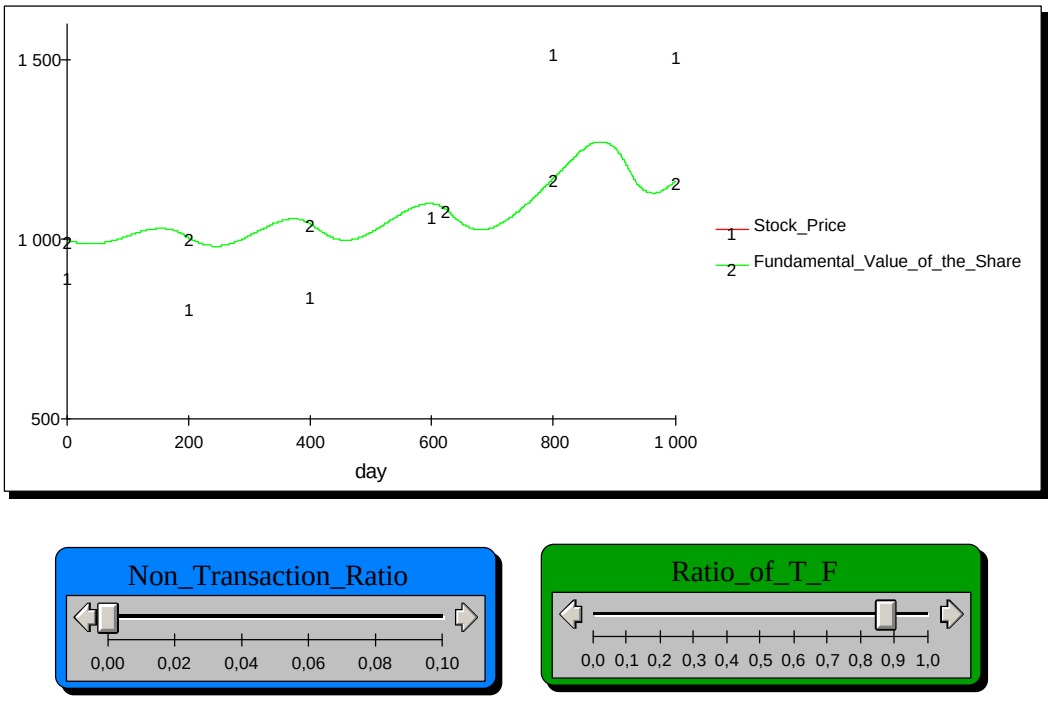

Figure 15: Stock price behavior when the rate of trend followers is 87,3% (Sim5).

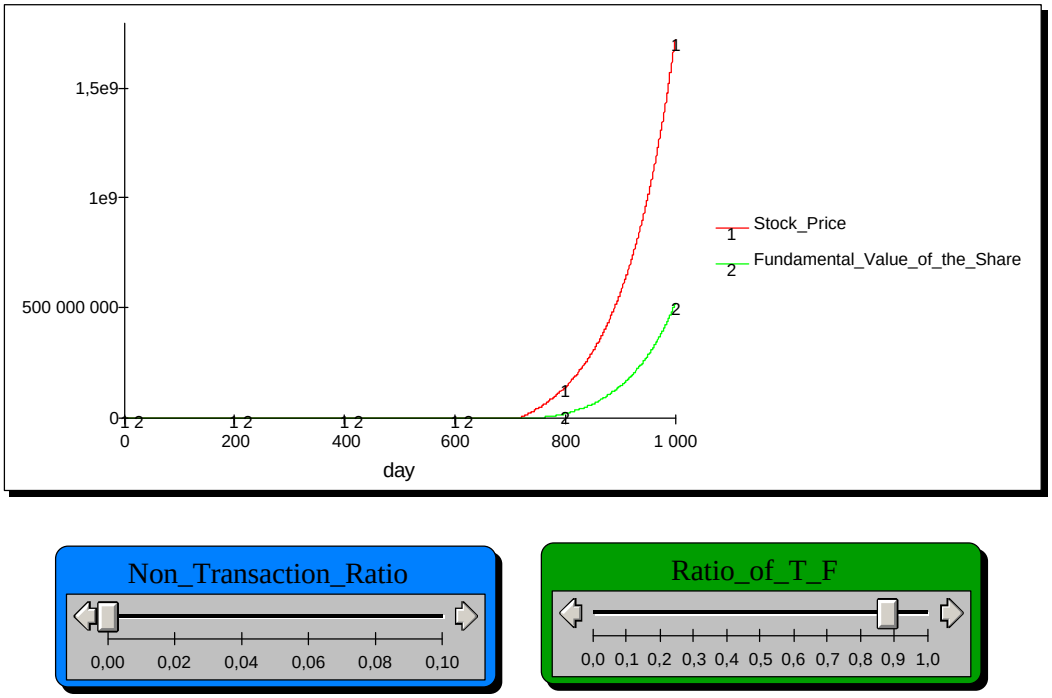

Figure 16: Stock price behavior when the rate of trend followers is 87.5% (Sim6).

The next simulation (figures 17, 18, 19, 20), instead, are made in the presence of a non-transaction ratio of 10%. Since inside the non-transaction interval the number of active professional traders varies during the trading activity their stabilizing influence varies as well and, as a consequence, the stock price is subjected to greater and wider oscillations.

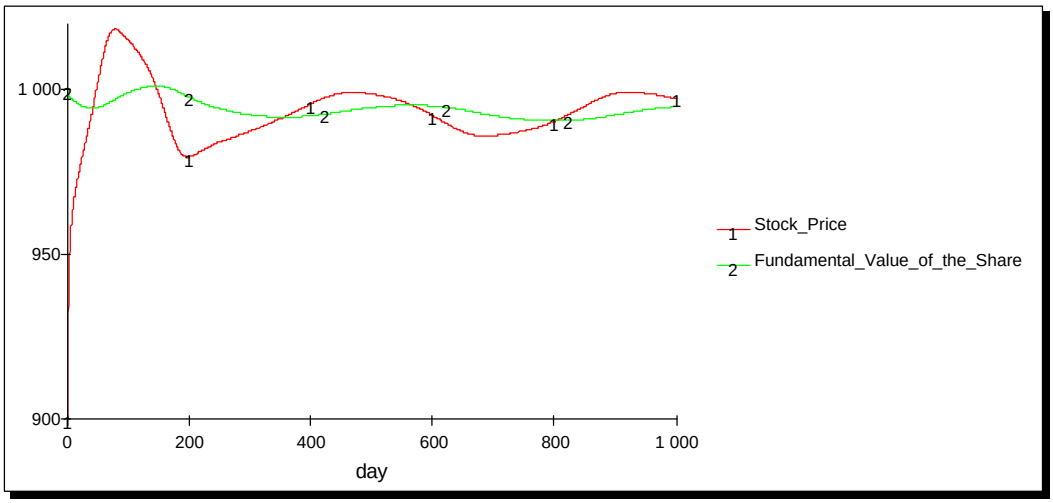

Figure 17: Stock price behavior when the rate of trend followers is 20% and the non-transaction ratio is 10%(Sim7).

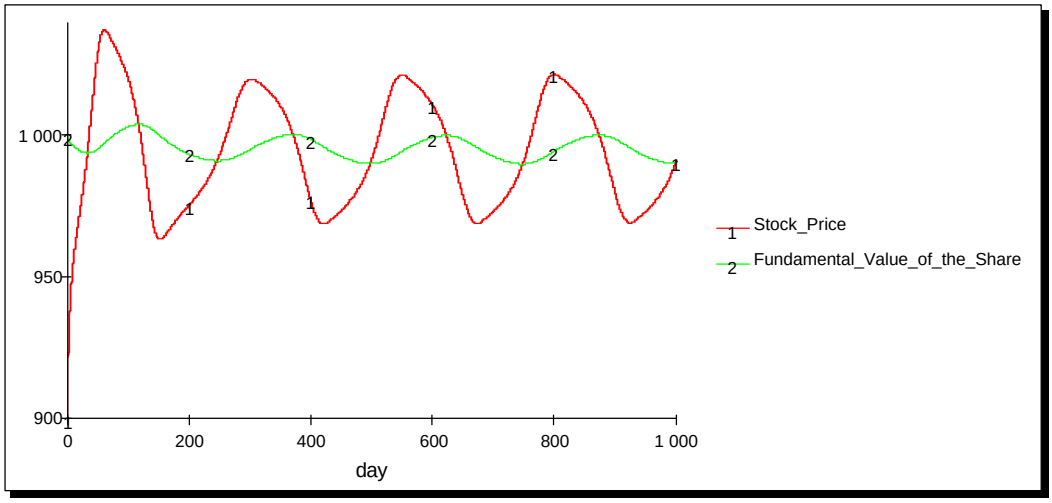

Figure 18: Stock price behavior when the rate of trend followers is 50% and the non-transaction ratio is 10% (Sim8).

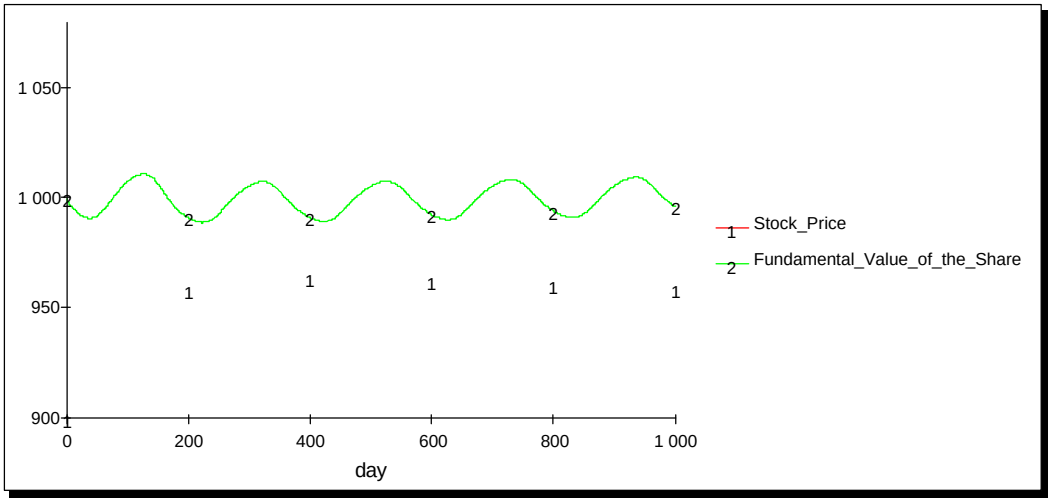

Figure 19: Stock price behavior when the rate of trend followers is 80% and the non-transaction ratio is 10%(Sim9).

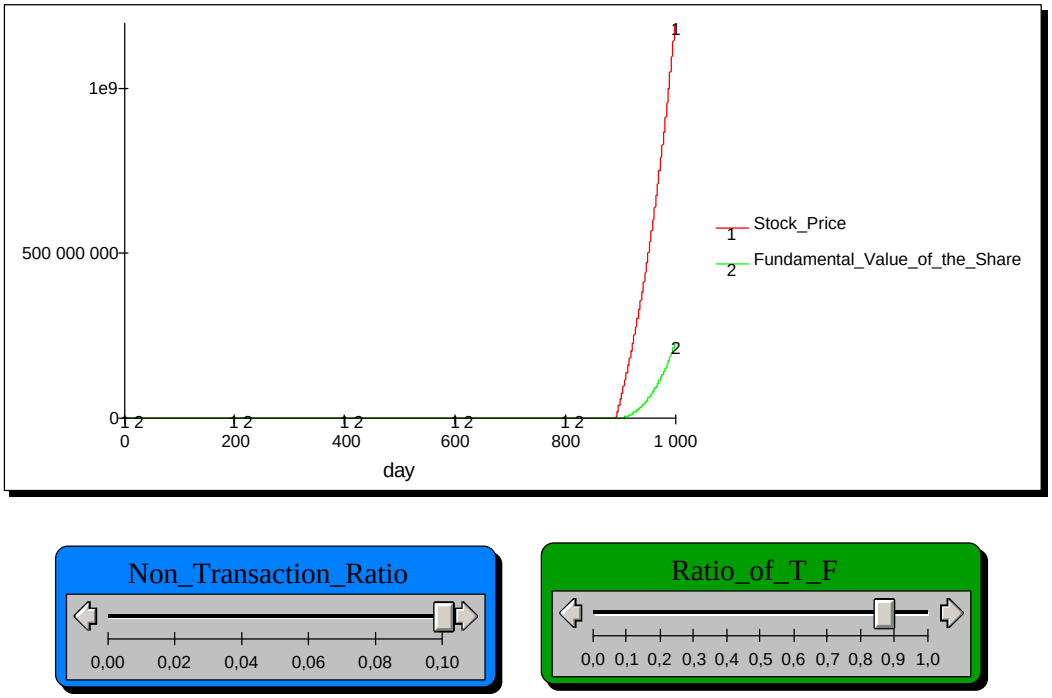

Figure 20: Stock price behavior when the rate of trend followers is 87% and the non-trading ratio is 10%(Sim10).

Conclusion.

To model the stock market dynamics and characterize asset price and wealth dynamics arising from the interaction of heterogeneous agents, a system dynamics model has been built with a very simple characterization of traders.

Professional traders can assess the fundamental value of the share, whereas trend followers decide their investment attitude on the basis of the price trend. This implies that trend followers use only data about past and present prices in order to forecast the future price.

With these simple assumptions, the model illustrates how commonly used trading strategies operate as signal processing elements. Trend followers' strategy acts as signals filter (the price is increasing, it will increase in the future as well) and induce positive autocorrelations in stock price, whereas professional traders' strategy acts as signals transducer (the stock price is above the fundamental value of the share, the share is overvalued) and incorporates information about value into stock prices inducing negative autocorrelations.

The simulations made with the system dynamics model confirm the financial theory results, namely:

1. a large fraction of professional traders tends to stabilize the speculative price and tend to lead it toward the fundamental price (figure 11 and 12);

2. a large fraction of trend followers tends to destabilize the stock price and is responsible for instability (figure 20);
3. the trading activity between professional traders and trend followers generates various pattern of speculative dynamics including speculative bubbles (figure 13) and large slowly decaying swings away from the fundamental price (figure 15). In particular figure 14 shows what is called, in mathematical jargon, limit cycle meaning the limit toward which the oscillating system tends when the equilibrium position losses its stability.

These simulation results are consistent with those of the financial literature following the early 1980's and challenge the "efficient market hypothesis" that is typical of neoclassic formulations.

Furthermore, contrary to what neoclassic formulations claim, this model demonstrates that positive-feedback investors can survive in the market even though their trading strategy is not completely correct; their wealth never goes to 0.

In the simulations Sim17, Sim18, Sim19 and Sim20, the introduction of a non-transaction ratio demonstrates that every time in the structure there is a factor that reduces professional traders reaction upon the difference between actual and fundamental price, the strength of professional traders stabilizing power reduces as well and the stock price shows greater and wider oscillations. This result is consistent with the financial literature and represents an important point in the new financial markets theory.

In conclusion, the use of system dynamics modeling for a financial market represents a valid alternative to pure mathematical models for several reasons. First of all, a system dynamics model can represent very complex systems, as a stock market, without abandoning to much the reality, secondly they allow to test different alternative gaining knowledge about the actual behavior of the system and, finally but very important, causal loop and stock and flow diagrams enlarge the model understanding to those who don't have a mathematical background.

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APPENDICES.

Enumerated list of parameter values characterizing each run.

Sim0

Stock_Price = 1000
Delay_Time_P_T = 5
Delay_Time_T_F = 10
Interest_Rate = 0.01
Money_per_Trader = 1000 currency units
Non_Transaction_Ratio = 0
Ratio_of_Inactive_P_T =
GRAPH(Non_Transaction_Interval,0,0.1,[1,0.97,0.9,0.79,0.61,0.36,0.19,0.08,0.03,
0.01,0"Min:0;Max:1;Zoom"])
Ratio_of_P_T = 0.5
Ratio_of_T_F = 0.5

Reactivity_Coefficient = 0.02
Reference_Value_of_the_Share = 1000
Reference Shares_per_Trader = 1
THRC_for_LR_Trend = 125
THRC_for_SR_Trend = 62
Time_to_Adjust_Fundamental_Value = 20
Total_Number_of_Traders = 1000
TPLR_Trend = 10
TPPC_for_LR_Trend = 21
TPPC_for_SR_Trend = 10
TPSR_Trend = 5
Weight_on_LR_Trend = 0.3
Weight_on_Stock_Price = 0.1
start = 0.00000
stop = 1000.00000
dt = 0.25000
method = Euler (fixed step)

Sim1

Stock_Price = 900
Ratio_of_P_T = 0.8
Ratio_of_T_F = 0.2
The other parameters being unchanged with respect to Sim0.

Sim2

Ratio_of_P_T = 0.5
Ratio_of_T_F = 0.5
The other parameters being unchanged with respect to Sim1.

Sim3

Ratio_of_P_T = 0.2
Ratio_of_T_F = 0.8
The other parameters being unchanged with respect to Sim1.

Sim4

Ratio_of_P_T = 0.13
Ratio_of_T_F = 0.87
The other parameters being unchanged with respect to Sim1.

Sim5

Ratio_of_P_T = 0.127
Ratio_of_T_F = 0.873
The other parameters being unchanged with respect to Sim1.

Sim6

Ratio_of_P_T = 0.125
Ratio_of_T_F = 0.875
The other parameters being unchanged with respect to Sim1.

Sim7

Ratio_of_P_T = 0.8
Ratio_of_T_F = 0.2
Non Transaction Ratio = 0.1
The other parameters being unchanged with respect to Sim1.

Sim8

Ratio_of_P_T = 0.5
Ratio_of_T_F = 0.5
Non Transaction Ratio = 0.1
The other parameters being unchanged with respect to Sim1.

Sim9

Ratio_of_P_T = 0.2
Ratio_of_T_F = 0.8
Non Transaction Ratio = 0.1
The other parameters being unchanged with respect to Sim1.

Sim10

Ratio_of_P_T = 0.13
Ratio_of_T_F = 0.87
Non Transaction Ratio = 0.1
The other parameters being unchanged with respect to Sim1.

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