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Output and Price Behaviour in a System Dynamics Model

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RESEARCH PAPER 2011-022
DECEMBER 2011

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D/2011/1169/022

Output and Price Behaviour in a System Dynamics Model

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Abstract

This paper introduces a small-scale experimental model intended as a first stage to developing a fully-fledged system dynamics macroeconomic model of a new generation. The model economy incorporates important real-world features that are missing in the mainstream macroeconomic literature. The agents representing the demand and supply side dispose over a limited information set. Their interactions are not constrained by a priori imposition of equilibrium conditions. The exercise shows that, unlike in general equilibrium models, booms and busts in output and price endogenously arise due to the stock variable representation of demand and supply and modelling the agents' decisions as autonomous. It is also demonstrated that bad times and good times are driven by the same causal mechanisms. The insights are paramount for an appropriate understanding of the true possibilities of macroeconomic policies and provide fruitful material for further exploration.
JEL: E31, E32.
Keywords: system dynamics, stock variables, disequilibrium model, bounded rationality, backward looking solution.

1 Introduction

This paper introduces a small-scale system dynamics (SD) model incorporating important real-world features that are missing in the mainstream macroeconomic literature. The agents representing the demand and supply side are boundedly rational and their interactions are not constrained by a priori imposition of equilibrium conditions. The exercise provides important conceptual insights about the dynamics of output and price. In particular, it is demonstrated that the booms and busts originate in the stock-flow model structure and owe to coordination problems between the agents.

The paper is a part of a broader research work that investigates by means of high-level mathematical tools the joint macroeconomic dynamics and asset pricing. This particular paper is intended as a first stage to developing a fully-fledged system dynamics macroeconomic model of a new generation. The effort links back to the older generation of disequilibrium system dynamics (DSD) models originating at the MIT in the 50-80's. Those medium- to large-sized behavioural models included the prominent System Dynamics National Model of the U.S. economy (Forrester, 1980; Sterman, 1986), the model of Mass (1975) and others[1]. The group of researchers led by Jay W. Forrester departed from the mainstream economic literature of that time which was busy with adopting the rational expectation hypothesis (cf. Blanchard and Kahn, 1980; Kydland and Prescott, 1982; Shiller, 1978). Later on the mainstream evolved to the more recent general equilibrium based literature, including the Real Business Cycle (RBC) and the Neo Keynesian / New Neo-classical Synthesis (NK/NNS) school (cf. Blanchard, 2000; Karagedikli et al. 2007; Prescott, 1986; Rebelo, 2005). Hand in hand with the wide-spread popularity of these models, however, the criticism of the mainstream approach intensifies (see e.g. Colander, 2011; and references therein).

By its design, the model presented in this paper differs from the older DSD models which were set up as large multi-sector models. The scope is intentionally reduced to a minimum that is necessary to represent a single market economy. The purpose is to explore what sorts of causal relationships do operate at its core and how they relate to the observed output and price dynamics. Rather than focusing on the supply side, the model closes the two sides of the market in the main balancing loop. Important features of the paper include:

[1.] Stock variable representation of demand and supply[2,3]. This approach, advocated in Mass (1980), was implemented in most of the first generation DSD models. By contrast, the flow-based view dominates in the mainstream macroeconomic literature. The aggregate

[1] It is worthwhile noting that the DSD literature is based on fundamentally different principles and has not much in common with the so called 'disequilibrium economics' that is surveyed e.g. in Backhouse and Boianovsky (2005).

[2] To avoid confusion, this problem is not about the so-called 'stock-flow consistency' which has been a vitally discussed issue in the literature and remains on agenda in heterodox economic circles (e.g. Dos Santos and Zezza, 2007).

[3] No statement on a variable being a stock or a flow is complete without realizing with respect to what one makes such a consideration. In a $\dot{x} = \nu$, $\dot{\nu} = a$ problem, ν is a flow with respect to x and it is a stock with respect to a. In that sense, this paper takes the view that the stock of aggregate demand and supply change by the flow of consumption.

demand is modelled as a sum of flow variables (consumption, investment and other expenditures) and aggregate supply is measured as the rate of production (cf. Smets and Wouters, 2007).

[2.] Deterministic **exogenous dynamics**. In line with the principles dictated by the system dynamics methodology, all exogenous inputs to this model are deterministic and as simple as possible. In a sharp contrast, the mainstream macroeconomic papers work with stochastic exogenous dynamics. Random disturbances and stochastic excitations are also considered in the statistically based papers, such as Stock and Watson (2002), and in papers based on bifurcations and chaos theory, e.g. Huang et. al. (2010).

[3.] **Realism** in important features. The mainstream macroeconomic literature has been increasingly criticized for basing the models on a range of strong assumptions that have no counterparts in reality. This paper takes seriously some of those criticisms, in particular:

• Equilibrium market conditions are not a priori imposed (cf. LeBaron and Tesfatsion, 2008).

• The agents do not know the entire model, unlike in the rational expectation hypothesis based papers (cf. De Grauwe, 2010). More specifically, the agents are cognitive (boundedly rational) with an imperfect set of information. Whilst they do know the past common variables and the own current variables, they do not know the current aggregate variables, as these are determined by the mutual interactions (cf. Angeletos and La'O, 2009). At this stage of model development, their decisions are governed by simple behavioural rules.

• Model simulations do not impose terminal conditions such as the transversality condition (cf. Meeusen, 2009) which means that scenarios such as severe downturns are not a priori ruled out.

[4.] **Extreme** market conditions. The model is intended as a simulation model, not to serve estimation or forecasting purposes. Thus one has the freedom to position it as an open-end system (cf. LeBaron and Tesfatsion, 2008). This is achieved by removing the profit-income link between the firm and the household within the model scope. Those and many other possible exogenous factors are instead represented in the form of parameter based behavioural constraints such as e.g. the household financing constraint. As a result, extreme cases of market coordination success as well as failure can be simulated (cf. Foley, 2010; Meeusen, 2011).

[5.] The paper makes use of more **advanced mathematics** than the mainstream macroeconomic papers, a point that is often criticized (cf. Colander, 2011). The model is built using system dynamics, a methodology suitable to study complex dynamical systems (cf. Sterman, 2000). Most of the model's equations are nonlinear and the model is so simulated, in contrast to the practice of linearizing models around a steady state (cf. Rebelo, 2005; Smets and

Wouters, 2007).

Section 2 introduces the model including the visual and mathematical representation. This section also describes the feedback loops and explains what forces may lead to stability of the dynamical system at hand. Section 3 gives an overview of the simulation results. The final fourth section interprets the results and discusses the implied insights in the context of the recent macroeconomic literature.

2 The model

This section introduces an experimental system dynamics model of an abstract market with a single generalized good. The model framework allows two alternative perceptions, a microeconomic and a macroeconomic.

On the micro level, the model can be viewed as a reduced form equation representation of an abstract market. It captures in an intuitive behavioural way some important real world issues, such as the presence of financing and capacity constraints, and imperfect information. Some readers will see it as a non-linear relative of the cobweb type of market models with a complicated price adjustment process (e.g. Hommes, 1994). They would assess that the paper studies the behaviour of this dynamical system by an appropriate technique.

The focus of this paper is, however, on the macro level. The presented model is a minimalist demonstration of the stock-variable principle of Mass (1980). Mass established that the aggregate demand and supply are stock variables with respect to the flow of consumption or investment. Thus the model represents a closed economy with a representative household and firm. Using the standard textbook notation, the real activity in the model economy would correspond to "Y := C + I", with "Y" - output, "C" - private consumption and "I" - private investment. However, in the case of a disequilibrium system dynamics model, this is only true as an ex post snapshot.

Sections 2.1-2.2 introduce some general properties of the model. In Sections 2.3 and 2.5 respectively, the model equations are listed and the distinction is made between the disequilibrium and equilibrium market conditions.

2.1 Generalizations

By intention, the model is highly reduced in scope and generalized in a number of aspects:
[1.] The demand and supply side of the one-sector economy may be viewed as a representative 'household' or 'consumer' and a representative 'firm' or 'enterpreneur', as long as one

accepts the convenience that the household represents the demand side and the firm the supply side of the abstract market. But this is just one of the possibilities. More generally, one could speak about agent(s) demanding and supplying the good. Especially on the demand side, the potential good's buyer may enter the market for fairly diverse reasons. Housing turns out to be a good illustration. Here, agents demanding the good may do so for reasons of living (individuals), investment consideration (individuals or corporations), speculation on a price rise (institutional investors) or others. The focus of this paper is on mapping the general outcome of such choices, the demanded quantity. Analogy applies to the affordability coefficient that is mapping the aggregate percentage of the potential demand effectively backed by financial means, no matter if the financial means are personal income or corporate profits or something else.

[2.] The problem of borders and of the exchange rate is neglected. Market participants as well as the good itself may be both domestic and foreign.

[3.] The good is made universal in terms of durability, tradability, usage, exclusiveness and a number of other features.

Universal durability is achieved by the stock representation of the good. Durable goods such as cars or housing remain in the stock for a long time (the outflow rate is small), whereas semi- and non-durables such as clothes or foods are characterized by high outflow rates.

The assumption of the good's homogeneity implies that transactions with the existing goods (those bought before and now in the hands of the owner) have no influence on the real variables and the price in the model. Illustrated on the example of housing, trading down or renting the existing dwellings would not impact anything in the model, as there would be no reason to engage in such exchanges.

And so on. The universal character of the good enables one to simulate the model for the overall economy as well as partial sectors.

[4.] Transactions proceed in a simple way; bargaining, price matching or auctions are neglected. The good's sales and the price update factor are determined as the minimum and the ratio of the demanded and supplied quantity, respectively.

[5.] Units are continuous (not integers).

[6.] All flows streaming in the model are real. At this modelling stage, money is ommitted as a special type of a good (medium of exchange, alternative asset, etc.).

[7.] The model describes the simplified economy on a macroscopic level and the variables represent aggregate quantities. Stochasticity eventually arising from agents' heterogeneity, dispersed information, etc. is neglected[4].

[4]The system dynamics model is well suited as an input for an agent based modelling (ACE) exercise,

2.2 Underlying philosophy

Much of the model design owes the philosophy of system dynamics (SD). More than just a quantitative technique, it is the way of system thinking. In this case, the dynamic system to investigate consists of the core mechanisms of the abstract market or economy sector.

A reader with a background in RBC or NK/NNS literature (refer to the introductory section) would notice a few features that distinguish this SD model from that class of models.

In particular, the model does not use explicit mathematical formulae in the form of objective functions and constraints. Some optimal choices and constraints enter the model exogenously (as discussed in Section 2.1, point [1.]), some others are taken in the model and follow the form of behavioural rules.

The power of this approach lies in the dynamics endogenously generated by the system of stock variables. In comparison to the DSGE class of models (e.g. Rebelo, 2005; Smets and Wouters, 2007), there is an additional layer of stock variables. The variables the DSGE models work with, represent the rates of flow corresponding to these stock variables. In particular, the stock of demand and supply in my model change by the flow of consumption (cf. Mass, 1980). Closing all stock variables in a single loop (in my case, the main balancing loop) creates a dynamical system with a strong endogenous dynamics.

Another major basis for the model design is the aim to come up with a minimum setup that is necessary to endogenously generate output and price dynamics. As a result, the model is distilled from a large part of the agents' life choices. There is a simplified profit-cost analysis on the supply side and a the demand side omits a fully fledged consumer (or investor) problem. Moreover, links between the two market sides other than regarding the transactions with the good are omitted. The model is formulated in aggregate terms (agents are representative) and explicit formulation of the underlying micro-agent problem is omitted.

2.3 Visual and mathematical representation

Figure 1 provides a visual representation of the model and Table 1 summarizes the variables and parameters.

although it would need to grow in scope. One would need to define appropriately diverse classes of individual agents (households, investors, firms, etc.). The individuals would be characterized by specific preferences and constraints. Such an exercise would need to specify precisely the way in that the individuals interact and decide on transactions. To obtain macroscopic variables such as the overall price level and overall output one would aggregate the large number of locally determined prices and quantities.

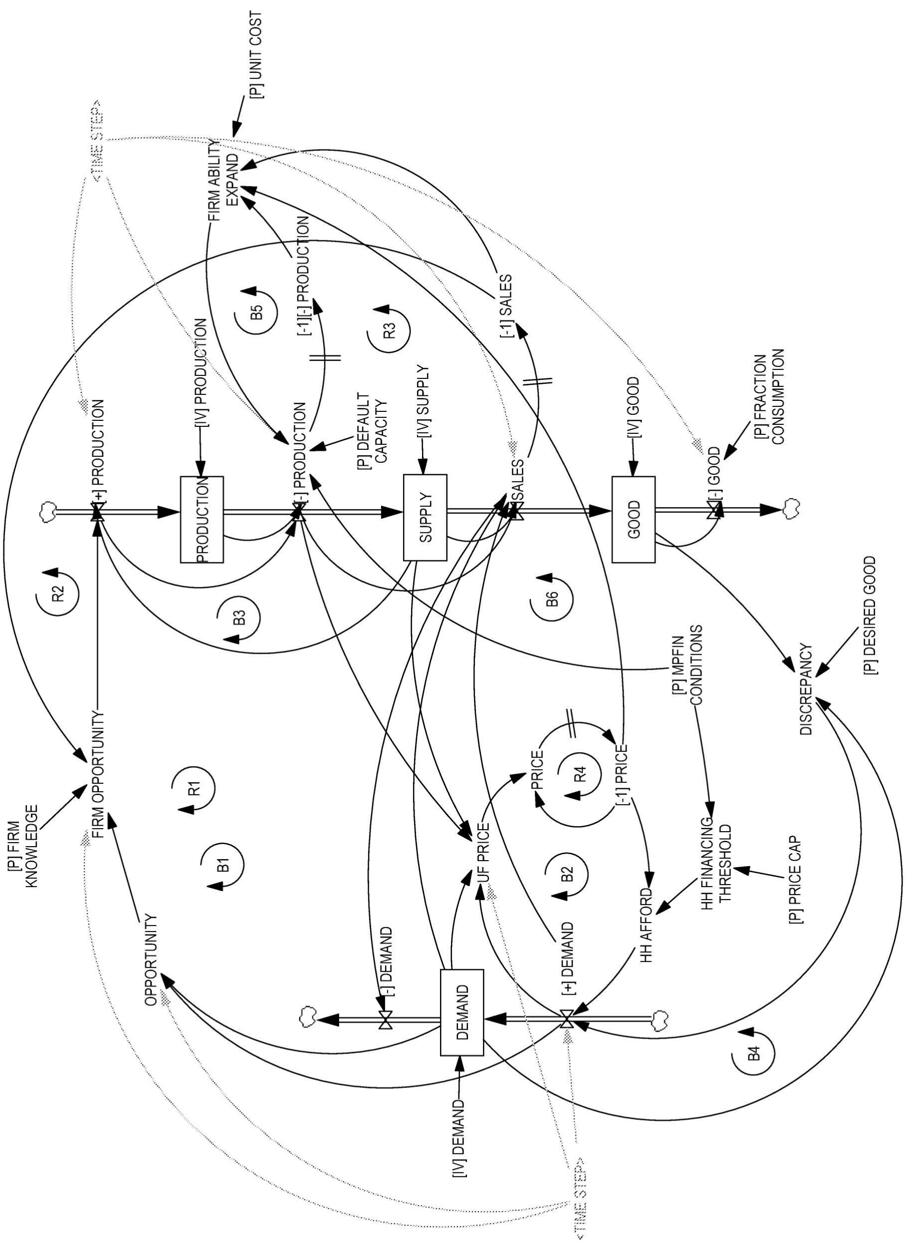

Figure 1: The stock flow diagram of the system dynamics experimental model

Note: Created in Vensim (registered trademark), 2010. Capital R denotes reinforcing (positive) feedback loops, B denotes balancing (negative) loops.

Table 1: Summary of variables and parameters

Symbol	Diagram notation	Variable description
Endogenous Variables other than State Variables		
N	DISCREPANCY	Difference between the desired and the actual stock of goods
P^F	HH FINANCING THRESHOLD	Maximum price household is able of paying given the monetary and financial conditions
a	HH AFFORD	Affordability coefficient
u	UF PRICE	Price update factor
P	PRICE	Price
O	OPPORTUNITY	Objective opportunity to sell goods
$\widehat{O}$	FIRM OPPORTUNITY	Opportunity to sell goods perceived by firm
r	FIRM ABILITY EXPAND	Firm ability to expand production capacity based on revenue cost ratio
State Variables and Corresponding Rates of Change		
D, D^+, D^-	DEMAND, [+] DEMAND, [-] DEMAND	The effective demand increases with potential purchases and diminishes with satisfied buyers.
R, R^+, R^-	PRODUCTION, [+] PRODUCTION, [-] PRODUCTION	The stock of goods in the production process increases with accepted volumes and diminishes with finished goods.
S, R^-, S^-	SUPPLY, [-] PRODUCTION, SALES	The supply of goods increases with finished goods and diminishes with sales.
G, S^-, G^-	GOOD, SALES, [-] GOOD	The stock of goods increases with sales and diminishes with consumed goods.
Exogenous variables		
$\widetilde{G}$	[P] DESIRED GOOD	Desired stock of goods
$\bar{P}$	[P] PRICE CAP	Maximum price household is able of paying
F	[P] MPFIN CONDITIONS	Monetary and financial conditions
w	[P] FIRM KNOWLEDGE	The extent to what the firms know the objective opportunity
ϕ	[P] DEFAULT CAPACITY	Default volume of goods that can be produced each period
c	[P] UNIT COST	Production cost per unit
z	[P] FRACTION CONSUMPTION	Fraction of goods consumed each period
D_0, R_0, S_0, G_0	[IV] DEMAND, [IV] PRODUCTION, [IV] SUPPLY, [IV] GOOD	State variables' initial values
P_0, R_0^-, S_0^-		Delayed variables' initial values

The model consists of two building blocks, the demand and the supply side, interaction of which generates the dynamics in a set of real variables and in the good's price.

The model is used to simulate the response of the market to a positive discrepancy between the actual and the desired stock of the good. This is done under eight different model setups. The equations below give the most general case[5] and Table 2 summarizes what is done differently in the other setups.

At the beginning of each period, the values of the stock variables update for the corresponding inflows and outflows of the previous period. The four stock variables are the effective demand D_t, goods in the production process R_t, supply (or inventory) of goods S_t and goods in use G_t. The distinctive feature of the stock variables is that they provide the dynamical system with memory and are the source of delays (lags). For instance, under D_t one should imagine potential purchases of buyers backed by financing resources (be them own or borrowed), hovering around until they find and get what they were looking for. This 'waiting time' is most easy to associate with durables such as cars or housing. But even goods of daily use may, under exceptional circumstances, witness 'standing in queues'. On the supply side, things do not happen at once either. The stock of goods in production and the stock of inventory accumulate over time. So does the stock of goods in the hands of the owners.

$$D_t = (D^+_{t-\mathbf{T}} - D^-_{t-\mathbf{T}}) \cdot \mathbf{T} + D_{t-\mathbf{T}} \tag{1}$$

$$R_t = (R^+_{t-\mathbf{T}} - R^-_{t-\mathbf{T}}) \cdot \mathbf{T} + R_{t-\mathbf{T}} \tag{2}$$

$$S_t = (R^-_{t-\mathbf{T}} - S^-_{t-\mathbf{T}}) \cdot \mathbf{T} + S_{t-\mathbf{T}} \tag{3}$$

$$G_t = (S^-_{t-\mathbf{T}} - G^-_{t-\mathbf{T}}) \cdot \mathbf{T} + G_{t-\mathbf{T}} \tag{4}$$

$\mathbf{T}$ denotes a discrete time interval. It is convenient to assume that t takes integer values, $t = 0, 1, 2, ...$, implying that $\mathbf{T} = 1$. In period $t = 1$, the stock variables take their initial values, $D_0 = R_0 = S_0 = 0$ and $G_0 = 1$. All stock variables are expressed in terms of [good.][6].

Now the stuff starts happening out there. The consumer determines the need for new goods N_t by comparing the actual stock of goods G_t with the desired level $\widetilde{G}$. To avoid mutliple counting, the measurement of the discrepancy needs to be adjusted for the outstanding demand stock.

$$N_t = (\widetilde{G} - G_t) - D_t \quad \text{[good.]} \tag{5}$$

[5]The equations give a simplified version of the code, in particular they omit problems as division by zero, making the flows non-negative, etc..

[6]The following abbreviations for the units are used: [good.] stands for goods units, [good./time int.] are goods units per time interval, [dmnl] stands for "dimensionless", and [$/good.] are currency units per goods unit.

The household (potential buyer) is financially constrained. As a result, the stock of effective demand does not increase by the total of the need for new goods, but only by its a_t-fraction. The affordability coefficient a_t is a decreasing linear function of the good's price on the interval $\langle 0.01, 0.9 \rangle$. The corresponding price interval lies between 0.1 and $P_t^F = F \cdot \bar{P}$ (in [$/good.]). The upper bound of the price interval is the maximum price the potential buyer is able or willing to pay for a unit of the good, and depends positively on the monetary and financial conditions F, in [dmnl]. In a dynamic viewpoint, higher good's price and worsened possibilities to borrow are two forces to dampen the demand side. The financing constraint imposed in the form the behavioural rule may be viewed as a paralell to a 'budget constraint' used in macroeconomic models (cf. Rebelo, 2005; Smets and Wouters, 2007). However, the difference is that those models include the agents' income as one of the endogenous variables. For reasons discussed in Sections 2.1-2.2, doing so is avoided here as it would inevitably grow the model in scope. Instead, the financing constraint uses the good's price, one of the key endogenous variables.

$$D_t^+ = (a_t \cdot N_t)/\mathbf{T} \quad \text{[good./time int.]} \tag{6}$$

$$a_t = \begin{cases} 0.9 & \text{if } P_{t-\mathbf{T}} < 0.1, \\ 0.01 & \text{if } P_{t-\mathbf{T}} > P^F, \\ \beta_1 \cdot P_{t-\mathbf{T}} + \beta_0 & \text{otherwise [dmnl]} \end{cases}$$

with $\beta_1 = (0.01 - 0.9)/(P^F - 0.1)$ and $\beta_0 = 0.9 - 0.1 \cdot \beta_1$.

Potential purchases create opportunity at the market to sell new goods O_t, which is, however, unobservable to the firm. The opportunity the firm actually perceives is a linear combination of the objective opportunity and past sales. The weight of the true opportunity is given by the information parameter $w \in \langle 0, 1 \rangle$. In the initial period, $S_0^- = 0$.

$$O_t = D_t^+ \cdot \mathbf{T} + D_t \quad \text{[good.]} \tag{7}$$

$$\widehat{O_t} = w \cdot O_t + (1 - w) \cdot S_{t-\mathbf{T}}^- \cdot \mathbf{T} \quad \text{[good.]} \tag{8}$$

The stock of goods in the production process increases by the perceived opportunity. The adjustment for the outstanding supply of finished goods reflects the preference of the firm to get rid of the previously accumulated inventory.

$$R_t^+ = (\widehat{O_t} - S_t)/\mathbf{T} \quad \text{[good./time int.]} \tag{9}$$

The firm faces a capacity constraint. Consequently, the volume of goods that can be produced over the time interval $\mathbf{T}$ depends on three sorts of factors: the default production capacity ϕ (in [good./time int.]), the firm's ability to expand out of own resources r_t and the access to external financing F. The ability to expand is a dimensionless coefficient computed as the ratio of revenues to the production costs. Whilst ϕ and F are exogenous to the model, r_t is endogenously generated. Due to r_t, the total capacity $\phi \cdot r_t \cdot F$ may be quite volatile. Again, there is a paralell between the capacity in this model and the investment process in the Ramsey class of models. Though investment and stock of capital are not introduced to this model as endogenous variables, it is relatively easy to 'reconstruct' them from the total capacity. The production capacity expansions and contractions may be viewed as an implicit investment process, 'elastic' to the flow of cash. The model does not distinguish between physical and human capital and there is no explicit production function. The idea is that a better rentability makes easier acquisition of additional production factors. Note that the pass-through from r_t is not 100%, as the coefficient is constrained to $\langle 0.8,\ 1.2 \rangle$.

$$r_t = (P_{t-1} \cdot S^-_{t-1})/(c \cdot R^-_{t-1}) \qquad \text{[dmnl]} \tag{10}$$

$$R^-_t = \min(R^+_t + R_t/\mathbf{T},\ \phi \cdot r_t \cdot F) \qquad \text{[good./time int.]} \tag{11}$$

In the initial period, the production volume $R^-_0 = 0$. In contrast to some other SD models with multi-stage supply chains, this paper features a simple, single stage supply side. The source of delays (lags) is solely the stock representation of the production R_t and supply S_t.

The demand and supply side of the market now come together to result in the good's purchases S^-_t. The price is a multiple of the price update factor u_t and the price of the previous period (initially, $P_0 = 1$). The effective demand is decreased by sales. Finally, the stock of goods eventually diminishes by fraction z.

$$S^-_t = \min((D^+_t \cdot \mathbf{T} + D_t),\ (R^-_t \cdot \mathbf{T} + S_t))/\mathbf{T} \qquad \text{[good./time int.]} \tag{12}$$

$$u_t = (D^+_t \cdot \mathbf{T} + D_t)/(R^-_t \cdot \mathbf{T} + S_t) \qquad \text{[dmnl]} \tag{13}$$

$$P_t = u_t \cdot P_{t-\mathbf{T}} \qquad \text{[\$/hous.]} \tag{14}$$

$$D^-_t = S^-_t \qquad \text{[good./time int.]} \tag{15}$$

$$G^-_t = z \cdot (S^-_t + G_t/\mathbf{T}) \qquad \text{[good./time int.]} \tag{16}$$

The model includes only one macroeconomic policy variable, the monetary and financial conditions F. The way this parameter is implemented in the model is characteristic. Again, to preserve the small-scale character of the model, F is exogenous and it is made part of the financing and capacity constraint. The primary role of the parameter is to represent the setting of monetary policy (mainly interest rates and liquidity conditions). In a broader view, F captures various factors that influence the consumer's and firm's access to borrowing such as loan-to-value and loan-to-income ratios, and others. Though fiscal policy is not present in the model, F demonstrates the way it could be implemented. Fiscal measures such as excise and income tax would be a part of the demand financing constraint, whereas corporate income taxes and subsidies would enter the supply side capacity constraint.

The most general specification of the model as laid out by the equations (Setup 8) includes three sorts of features:

• Imperfect information: The parameter w in (8) controls to what extent the firm is informed on the true stock of demand. The firm is perfectly informed if $w = 1$.

• Financing constraint: With a higher price, the household can afford relatively less. This is controlled by the affordability coefficient a_t in (6). The household is financially unconstrained if $a = 1$.

• Capacity constraint: With higher production volumes, the firm finds production increasingly difficult. The capacity constraint in (11) is relaxed if $R_t^- = R_t^+ + R_t/\mathbf{T}$.

The remaining model specifications (Setup 1 to 7) differ in at least one of these features (Table 2). The purpose of presenting the eigth setups is to make clear the effect of each of the constraints (its absence, presence and tightness) on the model dynamics.

Table 2: Comparison of model setups

	1	2	3	4	5	6	7	8
Imperfect knowledge	-	-	-	-	√	√	√	√
Financial constraint	-	-	√	√	-	-	√	√
Capacity constraint	-	√	-	√	-	√	-	√

2.4 Feedback loop structure

The model structure consists from the following feedback loops (Figure 1):

• B1 is the main balancing loop linking the four stock variables, demand, production, supply and goods. It may be viewed as a behavioural representation of the household problem to optimize. The objective (goal) is to hold an optimal stock of goods. The discrepancy between the desired and the actual stock of goods stimulates corrective actions on the demand and supply side which in turn diminish the discrepancy.

• B2 is the balancing loop linking the effective demand and the price. Demand pushes the price upwards, which in turn limits the purchasing power of the potential buyer.

• B3 links the production volume with the inventory stock. The inflow to production is

smaller at higher levels of inventory.
• B4 links the discrepancy with the demand stock and reflects the adjustment in the discrepancy measurement to avoid multiple counting.
• B5 links finished goods with the firm's ability to expand. The more goods are finished, the higher is the total production cost which in turn decreases the revenue to cost ratio.
• B6 links the good's price and the stock of supply. Higher price boosts rentability which makes it easier to finish more goods per period. Larger supplied quantity pushes in turn the price downwards.
• R1 is the main reinforcing loop that links the demand, production, supply and price. The effective demand boosts the supply of goods through the opportunity to sell perceived by the firm. Larger supply lowers the price, which in turn stimulates demand through increased affordability.
• R2 links sales (outflow from the inventory) with the perceived opportunity to sell. Higher sales stimulate the perception of the firm that the demand for the good is strong which in turn boosts the production.
• In R3, sales potentially increase the production through the improved ability of the firm to expand the production capacity.
• R4 is the powerful reinforcing loop governing the price. It is this loop that causes the price to "boom" and "bust" depending on the relative strength of the two market sides.

System dynamics sees the causation (or feedback) as a two-way phenomenon. Practically it means that each of the variables in a loop affects the remaining ones in turn (cf. Meadows and Robinson, 1985; Wheat, 2007).

2.5 Properties of the DE system

The system of difference equations (DE) in Section 2.3 is characterized by an attractor type of equilibrium point. Mathematical investigation of the DE system suggests, that the dynamic behaviour of some of the variables (mainly good's price, profit, revenue to cost and inventory) will differ between the eigth model setups.

There are two principal cases.

In Setup 1 and 3, the demanded and supplied quantity are equal all times: $D_t^+ + D_t = R_t^- + S_t \; \forall \; t = 0, 1, 2, \dots$. Setting $w = 1$ in equation (8) and considering that $R_t^- = R_t^+ + R_t/\mathbf{T}$ in (11) yields: $R_t^- = \max(0, (D_t^+ \cdot \mathbf{T} + D_t - S_t)\mathbf{T} + R_t/\mathbf{T})$. This must hold for any t. In the initial period, D_0, S_0 and R_0 equal zero which implies $R_0^- = \max(0, D_0^+)$. This in turn causes that in the following period $D_1 = S_1 = R_1 = 0$ again. The price update factor is then $u_t = D_t^+ \cdot \mathbf{T}/R_t^- \cdot \mathbf{T} = 1 \; \forall \; t = 0, 1, 2, \dots$. From this follows $P_t = u_t \cdot P_{t-1} = P_0 = 1$. The level of inventory S_t and firm profit are zero all times.

In the remaining Setups 2, 4-8, the equality between the demanded and supplied quantity is distorted. This is either because of imperfect knowledge ($w < 1$) or because of the capacity constraint or both. Suppose a preference shock to the desired level of the good such that $\widetilde{G}_t \neq G_t$. The stock of inventory is non-zero. The model converges to a new equilibrium with $\widetilde{G}^* = G^*$. The price update factor $u^* = (D^{+,*} \cdot \mathbf{T} + D^*)/(R^{-,*} \cdot \mathbf{T} + S^*)$. Thus $u^* = 0/S^* = 0$. The new equilibrium price asymptotically satisfies $P^* = u^* \cdot P^* = 0$.

The parameters have the following effect on the dynamics. A positive shock to the discrepancy N_t, caused either by a shock to the desired good stock $\widetilde{G}_t$ or by a shock to z (in G_t^-), will result in a disequilibrium situation. All other parameters[7] do affect the convergence dynamics, but do not cause a disequilibrium situation by themselves.

3 The results

The model generates fluctuations in real variables and price with a time-varying mean and volatility.

This section reviews the results of two sorts of model simulations. First, in Section 3.1 the response to a one-off increase in the desired good stock $\widetilde{G}_t$ is simulated and compared across the eigth setups. This gives an idea on the overall role of various constraints for the generated dynamics. Second, in Section 3.2 the response to a time trend in $\widetilde{G}_t$ is simulated under various values of selected parameters. The purpose is to understand in what way the length and amplitude of fluctuations depend on the tightness of the constraints.

The simulations avoid using randomness in the exogenous inputs [8]. Both the one-off shocks and the time trend are deterministic. Hence, 100% of the generated "oscillatory" pattern has its origin in the feedback loop structure of the system dynamics model.
The descriptive variables (apart from those mentioned in Section 2.2) are computed as follows:
$\text{demand}_t = D_t^+ \cdot \mathrm{T} + D_t$
$\text{supply}_t = R_t^- \cdot \mathrm{T} + S_t$

[7]The parameters encompass in a behavioural way some of the shocks standardly used in the macroeconomic literature on BCs. Shocks to the desired good's stock $\widetilde{G}_t$ are in fact preference shocks. Monetary policy and interest rate shocks are approximated by the monetary and financial conditions parameter F. Finally, shocks to the default capacity ϕ may be viewed as a parallel to the technology or productivity shocks (cf. Smets and Wouters, 2007).

[8]The exogenous series discussed in this section are constructed as $\widetilde{G}_t = (1+\gamma_1)^t \cdot \gamma_0$ and $\phi_t = (1+\delta_1)^t \cdot \delta_0, t = 0, 1, 2, ...$

profit$_t$ $= P_t \cdot S_t^- - c \cdot R_t^-$
revenue to cost$_t$ $= (P_t \cdot S_t^-)/(c \cdot R_t^-)$
capacity utilization$_t$ $= (R_t^-/(\phi_t \cdot r_t \cdot F_t)) \cdot 100$
inventory$_t$ $= S_t$
output$_t$ $= P_0 \cdot S_t^- + c \cdot (R_t^- - S_t^-)$
growth$_t$ $=$ (output$_t$/output$_{t-1}$ $- 1) \cdot 100$
inflation$_t$$= (P_t/P_{t-1} - 1) \cdot 100$
Output is considered at constant prices of the initial period, $P_0 = 1$ and the corresponding period-to-period rate of change gives the real growth rate.

Finally, the list of variables is complemented by a translation of the key variable names into the textbook macroeconomic jargon: The "C" (private consumption expenditure in real terms) would correspond to the model variable sales S_t^-. Private investment "I" would correspond to the sum of new investment and the change in inventories, $c \cdot (R_t^- - S_t^-)$. (New investment can be reconstructed from the evolution of the overall capacity, if one normalizes the initial value of the capital stock to 1. One obtains a procyclically behaving variable.) The following Sections 3.1 and 3.2 make clear that this model does generate endogenously volatile consumption and investment, starting with zero initial values. This is in a sharp contrast to the mainstream macroeconomic papers which construct volatile series using autoregressive (AR) processes with positive initial values and exogenous stochastic shocks.

3.1 Response to a one-off shock in $\widetilde{G}_t$

Figures 2-3 (in Appendix) give the response of the eight model setups (columns 1 to 8) to a one-off increase in the desired level of the good. For the first few periods, $\widetilde{G}$ equals the initial value of the good's stock $G_0 = 1$, then it makes a one-off jump to 1.05 and remains at that level for the remaining periods.

The values of the remaining parameters are: price cap $\bar{P} = 5.1$, the default capacity $\phi = 0.02$, unit cost $c = 1$, monetary and financial conditions $F = 1$. The knowledge parameter w equals 1 in Setup 1 to 4 and is set to 0.5 in Setup 5 to 8. Finally, the fraction of the good stock consumed each period $z = 0$ so that the outflow rate G_t^- is zero.

As follows from the discussion in Section 2.5, the behaviour of the variables differs between the eigth model setups. In Setup 1 and 3, the value of the price never changes ($P_t = 1 \ \forall \ t = 0, 1, 2, \ldots$) and inventory is zero all times. The other variables make a "jump" from the initial equilibrium value to the new equlibrium value in just one time step. The remaining setups 2, 4-8, are characterized by inventory build-up and. The other variables follow a less or more complicated trajectory from the initial equilibrium value to the new equilibrium value (the convergence takes longer to proceed than just one time step).

3.2 Scenarios

The response of the market to a sequence of shocks to the desired good's stock is simulated under different values of the following parameters: the default capacity δ_0, the maximum payable price $\bar{P}$, the monetary and financial conditions F and the knowledge parameter w. These parameters are involved in the behavioural constraints on one or both the demand and supply side. The time trend in $\widetilde{G}_t$ is constructed with $\gamma_0 = 1.05$ and $\gamma_1 = 0.005$. The default values of other parameters in this bunch of simulations are: $\delta_0 = 0.01$, $\delta_1 = 0.02$, $\bar{P} = 5.1$, $F = 1$, $c = 1$, $z = 0$. The parameter w by default equals 1 in Setup 1 to 4 and is set to 0.5 elsewhere.

In analogy to the one-off simulations in Section 3.1, Setup 1 and 3 yield a quick convergence to the dynamic equilibrium, whilst in the remaining setups the convergence is more complicated.

Figures 4-7 (in Appendix) illustrate the results for the most general model Setup 8. Comparison of trajectories under different parameter values shows that the amplitude of the "oscillatory" pattern in the real variables and price is sensitive to the tigthness of the behavioural constraint. The knowledge parameter plays a specific role in the model. The extent to what the supply and the demand side are "connected" in terms of information has a dramatic effect on the generated dynamics.

Despite making an impression of 'irregularity' or 'chaotic' behaviour, from the mathematical viewpoint the generated dynamics is deterministic.

3.3 Sensitivity results

Sensitivity analysis quantifies the robustness of the model behaviour with respect to the assumptions (parameters).

Two types of analyses have been performed: univariate and multivariate, involving one or all of the parameters the ϕ, $\bar{P}$, F and w.

The sensitivity tests confirm that price and sales (i.e. the 'real' part of output) are 'behaviour mode' sensitive with respect to each of the behavioural constraints: the demand side financing constraint, the supply side capacity constraint and the knowledge parameter (see the classification of Sterman, 2000, p. 883).

Selected results of the multivariate sensitivity tests, performed for the price and sales (de facto the 'real' part of the output), are included in Figure 8a-b (in Appendix). More results are available upon request.

3.4 Model dynamic behaviour

The simulation results illustrate the power of building causal models. The structure consisting of reinforcing and balancing feedback loops (discussion in Section 2.3) generates patterns of behaviour that seem very different from each other if not "opposing".

A relatively simple example regards the good's price. The 'boom and bust' pattern is driven by the reinforcing loop R4 and the price update factor u_t. This simple structure pushes the price upwards if $u_t > 1$, keeps it unchanged if $u_t = 1$ and drags it downwards if $u_t < 1$.

The supply side of the model represents a more complicated example, involving a larger number of loops: B3, B5, B6, R2 and R3 that work together with the two main model loops B1 and R1. In this case the direction (rise or fall) and intensity (moderate or strong) of the supplied quantity dynamics result from the dominance of balancing or reinforcing loops.

4 Discussion

This paper takes seriously some of the criticisms levelled at the mainstream macroeconomic models. To this end, the paper makes use of the system dynamics methodology, including some of its applications in the older generation of SD macroeconomic literature. Section 2 introduces a small-scale model that endogenously generates fluctuations in real variables and price with a time-varying mean and volatility. There are two possible interpretations of the model, microeconomic and macroeconomic, though the focus of the paper is on the latter. The model represents a closed economy with a boundedly rational consumer and firm that do interact at the market with an abstract good. As one of the key characteristics, this is a disequilibrium model which means that one does not a priori impose the market equilibrium condition.

The model serves experimental purposes and is intended as a first stage to developing a fully-fledged macroeconomic model, thus it is highly reduced in scope. Many features are simplified, such as the decision-making problems of the agents or the linear financing constraint. At later stages, when the model is expanded to a larger macroeconomic setup, some of these elements automatically drop, some others are replaced by more appropriate (possibly nonlinear) relationships, and economic choices are modelled in-depth. Also, the representative character of the agents is felt as a simplification, which, if necessary, may well be overcome by translating the SD model into an agent-based model (ACE).

Compared to the mainstream literature which is based on rational expectation hypothesis and general equilibrium, this paper incorporates many ad hoc features. This is because economics has nothing like generally acceptable 'standards' for the behaviour of individuals with limited cognitive abilities. As De Grauwe (2010) puts it, once we leave the comfortable world of rational expectations, ad hoc assumptions are inevitable. I believe that establishing appropriate 'standards' for boundedly rational economic agents will need to take into account the results of experiments with humans and their socio-economic choices.

The results of simulations in Section 3 with the exploratory model imply useful insights in the following three areas:

[1.] The first area relates to the **economy structure**. Given that there is no agents' heterogeneity and the exogenous dynamics is deterministic and simple, the model-generated dynamics must be attributed to the structure of the model economy. More precisely, it owes to the coordination problems between the consumer and the firm.

The known SD models of older generation too gave rise to short- to long-run cycles in economic activity. Those models were large-sized models with many interacting sectors or with complicated multiple-stage supply chains (cf. Forrester, 1980; Mass, 1975; Sterman, 2000). This paper shows that it takes less than many interacting sectors or supply chain stages with intermediate delays for the economic fluctuations to arise. In fact, a simple stock-based representation of the supply side suffices to account for the "oscillatory" patterns in output, provided that the information about the true demanded quantity is imperfect and the capacity is constrained. Thus this reconfirms the intuition of Foley (2010) and others that social coordination are central to macroeconomic dynamics.

As a consequence, the model does not show any straight way for macroeconomic policies to reduce volatility in real output and price. These dynamics appear as symptoms of the real-world market inefficiencies. On the other hand, structural policy measures appear as a good idea in order to improve the coordination between the demand and supply side of the markets (by improving the information, increasing the flexibility of the labour market, etc.). In the language of the model, such measures would work toward eliminating the behavioural constraints.

Also, the simulation results encourage strengthening frameworks for timely microeconomic surveys on variables that are currently regarded as "unobservables", namely the demand and supply as stock-variable based concepts, the actual capacity utilization and some others, as these appear crucial for a proper understanding of the business cycle phasing.

[2.] The second area relates to the **external factors** that influence the simple model economy. The model is reduced in scope so that income flows, labour and capital market dynamics and many other factors are represented in the form of parameters or behavioural constraints (Sections 2.2-2.3). This gives the modeller the possibility to experiment with extreme conditions. Section 3.2 then shows that the properties of the fluctuations in real variables and the good's price, once they arise, are sensitive to the tightness of those behavioural constraints. In other words, the external factors such as other markets, the financial system or macroeconomic policies have the potential to impact the market dynamics through both sides of the demand-supply mechanism.

To give a specific example, Figure 5 (in Appendix) shows that relaxing the financing constraint on the demand side creates room for building up of price "bubbles". In practice, something like this could be achieved e.g. through tax cuts or monetary policy easing. A recent example of this sort of cause-and-effect could be the low interest rate policy of the Fed to result in the housing market bubble (see e.g. Taylor, 2007).

[3.] The third area relates to the true **possibilities of macroeconomic stabilization**. The results of this paper, illustrated by Figures 4-7 (in Appendix), establish two sorts of stylized facts. The first is that the proportion between the rises and falls in output is virtually one-to-one. The second is that the booms and busts are driven by the same causal mechanisms. In the simulations, both good and bad times follow after a prolonged sequence of demand pull shocks (Section 3.2). Taken together, these stylized facts could be understood as 'stabilization disillusion'. This is a very serious preliminary result that can have dramatic consequences for the current understanding of macroeconomic policy making. It must be tested further with utmost care. At this stage, however, it can be said that this paper makes an important step to address the need to model the abnormal times as a special case of normal times. According to some it is the necessary condition for a model to serve as a fundamental scientific model (cf. Colander, 2011).

To conclude, by using high-level mathematical tools and formalizing some of the important criticisms of the mainstream, this paper provides research material that is worthwhile to expand further. The first results document that the disequilibrium system dynamics modelling is a promising alternative to the prevailing general equilibrium models.

Acknowledgements

I thank Johan Springael for encouraging suggestions while developing the experimental model and many useful examples (such as the $\dot{x} = v$, $\dot{v} = a$ problem), and My Wise Teacher for the mixture of curious interest and constructive disagreement. Thank is due to Guido Erreygers for valuable editing comments and to the participants of the doctoral seminar held at the Department of Economics of the University of Antwerp in April 2011, in particular Andre Van Poeck, Jacques Vanneste and Walter Nonneman, for the interesting discussion. Responsibility for the text and the remaining errors is my own. Financial support of the University of Antwerp is gratefully acknowledged.

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Appendix

Figure 2: Response to one-off shocks in $\tilde{G}_t$

Figure 3: Response to one-off shocks in $\widetilde{G}_t$

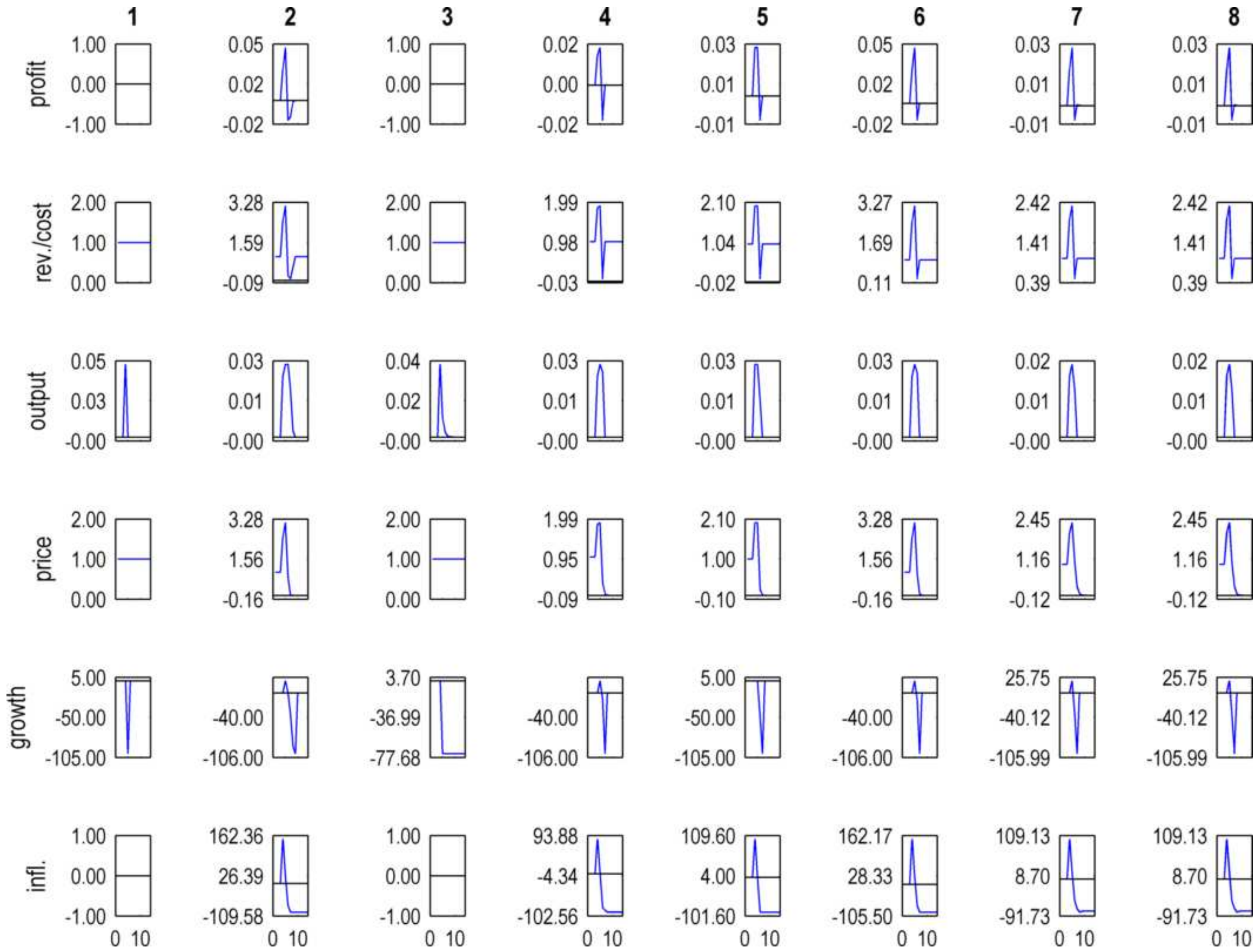

Figure 4: Scenario simulation (capacity constraint)

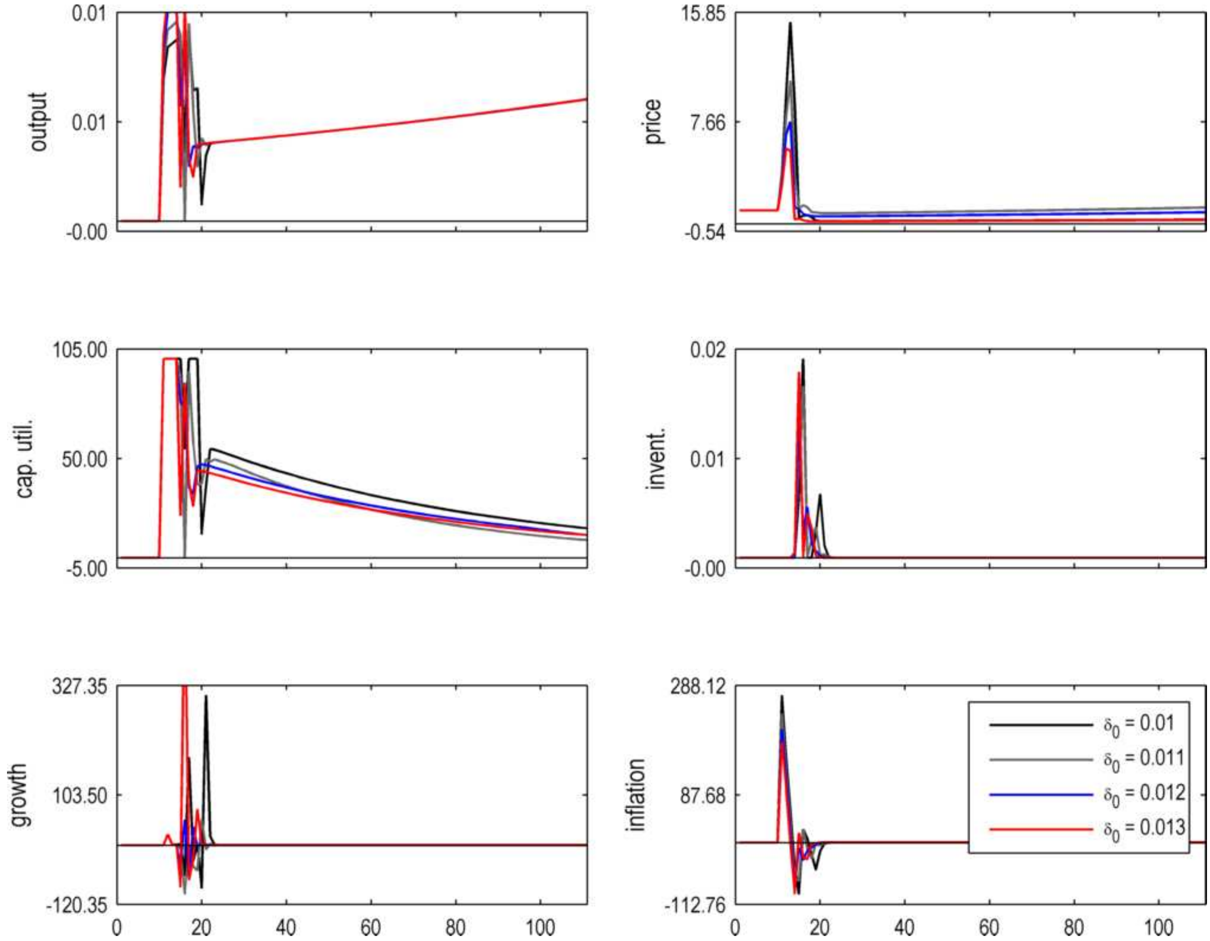

Figure 5: Scenario simulation (financing constraint)

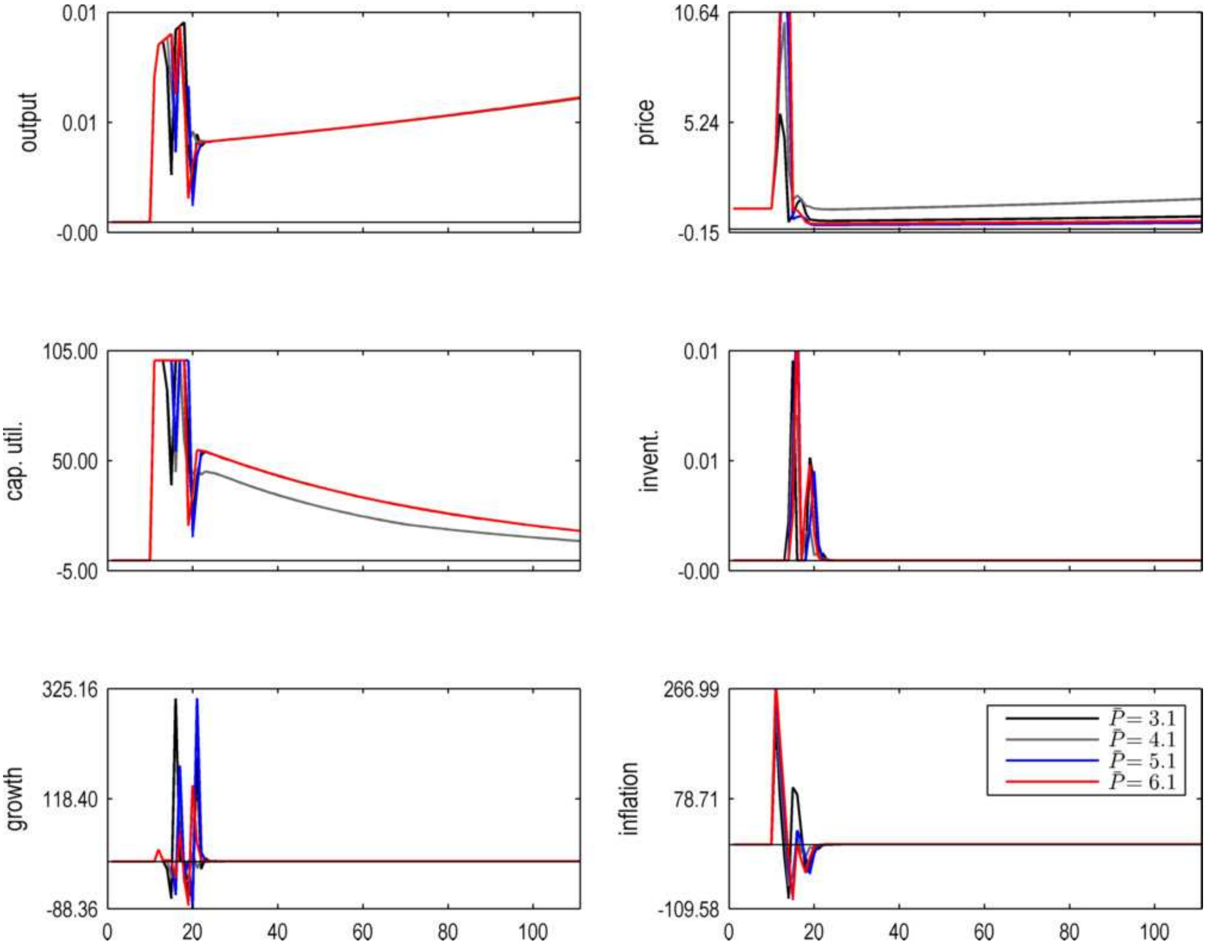

Figure 6: Scenario simulation (information)

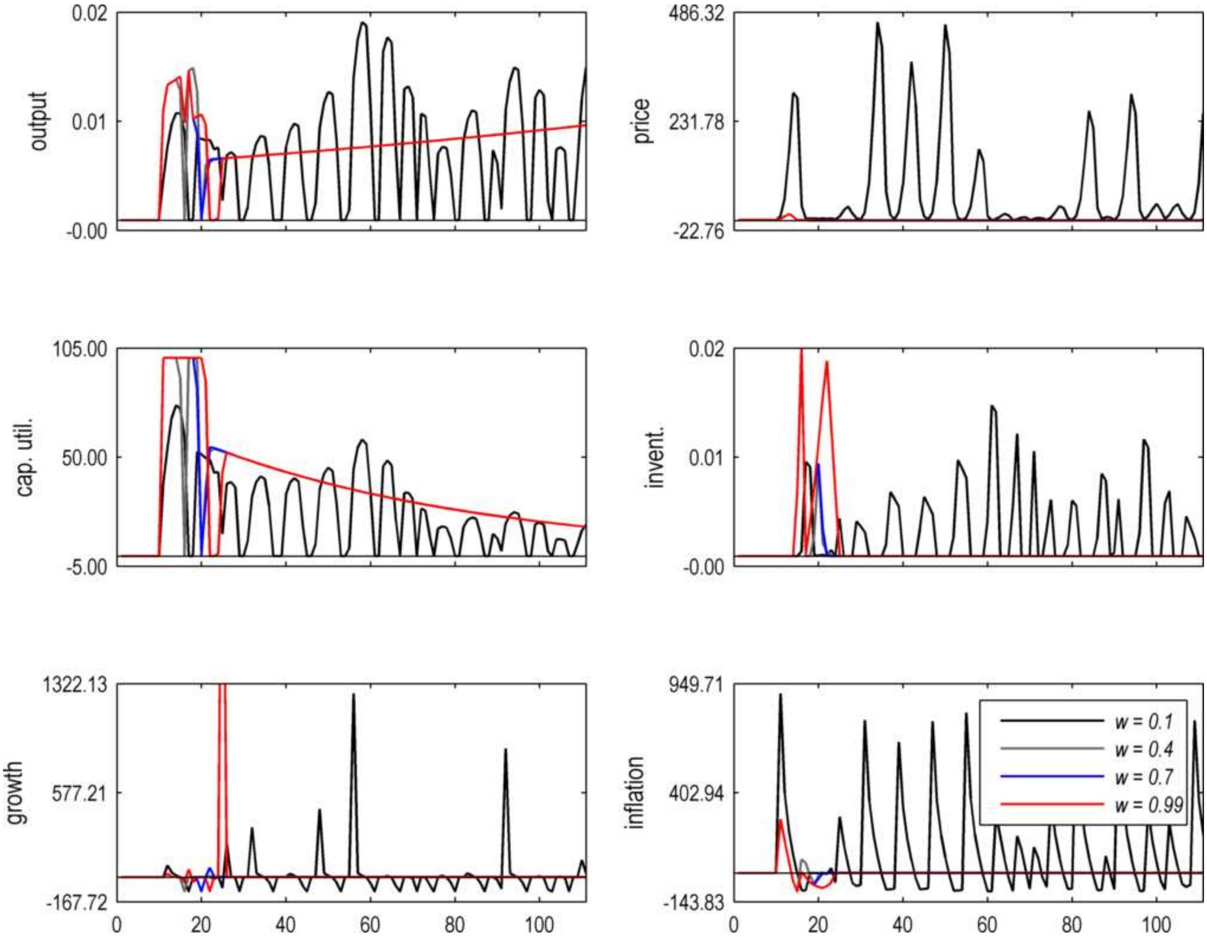

Figure 7: Scenario simulation (monetary and financial conditions)

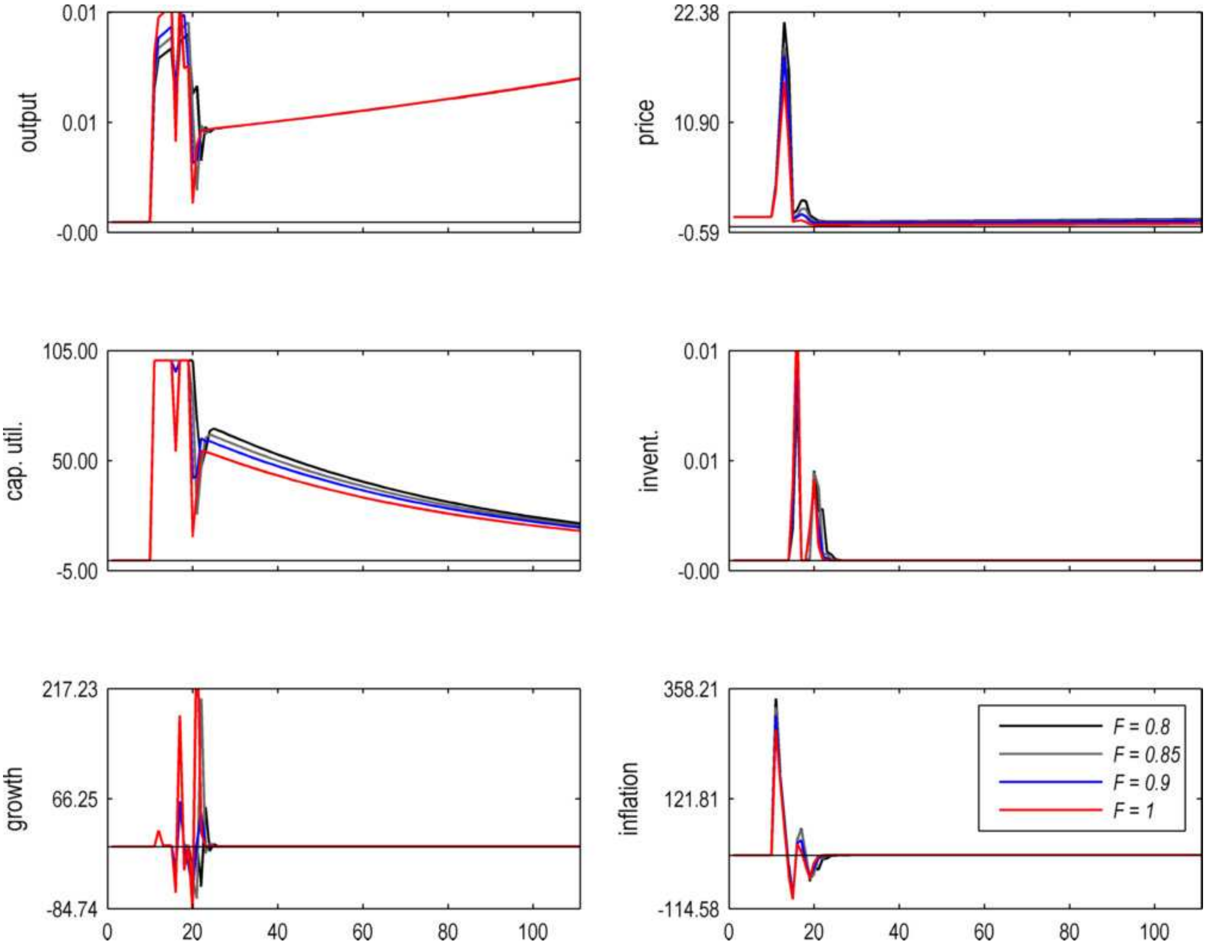

Figure 8a: Sensitivity analysis (good's price)

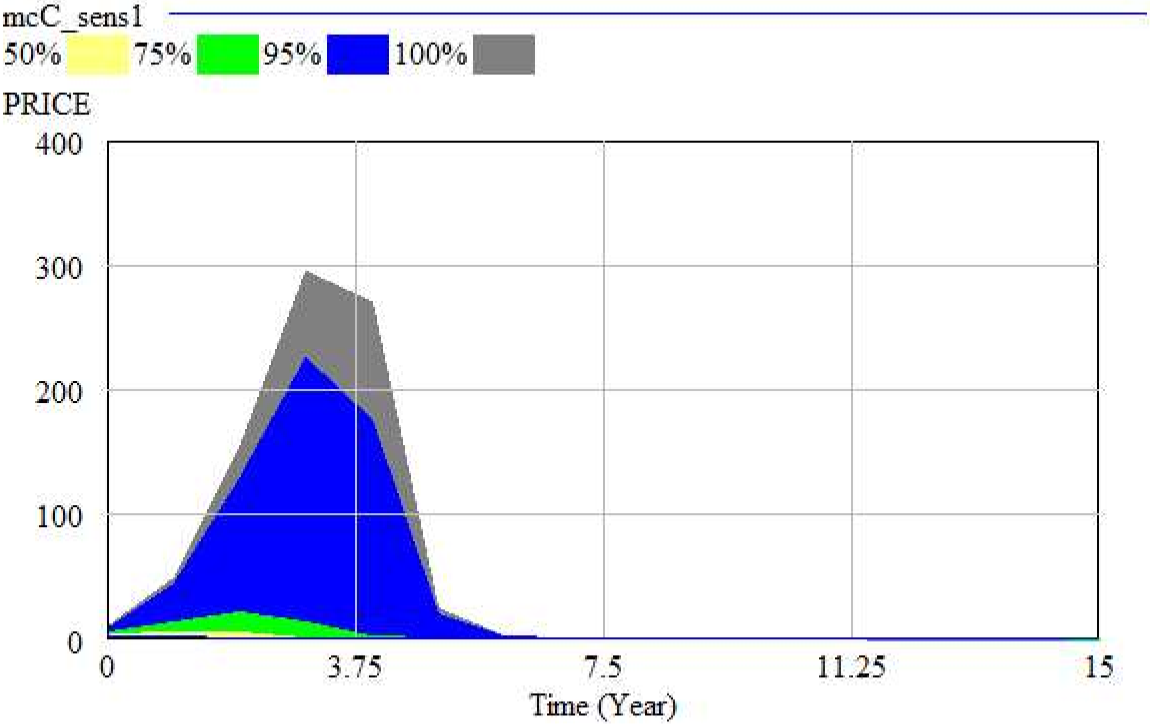

Figure 8b: Sensitivity analysis (sales)