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Harrodian instability in decentralized economies: an agent-based approach

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Abstract

This paper presents a small-scale agent-based extension of the so-called neo-Kaleckian model. The aim is to investigate the emergence of Harrodian instability in decentralized market economies. We introduce a parsimonious microfoundation of investment decisions. Agents have heterogeneous expectations about demand growth and set idiosyncratically their investment expenditures. Interactions occur through demand externalities.

We simulate the model under different scenarios. First, when heterogeneity is ruled out, Harrodian instability is showed to emerge as for the aggregate model. Instead, when heterogeneity is accounted for, a stable dynamics with endogenous fluctuations arises. At the same time, in this second scenario, all the Keynesian implications are preserved, including the presence of macroeconomic paradoxes. Sensitivity analysis confirms the general robustness of our results and the logical consistency of the model.

Keywords Harrodian Instability · Agent-Based Models · Coordination Failures · Heterogeneous Expectations · Neo-Kaleckian model.

JEL classification E03 · E12 · E27

1 Introduction

This paper contributes to the open and vivid debate on Harrodian instability (H-I) in post-Keynesian macro models. To this purpose, we develop an agent-based model to analyze the impact of H-I in an economy with decentralized and heterogeneous investment decisions.

In light of the Great Recession post-Keynesian theory has gained renewed popularity given the importance ascribed to aggregate demand and income distribution. Nevertheless, the approach still faces some important puzzles which need to be solved. Among them, the emergence of H-I is certainly one of the most relevant. As originally put forward by Harrod (1939), equilibrium growth paths tend to be highly unstable in models featuring both multiplier and accelerator effects. Any deviation from the steady-state will be self-reinforcing, driving the economy either to hyperinflation or to never-ending recession.

To discuss the problem of H-I we take as a benchmark the so-called neo-Kaleckian (N-K) model (Dutt, 1984; Rowthorn, 1981). The latter achieved increasing consensus among heterodox scholars in recent years. Part of its success is due to the simple linear structure adopted, which overcomes some theoretical problems found in the first generation of post-Keynesian growth models (Kaldor, 1957; Robinson, 1956). In a famous extension, Bhaduri and Marglin (1990) introduced the possibility to study the links between growth and functional distribution under various demand regimes.

It has been showed (Hein et al., 2010) that instability in the N-K framework emerges when demand expectations are allowed to adjust adaptively. Hence, the model faces an important trade-off between learning and stability. In particular, H-I can be seen as a coordination failure: it originates from entrepreneurs inability to internalize demand externalities associated with new investments.

A large literature has investigated coordination mechanisms and failures (Cooper and John, 1988; Howitt, 2006*a*,*b*; Leijonhufvud, 1972). While the N-K model is aggregative, analyzing in depth problems of coordination, instead, usually requires a multi-agent perspective. For instance, *New Keynesian* models have incorporated a game theoretic framework to deal with demand externalities (Blanchard and Kiyotaki, 1987; Diamond, 1982). An alternative growing field of research, the so-called agent-based computational economics (ACE), has instead considered the economy as a *complex evolving system*[1]. In agent-based models (ABM) the aggregate dynamics emerges as a result of decentralized interactions among boundedly rational, heterogeneous agents[2]. In this respect, ABM are well-suited to study coordination (or lack of) of investment decisions and expectations, which, as already discussed, lies at the heart of instability problems.

Most of the solutions to H-I proposed so far are focused on modifications of the aggregate investment function. Our approach is, instead, to develop a simple ABM version of the N-K model. In particular, we build an artificial economy with decentralized investment decisions. Agents are assumed to modify their expectations in an adaptive way and heterogeneity is introduced by idiosyncratic shocks. In such context, we address some important questions concerning: (i) the stability

[1] For an introduction to the methodology see Tesfatsion and Judd (2006).

[2] Examples of macro ABM can be found in: Gatti et al. (2010), Ashraf et al. (2011), Dawid et al. (2014), Riccetti et al. (2015), Seppecher and Salle (2015), Dosi et al. (2013, 2015, 2010, 2017); Lamperti et al. (2017), Caiani et al. (2016) and Popoyan et al. (2017). For a detailed review of the literature see Fagiolo and Roventini (2012, 2016).

properties of the model with decentralized investments; (ii) the impact of learning and adaptation upon stability; (iii) the nature of growth, whether it is still demand-driven or not; (iv) the presence of macroeconomic paradoxes; (v) the characteristic of the process governing the evolution of aggregate capacity utilization.

Similar efforts have recently been made in relaxing some assumptions of DSGE models to incorporate heterogeneity (Massaro, 2013) and interactions (Guerini et al., 2017). The lack of parallel attempts in a post-Keynesian framework is somehow surprising. While the development of large-scale ABM exhibiting Keynesian features turned out to provide important results, more parsimonious approaches have not yet been systematically explored[3]. Nonetheless they can be equally promising in addressing specific relevant issues. Here we try to fill this gap by isolating a single aspect (i.e. Harrodian instability) and studying how it can be affected by a small deviation from the canonical model.

As a first step, we simulate our economy removing heterogeneity and show that results are symmetrical to the aggregate N-K model: H-I emerges when firms are allowed to adapt their expectations. Then, we introduce idiosyncratic random prediction errors. In this second scenario aggregate dynamics becomes stable. The evolution of national capacity utilization, consistently with the empirical evidence (Nikiforos, 2015), is described by an I(1) process which do not exhibit any strong trending behaviour. Since prediction errors are transitory, expectations are still linked to the evolution of demand. Therefore, the above-mentioned trade-off between learning and stability is overcome. At the same time, the economy is showed to preserve all the features found in Keynesian growth models, including the endogeneity of utilization rates and the presence of macroeconomic paradoxes.

The intuition underlying these results is rather simple: when heterogeneity is introduced, optimistic firms will coexist with pessimistic ones. Investment decisions cease be symmetrical and uni-directional. As a consequence, in response to a shock, entrepreneurs will not coordinate anymore towards ever-rising (-decreasing) investment levels.

Our results are particularly important from a methodological point of view. We stress the crucial role played by heterogeneity and individual biases in stabilizing the system as they can break self-reinforcing patterns of bad coordination. More efforts should be devoted to the implementation of these features in post-Keynesian models. Finally, well in tune with the works of Keynes himself, they also show the importance of complexity-based microfoundations which are able generate intriguing macroeconomic phenomena as emergent properties of the system.

The reminder of this paper is organized as follows: Section 2 discusses H-I in the standard N-K model; Section 3 presents an overview of the existing literature; Section 4 introduces the model; results and sensitivity tests are reported in Section 5; finally, Section 6 concludes.

[3]Large-scale Kaleckian ABM are presented in Gibson and Setterfield (2015); Setterfield and Budd (2011)

2 Harrodian instability in the baseline model: a coordination failure

The standard textbook version of the neo-Kaleckian model is composed by three equations:

$$g_i = \frac{I}{K} = g^e + \gamma_u(U - u_n) \tag{N-K 1}$$

$$g_s = \frac{S}{K} = s_p R \tag{N-K 2}$$

$$R = \frac{mU}{v} \tag{N-K 3}$$

Equation (N-K 1) is the investment function. Capital accumulation (g_i) is assumed to be affected by an exogenous thrift (g^e) and by discrepancies between actual capacity utilization U and the targeted level u_n[4]. As pointed out in Committeri (1986), the term g^e has to be interpreted as the "animal spirits" component, representing expectations about long-run demand growth. Intuitively, when capacity is utilized at the desired level ($U = u_n$) entrepreneurs will invest just to accommodate future expected demand movements. Target utilization (u_n), in this simple version, is assumed to be exogenous and less than 100%. In tune with the empirical evidence (Steindl, 1952), firms want to keep a portion of idle capacity in order to match unanticipated demand flows.

Equation (N-K 2) is the dynamic version of the standard Cambridge saving function. When workers consume all their income, the growth rate of savings (g_s) is given by the profit rate R times capitalists propensity to save (s_p).

Finally, Equation (N-K 3) is an accounting identity implicitly derived from the assumption of a simple mark-up pricing rule. It links the realized rate of profit R to: the mark-up ratio m, the capital to capacity ratio v and the utilization of capacity U. By imposing the long run equilibrium condition $g_i = g_s$, the steady-state level of capacity utilization can be obtained:

$$U^* = \frac{g^e - \gamma_u u_n}{s_p m/v - \gamma_u}$$

At the steady state, in absence of technical change, total output and employment grow at a constant rate. The primary source of income growth are entrepreneurs animal spirits since they drive investments and capital accumulation.

In order for the solution to be stable, the so-called *Keynesian stability* condition is imposed. It requires the accumulation function to be less steep than the saving one. Loosely speaking, investments must not be too sensitive to variations in the utilization rate, as it was the case in Keynes short-run theory of income determination. In mathematical terms this amounts to:

$$s_p r_n / u_n > \gamma_u$$

Two important features of the equilibrium just obtained must be emphasized:

[4]Given the focus on instability problems, we use the functional form presented by Hein et al. (2010). For the sake of simplicity, it includes neither the realized profit rate nor the profit share. We therefore exclude the possibility of profit-led regimes.

- U^* is endogenous and does not coincide, if not by chance, with the target u_n. Demand conditions play a central role in determining utilization of productive resources.
- $\frac{\partial U^*}{\partial m} < 0$ and $\frac{\partial U^*}{\partial s_p} < 0$. The model implies the paradox of thrift and that of costs. A positive shock in the propensity to save, instead of promoting investments, will bring about lower utilization rates and capital accumulation because of the fall in aggregate expenditure. Symmetrically, a rise in the mark-up (i.e. a fall in real wages), contrary to the standard intuition, will have detrimental effects on growth, capacity utilization and employment. Wages are indeed both a cost for firms and an important component of aggregate demand.

Such conditions make growth unambiguously demand-led. In discussing different solutions to H-I we will always take these two implications as benchmarks for comparisons.

So far, however, the expectation term is an exogenous parameter. In addition to this, the obtained equilibrium requires expectations to be continuously unfulfilled in order to be sustained. The constant prediction error can be computed from Equation (N-K 1):

$$g^* - g^e = \gamma_u(U^* - u_n)$$

Hence, the endogeneity of U arises from a permanent collective failure to anticipate demand evolution. Entrepreneurs have to keep their forecasts fixed notwithstanding their sales steadily grow at a different rate. It seems more realistic instead to assume that, in the medium run, firms try to revise expectations adaptively. This implies a fourth differential equation:

$$\dot{g}^e = \theta(g^* - g^e) \tag{N-K 4}$$

The expectation term g^e is now endogenized. Since g^e refers to the expected trend of demand, the adjustment is generally assumed to occur slowly, entailing a relatively small θ. Once augmented with the learning equation (N-K 4) the only possible equilibrium solution implies:

$$U^* = u_n \quad \text{and} \quad g^* = g^e$$

Notice that the endogeneity of U is now lost. Furthermore, it can be proven that such new equilibrium is not stable anymore. Intuitively, let us suppose that a positive demand shock drives the economy away from the balanced growth path to a state with: $U > u_n$. Entrepreneurs will respond to over-utilization by increasing the speed of investment (cfr Eq. N-K 1). This, in turn, lead to higher income growth. Expectations will slowly adjust to the new trend of demand. As a result, the investment function will shift upwards rising once again the growth rate of the economy. Cumulative feedbacks between revision of expectations and demand growth bring about ever-rising (ever-decreasing) levels of utilization. To put it differently, individual attempts to adjust capacity and expectations lead to aggregate instability. This is a typical coordination failure (Cooper and John, 1988). When evaluating new investments plans, agents only consider the private effect while they do not internalize the underlying demand externality[5]. This is how *Harrodian instability* emerges in the N-K model.

[5]Differently from the standard definition (Cooper and John, 1988), the coordination failure associated to H-I does

The model presented so far is aggregative. The investment function is obtained for a representative firm. In this respect, the long run expectation g^e constitutes a black-box. One can reasonably conjecture that it results from some microeconomic mechanisms which, nevertheless, are not sketched and cannot be grasped by focusing exclusively on aggregate equations. The purpose of this paper is to open the black-box, introducing a simple ABM microfoundation for investments. We will show how standard conclusions about H-I can be reverted in such new setting.

3 Review of the literature

Our approach differs in many respects from other solutions to H-I found in the literature[6]. These have been primarily concerned with the identification of the so-called *traverse* mechanisms. The system of equations is conveniently modified to achieve the consistency condition: $U = u_n$. A *traverse* mechanism slowly drives the economy towards the target utilization level. Therefore it allows the model to move from the short- to the long-run.

Kaleckian authors have proposed a specific *traverse* in which the target rate of utilization slowly converges to the realized one (Dutt, 1997; Lavoie, 1995). According to them, u_n becomes endogenous in the long run, being affected by past realizations of U. From a formal point of view the argument is correct. Once coupled with this mechanism, stability is restored as well as all the implications found in the canonical model. However, the whole adjustment has been severely criticized for lacking of an economic rationale (Palumbo and Trezzini, 2003; Shaikh, 2009; Skott, 2012). In fact it implies a sort of unrealistic satisficing behaviour: firms will respond passively to situations with excess of (shortage of) capacity. They will simply modify targets instead of adjusting their capital stocks. Other specific assumptions such as economies of scale in production (Nikiforos, 2015) and conflicting claims between managers and shareholders (Dallery and Van Treeck, 2011) have been introduced to make Kaleckian arguments more solid. Although interesting, none of these solutions will be considered in our model. We indeed want to stress how, once heterogeneity in expectations is accounted for, neither satisficing behaviours nor other specific hypothesis are needed to rescue the N-K model from instability.

Marxian and Sraffian economists, on the other side, have put forward an opposite *traverse* mechanism. In their models the actual rate of utilization happens to gravitate around the target in the long run. This is ensured by an investment function which typically embeds a stock-flow adjustment *à la* Hicks (1950). Desired utilization remains an exogenous variable which coincides with the point of lower unit costs and is therefore merely affected by technical conditions (Kurz, 1986). Different stabilizing forces involve the role of monetary policy (Duménil and Lévy, 1999), the retention ratio (Shaikh, 2009) and autonomous expenditures (Allain, 2014; Lavoie, 2014). A major implication is that in the long run both the paradox of costs and that of thrift do not hold anymore. Permanent

not imply convergence to a Pareto-dominated equilibrium. On the contrary, instability arises exactly because agents found themselves persistently out of the steady state (i.e. $U \neq u_n$). The system is continuously in motion. This is an important aspect which suggests that an ABM approach should be preferred to a game theoretic one.

[6] The review proposed in this section aims to give only a broad picture of the literature. By no means it should be intended as fully-comprehensive. For large surveys on the topic see Hein et al. (2010) and Hein et al. (2012).

variations in wages and in propensity to save only have a "level" effect since the degree of utilization is constrained to fluctuate around u_n. As argued in Palumbo and Trezzini (2003) and Hein et al. (2010), this process imposes strong requirements in terms of information and coordination among firms. In order for the system to gravitate around u_n, it seems necessary for entrepreneurs to act as a "body", undertaking investment decisions in a cooperative fashion. In our ABM we can explicitly test for this conjecture. Agents are allowed to continuously adapt expectations and investment rates in order to pursue their targets. Then, it is possible to investigate the emergent dynamics for U. As it will be discussed, the latter do not in fact imply gravitation around u_n. On the contrary, average aggregate utilization levels will still be endogenously determined.

The two main solutions discussed so far have radically different implications but share two important features. First, they are build upon an aggregate investment function and, as a consequence, cannot directly study problems of coordination. Second, they are both concerned with the determination of a long run equilibrium. Over a sufficiently large time horizon, system variables will oscillate in a neighborhood of their steady-state values.

In this work, instead, we take a bottom-up approach. Aggregate relations are not imposed but emerge from the behaviour of heterogeneous firms. Furthermore, we do not constrain our analysis to the identification of a stationary solution. In ABM, convergence towards a fixed point is only one of the possible long run outcomes whereas a more complex and chaotic macrodynamics can also be accounted for. In particular, as simulation results will show, the process for U displays a unit root. Rather than tending towards a final state of rest, aggregate capacity utilization follows an open trajectory, being persistently affected by temporary shocks.

4 The Model

The model is populated by N firms producing an homogeneous good that can be either consumed or accumulated as capital stock. Some simple assumptions are needed to make it comparable to the baseline N-K specification. There is no technical change: labour productivity and the capital-to-output ratio are exogenous parameters. The supply of labour is infinite. Wages, prices and mark-ups are constant and given so that we can exclusively focus on the dynamics of produced quantities.

4.1 The timeline of events

Within each time step events proceed as follows:

- Firms form expectations, set their investment expenditures and hire workers.
- Wages are anticipated to workers.
- Consumption plans are formed. Workers spend all their income while capitalists only consume a fraction c_p of past profits.
- Aggregate demand is computed summing up investment and consumption.

- Firms receive a fraction of total demand according to their market shares. They produce to accommodate their demand.
- Individual and aggregate capacity utilization levels are computed.
- The part of total output not consumed is delivered to firms according to their individual investment plans. It becomes part of capital stock at time $t+1$.

4.2 Model equations

Let us start our discussion by defining some microeconomic variables[7]. First, we assume an investment function at the firm level which is symmetrical to that in Equation (N-K 1):

$$i_{i,t} = [g^e_{i,t} + \gamma_u(u_{i,t-1} - u_n)]k_{i,t} \tag{1}$$

Here g^e, u and k are respectively firm-specific demand expectations, capacity utilization and capital stock. The target utilization rate u_n is an exogenous parameter. Its interpretation remains therefore open. It can be seen either as coinciding with the point of lower unit costs Kurz (1986) or as the result of firm heuristics related to past demand volatility (Steindl, 1952).

Notice also that there is no lower negative bound for net investments (i). It simply entails that capital depreciation is endogenous and determined by demand conditions. Firms unique goal is to achieve target utilization. In order to do so, they can always acquire or scrap the desired amount of capital stock without constraints [8]. This implies the following law of motion for capital:

$$k_{i,t} = \max\left\{k_{i,t-1} + i_{i,t-1}; 0\right\} \tag{2}$$

Well in line with the empirical evidence (Gigerenzer et al., 1999; Hommes, 2013; Tversky and Kahneman, 1986), agents are assumed to form expectations using simple behavioural rules and heuristics. In order to be parsimonious, here we endogenize demand expectations imposing a basic adaptive form:

$$g^e_{i,t} = g^e_{i,t-1} + \theta(g_{i,t-1} - g^e_{i,t-1}) + \epsilon_{i,t} \quad \text{where:} \quad \epsilon_{i,t} \sim \mathcal{N}(0,\sigma) \tag{3}$$

Hence, long-run forecasts are revised in light of past observed demand growth (g). Moreover, in adjusting g^e, firms are affected by an idiosyncratic noise ϵ. The latter introduces across-agents heterogeneity as well as persistent fluctuations over time in individual expectations. It is outside of the scope of this paper to provide a deep theoretical justification for the presence of ϵ. We instead simply want to show how micro disturbances in expectations formation may tame coordination failures,

[7] Lower case are used to distinguish micro variables from aggregate ones. The subscript i refers to firms while t is the time index.

[8] This assumption is made to make our results as transparent as possible. Imposing a fixed depreciation rates generates an asymmetry between capacity expansion (which is unbounded) and scrapping (which can only happen at a constant rate). In this way we remove potential biases, allowing capacity adjustments to be fully flexible. Notice also that assuming a variable depreciation rate, affected by demand conditions, is broadly in line with the empirical evidence (Eisner, 1972; Goolsbee, 1998).

bringing back stability into the system[9]. The error term can nonetheless be seen as capturing all those (firm-specific) factors affecting demand expectations, other than mechanical adaptive adjustments[10]. In our analysis, we will "switch on and off" the shocks to investigate different scenarios. In particular, depending on the specification of θ and σ one can define four cases:

1. $[\boldsymbol{\theta = 0; \sigma = 0}]$: Identical firms with no learning.
2. $[\boldsymbol{\theta \in (0,1); \sigma = 0}]$: Identical firms with adaptive learning.
3. $[\boldsymbol{\theta \in (0,1); \sigma > 0}]$: Heterogeneous firms with adaptive stochastic expectations. The process for g^e is stationary, the effect of shocks is temporary. Hence, g^e will fluctuate around a time-drift given by the evolution of g.
4. $[\boldsymbol{\theta = 0; \sigma > 0}]$: Heterogeneous firms with random walk expectations. The process for g^e is I(1), shocks have a permanent effects while g do not play any role.

Cases 1 and 2 rule out heterogeneity and will be discussed in Section 5.1. The focus of this paper is on case 3 since it describes a scenario where expectations are heterogeneous and linked to the dynamics of demand. When $\theta = 0$ (case 4) g^e degenerates to an I(1) process, expectations become purely random and disconnected from actual demand growth.

Firms are assumed to keep a fixed proportion between capital and labour:

$$l_{i,t} = \frac{k_{i,t}}{av} \tag{4}$$

Where a is labour productivity and v is the capital-to-output ratio. Firms start the production only after they know their level of demand[11]. They produce exactly to match demand, up to capacity constraints:

$$y_{i,t} = \min\left\{AD_t f_i; \frac{k_{i,t}}{v}\right\} \tag{5}$$

Where AD is total aggregate demand, f stands for the individual market share and $\frac{k}{v}$ is maximum capacity output. Modelling the evolution of f would imply making some other assumptions about competition and market selection mechanisms. Instead, we want to keep our model as simple as possible and therefore market shares are assumed to be constant and exogenous. In other words, simulations are performed imposing an invariant distribution of firm size. Nonetheless, we allow for three different specifications for the distribution of f:

[9] We leave for future extensions the possibility for agents to chose from menu of different forecasting rules (Anufriev et al., 2013; Anufriev and Hommes, 2012; Brock and Hommes, 1997). Examples of macroeconomic models which allow for switching and rules selection are De Grauwe (2012) in a DSGE framework and Roventini et al. (2016) for the "K+S" model. Nonetheless, we posit that dealing with heterogeneity in a more complex fashion would only strengthen our results.

[10] Palumbo and Trezzini (2003) provide several reasons for which the adjustment of capacity to demand should be considered as neither automatic nor instantaneous.

[11] For the sake of transparency, we remove the uncertainties associated to the production process. As a consequence, we can escape modelling inventories. In this way agents are only affected by uncertainty when undertaking investment decisions.

- **Baseline**: $f_i = 1/N \quad \forall i$.
- **Pareto**: $f_i \sim$ Pareto(1,1).
- **Lognormal**: $f_i \sim$ Lognormal (0,1).

We therefore allow for a benchmark case in which firms have identical shares as well as two alternative scenarios with right-skewed distributions of size[12]. Given output levels and the capital stock it is possible to compute the degree of capacity utilization as:

$$u_{i,t} = y_{i,t} \frac{v}{k_{i,t}} \tag{6}$$

We can now discuss aggregate variables. As in Equations (N-K 2) and (N-K 3) total consumption and the profit rate are given by:

$$C_t = c_p \Pi_t + wL_t \quad \text{Where:} \quad \Pi = R_t K_t \tag{7}$$

$$R_t = \frac{mU_t}{v} \tag{8}$$

If we normalize the price to 1, there is the following negative relation between wages and mark-up:

$$m = \frac{a - w}{w} \tag{9}$$

Aggregate demand is the sum of consumption and investments:

$$AD_t = C_t + \sum_{i=1}^{N} \max \left\{ i_{i,t}; 0 \right\} \tag{10}$$

Finally, average capacity utilization and national income are also obtained as:

$$Y_t = \sum_{i=1}^{N} y_{i,t} = AD_t \tag{11}$$

$$U_t = \sum_{i=1}^{N} u_{i,t} \frac{k_{i,t}}{K_t} = \frac{Y_t v}{K_t} \tag{12}$$

5 Results

The stability of the system will be investigated under different scenarios. We start by assuming homogeneous expectations and show that the ABM version behaves symmetrically to the aggregative

[12] The right-skewness of the firm size distribution is a robust stylized fact of industrial dynamics Dosi et al. (2007). Here we use two density functions widely found in the empirical literature: the Lognormal (Stanley et al., 1995) and the Pareto (Axtell, 2001). Specifically, at the beginning of the simulation a random number drawn from the assumed distribution is assigned to each firm. Market shares are then obtained by normalizing for the overall sum, in order to ensure: $\sum_{i=1}^{N} f_i = 1$.

model. Then, we introduce idiosyncratic shocks and heterogeneity. In this second case H-I does not arise anymore.

In all the scenarios the system is initialized in a steady-state where each firm utilize its capacity at the desired level (see Appendix for details). We let the economy grow in equilibrium for 10 steps and then we introduce a permanent 2% shock on wages and study the model response[13].

Parameters value are presented in Table 1.

5.1 Equilibrium and Harrodian instability with homogeneous expectations

By "turning off" the shocks in Equation (3) (i.e. $\sigma = 0$) it is possible to study a scenario with homogeneous agents. To create a parallel with the standard model we allow both for fixed (no learning) and adaptive expectations.

Results are reported in Figure 1[14]. In the case with no learning (solid line), after the permanent shock in wages, U rapidly converge to a new higher steady-state level. Instead, if expectations are adaptive (dotted line), the model is not able to reach a new equilibrium after an external perturbation. Harrodian instability emerges and U increases exponentially.

Hence, our ABM extension, when expectations are homogeneous, is proved to be isomorphic to the aggregate model. A balanced growth path is sustainable only insofar as agents do not revise their predictions in light of past information. This result is intuitive but important since it implies a general consistency of the ABM microfoundations adopted, allowing us to make robust comparisons with the canonical N-K model.

5.2 Heterogeneous expectations

In this section we explore the more general case with adaptive stochastic expectations. Figure 2 display the evolution of U after the shock for a single realization, adopting three different specifications of the size distribution. Imperfect adjustments of g^e at the micro level generate, as an emergent property, endogenous fluctuations in aggregate capacity utilization. Also, U evolves within realistic values. Bad coordination and H-I are not present. Interestingly, fluctuations do not necessary occur around the target value u_n, thus, the endogeneity of U is preserved.

To test whether these results are robust to different realizations of the random component, we report some Monte Carlo statistics in Table 3. Results confirm the general picture given so far: the average utilization is significantly different from u_n while the volatility of the series is always positive. Moreover, consistently with the "granular hypothesis" (Gabaix, 2011), volatility appears to be positively related to the skewness of the firm size distribution. When market shares are

[13] We assume a permanent shift to avoid any ambiguity, as common in the literature Hein et al. (2010). Results for the case of a temporary shock are available upon request.

[14] Simulations are run using Laboratory for Simulation Development (LSD). A complete description of the software is given in Valente (2008).

Pareto-distributed, fluctuations are stronger than respectively in the Lognormal and in the baseline case.

To investigate instability we use three different measures:

- **Deterministic trend**: the slope of the regression $U_t = \alpha + \beta_T t$ can be used to check whether U displays a trending behaviour.
- **Unit root test**: the augmented Dickey-Fuller test is performed to identify the presence of stochastic trends.
- **Instability ratio**: it is given by x/T. Where x is the number of observations that lie above 0.95 or below 0.3 and T is the total number of time steps.

By looking at β_T we can conclude that capacity utilization does not exhibit any deterministic tendency to rise (fall). The instability ratio is zero on average. Therefore, across-simulations, U almost never approaches either full-capacity or unrealistically low values. On the contrary, well in tune with recent findings in Nikiforos (2015), it is not possible to reject the unit root hypothesis for U. The dynamics of U is thus path-dependent, being triggered by the accumulation of random shocks. Nevertheless, the presence of stochastic trends never leads to explosive patterns, as suggested by both β_T and the instability ratio.

At this stage, two aspects are worth to be stressed. First, the presence of a unit root is an emergent property of the system. As already discussed, for $\theta > 0$, micro-shocks are persistent but not permanent and individual expectations follow a stationary process. Interactions and continuous adjustments at the micro level generate an aggregate time series for U which is well approximated by an I(1) specification. Second, weak trends in U do not bring about any adjustment in u_n. No satisficing behaviours are assumed and the target rate of utilization remains constant during the simulation. According to our results, it can be misleading, as done in Nikiforos (2015), to interpret the trend component of U as reflecting slow variations in desired utilization rates. As we will argue in the next section, secular movements in U should be seen as the result of phases where microeconomic behaviours tend to weakly comove.

5.3 A general discussion

In the previous sections two important results have been showed. Instability arises when agents are identical while it vanishes when micro-heterogeneity is introduced. Moreover, firms' attempts to achieve target utilization will result in a collective failure to drive U towards u_n. This is a typical example of emergent property: an aggregate outcome which cannot be predicted by looking at isolated micro behaviours.

The mechanisms underlying these results are rather intuitive. Firms have to set their investment expenditures simultaneously without any information about other agents behaviour. Expectations, on the one hand, directly affect individual capital growth (gk) while, on the other, contribute to overall income growth (g) through aggregate demand externalities. Formally:

$$gk_{i,t} = f(g^e_{i,t-1})$$

$$g_t = f(g^e_{1,t}, ..., g^e_{N,t})$$

From Equation (6) the growth rate of u can be written as:

$$gu_{i,t} = g_t - gk_{i,t}$$

Agents interact via the macroeconomic level since their decisions determine the formation of aggregate demand[15]. Each firm has a theoretical optimal expectation value $g^e(*)$ which, given g, allows to achieve target utilization. However, since the value of g is not given but depends on what other agents are doing, we are in presence of *strategic complementarietes* (Cooper and John, 1988). The individual optimal strategy $g^e(*)$ is positively affected by the behaviour of the other $N-1$ firms.

In absence of shocks and heterogeneity (see Section 5.1), *strategic complementarietes* and aggregate demand externalities lead to mutually reinforcing patterns and instability. There is perfect correlation in microeconomic behaviours. After a positive (negative) shock, expectations are continuously revised upwards (downwards) and capital stock never fully adjusts to demand. All firms will be in a persistent situation with excess (shortage of) capacity. The induced component $\gamma_u(u - u_n)$ drives a positive (negative) wedge between g and g^e. As a result, all expectations will be persistently negatively (positively) biased which, in turn, entails a positive (negative) discrepancy between the growth rate of income and that of capital. Individual and aggregate utilization will therefore ever-rise up to the full-capacity limit.

Instead, idiosyncratic shocks generate heterogeneous forecasts. Agents who underestimated their demand growth ($g_k < g$) will experience an increase in their utilization rates ($gu > 0$) while an inverse dynamics characterize optimistic firms ($g_k > g$). Hence, at any point in time firms with $u > u_n$ coexist with others displaying $u < u_n$. This pattern can be grasped by looking at the empirical distribution of u (Figure 3). Indeed, micro utilization rates tend to be dispersed around the target level during the simulation[16]. As a consequence, the catching-up component ($\gamma_u(u - u_n)$) does not operate anymore as a destabilizing force, since adjustments in different directions occur contemporaneously. To put it differently, the simultaneous presence of excess capacity and under-utilization brings about investment responses that are neither perfectly correlated nor uni-directional. It introduces a negative feedback in the system which breaks the self-reinforcing process underlying H-I.

Random noises are exactly responsible for continuously disrupting any tendency over equalization of expectations. They generate persistent disequilibrium at the micro level. In other words, agents never settle in a state with $u = u_n$. Monte Carlo statistics (Table 3) using firm-level data on utilization corroborate this idea. Both the standard deviation (second column) and the average absolute deviation from u_n (third column) are positive and significant. The mean value of pooled observations for u is different from the target level, suggesting that agents do not achieve the target

[15] This is reminiscent of late contributions embedding demand externalities and multiplier effects in a neoclassical framework (Angeletos and La'O, 2013; Beaudry et al., 2017). Even more importance to Keynesian features is given in agent-based models belonging to the "K+S" family. Within such tradition, demand externalities and coordination issues have been recently linked to labour market dynamics in Dosi et al. (2017).

[16] The distribution is right censored since u cannot exceed 1 (full capacity).

not even on average[17]. Finally, we present the instability ratio in the fourth column. For a sample size of $N \times T$, only 20% of observations lie above or below the threshold values. The ratio is larger than the one computed using macro data (see Table 2). As expected, higher microeconomic turbulence tends to be partially averaged out in the process of aggregation.

As common in evolutionary environments, a relatively stable macrodynamics emerges exactly out of persistent disequilibrium at lower levels of aggregation. Notice however that, although stability is achieved, the model can at the same time account for the cyclical behaviour of U. Endogenous booms and recessions arise as a result of weak correlation in investment behaviours. Expectations may, in fact, show some short-lived phases of convergence, driving both expansions and downturns.

Let us finally compare our solution to these discussed in Section 3 . First, we escape from introducing satisficing behaviours, thus, u_n remains an exogenous variable. Furthermore, expectations are endogenous and realistically linked to past demand dynamics. Figure 4 plots the (pooled) distribution of g^e. Forecasts appear to be centered around actual average demand growth. Monte Carlo statistics for g and g^e are described in Table 4 to support more robust inference. The actual growth rate of total output gravitates around a value of 4,7 %. Interestingly, demand expectations (third column) are not significantly different, on average, from this value and the mean prediction error (fourth column) tends to be relatively small. Such results are not surprising since, as already discussed, g^e is modeled as an AR(1) process which includes g as time-drift.

Nevertheless, in contrast to Marxian-inspired models, continuous expectations revisions do not lead the system to gravitate around u_n. This failure is due to the presence of spillovers and interactions, whose effects cannot be properly captured by purely aggregative models.

5.4 Macroeconomic paradoxes

In this section we test whether macroeconomic paradoxes are retained in our ABM extension when heterogeneity is present. It is straightforward that comparative dynamics exercises make little sense if our variable of interest is I(1). We cannot expect, as for the baseline case with a steady-state solution, that permanent increases in w or c_p will lead to a new equilibrium with higher growth rates and capacity utilization. Since the process for U displays a unit root, the trajectory of the system is driven by the accumulation of shocks. Hence, the initial positive effect of a rise in wages or in propensity to consume may be reverted for some specific realizations of the random component.

Instead of focusing on within-simulation shifts in utilization rates, macroeconomic paradoxes should be studied by means of between-simulations comparisons. To put it another way, we compare the evolution of U when a 2% permanent shock (either on w or c_p at $t = 10$), *vis-à-vis* a counterfactual scenario in which everything has remained unaltered. Results for a single realization are presented in Figure 5 while Figure 6 displays Monte Carlo averaged dynamics. A positive and significant difference in U is found with respect to the "no shock" scenario. Under this perspective, the model presented

[17] There is a discrepancy between the mean of U (Table 2) and that of u (Table 3). This can be explained by looking at the construction of U. Aggregate utilization is a weighted average of micro data. Higher weights are associated to big firms which over-accumulated capital stock and display large excess capacity. This will introduce a negative bias which instead is not present when we simply pool all the observations for u and take the mean.

here preserves the paradox of thrift and that of costs together with their policy implications. A boost in aggregate consumption brings about greater rates of utilization relatively to what would have happened otherwise.

A similar approach is also found in recent models assessing the impact of austerity measures in presence of investment hysteresis (Bassi and Lang, 2016). In such framework, the impact of negative demand shocks is necessarily evaluated with respect to a counterfactual world where contractionary fiscal policies have not been implemented. Our results have strong implications for the empirical tests of macroeconomic paradoxes. Econometric works so far have been focusing on standard techniques which requires stationarity assumptions (Stockhammer et al., 2009), largely neglecting the possibility of integrated processes. In other words, the statistical framework adopted so far appears better suited to perform comparative dynamics than to deal with integrated variables.

5.5 Sensitivity analysis

So far we presented results for a benchmark parametrization. Now we explore their robustness under different configurations. Let us start the discussion by looking at the stability indicators. The two parameters that can be related to H-I are θ and σ since they regulate expectations and investment behaviours[18]. We explore a two-dimensional parameter space (S) given by:

$$S = \{(\theta, \sigma) \mid \theta \in [0.05, 0.3] \quad \text{and} \quad \sigma \in [0.001, 0.015]\}$$

Contour plots are presented in Figure 7[19]. They show the sensitivity of our three instability indicators for different specifications of the firm size distribution. Plots on the left show that we can never reject the unit root hypothesis for U. The estimated $p-$value of the augmented Dickey-Fuller test is always larger than 0.3. By focusing instead on the other two indicators we can make some conclusions about H-I. Upward instability emerges when θ is relatively larger than σ. In this region of the parameter space the slope of the trend is positive and the instability ratio is high. As expected, when the idiosyncratic component shrinks relatively to the adaptive one, the model converges to the case with homogeneous expectations described in Section 5.1.

When instead σ increases excessively with respect to θ, downward instability emerges. In this case, the slope of the time trend is negative and the instability ratio is high. Since u can vary in a range from 0 to 1 and u_n is set relatively close to full capacity limit, large shocks are more likely to drive firms far below u_n than far above. When the share of firms with excess capacity becomes extremely large, the induced adjustment component will act as a destabilizing force and agents will converge towards ever-lower expectations.

However, it is also clear that for a significantly large portion of S the model displays a non-trending behaviour and an instability ratio close to zero. In other words, stable patters emerge when the adaptive component and the idiosyncratic one are sufficiently balanced. Sensitivity tests

[18] Notice that the parameter γ_u only affect *Keynesian instability*.

[19] Scatter plots are obtained as follows. First, the variable of interest is computed for all the points in a discrete subset of S given by: $\{0.05, 0.06, ..., 0.3\} \times \{0.001, 0.002, ..., 0.015\}$. Second, we fit a local polynomial regression to explore the whole S.

confirm that there is room for adaptive learning in the N-K setting. They also highlight the crucial role played by idiosyncratic errors. For a given σ, the more we move towards a purely mechanic adaptive adjustment by increasing θ, the higher will be the probability to observe unstable patterns. In other words, errors and biases in predicting demand growth are needed. Purely mechanical, uni-directional adjustments cannot be sustained. This result is consistent with a large literature on learning and expectations in complex environments (Dosi et al., 2001; Gigerenzer et al., 1999). In a decentralized world characterized by heterogeneous interacting agents, individual behaviours close to rationality may lead to undesired consequences at the aggregate level. Instead, as in our case, naive agents whose decisions are largely driven by random forces, may act as stabilizers.

Another important result of the model concerns the emergence of macroeconomic paradoxes. We finally check whether this property survives to different parameter configurations. Once again, we focus on θ and σ. For each point in S the following variable is computed:

$$\Delta\bar{U} = \bar{U}^S - \bar{U}^{NS}$$

Where $\bar{U}^S$ and $\bar{U}^{NS}$ are (Monte Carlo averaged) mean utilization respectively for a scenario with a 2% permanent shift on w and for the case with no shocks. [20]. Figure 8 presents the evolution of $\Delta\bar{U}$ in response to parameters variations. Not surprisingly, the gap between the two scenarios becomes zero only when the volatility of expectations is extremely high. On the contrary, in normal conditions, there is a positive and significant gap in mean utilization. Therefore, we can conclude that the model robustly preserves also macroeconomic paradoxes commonly found in Keynesian economics.

6 Conclusion

In this paper we presented a simple ABM extension of the standard N-K model. A parsimonious microfoundation of investment decisions has been introduced. Then, we used the model as a tool to analyze the stability properties of the system. Such approach is in line with the interpretation of Harrodian instability as a coordination failure.

We first showed that if demand expectations are homogeneous the model is isomorphic to the case with a representative firm. Firm-specific shocks affecting demand forecasts were then introduced. It was showed that dealing with heterogeneity in such a conservative form is already sufficient to draw alternative conclusions with respect to standard aggregate analysis. Under this new specification, capacity utilization does not exhibit an explosive dynamics anymore. A non-trending process with endogenous oscillations emerges as a result of decentralized and imperfect learning efforts. In this respect, our approach overcomes the typical trade-off between learning and stability present in the baseline version of the N-K model.

Differently from other solutions to the instability problem found in the literature, our proposal has been showed to preserve both the presence of macroeconomic paradoxes and the demand-led

[20] ΔU is set to zero when not significant at the 5%. We do not report sensitivity analysis for a parallel shock on c_p since it leads to the same conclusions. Nonetheless, results are available upon request.

nature of growth.

Sensitivity analysis has confirmed the general robustness of our results.

In the final part of the paper, the emphasis on idiosyncratic random prediction errors as stabilizers has been roughly linked to a series of well-known results in the field of learning in complex systems. A more sophisticated characterization of heterogeneity is however required to further investigate the issue. For instance, similarly to De Grauwe (2012) and Roventini et al. (2016), one may be interested in adapting the heuristic switching model to the N-K setting. Symmetrically, one can introduce technical change and firm-specific productivity shocks as well as evolutionary market selection mechanisms. This will be exactly the direction of our future research.

The key contribution of this work must instead be found in its methodological proposal. We suggested that the N-K model should be extended to study expectations formation and coordination mechanisms, adopting an agent-based perspective. A similar task may provide complementary results to purely aggregative models and, as in the case presented here, it may outperform them in solving some important theoretical puzzles.

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Appendix. Equilibrium solution and initialization

Our strategy is to initialize the model in a steady state with desired utilization and no bias in expectations. In this way we can explore whether the system is able to restore the equilibrium after an exogenous disturbance. A stady-state solution for the model can be derived when firm expectations are exogenous and identical. Simple aggregation of investment equations (cfr. Eq. 1) leads to:

$$\frac{I_t}{K_t} = g^e + \gamma_u(U_{t-1} - u_n)$$

This formula is the discrete-time version of Equation (N-K 1). Symmetrically, total employment is obtained aggregating hiring decisions (cfr. Eq. 4):

$$L_t = \frac{K_t}{av}$$

The latter two relations form together with Equations (7)-(12) a dynamical system which has an equilibrium solution for U given by:

$$U^* = \frac{g^e - \gamma_u u_n - 1/[v(1+m)]}{1/v(1-c_p m) - \gamma_u}$$

Notice that macroeconomic paradoxes still hold since: $\frac{\partial U^*}{\partial m} < 0$ and $\frac{\partial U^*}{\partial c_p} > 0$. As a final step we compute the value of g^e which ensures $U^* = u_n$. Therefore we have:

$$g^e = \frac{u_n(1-c_p m) - 1/(1+m)}{v}$$

Using this condition we set parameter values. Table 1 reports the benchmark parameter configuration. The values of θ and σ depend on the scenario studied.

Finally, individual demand and capital stock are initialized in order to guarantee target utilization for each firm at $t = 0$.

Table 1: Initial parameter configuration

Description	Parameter	Value
Case 1: Fixed homogeneous expectations		
Adaptive expectations parameter	θ	0
Standard deviation (idiosyncratic shocks)	σ	0
Fixed Demand expectation	g^e	0.027
Case 2: Adaptive homogeneous expectations		
Adaptive expectations parameter	θ	0.1
Standard deviation (idiosyncratic shocks)	σ	0
Case 3: Adaptive heterogeneous expectations		
Adaptive expectations parameter	θ	0.1
Standard deviation (idiosyncratic shocks)	σ	0.005
Invariant Parameters		
Target utilization rate	u_n	0.75
Capitalists' propensity to consume	c_p	0.1
Capacity adjustment speed	γ_u	0.03
Mark-up ratio	m	0.45
Labour productivity	a	1.45
Capacity-to-output ratio	v	1
Number of firms	N	50
Time steps	T	500
Number of Monte Carlo simulations		500

Size Distribution	Mean (U)	Std. Dev. (U)	Det. Trend slope	ADF test (p-value)	Instability Ratio
Baseline	0.7299	0.0155	−0.0000	0.5072	0.0000
	(0.0006)	(0.0002)	(0.0001)	(0.0123)	(0.0001)
Lognormal	0.7332	0.0200	−0.0000	0.4952	0.0000
	(0.0008)	(0.0003)	(0.0001)	(0.0123)	(0.0001)
Pareto	0.7416	0.0264	−0.0000	0.4785	0.0071
	(0.0015)	(0.0012)	(0.0001)	(0.0134)	(0.0024)

Monte Carlo standard errors in brackets.

Table 2: Monte Carlo Statistics - Aggregate utilization

Size Distribution	Mean (u)	Std. Dev. (u)	Abs. Dev. from u_n	Instability Ratio
Baseline	0.7754	0.1532	0.1295	0.1933
	(0.0005)	(0.0002)	(0.0002)	(0.0009)
Lognormal	0.7788	0.1546	0.1327	0.2084
	(0.0011)	(0.0003)	(0.0003)	(0.0021)
Pareto	0.7772	0.1601	0.1435	0.2392
	(0.0026)	(0.0008)	(0.0013)	(0.0044)

Monte Carlo standard errors in brackets.

The absolute deviation from the target is computed as the average of: $\mid u_{i,t} - u_n \mid$.

Table 3: Monte Carlo Statistics - Firm-level utilization

Size Distribution	Mean (g)	Std. Dev. (g)	Mean(g^e)	Prediction Error
Baseline	0.0454	0.0154	0.0448	0.0088
	(0.0007)	(0.0002)	(0.0007)	(0.0001)
Lognormal	0.0472	0.0184	0.0465	0.0090
	(0.0010)	(0.0003)	(0.0010)	(0.0001)
Pareto	0.0479	0.0237	0.0471	0.0094
	(0.0017)	(0.0006)	(0.0016)	(0.0001)

Monte Carlo standard errors in brackets.

The absolute deviation from the target is computed as the average of: $\mid g^e_{i,t} - g_t \mid$.

Table 4: Monte Carlo Statistics - Expectations vs. growth rate

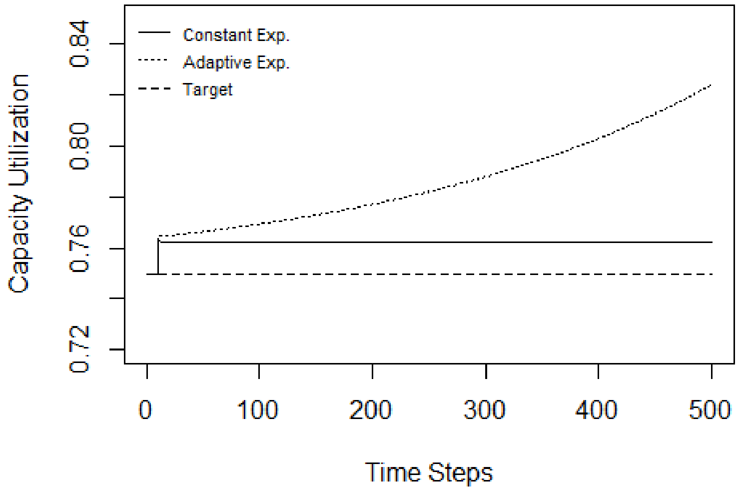


Figure 1: Model response to a permanent shock. Fixed vs. adaptive expectations

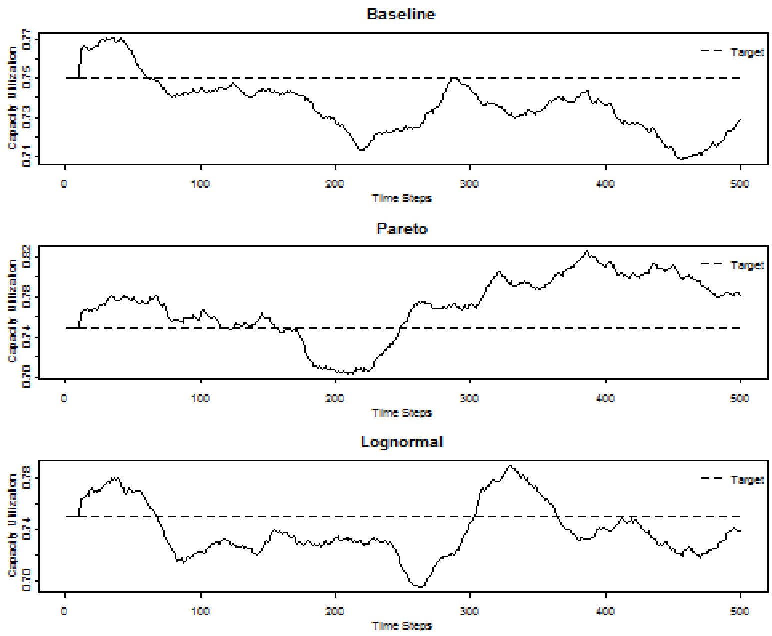


Figure 2: Model response to a permanent shock under heterogeneous expectations - Different distributions of firm size

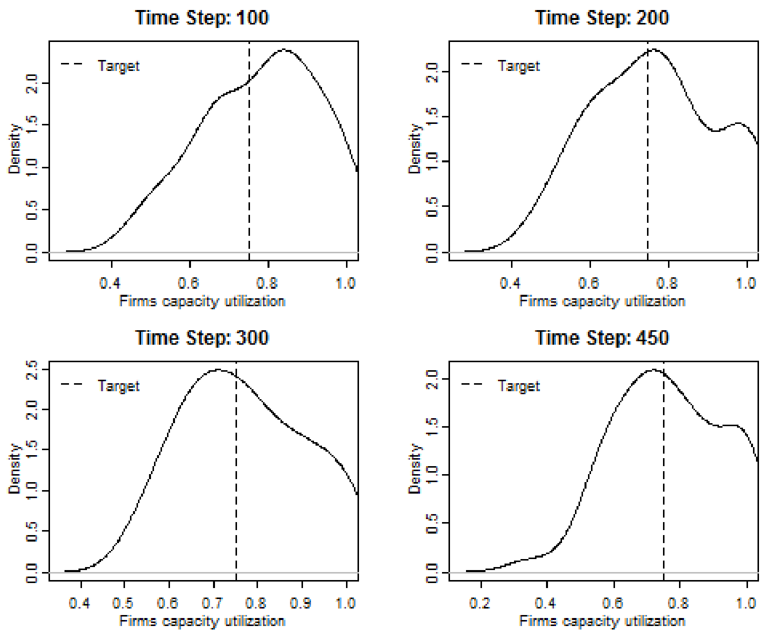


Figure 3: Firm-level utilization - Kernel density estimation

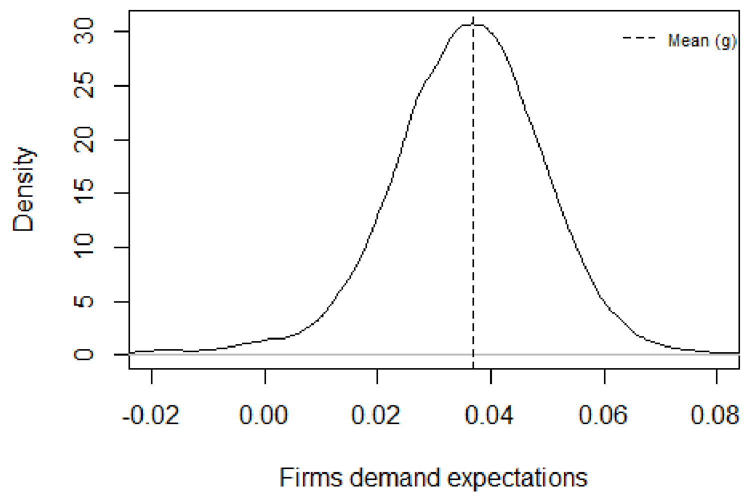


Figure 4: Firm-level expectations - Kernel density estimation

Figure 5: Capacity utilization evolution (single realization) - Shock vs. No shock scenarios

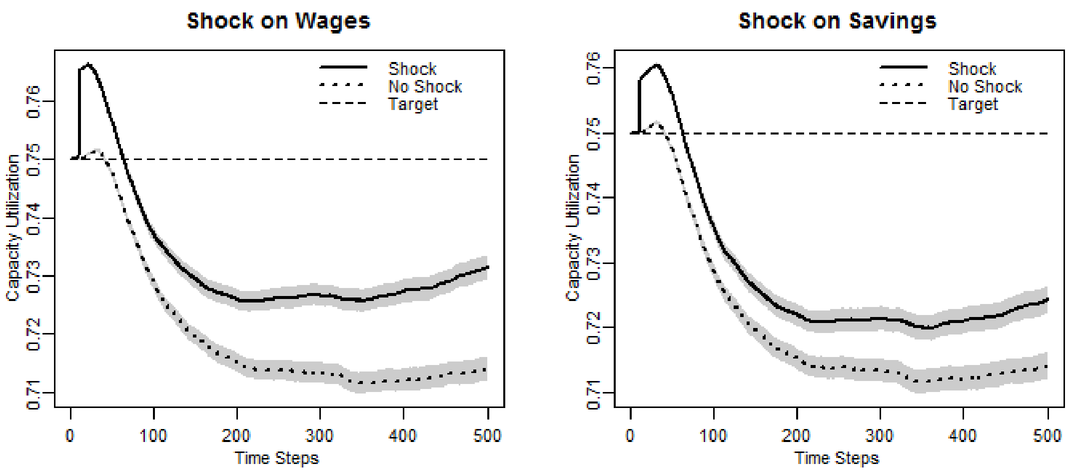
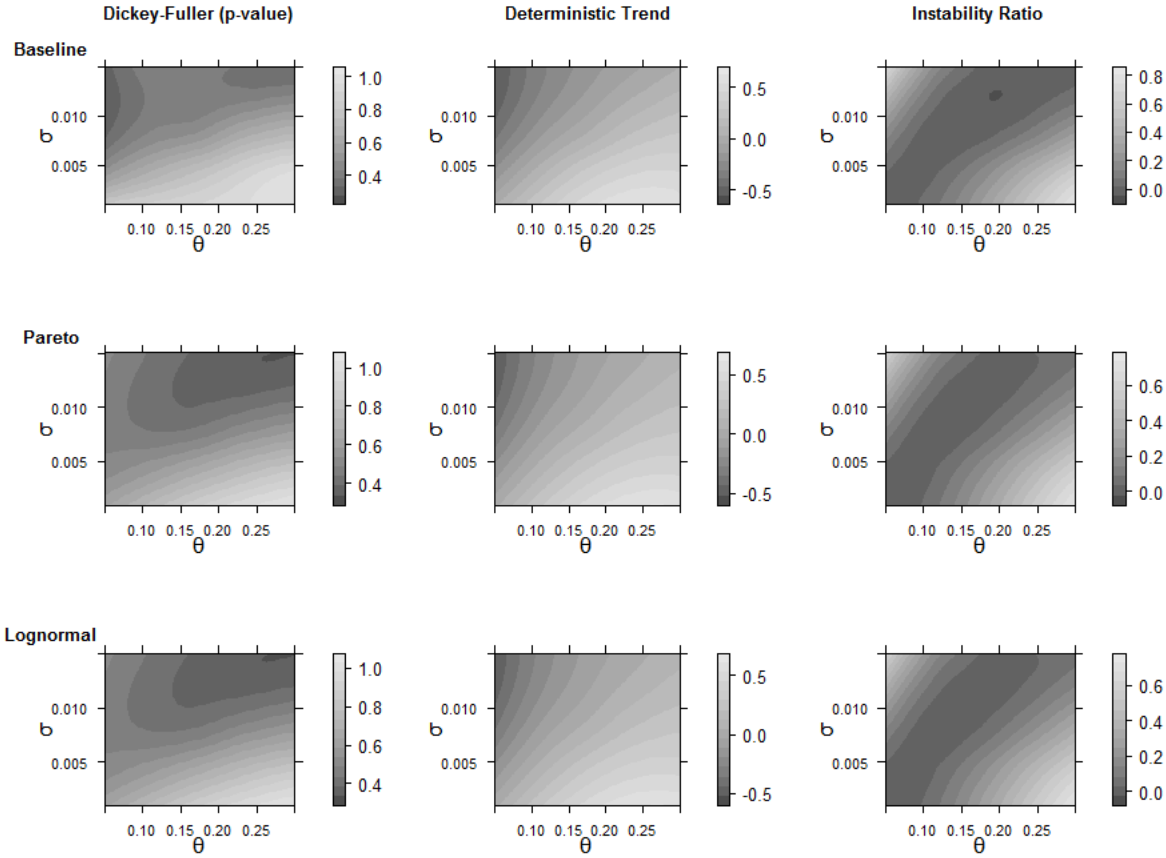


Figure 6: Monte Carlo averaged capacity utilization evolution (Confidence-intervals in grey) - Shock vs. No shock scenarios



Note: Each row display a different specification for the firm size distribution. Each column is associated to a specific instability measure. The slope of the deterministic trend is scaled up by a factor of 1000.

Figure 7: Sensitivity analysis - Instability measures

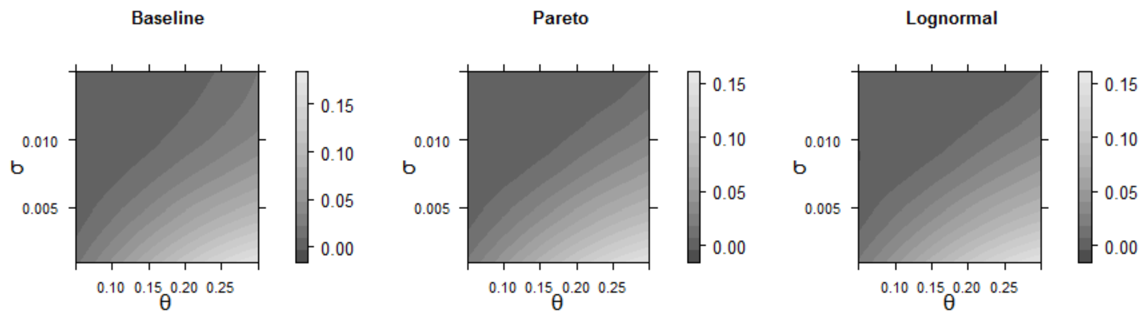


Figure 8: Sensitivity analysis - Macroeconomic Paradoxes