A SHORT WALK ON THE WILD SIDE: AGENT-BASED MODELS AND THEIR IMPLICATIONS FOR MACROECONOMIC ANALYSIS

Mauro Napoletano
Sciences Po, OFCE ; SKEMA Business School and University Côte d'Azur (GREDEG), and Institute of Economics, Scuola Superiore Sant'Anna Italy

This article discusses recent advances in agent-based modelling applied to macroeconomic analysis. I first introduce the building blocks of agent-based models. Furthermore, by relying on examples taken from recent works, I argue that that agent-based models may provide complementary or new lights with respect to more standard models on key macroeconomic issues like endogenous business cycles, the interactions between business cycles and long-run growth, and the role of price vs. quantity adjustments in the return to full employment. Finally, I discuss some limits of agent-based models and how they are currently addressed in the literature.

Keywords: agent-based models, macroeconomic analysis, endogenous business-cycles, short and long-run dynamics, monetary and fiscal policy, price vs. quantity adjustments.

This paper discusses recent advances in agent-based modelling applied to macroeconomic analysis. The main goal is to illustrate the main building blocks of agent-based models and to argue – with examples taken from recent works – that this new class of models can provide complementary or new lights with respect to more standard models on several issues.

Agent-based models (ABMs) represent an economy as a dynamical system of heterogeneous interacting agents. Heterogeneity involves agent's characteristics (e.g. the size of firms or the income of households) and/or the behavior of agents (e.g. their expectation rules). Agents in these models can interact globally *via* prices (as they typically do in traditional macroeconomic models) but also locally *via* non-price variables (e.g. the imitation of a technology or of an expectation rule adopted by another firm in the economy). In addition, agents' heterogeneity and the structure of their interaction networks are not fixed, but *evolve* over time together with the dynamics of the whole system. Another important building block of these models is their non-exclusive focus on equilibrium states of the economy. In other words, these models also analyze the dynamics of the system in situations where some markets do not clear and/or where agents are not optimizing their behavior and thus have incentives to change it.[1] Accordingly, agent-based models also dispense with the assumption of perfect rationality of agents, in the sense of agents taking decisions out of the solution of an inter-temporal optimization problem. In contrast, these models assume bounded rationality of agents, i.e. in ABMs agents have very simple rules of behavior for coping with an environment that is too complex for anyone fully to understand (Howitt, 2011, Tesfatsion, 2006). Boundedly rational behavior may range from static or evolutionary optimization to more routinized rule-of-thumb behavior rooted on experimental or empirical evidence. Finally, one important concept associated to agent-based models is the one of *emergent property*. More precisely, an agent-based model typically lacks any isomorphism between aggregate properties of the system and specific assumptions on the characteristics or behavior of a single agent populating the system itself. Aggregate properties stem from the interaction of the agents populating the economy (Turrell, 2016). This *bottom-up* modelling philosophy echoes the one that has been applied for almost a century by quantum mechanics to study the physics of interacting particles.

One straightforward consequence of assuming evolving agents' heterogeneity and interaction structures is that the dimensionality and the non-linearity of the dynamical system that represents the economy become huge, and this precludes closed form solutions of the system. Thus agent-based models are typically analyzed via extensive Monte Carlo simulations, in a way similar to bootstrap analyses widely employed in econometrics and statistics.

Agent-based models have a long and established tradition in scientific disciplines different from economics like, for instance, physics,[2]

1. Accounting for disequilibrium states also implies that the behavior of the system is not described by the evolution of state variables resulting from the solution of a system of equations. In agent-based models all variables are instead updated following a precise time-line of events.

biology, computer science. They have also become more and more diffused in social sciences like sociology and archeology. They have had a much harder life in economics, although the Great Recession, and the critiques to standard macroeconomics models that followed, have contributed to pull ABMs out of the far periphery of economic theorizing. Since then, ABMs have received increasing attention as useful tools for the analysis of key markets, like financial and energy markets (see e.g. Le Baron, 2006, Tesfatsion, 2006 and Weidlich and Weit, 2008), as alternative tools for the analysis of economic and climate change dynamics (see e.g. Balint *et al.* 2017), and for macroeconomic analysis (see Haldane, 2016).

This paper will not attempt to provide a survey of the state of the art of agent-based models in macroeconomics. Good and updated surveys can for example be found in Fagiolo and Roventini (2017) and in Turrell (2016), and recent collections of research works using agent-based macro models can be found in Delli Gatti *et al.* (2011), Gaffard and Napoletano (2012), and in Gallegati *et al.* (2017). This paper will instead try to explain, by means of examples taken from recent works by the author and co-authors, the consequences of some fundamental concepts of the agent-based models. It will then show how the use of these concepts generate results that offer *complementary if not totally new perspectives* on key issues in macro-economics, like the emergence of aggregate fluctuations from microeconomic idiosyncratic shocks, the persistent effects of business cycles (and of monetary and fiscal policies) in the long-run and the role played by prices in favoring the return of the economy to full-employment. Finally, it will discuss some of the critiques raised against macroeconomic agent-based models and how they have recently been addressed in the literature.

1. Agent-Based Models, Emergent Properties and the Generative Approach in Economics

We already mentioned in the introduction that one workhorse of agent-based models is the concept of emergent property, i.e. an aggregate property of the system (e.g. business cycles) that cannot be deduced from assumptions made on single components of the system itself (the household or the firms). Agent-based models thus take a

2. Interestingly, Turrell (2016) remarks that one of the first scientists to apply agent-based model techniques was Enrico Fermi, to solve problems involving the transport of neutrons through matter.

generative approach to science. In this perspective, the goal of the model provides a micro-specification regarding the nature of agents' heterogeneity and the nature of their interaction. The model is then validated – i.e. it provides an explanation of a given macro phenomenon – if it is able to grow up that phenomenon out the specified interaction among heterogeneous agents. As Epstein (2007, Chap. 1) puts it:

> “Agent-based models provide computational demonstrations that a given microspecification is in fact *sufficient to generate* a macrostructure of interest. Agent-based modelers may use statistics to gauge the generative sufficiency of a given micro-specification – to test the agreement between real-world and generated macro structures […] A good fit demonstrates that the target macrostructure – the explanandum – be it a wealth distribution, segregation pattern, price equilibrium, norm, or some other macrostructure, is effectively attainable under repeated application of agent-interaction rules: It is effectively computable by agent society. [..] Thus, the motto of generative social science, if you will, is: If you didn't grow it, you didn't explain its emergence”

The generativist approach followed by agent-based models stands in sharp contrast with the reductionist approach, according to which the explanation of a phenomenon can be reduced to some fundamental laws governing the behavior of single components of the system. Reductionism is still very much popular in economics[3], and it is the candid opinion of the author of this paper that such a predominance explains a good deal of the diffidence towards agent-based models, and especially their perception as “black-boxes”, i.e. models where the causes and mechanism driving results are blurred. In contrast, reductionism is rather questioned in other scientific disciplines like physics. The dissatisfaction is very well explained by the physics Nobel laureate Phillip Anderson (see Anderson, 1972):

> “The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe. In fact, the more the elementary particle physicists tell us about the nature of the fundamental laws, the less relevance they seem to have to the very real problems of the rest of science, much less to those of society. [..] The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few

3. The popularity of reductionism resists despite key results in general equilibrium theory (the Sonneschein-Mantel-Debreu theorem) show the impossibility of obtaining well-behaved aggregate excess demand functions directly from assumptions about the micro-behaviour of agents (see Kirman, 1992, for an account).

> particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other."

It follows that in the generative approach (also known as "bottom-up" approach) one should not search for simple "causes" of a given phenomenon but rather check whether starting from simple assumptions about agents' behavior and their interaction structures the model is able to reproduce that phenomenon at the macro level or not. The approach is also close to the concept of "sequential causality" outlined by Hicks (1979). In that, a given "phenomenon" (e.g. a recession) may or may not be the direct consequence of a specific "cause" (e.g. an exogenous shock) according to the sequence of decisions (and of resulting constraints) that occur in the time lapse between the two. That sequence can change the path leading to the emergence of a given property in a fundamental way, so that it is not always possible to establish a direct link between the specific cause and its effects.[4]

Let us now provide an illustration of emergent property in a macro agent-based model, by means of the "Keynes+Schumpeter" (K+S) agent-based model developed in Dosi *et al.* (2010,2013,2015,2017).[5] In one of its most extended versions the micro-specification of the model portrays an economy composed of heterogeneous capital- and consumption-good firms, a labour force, heterogenous banks, a government, and a central bank. Capital-good firms perform R&D and produce heterogeneous machine tools. Consumption-good firms invest in new machines and produce a homogeneous consumption good. The latter type of enterprises finance their production and investments first with their liquid assets and, if these are not enough, they ask their bank for credit (which is more expensive than internal funds). Higher production and investment levels rise firms' debt, eroding their net worth and consequently increasing their credit risk. Banks, in turn, increase the level of credit rationing in the economy and force firms to curb production and investment, thus possibly triggering a recession. Bank failures can endogenously emerge from the accumulation of loan losses on banks' balance sheets. Banking crises imply

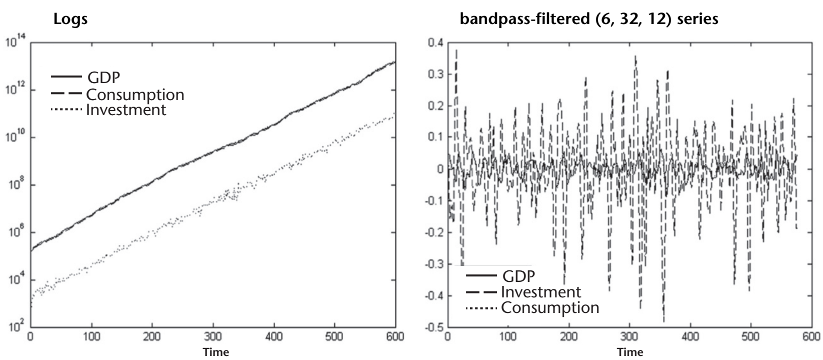
4. The notion of sequential causality should be contrasted to the one of "contemporaneous causality", which is typical of standard models, and according to which a specific phenomenon can always be linked to a specific cause and the sequence of decisions and constraints occurring in between is irrelevant in that respect.

5. The K+S model has also been extended to analyze the consequences of different policies in the labor market (Napoletano *et al.* 2012, Dosi *et al.* 2016, 2017) and as a tool for integrated assessment analysis of the co-evolution of economic and climate change dynamics (see Lamperti *et al.*, 2018).

direct bailout costs on the public budget and may therefore affect the dynamics of Government deficit and debt. The latter can also vary with changes in tax revenues and unemployment subsidies over the business cycle.

The K+S model generates as emergent properties the main stylized facts at the macroeconomic level. For instance, it generates time series of GDP, consumption and investment displaying long-run growth (see Chart 1, left). As well as business cycle fluctuations in the short-run (see Chart 1, right). Furthermore, the list of stylized facts is not limited to the highest level of aggregation. The model also generates a wide array of facts characterizing the cross-sectional dynamics of firms, e.g. tent-shaped distributions of firm growth-rates.[6] It is important to stress that none of these properties is the direct consequence of specific assumptions on the behavior of firms. For instance, recessions and expansions are not generated from a specific response of firms to some aggregate shock. All the above properties are instead generated as the result of firm idiosyncratic technology shocks that diffuse from the capital good to the consumption good sector via investment interactions.[7]

Chart 1. Output, consumption and investment time series



Source: Dosi *et al.* (2015).

The diffusion of technology is heterogeneous across firms as their investment levels differ because of different expectations about final demand and because of different levels of financial constraints. The

6. In that, the model follows the call of Anderson (1972) for providing explanations at different layers of complexity.
7. Not even a mild cross-sectional agents' heterogeneity is imposed ex-ante. On the contrary, firms are assumed to be completely homogeneous at the beginning of each Monte-Carlo iteration..

resulting aggregate level of investment in turn affects the overall level of economic activity, but it also affects future credit availability because firms accumulate debt out of investment and production activities and may therefore become more financially fragile and even go bankrupt, thereby lowering aggregate credit supply and increasing credit rationing. The foregoing tension between change (induced by innovation and diffusion of new technologies) and coordination (induced by effective demand and by credit constraints) does not only set the long-run growth of the economy, but it also creates business cycles in the model.

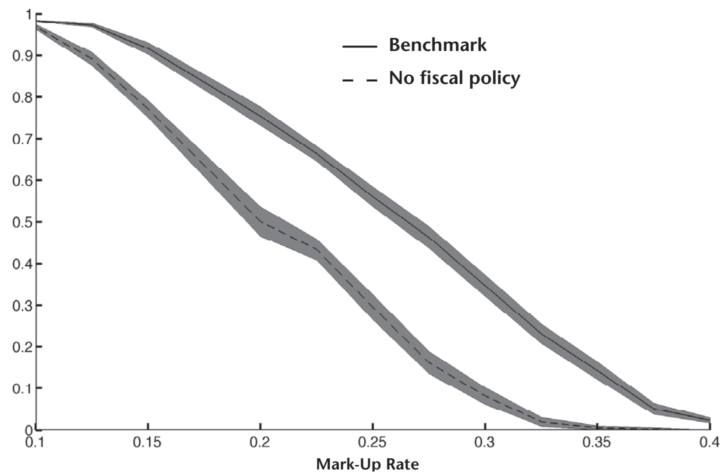
In the next section I further develop the above points and discuss how agent-based models may provide new perspectives on several macroeconomic issues.

2. Some Implications of Agent-Based Models for Macroeconomic Analysis

Agent-based models have applied the generative approach discussed in the previous section to explain a wide array of phenomena in macroeconomics as well to test the impact of several macroeconomic policies (and of their combination). The list includes, but it is not limited to, the generation of business cycles and long-run growth out of the combination between Schumpeterian dynamics of innovation and Keynesian demand dynamics (the K+S model of Dosi *et al.*, 2010, 2013, 2015), the generation of business fluctuations out of evolving distributions of firms' bankruptcy risk (e.g. Delli Gatti *et al.*, 2005, 2010, Cincotti *et al.*, 2010, Mandel *et al.*, 2015), the analysis of the interactions between inequality and growth (Dosi *et al.*, 2013, Ciarli *et al.*, 2010, Cardaci and Saraceno, 2015, Caiani *et al.*, 2016), the analysis of combinations of fiscal and monetary policies (e.g. Dosi *et al.*, 2013, 2015), the analysis of structural policies affecting R&D and innovations (e.g. Dosi *et al.*, 2010, Russo *et al.*, 2007), the impact of labor market policies on aggregate dynamics (Napoletano *et al.*, 2012, Dosi *et al.*, 2016, 2017) and of cohesion policies on regional convergence (Dawid *et al.*, 2014), the impact of the combination of monetary and macro-prudential policies (Ashraf *et al.*, 2017, Popoyan *et al.*, 2017).

The above long list reveals the great flexibility of ABMs to be used for both positive and normative analyses in macroeconomics. As I already mentioned above, providing an account of all the results obtained by macro agent-based models is beyond the scope of this article. I shall rather focus on some examples that briefly illustrate the ability of ABMs to address some key issues in macroeconomics from a new perspective with respect to more standard macroeconomic models.

Chart 2. Frequency of full employment in the benchmark scenario (solid line) and in the scenario with zero fiscal policy (dashed line; 95% confidence bands in gray



Source: Dosi *et al.* (2013).

Example 1: endogenous business cycles

Agent-based models have a clear advantage with respect to typical DSGE macro models, even those with heterogeneous agents. In those models, expansions and recessions are the result of respectively positive and negative aggregate shocks hitting a representative agent or (in more recent works) a set of heterogeneous agents. In contrast, in macro agent-based models, the system can generate both situations where the economy is in full employment as well as mild and deep recessions, *and it endogenously switches across them* (see Chart 1 and discussion in the previous section). Endogenous business cycles arise in agent-based models because agents' heterogeneity and interaction mechanisms introduce several non-linearities in the dynamical system that describes the economy. [8]

The ability of agent-based models to endogenously generate business fluctuations is not only important from a purely theoretical viewpoint. It also means that these models can be used as useful tools to explore (and possibly control *via* specific policies) the economic mechanisms that trigger instabilities during an expansionary phase and put the seeds of a recession. For instance, the frequency of full employment states of the economy can be linked to some key parameters capturing institutional and policy scenarios (e.g. the structure of interaction in markets, the level of income inequality or the intensity of fiscal policy). For instance, in Dosi *et al.* (2013) the average frequency of full employment states, i.e. the time the economy spends on average in the full-employment equilibrium is inversely related to the inequality in the functional distribution between profits and wages (and captured by the level of the mark-up rate, see Chart 2). In addition, the incidence of full-employment equilibria falls for any level of inequality if fiscal policy is completely absent (no fiscal policy scenario).[9]

Another example that illustrates the role played by agents' heterogeneity and interactions generating endogenous business cycles is provided by the work of Guerini *et al.* (2017). This paper analyzes the behavior of an economy under two different matching protocols: (a) a centralized matching scenario, where a fictitious auctioneer solves any possible coordination problem among the agents, and (b) a decentralized matching scenario, where agents locally interact in the markets. In such a regime, matching frictions and agents' heterogeneity may lead to imperfect allocations of goods and labor. Furthermore, households face liquidity constraints (their consumption is limited by changes in wealth). The authors initialize the variables of the model (consumption, wages, prices, production, firms' net worth, households' wealth, etc.) at values compatible with the full-employment, homogeneous-agents' equilibrium of the economy. They then let idiosyncratic (and autoregressive) negative technology shocks hit the economy at the firm level and they study the stability of the full-employment equilibrium and the convergence properties of the model. The behavior of the model under

8. Previous works showed that endogenous business cycles may emerge also in equilibrium models (e.g. Grandmont, 1985) or in models with infinitely-lived agents and rational expectations (see e.g. Baumol and Benhabib 1989 for a discussion, and the papers contained in Benhabib, 1992). All these models were however representative-agent models, or models where heterogeneity was small (e.g. like in overlapping generation models) and typically not evolving over time. These models also did not allow one to analyze how small perturbations of the system at the micro-level (e.g. because of a small exogenous shock) could be magnified via a network of agents' interactions. Agent-based models improve on all these aspects, because they allow one to generate endogenous business cycles in a framework with more realistic assumptions on agents' heterogeneity and mechanisms of interactions across agents.

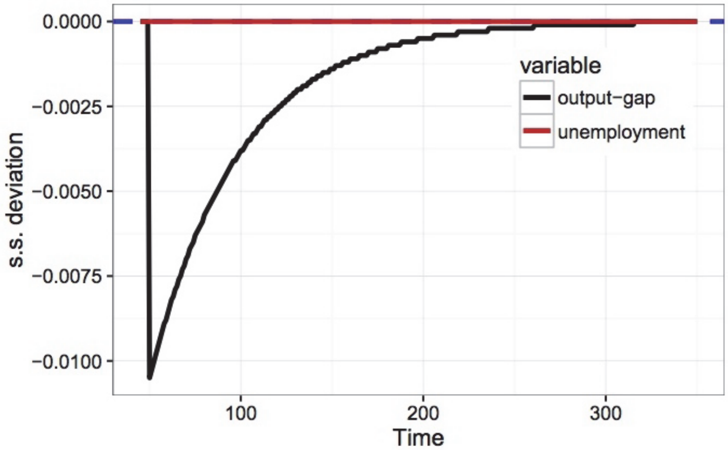
9. In a similar fashion, Gualdi *et al.* (2015) show the existence of multiple equilibria characterized, respectively, by high and low unemployment. The transition between the equilibria is induced by an asymmetry between the rate of hiring and the rate of firing of the firms. The unemployment level remains small until a tipping point, beyond which the economy collapses. Finally, if the parameters of the model are such that the system is close to this transition, any small fluctuation is amplified as the system jumps between the two equilibria.

the two matching protocol scenarios is very different. In the centralized scenario, the economic system is always able to get back to full-employment after the productivity shocks. In addition, the impulse-response functions generated by the model mimic the ones generated by standard DSGE models (see Chart 3) and, finally, agents' heterogeneity fades away. In contrast, in the decentralized scenario the economy fluctuates around an underemployment equilibrium (Chart 4) and it is characterized by persistent heterogeneity in firms and household behavior. This completely different outcome across the two scenarios is generated by the fact that the decentralized scenario produces frictional unemployment. Liquidity constraints faced by households amplify the effect of such a frictional unemployment an lead to lower aggregate demand in the goods market, which in turn feeds back in lower aggregated demand and higher unemployment in the labor market.

The last example shows quite well how the structure of interaction has a great effect on the properties of the aggregate dynamics of an economy and how it can greatly amplify even small degrees of heterogeneity across agents, e.g. due to the unemployment status created by frictions in the allocation of labor across firms.

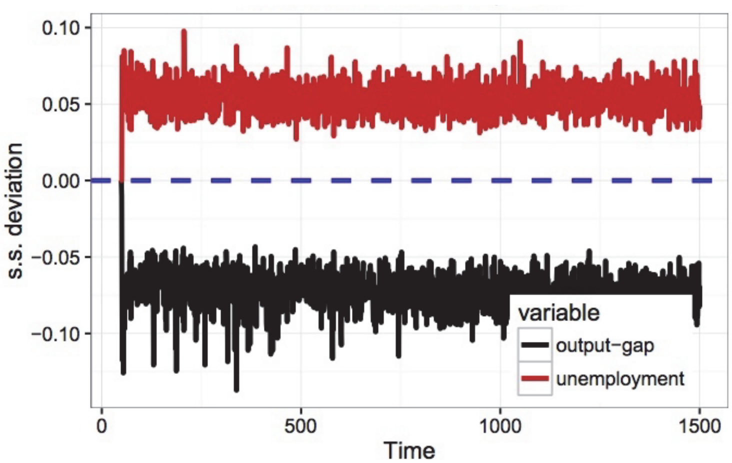
3. Output and Unemployment

Chart 3. Impulse response of output and unemployment in the model of Guerini *et al.* (2017) under the centralized matching scenario



In the figure "s.s. deviation" stands for deviations from the full-employment equilibrium.
Source: Guerini *et al.* (2017).

Chart 4. Impulse response of output and unemployment in the model of Guerini *et al.* (2017) under the decentralized matching scenario



In the figure "s.s. deviation" stands for deviations from the full-employment equilibrium.
Source: Guerini *et al.* (2017).

Example 2: Interactions between the short- and the long-run dynamics of an economy

Macroeconomic theory has been characterized by a sharp distinction between the analysis of long-run growth processes and the one of business cycles. This separation comes from the assumption that any coordination problem is solved in the long-run. It follows, that long-run growth mainly stems from supply factors, in primis technological change. In contrast, some coordination failures may arise in the short-run due to aggregate demand deficiencies. This framework has however several limitations, because it prevents the understanding of how technical change can map into higher growth and how the inherent instability of technical change processes can be mitigated. In one direction, technological innovations may impact upon the long-term rate of growth of the economy, as well as on the short-term evolution of output (and unemployment) over the business cycle. In the other one, macroeconomic conditions (i.e. aggregate demand, credit availability, etc.) are likely to modulate the creation and diffusion of technological innovations and the long-run performance of the economy (Dosi *et al.*, 2017). As it is argued at more length in the article by Jean-Luc Gaffard in this special issue, answering the above questions requires one to seriously consider the issue of time in economic analysis, and to reject the idea of the presence of an equilibrium growth path towards which the economy converges in the long-run. In contrast, the long-run evolution of the economy is the results of a sequence of short-run states characterized by imperfect coordination[10] (see Gaffard, 2017, Dosi and Virgillito, 2017). Agent-based models are very good candidates for this type of analysis. This is because they do not have an exclusive focus on equilibrium states of the economy. They can therefore be used to understand how structural change (e.g. resulting from technology-induced structural changes) and/or coordination failures (e.g. resulting from aggregate demand shortages) may affect the long-run dynamics of an economy, and how different types of macroeconomic policies can intervene in this context. An example of this type of exercise is provided by the series of results obtained with the K+S model by Dosi *et al.* (2015) about the short- and long-run effects of the fiscal and monetary policy mix. Tables 1 and 2 – taken from Dosi *et al.* (2015) – show the effects of different combinations of fiscal and monetary policies on, respectively, the average growth rate of real GDP and the unemployment rate. The fiscal policies considered are an unconstrained fiscal policy (*norule*), two constrained fiscal policies (stability and growth pact, *SGP*, and fiscal compact, *FC*) and – finally – the same constrained fiscal policies but with escape clauses for recessionary phases (SGP_{ec} and FC_{ec}). The monetary policies considered are a conservative Taylor rule, targeting only the inflation rate (TR_{π}), a dual-mandate Taylor rule targeting both inflation and unemployment ($TR_{\pi,U}$), and the same dual-mandate rule but augmented with a government-debt dependent spread on bonds in order to account for possible feedbacks from high government debt levels on interest rates.

Values in the table are relative to the benchmark featuring an unconstrained fiscal policy and a pure inflation-targeting monetary rule. The striking results emerging from the analysis of the two tables is that both fiscal and monetary policies have not only significant real short-term effects, as captured by significant differences in unemployment rates across policy scenarios. They also matter for the determination of the long-rung growth rate of the economy. More precisely, constraining fiscal policy has a deleterious effect on both unemployment and the long-run growth rate of the economy, which is only mitigated by the introduction of escape clauses or by a dual-mandate monetary policy.

10. This idea of long-run patterns emerging from a sequence of imperfect short-run adjustments is also very much in line with the generative approach discussed in the previous section.

Table 1. The effects of the interactions between fiscal and monetary policy on the average growth rate of GDP

Monetary policy	Fiscal policy		
	TR_{π}	$TR_{\pi U}$	*Spread*
Norule	1	1.019**	0.994
		(3.730)	(1.017)
SGP	0.527**	1.014	0.794**
	(6.894)	(1.157)	(3.982)
FC	0.572**	0.958	0.765**
	(6.499)	(1.296)	(4.863)
SGP_{ec}	0.995	1.013**	0.991*
	(0.876)	(2.572)	(1.665)
FC_{ec}	0.992	1.021**	0.997
	(1.388)	(4.169)	(0.524)

* significant at 10% level ; ** significant at 5% level.
Fiscal and monetary policy interactions. Normalised values of average GDP growth rates across experiments. Absolute value of simulation *t*-statistic of H_0 : "No difference between baseline and the experiment" in parentheses; *Fiscal policies:* no fiscal rule (*norule*); 3% deficit rule (*SGP*); debt-reduction rule (*FC*); SGP with escape clause (SGP_{ec}); *FC* with escape clause (FC_{ec}). *Monetary policies:* Taylor rule indexed on inflation only (TR_{π}); dual-mandate Taylor rule ($TR_{\pi,U}$); bonds spread adjustment policy (*spread*).
Source: Dosi *et al.* (2015).

Table 2. The effects of the interactions between fiscal and monetary policy on the unemployment rate

Monetary policy	Fiscal policy		
	TR_{π}	$TR_{\pi U}$	*Spread*
Norule	1	0.322**	1.068
		(5.903)	(0.468)
SGP	5.692**	0.909	4.201**
	(8.095)	(0.555)	(6.842)
FC	5.706**	1.383	4.963**
	(7.585)	(1.350)	(7.443)
SGP_{ec}	1.419**	0.343**	1.680**
	(2.088)	(5.527)	(3.495)
FC_{ec}	1.948**	0.317**	1.679**
	(3.928)	(5.886)	(3.139)

* significant at 10% level ; ** significant at 5% level.
Fiscal and monetary policy interactions. Normalised values of average GDP growth rates across experiments. Absolute value of simulation *t*-statistic of H_0 : "No difference between baseline and the experiment" in parentheses; *Fiscal policies:* no fiscal rule (*norule*); 3% deficit rule (*SGP*); debt-reduction rule (*FC*); SGP with escape clause (SGP_{ec}); *FC* with escape clause (FC_{ec}). *Monetary policies:* Taylor rule indexed on inflation only (TR_{π}); dual-mandate Taylor rule ($TR_{\pi,U}$); bonds spread adjustment policy (*spread*).
Source: Dosi *et al.* (2015).

Besides the effects arising from specific combinations of monetary and fiscal policies, the above results are important because they indicate the breaking down of the classical dichotomy which occupies a central stage in standard macroeconomic models, and they shed light on the effects that fiscal and monetary policies can have on long-run real drivers of an economy.

However, how do the above results emerge? The mechanism of transmission can be casted in a series of short-run adjustments mapping on the long-run rates of technological innovation and diffusion. The constraints imposed on fiscal policy reduce the ability of this policy to act as a parachute in case of demand shortages. Accordingly, the system becomes closer to one without fiscal policy, and the incidence of underemployment states rises (see also Chart 2 above). Higher unemployment and lower aggregate demand also imply a lower incentive of firms to invest (investment and production follow the principle of effective demand in the K+S model). In its turn, lower investment translates into a slower diffusion of new technologies, which are embodied in new machines sold by the capital-goods sector. In addition, by lowering demand for capital good firms, a decrease in in investment also reduces the incentives of those firms to invest in R&D, which maps into lower innovation rates.[11,12]

The next section briefly discusses a third example of macroeconomic issues where ABMs can bring new lights: the ability of price and wage adjustments to promote the return to full employment.

Example 3: wage and price adjustments and unemployment

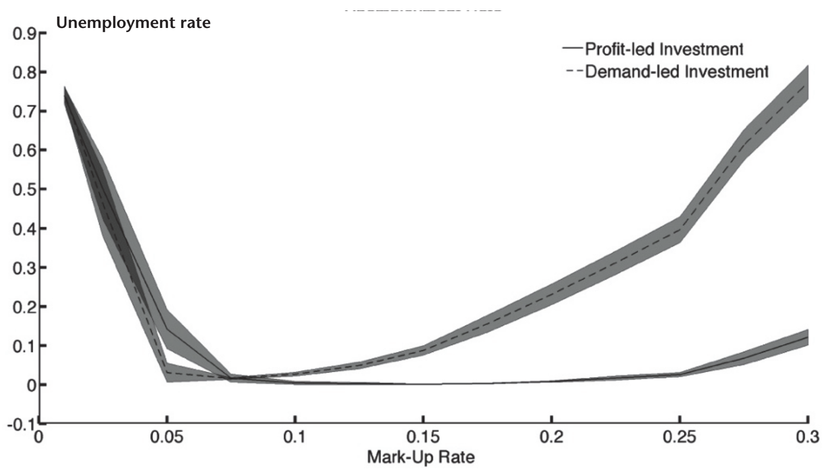
Since Keynes' General Theory (1936) one of the most debated questions in macroeconomics is whether changes in real wages are able to mop up or not disequilibria in the labor markets and to restore full employment. Nowadays, the idea of an inverse relation between real wages and unemployment is strongly embedded in standard macroeconomic models.[13] Recent results in the ABMs literature show that the shape of the relation between real wages and unemployment is instead very much context-dependent: it is determined by the specific rules

11. See also Dosi *et al.* (2016) for a detailed examination of the effects on technological innovation and diffusion.

12. The better performance of the economy under the dual mandate monetary policy is instead explained by the beneficial effects that this policy has on Basel-like capital buffer requirements imposed on banks (see Dosi *et al.*, 2015, for more details).

used by firms in the market of goods and of labor, and by the specific protocols of interactions of agents in the two markets. Accordingly, the inverse relation between real wages and unemployment arises only in very specific cases. For instance, the plots in Chart 5 show that the inverse relation between real wages and unemployment depends on the specific rule used by firms to set the level of investment. The Chart is taken from the work of Napoletano *et al.* (2012) that uses the K+S model described in the previous sections to analyze the behavior of the economy under two scenarios for firm investment: a "profit-led" scenario where firm desired investment is a function of firm past profits, and "demand-led" scenario where desired investment depends instead on expected demand in the goods markets. Notice that the first archetype captures a scenario where investment is determined by financial constraints (profits affect cash flows in the model). The second archetype closely mimics Keynes' idea of effective demand.

Chart 5. The relation between the average unemployment rate and the mark-up rate in the K+S model



Source: Napoletano *et al.* (2012).

13. This is for instance illustrated by the positive effects that a reduction in the real wage has on long-term unemployment of a closed economy in the WS-PS model (see e.g. Carlin and Soskice, 2016), which is a good simplification of the main functioning of the labor market of any standard DSGE model featuring unemployment.

The plots in the above Chart show the relation between unemployment and the mark-up rate set by firms in the goods market. As we move from left to right the mark-up rate increases. Accordingly, the share of output per worker that workers as real wages decreases. Unemployment decreases with the mark-up rate in the profit-led scenario. It follows that lowering real wages result into lower unemployment rates, as in the standard macroeconomic models. This is explained by the fact that a lower level of real wages increases profits of firms, thus resulting in a stronger incentive of firms to invest in new capacity and to hire workers.

The picture changes significantly if firms set investment based on expected demand. In this demand-led scenario the relation between the mark-up rate and unemployment is U-shaped. This indicates that both high and low real wages generate high unemployment. This seemingly surprising result is explained by the dual role that real wages play. On the one hand, real wages determine consumption and thus the final demand faced by firms. It follows that consumption demand decreases as we move from left to right in the Chart, which explains the low incentives of firms to invest and the high unemployment observed in correspondence of high mark-up rates. On the other hand, real wages affect profits and thus the ability of firms to internally finance investment. It follows that at low mark-up rates firms have strong incentives to invest, but their investment is hampered by the financial constraints they face because of low profits. It turns out that effective investment is low and unemployment high. Napoletano *et al.* (2012) also analyze the effects of flexibility in money wages on unemployment. They find that more flexible money wages are beneficial for unemployment in the profit-led scenario but not in the demand-led scenario. Dosi *et al.* (2017) generalize the above results by exploring a richer set of rules for wage and output determination.[14]

Agent-based models have also been used to show that the structure of interactions across agents matters much more for aggregate outcomes than wage and price adjustments. For instance, Howitt and Clower (2000) study a primitive exchange economy populated by

14. The above results about the context-dependent role of real wage adjustments are not completely new to the literature. They had for instance been stressed by works in the so-called French "Régulation" school (see e.g. Boyer, 1988, Aglietta, 2000) and by works like Amendola *et al.* (2004) and Howitt (1986). The contribution of agent-based models is however to have obtained the above results in the context of fully microfounded models with heterogeneous interacting agents and that explicitly allow for the possibility of market disequilibrium.

people with no understanding of their environment other than what has been learned from random meetings with other people, and with a desire to exchange their endowments for something they might want to consume. Starting in an autarkic situation, with no trade organization, they show the emergence of a coherent network of trade facilities (the "shops") that allows almost all the potential gains from trade to be fully exploited. Howitt (2006) shows that the same economy generates a multiplier process, wherein the failure of one trading firm may trigger a cascade of other firm failures and cause a large aggregate output loss until a suitable set of replacement shops has emerged. In that situation, price or wage flexibility can do nothing to speed up the recovery process because what is needed is not different prices but the re-introduction of organizational structures that allow trade relations to orderly unfold. In a similar fashion, Guerini *et al.* (2017) study the effects on unemployment and the output gap of a better matching process in the market for goods and labor. They show that when search in labor and good markets is less the economy gets closer to full employment. This is because the economy gets closer to a centralized matching scenario where coordination problems are solved. Moreover, they show that such a result holds independently of the fact that real wages are fully flexible or completely fixed. The reason is that quantity adjustments matter much more than price adjustments. Accordingly, moving towards a centralized scenario reduces the frictions from the job allocation process as well as their amplification via demand feedbacks from the goods market.

4. By Way of Conclusion, Agent-Based Macroeconomics: A Summary of its Results and a Discussion of its Limitations

In this article, I have discussed the building blocks of agent-based macroeconomic models, and explained that these models employ a generative approach to the analysis of macroeconomic issues, which is different from the reductionist approach which is largely dominant in macroeconomics. I have also discussed examples that show how this new class of models can provide new insights on several central issues in macroeconomics. First, I illustrated how these models can generate endogenous business cycles out of the interaction among heterogeneous agents hit by idiosyncratic shocks. Second, I pointed out that these models can be used to analyze the interactions between the short- and long-run dynamics of an economy, as well as the persistent effects of monetary and fiscal policies. Third, I mentioned how these models can be used to shed lights on the conditions under which wage and price adjustments can or cannot promote the return of an economy to full-employment in the aftermath of shocks.

All the above results are hard to obtain in more standard macro models, like DSGE ones. The latter models have recently been improved to incorporate agents' heterogeneity (e.g. the HANK model, see Kaplan *et al.*, 2017) and to study their effects for the transmission of fiscal and monetary policies (e.g. Algan and Ragot, 2010, Challe and Ragot, 2011). And recent versions of these models can also account for equilibrium multiplicity (e.g. Farmer and Serletis, 2016). Finally, these models have also been modified to introduce elements of bounded rationality (e.g. Gabaix, 2016, Woodford, 2013, and the papers surveyed in Assenza *et al.*, 2014). Still, business cycles in these models arise from exogenous aggregate shocks. In addition, these models incorporate a sharp separation between the analysis of the short- and long-run dynamics of an economy. Accordingly, they cannot analyze how interactions between heterogeneous agents can generate aggregate dynamics that switch endogenously between phases of full utilization of resources and mild and deep recessions, and study how all this have persistent effects on long-run growth. Furthermore, by being nested in a full general equilibrium framework, DSGE models can hardly investigate the role played by quantity adjustments – versus price adjustments – in the generation of recessions and of subsequent recoveries.

Agent-based models thus represent a valid tool for macroeconomic analysis. At the same time, they also have limitations, some of which are currently tackled by recent works. I shall briefly discuss four critiques raised towards ABMs and of how they are addressed: i) the fact of being "ad hoc" and of letting one being lost in the "wilderness of bounded rationality" (the "ad hocerism" critique); ii) the poor understanding of their causal mechanisms (the "black box" critique); (iii)the inability of agents to respond to policies (the "Lucas critique"), (iv) the poor link with data (the "data validation" critique).

Let me start with the critique that ABMs are completely ad hoc. First, one must probably acknowledge that a similar degree of ad hocerism plagues also models with optimizing agents, where various functional forms for production and utility functions are used to obtain – out of constrained maximization – the behavioral rule of interest. Second, ABMs microfound their behavioral rules either by using empirical or experimental evidence about true agents' behavior. Finally, agent-based models typically undergo and indirect validation test, i.e. it must be able to reproduce – with the same values of parameters – a large set of stylized facts at the micro- and macroeconomic level.[15]

About the "black box" critique, I have already discussed above that this largely stems from the differences between the generativist approach used by ABMs and the reductionist approach traditionally used in economics. Furthermore, one must also remark that – even in very complicated ABMs – causal mechanisms can be detected through counterfactual analyses. More precisely, the structure of ABMs often allows one to control the presence of some dynamics in the model (through an appropriate setting of the parameters), and to test how results are different when such dynamics are switched off/on. Examples of this approach are the experiments with different types of fiscal and monetary policy discussed above or the example with different types of matching protocols in labor and goods markets or, finally, the phase diagram analysis performed in Gualdi *et al.* (2015). In addition, the counter-factual analysis can be pushed forward in ABM, up to build treatment and control groups and to apply the same methodologies used in econometrics to detect causal relations. The papers by Neugart (2008) and by Petrovic *et al.* (2017) are good examples of this approach.

Let me now turn to discuss the Lucas critique towards agent-based models. It is true that ABMs – in line with a vast amount of empirical and experimental evidence (see e.g. Assenza *et al.*, 2014) – do not assume rational expectations. In addition, many ABMs use agents with sticky behavioral routines and/or naïve expectations. This makes them more applicable to situations where agents face constraints in obtaining and processing relevant information about economic variables and/or to situations where financial and income constraints bind, and thus where agents' expectations are of little importance. At the same time, agent-based macro models have recently tried to address the Lucas critique and to introduce agents with more sophisticated expectation rules taken from the literature on learning in macroeco-

15. The K+S family of models discussed in this paper (Dosi *et al.* 2010, 2013, 2015, 2017) is a good example of this type of microfoundation methodology. Notice that, as it is argued in Napoletano *et al.* (2012), it is not just a matter of reproducing just one stylized fact but many at once! Indeed, the number of stylized facts that an ABM tries to reproduce is typically much larger than in standard models, and this already puts a lot of constraints on the set of parameters' values that can be selected. Moreover, differently from polynomial data-fitting exercises, in ABMs it is required that parameters' values must be economically meaningful.

nomics (e.g. Evans and Honkapoja, 2012). The works of Arifovic *et al.* (2010), Salle (2015) and of Dosi *et al.* (2017) provide good examples of this new research stream in agent-based macroeconomics.

Finally, agent-based models have been criticized for the lack of validation using macroeconomic data, which is instead extensively applied in the macro DSGE literature to calibrate and estimate models. It is true that ABMs currently lag behind DSGE models in the use of more sophisticated data-validation techniques, and this despite the ability of ABMs to produce a vast amount of micro and macro simulated data.[16] Several contributions in the last years have tried to fill the above gap. This literature has applied a large ensemble of approaches, ranging from simulated minimum distance methods, to machine learning techniques to, finally, data-driven identification in VAR models, either to estimate parameters in ABM or to check the ability of ABMs to reproduce the features of empirical time-series[17] (Fagiolo *et al.*, 2017, contains a survey of this recent line of research). For instance, Guerini and Moneta (2017), apply independent-component analysis to compare the causal structure of VAR models estimated on empirical time-series and on time-series generated by a macro ABM model. Interestingly, they find that the agent-based model they employ can reproduce between 65% and 80% of the causal relations entailed by a SVAR estimated on real-world data.

To sum up, agent-based models constitute a new tool that allows macroeconomist to explore new research avenues that were not or that cannot be paved by using more traditional macro models, even with recent improvements. Agent-based models were severely criticized for being too much ad hoc or for not being following some standard practices in the macroeconomic literature. Nevertheless, much of this criticism either applies to standard models as well, or it is currently addressed in the recent literature. In conclusion, macroeconomics can safely take a longer walk on the purported "wild side" of agent-based models.

16. Indeed, this critique applies only in part because, as we discussed above, ABMs already employ empirical (or experimental) evidence to microfound agents' behavior. In addition, ABMs are already indirectly calibrated, by checking their ability to reproduce moments of distributions both at the micro- and macro-models (see also above).

17. In addition, these validation techniques can also be applied to DSGE models. This open the way to the possibility of better comparisons between the performance of ABMs and of DSGE models.

References

Aglietta M., 2000, *A Theory of Capitalist Regulation: The US Experience*, Editions Verso.

Algan Y. and X. Ragot, 2010, "Monetary policy with heterogeneous agents and borrowing constraints", *Review of Economic Dynamics*, 13(2): 295-316.

Amendola M., J. L. Gaffard and F. Saraceno, 2004, "Wage flexibility and unemployment: the Keynesian perspective revisited", *Scottish Journal of Political Economy,* 51(5): 654-674.

Anderson P. W., 1972, "More is different", *Science,* 177(4047): 393-396.

Arifovic J., H. Dawid, C. Deissenberg and O. Kostyshyna, 2010, "Learning benevolent leadership in a heterogenous agents economy", *Journal of Economic Dynamics and Control,* 34(9): 1768-1790.

Ashraf Q., B. Gershman and P. Howitt, 2017, "Banks, market organization, and macroeconomic performance: An agent-based computational analysis", *Journal of Economic Behavior & Organization*, 135: 143-180.

Assenza T., T. Bao, C. Hommes and D.Massaro, 2014, *Experiments on Expectations in Macroeconomics and Finance. Experiments in Macroeconomics*, Emerald Group Publishing Limited, pp. 11-70.

Assenza T., D. D. Gatti and J. Grazzini, 2015, "Emergent dynamics of a macroeconomic agent based model with capital and credit", *Journal of Economic Dynamics and Control,* 50 : 5-28.

Balint T. F., Lamperti, A Mandel., M. Napoletano, A. Roventini and A. Sapio, 2017, "Complexity and the Economics of Climate Change: A Survey and a Look Forward", *Ecological Economics,* 138st(C): 252-265.

Baumol W. J. and J. Benhabib, 1989, "Chaos: significance, mechanism, and economic applications", *The Journal of Economic Perspectives,* 3(1): 77-105.

Benhabib J., 1992, *Cycles and Chaos in Economic Equilibrium*, Princeton University Press.

Boyer R., 1988, "Formalizing Growth Regimes", in G. Dosi, C. Freeman, R. Nelson, G. Silverberg and L. L. Soete (eds.), *Technical Change and Economic Theory*, Francis Pinter, pp. 609-629.

Caiani A., A. Russo and M. Gallegati, 2016, *Does Inequality Hamper Innovation and Growth?*, Technical report, University Library of Munich, Germany.

Cardaci A. and F. Saraceno, 2015, *Inequality, Financialisation and Economic Crises: An Agent-Based Macro Model*, Technical report, Department of Economics, Management and Quantitative Methods at Universit? degli Studi di Milano.

Carlin W. and D. W. Soskice, 2014, *Macroeconomics: Institutions, Instability, and the Financial System*, Oxford University Press, USA.

Challe E. and X. Ragot, 2011, "Fiscal Policy in a Tractable Liquidity-Constrained Economy", *The Economic Journal,* 121(551): 273-317.

Ciarli T., Lorentz A., Savona M. and Valente M., 2010, "The effect of consumption and production structure on growth and distribution. A micro to macro model", *Metroeconomica,* 61(1): 180-218.

Cincotti S., Raberto M. and Teglio A., 2010, "Credit Money and Macroeconomic Instability in the Agent-based Model and Simulator Eurace", *Economics: The Open-Access, Open-Assessment E-Journal*, 4.

Comin D. and Gertler M., 2006, "Medium-term business cycles", *The American Economic Review*, 96(3): 523-551.

Dawid H., Harting P. and Neugart M., 2014, "Economic convergence: Policy implications from a heterogeneous agent model", *Journal of Economic Dynamics and Control,* 44: 54-80.

Delli Gatti D., Desiderio S., Gaffeo E., Cirillo P. and Gallegati M., 2011, *Macroeconomics from the Bottom-up*, Vol. 1, Springer Science & Business Media.

Delli Gatti D., Di Guilmi C., Gaffeo E., Giulioni G., Gallegati M. and Palestrini A., 2005, "A new approach to business fluctuations: heterogeneous interacting agents, scaling laws and financial fragility", *Journal of Economic behavior & organization,* 56(4): 489-512.

Delli Gatti D., Gallegati M., Greenwald B., Russo A. and Stiglitz J. E., 2010, "The financial accelerator in an evolving credit network", *Journal of Economic Dynamics and Control,* 34(9): 1627-1650.

Dosi G., Fagiolo G., Napoletano M. and Roventini A., 2013, "Income distribution, credit and fiscal policies in an agent-based Keynesian model", *Journal of Economic Dynamics and Control*, 37(8): 1598-1625.

Dosi G., Fagiolo G., Napoletano M., Roventini A. and Treibich T., 2015, "Fiscal and monetary policies in complex evolving economies", *Journal of Economic Dynamics and Control,* 52: 166-189.

Dosi G., Fagiolo G. and Roventini A., 2010, "Schumpeter meeting Keynes: A policy-friendly model of endogenous growth and business cycles", *Journal of Economic Dynamics and Control,* 34(9): 1748-1767.

Dosi G., Napoletano M., Roventini A. and Treibich T., 2017, "Micro and macro policies in the Keynes+ Schumpeter evolutionary models", *Journal of Evolutionary Economics,* 27(1): 63-90.

Dosi G., M. Pereira C., A Roventini. and M. E. Virgillito, 2017, "When more flexibility yields more fragility: The microfoundations of keynesian aggregate unemployment", *Journal of Economic Dynamics and Control,* 81 : 162-186.

Dosi G, Napoletano M., Roventini A., Stiglitz J. E. and Treibich T., 2017, "Rational Heuristics? Expectations and Behaviors in Evolving Economies with Heterogeneous Interacting Agents", *LEM Working Paper*, 2017/31.

Dosi G. and M. E. Virgillito, 2017, "In order to stand up you must keep cycling: Change and coordination in complex evolving economies", *Structural Change and Economic Dynamics*, https://doi.org/10.1016/j.strueco.2017.06.003.

Epstein J. M., 2006, *Generative Social Science: Studies in Agent-based Computational Modeling*, Princeton University Press.

Evans G. W. and Honkapohja S., 2012, *Learning and Expectations in Macroeconomics*, Princeton University Press.

Fagiolo G., Guerini M., Lamperti F., Moneta A. and Roventini A., 2017, "Validation of Agent-Based Models in Economics and Finance", *LEM Working Paper,* 2017/23, Technical report.

Fagiolo G. and Roventini A., 2017, "Macroeconomic Policy in DSGE and Agent-Based Models Redux: New Developments and Challenges Ahead", *Journal of Artificial Societies & Social Simulation,* 20(1).

Farmer R. E. A. and Serletis A., 2016, "The evolution of endogenous business cycles", *Macroeconomic Dynamics,* 20(2): 544-557.

Gabaix X., 2016, A *Behavioral New Keynesian Model*, Technical report, National Bureau of Economic Research.

Gaffard J. L. and Napoletano M., 2012, "Agent-Based Models and Economic Policy", *Revue de l'OFCE*, 124.

Gaffard J.-L., 2017, "Vers une macroéconomie non walrasienne", *Revue de l'OFCE*, ce numéro.

Gallegati M., Palestrini A. and Russo A., 2017, *Introduction to Agent-Based Economics*, Academic Press.

Grandmont J.-M., 1985, "On endogenous competitive business cycles", *Econometrica: Journal of the Econometric Society*, 995-1045.

Gualdi S., Tarzia M., Zamponi F. and Bouchaud J.-P., 2015, "Tipping points in macroeconomic agent-based models", *Journal of Economic Dynamics and Control,* 50, 29-61.

Guerini M., M. Napoletano, and A. Roventini, 2018, « No man is an Island: The impact of heterogeneity and local interactions on macroeconomic dynamics », *Economic Modelling* 68, 82 - 95.

Guerini M. and Moneta A., 2017, "A method for agent-based models validation", *Journal of Economic Dynamics and Control,* 82: 125-141.

Haldane A., 2016, *The Dappled World*, Bank of England-GLS Shackle Biennial Memorial Lecture.

Hicks J. R., 1979, *Causality in Economics*, Basil Blackwell, Oxford.

Hommes C., 2013, *Behavioral Rationality and Heterogeneous Expectations in Complex Economic Systems*, Cambridge University Press.

Howitt P., 1986, "Wage flexibility and employment", *Eastern Economic Journal,* 12(3): 237-242.

Howitt P., 2006, "The microfoundations of the Keynesian multiplier process", *Journal of Economic Interaction and Coordination*, 1(1): 33-44.

Howitt P., 2012, "What have central bankers learned from modern macroeconomic theory?", *Journal of Macroeconomics,* 34(1) : 11-22.

Howitt P. and R. Clower, 2000, "The emergence of economic organization", *Journal of Economic Behavior & Organization*, 41(1): 55-84.

Kaplan G., B. Moll and G. Violante, 2015, "The macroeconomy according to HANK", *NBER Working paper*, 21897.

Keynes J. M., 1936, *General Theory of Employment, Interest and Money*, Atlantic Publishers & Dist.

Kirman A. P., 1992, "Whom or what does the representative individual represent?", *The Journal of Economic Perspectives*, 6(2): 117-136.

Lamperti F., G. Dosi, M. Napoletano, A. Roventini and A. Sapio, 2018, « Faraway, so close: coupled climate and economic dynamics in an agent based integrated assessment model », *Ecological Economics*, 150: 315-339,

LeBaron B., 2006, "Agent-based computational finance", *Handbook of computational economics*, 2: 1187-1233.

Mandel A., S. Landini, M. Gallegati and H. Gintis, 2015, "Price dynamics, financial fragility and aggregate volatility", *Journal of Economic Dynamics and Control,* 51: 257-277.

Napoletano M., G. Dosi, G. Fagiolo and A. Roventini, 2012, "Wage formation, investment behavior and growth regimes: An agent-based analysis", *Revue de l'OFCE,* supplément, 124: 235-261.

Neugart M., 2008, "Labor market policy evaluation with ACE", *Journal of Economic Behavior & Organization*, 67(2): 418-430.

Petrovic M., B. Ozel, A. Teglio, M. Raberto and S. Cincotti, 2017, "Eurace Open: An agent-based multi-country model" *Technical report*, 2017/09, Economics Department, Universitat Jaume I, Castellón (Spain).

Popoyan L., Napoletano M. and A. Roventini, 2017, "Taming macroeconomic instability: Monetary and macro-prudential policy interactions in an agent-based model", *Journal of Economic Behavior & Organization*, 134: 117-140.

Russo A., Catalano M., Gaffeo E., Gallegati M. and Napoletano M., 2007, "Industrial dynamics, fiscal policy and R&D: Evidence from a computational experiment", *Journal of Economic Behavior & Organization*, 64(3): 426-447.

Salle I. L., 2015, "Modelling expectations in agent-based models. An application to central bank's communication and monetary policy", *Economic Modelling*, 46: 130-141.

Sun J. and L. Tesfatsion, 2007, "Dynamic testing of wholesale power market designs: An open-source agent-based framework", *Computational Economics,* 30(3): 291-327.

Tesfatsion L., 2006, "Agent-based computational economics: A constructive approach to economic theory", *Handbook of computational economics*, 2: 831-880.

Turrell A., 2016, "Agent-based models: understanding the economy from the bottom up", *Bank of England Quarterly Bulletin,* 56(4): 173-188.

Weidlich A. and D. Veit, 2008, "A critical survey of agent-based wholesale electricity market models", *Energy Economics,* 30(4): 1728-1759.

Woodford M., 2013, "Macroeconomic analysis without the rational expectations hypothesis", *Annual Review of Economics*, 5(1): 303-346.