Eastern Economic Journal, **2008**, **34**, (441–463)

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SYMPOSIUM ARTICLE

Adaptive Microfoundations for Emergent Macroeconomics

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In this paper we present the basics of a research program aimed at providing microfoundations to macroeconomic theory on the basis of computational agent-based adaptive descriptions of individual behavior. To exemplify our proposal, a simple prototype model of decentralized multi-market transactions is offered. We show that a very simple agent-based computational laboratory can challenge more structured Dynamic Stochastic General Equilibrium models in mimicking comovements over the business cycle.
Eastern Economic Journal (2008) **34,** 441–463. doi:10.1057/eej.2008.27

Keywords: microfoundations of macroeconomics; agent-based economics; adaptive behavior

JEL: C63; E10; O11

INTRODUCTION

> It is not so easy … to continue telling macroeconomic stories that rely on a theory of general equilibrium dynamics abandoned over a decade ago by most serious investigators. The tâtonnement cannot be considered a harmless "as if" assumption if it is logically inconsistent with other assumptions in the models we use. [Weintraub 1977, p. 14]

Within just 5 years after Roy Weintraub's forceful warning against the inadequacy of the Walrasian auctioneer to logically produce any interesting real-time macroeconomic issues, the appearance of two complementary papers contributed to the establishment of the current dominant scientific standard in macroeconomics. The two papers were written by Robert Lucas [1980] and Fynn Kydland and Edward Prescott [1982]. Both of them (1) acknowledged as a relevant research question the analysis of macroeconomic fluctuations; (2) proposed a view of aggregate dynamics in terms of the general equilibrium response of rational maximizing individuals to random changes in production possibilities and resource constraints; (3) made use of the contingent-claim interpretation of a Walrasian general equilibrium, as originally proposed by Arrow [1964] and Debreu [1959]; and (4) identified (the former) and implemented (the second) a brand new strategy to assess the predictive success of theoretical statements. While the theoretical underpinnings of the resulting Real Business Cycle (RBC) model[1] were sensibly refined during the following three decades of active research — in that important non-Walrasian features like imperfect competition and incomplete intertemporal markets have been introduced — the core of the solution concept invariably rests (explicitly or not) on a fictitious centralized auctioneer that costlessly collects and disseminates information, adjusts prices and quantities, and organizes and executes trades.

The list of logical problems affecting microfoundations rooted in the Arrow–Debreu tradition is rather long and widely known. Just to cite some of them, it must be noticed that: (i) the conventional general equilibrium theory has difficulties in finding a role for monetary exchange; (ii) the equilibrium is neither unique nor locally stable under general conditions; (iii) the introduction of a representative agent (RA) is done without paying any attention to composition and aggregation fallacies; and (iv) any tâtonnement process occurs in a meta-time, and implies that the formation of prices precedes the process of exchange, instead of being the result of it. The interested reader can consult Kirman [1989], Hartley [1997], and Hildebrand [1994] for wide-ranging discussions.

In spite of all its weaknesses, the practice of modeling an economy worth several trillion dollars by means of a rational optimizing Robinson Crusoe in continuous equilibrium has become *the* scientific standard of modern macroeconomics, also known as Dynamic Stochastic General Equilibrium (DSGE) theory. Certainly, Weintraub's general idea that "… rich, flexible, and rigorous general equilibrium models help to provide a vision of the microfoundations of macroeconomics" [Weintraub 1977, p. 2] nowadays circulates almost undisputed among the profession. Sadly, his admonition to carefully work out the conceptual basis of the *type* of general equilibrium theory to be employed has, however, went almost unheard. The scientific practice of dominating macroeconomics today can be condensed by the sharp metaphor put forth by Axel Leijonhufvud [1998], according to whom economists doing research within the DSGE approach tell stories using the same expositive technique of Beckett and Pirandello: "… the economist of today expects to see a solitary representative agent, under the mathematical spotlight on a bare and denuded stage, asking agonizing questions of himself: 'What does it all mean?' […] or 'I know I have optimized, but — is that all there is?'" [Leijonhufvud 1998, p. 199].

In fact, it should be noted that modern mainstream macroeconomics is in striking contrast with the institutionally oriented, behaviorally adaptive, dynamically rich stories told by economists belonging to the British Classical Tradition [Leijonhufvud 1999]. Although giants of economic thought like Alfred Marshall sometimes used RAs as a modeling tool, those agents were employed only as a means of thinking through what sorts of variables belong in aggregate relationships. No attempts were made to derive aggregate functions from the solution of a dynamic optimization problem posed to a representative consumer/worker. Marshall's stories about the *ordinary business of life* were filled in with asymmetric information, incomplete contracting, exchange-supporting and coordination-enhancing institutions, and process-regarding preferences. The complexity resulting from the interactions of all these constituents clashes with the reductionist approach of modern macroeconomics, as well as with the mathematical tools employed by modern macroeconomists to substantiate it. As regards this latter point, advocates of DSGE typically use fixed-point theorems to solve choice-theoretic problems consistent with the tenets of Subjective Expected Utility theory. It must be noted, however, that equilibrium solutions can be derived only if one assumes that: (i) each agent has full knowledge of the problem; (ii) he is perfectly able to compute the solution; and (iii) there is common knowledge the all agents are operating under requirements (i) and (ii).[2] No surprise, therefore, that the classical way of writing economic tales does not "… appeal to modern tastes. Too many characters on stage: the consumer, the worker, the banker, the entrepreneur, the stock market speculator, and more. And who has patience with the antics that result from the rigid idiosyncrasies and informational asymmetries of this cast? It smack of Commedia dell'Arte" [Leijonhufvud 1998, p. 199].

In this paper we shall argue that a method to *construct* and analyze interesting macroeconomic issues with microfoundations based on heterogeneous, adaptive, decentralized processes of individual decision-making — *a là Commedia dell'Arte* — is not only feasible, but also that the models one obtains in this way can rival the explanatory power of DSGE models. Since we endorse the view according to which "… a general equilibrium model is simply some specification of states of the world and a set of rules that structure the manner in which those states change over time" [Weintraub 1977, p. 2], our theory is firmly rooted in the tradition of general equilibrium analysis. However, we depart from its Walrasian interpretation in that we explicitly model an evolving network of fully *decentralized* trades among *adaptive* agents. The explanations we propose, instead of being derived deductively from the exogenous imposition of a fictitious centralized auctioneer, are *generated* from a systematic analysis of general interactions by means of an *agent-based* computational laboratory.

The structure of the paper is as follows. The next section contains some methodological ruminations about how the agent-based computational approach can be employed to provide sound microfoundations to macroeconomic theory. The subsequent section presents the key features of a prototypical agent-based computational laboratory suited to address macroeconomic issues, while its ability to replicate some well-known stylized facts of the business cycle is assessed in the further section. The last section is a summary and conclusion.

A GENERATIVE APPROACH TO MACROECONOMICS

In his introduction to the equilibrium approach to business cycle theory, Lucas [1980] identified two key sources of scientific development. The first source consists in improvements in mathematical methods and computational capacity. The second one is the identification of statistical regularities — or stylized facts — that should help us in organizing theoretical reasoning and in devising assessment — that is, falsifying — strategies. Of course, these two principles can be accepted as universal pre-conditions of scientific progress holding regardless of the scientific paradigm one is working in. In briefly sketching the grounds for an agent-based approach to macroeconomics, we will elaborate on both in turn.

In the following we do not have any pretension of originality. The material we shall present is basically an idiosyncratic re-combination of hints and intuitions scattered in the pioneering work of towering figures like Armen Alchian, Friedrich von Hayek, Axel Leijonhufvud, Thomas Schelling, and Herbert Simon. Their influence is so pervasive that we prefer to give them full credit now, and to limit references in what follows, to save space. The value added of the present piece is merely to insert their insights into a unifying research program aimed at providing sound microfoundations to macroeconomic analysis.

It should be said at the outset that we convincingly endorse the view that any economy — and particularly *large* economies composed of millions of individual entities — may and should be described as a complex, adaptive, dynamic system [Arthur et al. 1997]. In such a system, complexity arises because of the dispersed, localized, non-linear interactions of a large number of heterogeneous components. While we can naturally observe and measure the aggregate output of the system — quantity and price indexes and their growth rates, for instance — aggregates could not be derived directly from an examination of the behavior of a typical individual in isolation. Global properties emerge from the market and non-market interactions of people without them being part of their intentions, a notion that clearly resembles the time-honored invisible hand metaphor of Adam Smith [Leijonhufvud 1995]. From this standpoint, a microfoundation strategy that assumes away individuals' heterogeneity and interactions like the RA approach is not just over-simplistic, it in fact represents an incorrect scientific practice.

This shift of perspective has two deep implications for economic theory. The first implication calls into question the rationality postulates usually advanced by mainstream economics to model human decision-making. By their very nature, optimization techniques guarantee the correspondence of substantive and procedural rationality if and only if all the consequences of alternative actions can be consistently conceived in advance, at least in a probabilistic sense. Unfortunately, for complex systems this possibility is generally ruled out, as interactive population dynamics gives rise to uncertainty that could not be reduced to risk in a Knightian sense[3] [Rosser 2001]. In turn, non-cooperative game theory Shubik [1975] does not provide a way out under rather general conditions. Whenever players are heterogeneous as regards their strategy and information sets, a full adherence to strategic behavior modeling returns computationally complex problems, that is problems whose solution time (measured as the number of simple computational steps required to solve it) increases exponentially in the problem size. As the number of players increases — for large industrialized economies, the typical order of magnitude of agents acting on markets is 10^6 — the size of the problem is too large to complete a search for an optimal solution within a feasible time horizon. By its very nature, macroeconomics is a discipline concerning *large worlds* [Savage 1954], that is situations in which economic agents do not possess well-defined models of the environment surrounding them.

It turns out that as we shift attention from microeconomic scenarios to typical macroeconomic ones — that is, as we move from single market to multi-market parables — the degree of rationality we can realistically ask to our models' characters should decline. In large worlds, deductive means of reasoning are inapplicable or ill-defined; individuals must instead build internal mental models to represent the world, learn from the outcomes of previous choices, and extrapolate from the particular to the general. Simply stated, agents must employ some form of induction [Arthur 1992; Denzau and North 1994].

In large interactive systems, individual decision processes become unavoidably adaptive, that is adjusted in the light of realized results, and the search for actions aimed at increasing individual performance stops as soon as a *satisficing* solution has been found [Simon 1987]. Adaptation is backward-looking, sequential, and path-dependent. Desired prices, quantities, inventories, portfolio compositions, and even the identities of those with whom we would like to trade are updated according to "error-correction" procedures. Expectations on the future course of events and results are clearly an important part of the decision-making process, but foresights are taken over finite horizons and are modified sequentially in the light of realized outcomes. While engaging in meaningful macroeconomics from a complex perspective, bounded rationality — both in terms of systematic reasoning errors and of costly deliberation activity — should be the rule, not the exception.

In complex economies, the key driver of evolution is not optimization, but selection. Whenever the enforcement of contracts is costly and trades occur through face-to-face bargaining, maximizing behavior may yield lower payoffs than adherence to recognizable, forecastable social norms like reciprocity and cooperation [Schelling 1978]. Furthermore, Witt [1986] and Dutta and Radner [1999] have shown that the famous *as if* argument used by Friedman [1953] to validate the profit maximization hypothesis — only firms whose managers maximize profits will survive in a competitive environment — does not hold even in more orthodox dynamical risky competitive models. In addition to sub-optimality at the individual level, aggregate outcomes emerging from selection processes need not result in the most efficient outcome [Dew et al. 2004]. We shall come back later to this point. For the moment, it must be noticed that the essence of this argument was made by Alchian almost six decades ago: "realized positive profits, not maximum profits, are the mark of success and viability. … The pertinent requirement — positive profits through relative efficiency — is weaker than 'maximized profits', with which, unfortunately, it has been confused. … The preceding interpretation suggests two ideas. First, success (survival) accompanies relative superiority; and, second, it does not require proper motivation but may rather be the result of fortuitous circumstances" [Alchian 1950, p. 213].

The second implication of the complexity approach to macroeconomics deals with the common practice of *closing* models through the exogenous imposition of a general equilibrium solution by means of some fixed-point theorems. The introduction of a Walrasian auctioneer inhibits the researcher from exploring the real question at stake in macroeconomics, that is to explain how self-interested trading partners happen to coordinate themselves in decentralized markets most of the time, but also why from time to time some major economic disaster occurs without any apparent external cause. Complexity offers a way out of this situation, and it suggests new perspectives. Complex adaptive economies display a tendency to self-organize towards rather stable aggregate configurations, occasionally punctuated by bursts of rapid change. Spontaneous order emerges in the process of individual buying and selling transactions taking place in real space and time, without the need of any central controller. Adaptive and imitative behaviors give rise to stable and predictable aggregate configurations, as stability implies predictability and vice versa. Since it is sometimes safer to be wrong in the crowd than to be right alone, imbalances can now and then accumulate to the point that a bundle of chained bankruptcies becomes inevitable. After the bubble has burst and the system has experienced episodes of wild instability, new modes of adaptive behavior, technological opportunities, and budget constraints co-evolve, leading the economy towards a new phase of aggregate stability.

Readers acquainted with Austrian economics will had already recognized that the picture we have just drawn embraces the notion of *spontaneous market order* put forward by Hayek [1978]. According to Hayek, a clear definition of the laws of property, tort, and contract is enough to regulate a set of trial and error exchange relationships, which succeeds in coordinating the plans of an interdependent network of individuals endowed with a multiplicity of competing ends. The process leading to a spontaneous market order takes place in real-time with exchanges occurring at out-of-equilibrium prices; it is irreversible, and fatal errors may drive agents out of the market. In contrast, Hayek argues that the notion of competitive general equilibrium based on the *tàtonnement* process, be it the no-trade-out-of-equilibrium version of Walras or the provisional contract version of Edgeworth, is ''unfortunate, since it presupposes that the facts have already all been discovered and competition, therefore, has ceased'' [Hayek 1978, p. 184]. This is not to say that the concept of equilibrium should be definitely abandoned, but simply that the tendency for demands and supplies to adjust so that markets clear can be successfully explained only if we can model it as an emergent feature of economic systems. Since the economy is a complex network of non-linear interactions among adaptive agents, the meaning and the properties of a macroeconomic equilibrium configuration — if it exists — must, however, be qualified. First, the presence of non-market interactions implies that decentralized and command solutions do not coincide. Second, even if we can operationally define a social welfare criterion to be somehow maximized, the surface of the objective function is in general very *rugged* and continuously changing market forces can drive the system towards a local optimum, and adaptive and imitative individual behaviors may contribute to make it persistent once reached. However, the resulting configuration can be quite far from the globally optimal one: market selection due to survival does not imply absolute individual *and* societal optimality.

Of course, the complexity view to macroeconomics needs appropriate conceptual and analytical tools. The abandonment of the Walrasian auctioneer implies that market outcomes must be derived from the parallel computations made by a large number of interacting, heterogeneous, adaptive individuals, instead of being deduced as a fixed-point solution to a system of differential equations. The process of removal of externally imposed coordination devices induces a shift from a top-down, reductionist perspective towards a bottom-up approach. Sub-disciplines of computer science such as distributed artificial intelligence and multi-agent systems — computer programs built as loosely coupled networks of software agents that interact to solve problems that are beyond the individual capacities or knowledge of each problem solver — are natural fields to look at. Agent-based computational economics (ACE) — that is the use of computer simulations to grow and study evolving artificial economies composed of many autonomous interacting agents — represents a promising tool for advancements along the research program sketched so far [Judd and Tesfatsion 2006].

ACE models are pieces of software describing artificial economies. They start from the definition of a population of objects with characterizing attributes, a set of behavioral, communication, and learning rules, and an environment in which interactions take place. Objects are programmed to pursue and assess their own self-interest, and to behave consequently — hence the name *agents*. The set of instructions defining the behavioral rules followed by agents reflects what we know about how actual people behave under alternative environmental settings, as can be elicited from the considerable amount of evidence available from controlled experiments with human subjects conducted in economics and psychology, and from survey data. Computational laboratories can be built by instructing software agents to follow specific behaviors in the context of specific economic institutions, in order to obtain conditional statements on the links between individual and aggregate phenomena. Such an approach is clearly at odds with the practice employed by mainstream economics of axiomatically describing human behavior and subsequently deducing market outcomes.

Once initialized, the artificial economy is free to evolve without any further external intervention. Simulations return artificial histories, which can be used for empirical and normative understanding. As argued by Epstein [2006], ACE models allow *generative* explanations. The agreement between artificial and real histories (measured according to a certain metric) demonstrates how aggregate structures of interest for macroeconomists — such as, for instance, business cycles, price inflation, or underemployment of resources — are effectively attainable starting from a given microstructure. In other words, target macrostructures emerge because they are effectively computable by the network of interacting agents, regardless of the fact that individual agents are not aware of it. Indeed, according to the ACE approach, a market economy works exactly like a distributed computational device, with markets playing the role of social institutions aimed at mobilizing and combining bits of knowledge scattered throughout the economy. The legacy of Hayek's [1948] thought on this view is patent.

Interestingly enough, the improvements in mathematical methods required to construct virtual economies obeying the complexity approach pose serious challenges to the basic mathematical foundations of standard economic theory. Suppose we are asked to apply the same methodology of ACE models to Walrasian ones. Instead of asking to deductively *prove* the existence of an equilibrium price vector p^* such that the aggregate excess demand function $F(p^*)=0$, we are supposed to explicitly *construct* it by means of an *algorithm* or *rule* describing how the solution may be found. Starting from an arbitrary price vector p, the algorithm should choose price sequences to check for p^* and halt when it finds it. In other terms, to find the general equilibrium price vector $F(p^*)=0$ means that halting configurations are decidable. As this violates the undecidability of the halting problem for Turing machines, from a recursion theoretic viewpoint such a solution is uncomputable [Richter and Wong 1999]. As a matter of fact, ACE modeling is posed on firmer constructivist grounds than Walrasian microfoundations.

As noted above, any effort aimed at grounding macroeconomic theories on models of individual behavior — whether associated to neoclassical or the complexity perspective — must be supplemented with a coherent strategy to assess the correctness of its explanations and predictions. Starting from Lucas [1980] and Kydland and Prescott [1982], advocates of the DSGE model have assumed that the central question to be answered by theories of the business cycles is not why aggregate activity periodically falls and rises, but is in fact comovements of aggregate variables over time. The success or the failure of a DSGE model is then obtained by comparing the correlations of the actual time-series to those resulting from simulations of the model using artificially generated series for a common technology shock, which is commonly considered the ultimate source of fluctuations. It is amusing to note that the practice to advance hypothesis — read models — aimed at matching stylized facts, without paying any commitment to historical accuracy, reflects a suggestion advanced by Kaldor [1965], who is one of the fiercest opponents of equilibrium economics.

Such an assessment strategy has been persuasively criticized as methodologically incorrect [Hartley et al. 1997]. For instance, when taking to the data a DSGE with an RA, it is not clear what we are trying to falsify, because conjectures regarding rationality, aggregation, and general equilibrium are advanced simultaneously. We mostly agree with such a criticism. In fact, the research agenda we have sketched above can easily address different and methodologically more correct procedures to falsify theoretical conjectures. Thanks to their inherent flexibility, the amount of data one can generate in ACE models is just a matter of computational capabilities. Empirical ex post validation exercises can thus be performed, in which the artificial history of any single agent can be tracked and compared with its actual counterpart as derived from panel survey data [Bianchi et al. 2007]. However, since this paper is mainly devoted to a comparison of two alternative methodologies to build macroeconomic models from sound microfoundations, a preliminary step is in order before we completely discard the old way for the new one. In particular, it seems worthwhile to evaluate whether the alleged goodness of DSGE models in mimicking stylized facts related to comovements can be challenged by a rival model inspired to alternative microfoundations. That is what we shall try to do in the section Simulation Results.

AN ACE MACROECONOMIC MODEL

In this section we offer a prototypical ACE macroeconomic model, which consists in *growing* a sequential economy populated by a finite number of *synthetic* firms, $i=1, \ldots, I$, workers/consumers, $j=1, \ldots, J$, and banks $b=1, \ldots, B$. Agents undertake decisions at discrete times, $t=1, \ldots, T$, on three markets: (1) a market for a homogeneous non-storable consumption good; (2) a market for labor services; and (3) a market for credit services. Notional prices and quantities are chosen adaptively, according to rules of thumb buffeted by idiosyncratic random disturbances. Markets are characterized by decentralized search and matching processes, which imply individual, and *a fortiori* aggregate, out-of-equilibrium dynamics. Owing to the absence of any exogenously imposed market-clearing mechanism, the economy is allowed to self-organize towards a *spontaneous order* with persistent involuntary unemployment, unsold production, excess individual demands, and credit rationing.

The framework that follows belongs to a suite of computational investigations of macroeconomic processes modeled as complex adaptive trivial systems (C@S). Other exemplifications of the C@S approach can be found in Delli Gatti et al. [2005], Gaffeo et al. [2007], and Russo et al. [2007]. The common modeling strategy is built on two pillars. First, the rules of individual behavior and market transactions that we translate into algorithmic language are inspired — where possible — by the evidence available from survey studies conducted by asking households and business people how they actually behave. Where several competing options are available, we conform to the dull version of the Occam's Razor principle known as KISS.[4] Second, as discussed at length above, we do not impose any centralized solving mechanism. Instead, we let the system of adaptive interacting agents evolve autonomously towards self-organizing configurations, if they exist.

The sequence of events

The sequence of events occurring in each period runs as follows.

1. At the beginning of any t, firms and banks check their financial viability as inherited from the past. They continue to operate if their net worth (a stock variable equal to the sum of past retained net profits) is positive. If, on the contrary, net worth is lower or equal to zero, they shut down due to bankruptcy. In the latter case, a string of new firms/banks equal in number to the bankrupted ones enters the market. Entrants are simply random copies of incumbents.

2. Individual productivity can be increased by an uncertain amount thanks to investments in R&D, determined as a fixed fraction of the last periods gross profits, π_{it-1}.
3. By looking at their past experience, each operating firm determines the amount of output to be produced (hence, the amount of labor to be hired) and the price. Expectations on future demand are updated adaptively.
4. A fully decentralized labor market opens. Firms then pay their wage bill W_{it} in order to start production.
5. If internal financial resources are in short supply for paying wages, and fill in a fixed number of applications to obtain credit, banks allocate credit collecting individual demands, sorting them in descending order according to the financial viability of firms, and satisfy them until all credit supply has been exhausted.
6. Production takes the whole period t, regardless of the scale of output. At the beginning of t, firms pay their wage bill in order to start production. If internal financial resources are in short supply for paying wages, firms can enter a fully decentralized credit market and borrow funds. The contractual interest rate is calculated applying a markup (function of financial viability) on an exogenously determined baseline.
7. After production is completed, the market for goods opens. Firms post their offer price, while consumers are allowed to muddle through searching for a satisfying deal. If a firm ends up with excess supply, it gets rid of the unsold goods at zero costs.
8. Firms collect revenues, calculate profits, update their net worth and, if internal resources are enough, pay back their debt obligations.

Production technology

Production is carried out by means of a constant return to scale technology, with labor L_{it} as the only input:

$$Y_{it} = \alpha_{it} L_{it}, \ \alpha_{it} > 0 \tag{1}$$

where α_{it} is labor productivity. The latter is assumed to evolve over time according to a first-order autoregressive stochastic process:

$$\alpha_{it+1} = \alpha_{it} + z_{it} \tag{2}$$

where z_{it} is the realization of a random process, exponentially distributed with mean $\mu_{it} = \sigma_{it}\pi_{it}/(p_{it}Y_{it})$, with $0 < \sigma < 1$: the higher the fraction of gross nominal profits (π) invested in R&D (scaled by nominal sales pY), the higher the expected increase in productivity. Hence, firms' investment in R&D may vary either because of variations in profits or because of variations of the behavioral parameter σ. In simulations, σ will be allowed to increase with the amount of gross nominal profits, according to a step function. Equation (2) and the operational underlying assumptions can be seen as a reduced form reflecting theoretical and empirical considerations suggested by a profusion of studies on the determinants of corporate R&D investment [Reynard 1979; Fazzari and Athey 1989].

In line with the literature on capital market imperfections, in our setting the amount of internal liquidity or net worth is the key variable measuring firms' viability. Put in the complexity perspective, this conjecture implies that the dynamics of operating cash flows drives selection mechanisms. The law of motion of net worth, A_{it}, is given by

$$A_{it} = A_{it-1} + (1 - \sigma_{it-1})\,\pi_{it-1} \tag{3}$$

Net worth is used to finance working capital. Firms can also borrow external funds — if internal ones are insufficient — from a banking sector. Clearly, the higher the amount of debt a firm has, the higher the probability to fail to repay it, ceteris paribus. In fact, if the net worth turns out to be negative, the firm becomes technically insolvent, and it is declared bankrupt. As a consequence, it exits the market and is replaced by a new entrant.

From the discussion above, it appears that firms face a trade-off when allocating operating profits between increasing productivity through R&D investment and limiting the resort to debt. Both decisions impinge on the probability a firm has to survive, but in opposite directions.

The labor market

Firms set their labor demand, L_{it}^{d}, on the basis of their desired level of production, Y_{it}^{d}. We will show momentarily how the latter is determined. From equation (1), it follows that the number of job openings set by firm i at time t is simply given by

$$L_{it}^{d} = \frac{Y_{it}^{d}}{\alpha_{it}} \tag{4}$$

We assume that workers supply inelastically one unit of labor per period. Each worker sends M applications to many firms: the first one to the firm in which he worked in the previous period (if employed), and $M-1$ at random (M if unemployed in $t-1$). Workers are therefore characterized by a sort of loyalty to their last employer, on the one hand, and by a desire to insure themselves against the risk of unemployment by diversifying in a portfolio of hiring opportunities, on the other.

The ith firm organizes all received applications into two blocks. The first one is composed of all its previous employees, as employers respond to the loyalty of their workforce by assuring them a priority in their hiring policy. The second block of the queue, in turn, is filled in by all other applicants. Firm i may face two alternative situations:

(a) $L_{it}^{d} \leqslant L_{it-1}$, that is the desired labor demand at time t is lower than the number of people employed during the previous period. In this case, the last $L_{it-1} - L_{it}^{d}$ workers (i.e., the ones with higher inherited wages) queuing in the first block are fired, while the remaining are kept. Fired workers have other $M-1$ opportunities to find a job elsewhere.

(b) $L_{it}^{d} > L_{it-1}$, that is firm i wants to increase its workforce. In this case, i keeps all its past employees and looks for $L_{it}^{d} - L_{it-1}$ new workers, who are selected from the second block of the queue.

Decentralized labor markets (i.e., one for each firm) are closed sequentially according to an order randomly chosen at each time step. Given that each worker is allowed to sign one labor contract per period, serious coordination failures could arise as the number of workers actually available does not necessarily correspond to the one inscribed in queues, especially for firms that are called to hire their workers late in the sequence.

When hired for the first time by a firm, a worker is asked to sign a contract that determines his nominal wage level for a fixed number of periods. The wage offered to him by firm i in period t is calculated according to the following rule:

$$w_{it}^{b} = \max(\hat{w}_t, w_{it-\tau}(1 + \xi_{it})) \tag{5}$$

where $\hat{w}_t$ is a minimum wage imposed by the law, while $w_{it-\tau}$ is the wage offered to the cohort of workers employed the last time firm i hired (period τ, with $\tau \geqslant 1$). Finally, ξ_{it} is an idiosyncratic shock uniformly distributed on the non-negative interval $(0, h_\xi)$. Workers who succeed in receiving more than one proposal accept the one that pays the higher wage.

The minimum wage is periodically revised upward, in order to neutralize price inflation. Wages contracted in previous periods that happen to fall below the minimum wage are automatically updated to it.[5] Besides hedging workers against the risk of losing purchasing power due to inflation, the updating of the minimum wage contributes to couple firms with their environment. For instance, in periods of *tight* labor market firms that are hiring increase their output price to preserve profit margins. Higher prices, in turn, drive the minimum wage upwards as an externality. The process works the opposite way when the market for labor is dull.

The labor market design we choose is consistent with the findings reported by numerous surveys of firms' wage-setting policies. First, there is clear evidence of nominal wage downward rigidity. Firms are particularly reluctant to cut nominal wages even during recessions because they fear that lower wage rates would increase turnover and decrease labor effort [Campbell and Kamlani 1997; Bewley 1999]. Second, downward rigidity is observed also for the pay of new hires, probably for reasons of perceived equity [Bewley 1999]. Finally, there is clear evidence that individual real wages are not fully insulated against inflation [Baker et al. 1994].

The market for the consumption good

At the beginning of each time period, firms can adaptively adjust their price and their output level to make an allowance for changed business conditions. In spite of the good being homogeneous, asymmetric information and search costs imply that consumers may end up buying from a firm regardless of its price not being the lowest. It follows that conditions for perfect competition are not satisfied, and the law of one price does not necessarily apply [Stiglitz 1989].

For simplicity, we constrain the two strategies to be mutually incompatible. Therefore, at each time period firms can choose to vary the quantity *or* the price. Such a dichotomy is aimed at reflecting the evidence in the survey data on price and quantity adjustment of firms over the business cycle [Kawasaki et al. 1982; Bhaskar et al. 1993]. While for expositional simplicity in this paper we retain the assumption that each non-mutual action is ex ante equally likely, in principle nothing prevents the calibration of such a probability according to real data. For instance, the available evidence suggests that for firms without cash-flow problems, price adjustments are more likely during recessions than during booms, whereas the reverse is true for quantity adjustments, while liquidity constrained firms are less likely to cut prices in recessions.

In our model, the revision strategy for both options depends on signals coming from an analysis of internal operating conditions and from the market. Let us describe the two adjustment mechanisms in turn. As regards prices, we assume that firms and consumers operate in a posted offer market. Prices are set considering the unsold quantities during the last period (S_{it-1}), the costs incurred in production, and the deviation of individual prices from the average price index during the last transaction round. Internal conditions are private knowledge, while the aggregate price index P during the previous round is common knowledge. More precisely, the ith manager sets his *satisficing* selling price according to the following rule:

$$P_{it}^{s} = \begin{cases} \max[P_{it}^{l}, P_{it-1}(1+\eta_{it})] & \text{if } S_{it-1} = 0 \text{ and } P_{it-1} < P \\ \max[P_{it}^{l}, P_{it-1}(1-\eta_{it})] & \text{if } S_{it-1} > 0 \text{ and } P_{it-1} \geqslant P \end{cases} \tag{6}$$

where η_{it} is an idiosyncratic random variable uniformly distributed on a positive support $(0, h_\eta)$, and P_{it}^{l} is the lowest price at which firm i is able to cover its average costs:

$$P_{it}^{l} = \frac{W_{it}}{Y_{it}} \tag{7}$$

The remaining combinations of signals regarding involuntary inventories and relative prices trigger adjustments of quantities. In this case, the level of production planned at the beginning of period t (Y_{it}^{d}) depends on expected demand, $Y_{it}^{d} = D_{it}^{e}$. Expectations on future total orders are revised adaptively according to the following:

$$D_{it}^{e} = \begin{cases} Y_{it-1}(1+\rho_{it}) & \text{if } S_{it-1} = 0 \text{ and } P_{it-1} \geqslant P_{t-1} \\ Y_{it-1}(1-\rho_{it}) & \text{if } S_{it-1} > 0 \text{ and } P_{it-1} < P_{t-1} \end{cases} \tag{8}$$

where ρ_{it} is an idiosyncratic shock uniformly distributed on a positive support $(0, h_\rho)$. Thus, expectations are revised upward if a manager observes excess demand for its output and its price is already above the average price on the market, and downward when the opposite holds true.

Aggregate demand depends on the total wage bill paid by firms to workers employed in $t-1$. The marginal propensity to consume out of labor income c varies according to the worker's total wealth, defined as the sum of labor income plus all accumulated past savings. These latter, in turn, are due to a typical precautionary motive in the face of income uncertainty: households hold assets to shield their consumption against unpredictable declines in income associated with spells of unemployment. In line with empirical evidence from the consumer expenditure survey [Souleles 1999], as well as with predictions from the theory of consumption under uncertainty [Carroll and Kimball 1996], the marginal propensity c of our artificial consumers is assumed to decline with personal wealth.

Given the lack of any market-clearing mechanism, and that bargains on the good market are fully decentralized, consumers have to search for satisfying deals. The information acquisition technology is defined in terms of the number of firms Z a consumer can visit without incurring any cost. In other words, search costs are null as the consumer enters the market, continue to be null if he remained confined into his local market of size Z, but become prohibitively high as soon as a consumer tries to search outside it. In what follows, the identity of the Z firms associated to a generic consumer j at any time period t is determined by a combination of chance and deterministic persistence. The search mechanism works as follows. Consumers enter the market sequentially, the picking order being determined randomly at any time period t. Each purchaser j is allowed to visit Z firms to detect the price posted by each one of them. In order to minimize the probability to be rationed, he definitely visits the larger (in terms of production) firm visited during the previous round, while the remaining $Z-1$ firms are chosen at random. Thus, consumers adopt a preferential-attachment scheme, where preference is given to the biggest firms. Posted prices (and the corresponding firms) are then sorted in ascending order, from the lowest to the highest. Consumer j tries to spend a fraction c out of the labor income gained in period $(t-1)$ — if employed — or of accumulated past savings — if unemployed — in goods of the cheapest firm in his local market. If the cheapest firm does not have enough available output to satisfy j's needs, the latter tries to spend his remaining income buying from the firm with the second lowest price, and so on. If j does not succeed in spending his whole income after he visiting Z firms, he saves (involuntarily) what remains for the following periods. For the sake of simplicity, the interest rate on savings is assumed to be equal to 0.

After the market for consumption goods has closed, the ith firm has made sales for Q_{it}, at the price P_{it}. Accordingly, i's revenues are $R_{it} = P_{it}Q_{it}$. Owing to the decentralized buying–selling process among firms and consumers, it is possible that a firm remains with unsold quantities ($S_{it} > 0$). In the following period, the variable S will be used as a signal in adjusting firms' prices or quantities, as explained above.

The credit market

If the net worth A_{it} is insufficient to pay for the current period wage bill, firm i can try to obtain additional funds by borrowing from one of a fixed number N of banks. The demand for credit is therefore simply given by

$$B_{it} = \begin{cases} W_{it} - A_{it} & \text{if } W_{it} > A_{it} \\ 0 & \text{otherwise} \end{cases} \tag{9}$$

Each bank offers to the generic firm i a standard single-period debt contract, which consists of an interest rate offer $r(\lambda_{it})$ — where $\lambda_{it} = B_{it}/A_{it}$ is i's leverage ratio — and the corresponding repayment schedule:

$$\begin{array}{ll} B_{it}(1 + r(\lambda_{it})) & \text{if } A_{it+1} \geqslant 0 \\ R_{it+1} & \text{if } A_{it+1} \leqslant 0 \end{array} \tag{10}$$

The contractual interest rate offered by bank n to firm i is determined as a markup over a discount rate set by a central monetary authority, which for simplicity we assume to be constant:

$$r_{it} = \bar{r}(1 + \phi_{nt}\mu(\lambda_{it})) \tag{11}$$

with $\mu' > 0$, while ϕ_{nt} is a random function with positive support $(0, h_{\phi})$. The markup the bank charges over the official discount rate reflects a risk premium that increases with the financial fragility of the borrower. Equation (11) can be seen as a reduced form from a model in which commercial banks can insure themselves against potential losses by borrowing from a central bank that acts as a lender of last resort [Acharya et al. 2008]. A by-product of this last assumption is that firms are never credit-constrained, since banks can obtain additional funds from the central monetary authority and price-discriminate among borrowers according to their quality. Finally, the stochastic shock ϕ captures random variations in banks' operating costs.

We assume that the demand for credit is indivisible, so that at each time period a firm can borrow from just one bank. A firm that needs external finance to implement its desired production program can explore the bank loan market by randomly picking H, with $0<H<N$, trials. Such a firm then sorts the offers it receives in ascending order, and chooses the bank ranked first.

SIMULATION RESULTS

In order to explore the general properties of the model, we simulate a baseline version recurring to the set of parameters presented in Table 1. All parameter values are allowed except those that create degenerating dynamical paths identifiable by visual inspection and conventional numerical values.[6] In particular, no attempt is made at this stage to calibrate the model — for instance, by means of genetic algorithms — so that simulation outcomes are forced to replicate some pre-selected empirical regularities. As we will see, in spite of this limitation the model works fine along several margins. An extensive analysis of robustness to changes in parameters through Monte Carlo methods as well as computational experiments based on the design of alternative treatments are left for presentation in companion papers.

As a general principle, the usefulness of a model is assessed by comparing its theoretical predictions with a selected set of *explananda*. What do we mean by successful ACE macroeconomic theorizing then? From the perspective we took in the second section, we believe that at least two questions are of key importance whenever one tries to *do* useful macroeconomic theory outside the *rationality-cum-equilibrium* approach. First, a macroeconomic model should be able to display, as a general feature, the ability to self-organize most of the time, but also to occasionally display severe coordination failures yielding great depressions without necessarily recurring to negative aggregate shocks. Models based on the Walrasian general equilibrium approach, on the contrary, usually possess the unsatisfactory property to exhibit either regular behavior all the time (whenever a stable equilibrium exists), or permanent degenerate behavior (whenever the previous condition do not hold). Second, the model should be able to replicate, at least qualitatively, one or more of

Table 1 Parameters

	Parameter	*Value*
I	Number of consumers	500
J	Number of firms	100
B	Number of banks	10
T	Number of time periods	1,000
c_P	Propensity to consume of *poor* people	1
c_R	Propensity to consume of *rich* people	0.5
σ_P	R&D investment of *poor* firms	0
σ_R	R&D investment of *rich* firms	0.1
H_ξ	Maximum growth rate of wages	0.05
H_η	Maximum growth rate of prices	0.1
H_ρ	Maximum growth rate of quantities	0.1
H_ϕ	Maximum amount of banks' costs	0.1
Z	Number of trials in the goods market	2
M	Number of trials in the labor market	4
H	Number of trials in the credit market	2

the macroeconomic stylized facts that are known to hold for the majority of industrialized countries. In particular, we are interested in building a virtual environment able to capture the emergence of aggregate regularities as the result of dispersed market and non-market interactions of a multitude of heterogeneous agents.

While the latter two points put the emphasis on qualitative assessment strategies to corroborate theoretical predictions from ACE models, it must be acknowledged that additional quantitative methods — in terms of ex-post validation — can be naturally devised. We prefer here to stick to qualitative measures of success, however, since this allows us to make a more direct comparison between our proposal and the DSGE research program. This could sound odd, since DSGE models are usually taken to the data by comparing quantitative theoretical predictions with figures summarizing key features of cyclical fluctuations in real economies. This impression is largely false, however. Since no formal metric is offered to measure the closeness of the model data to the actual data, the assessment exercise presented in almost every DSGE paper is ultimately qualitative. Hence, instead of reproducing the familiar table of figures based on actual and simulated data, we prefer to illustrate the performance of our ACE model in replicating first-order features of real economies with graphical methods.

In the following we will see that our ACE model can generate (i) a rather stable aggregate dynamics punctuated by sudden crisis; (ii) emergent macroeconomic regularities, such as parallel paths of the average labor productivity and real wage, a Phillips curve, and an Okun curve; and finally; (iii) comovements among aggregate variables. Regarding this last point, the benchmark we use against simulation outcomes is the postwar US economy. In particular, filtered-detrended[7] quarterly data for real GDP, employment, labor productivity, real wages, inflation, and bank loan interest rates obtained from the Federal Reserve web-based FRED database have been used to calculate leads and lags correlations.

In Figure 1 we present the dynamics of (log) real GDP (a), the rate of unemployment (b), the annual inflation rate (c), and the dynamics of labor productivity and real wage (d) for a representative simulation parameterized according to Table 1. Only the last 500 simulated periods are considered, in order to get rid of transients.

The time path of aggregate activity is characterized by sustained growth, punctuated by sudden, deep and rather short crises. In our simulations, big depressions are due to the failure of big firms, a phenomenon known to occur in the real world but systematically ignored by standard macroeconomic theory. It is worth noting that during depressions the unemployment of resources, here summarized by labor, average productivity, and average real wages follow a path similar to that of aggregate economic activity. If we let each simulated time period correspond to one-quarter, in our simulations the per-year probability of experiencing an economic disaster is between 0.8 percent and 1.7 percent. These figures are just slightly lower than estimates reported by Barro [2006], according to whom the per-year probability of a big depression (i.e., a drop in real GDP of 15 percent or higher) in OECD countries during the last 100 years is in the range 1.5–2 percent. Notice, however, that Barro includes wars in his calculation of major disruptions. Furthermore, in line with the long-run experience of industrialized countries, simulated data suggest that great depressions represent transitory disturbances, in that the long-run real GDP growth path is not sensibly affected by major displacements.

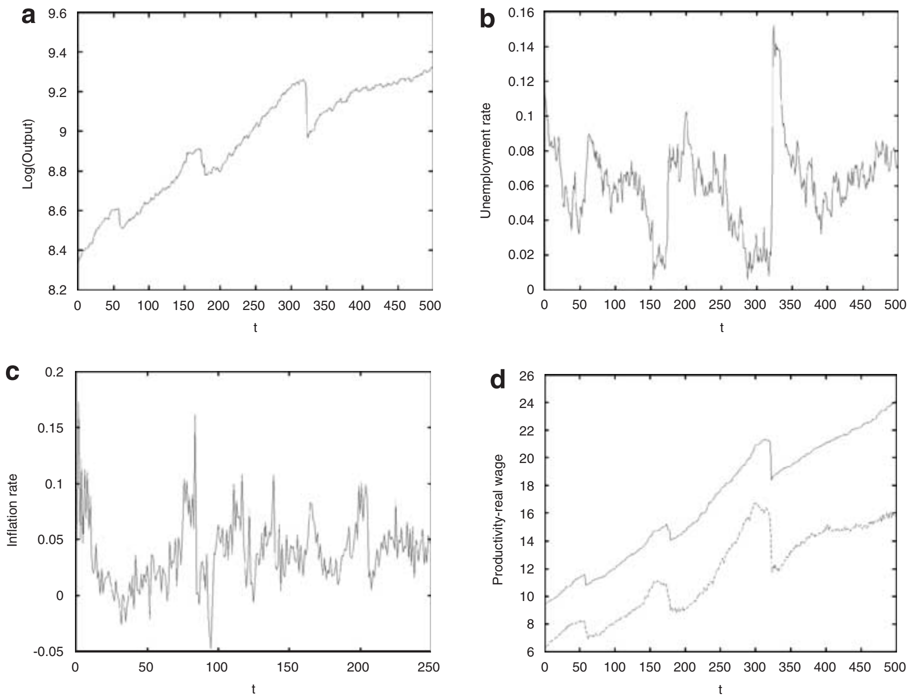

Figure 1. Emergent macroeconomic dynamics from simulations. (a) one GDP, (b) rate of unemployment, (c) annualized rate of inflation, (d) productivity (solid line) and real wage (dotted line).

Simulations have shown that the severity and likeliness of economic disaster depend positively on the importance we assign to the preferential-attachment scheme followed by consumers when searching in the goods market. This makes sense: if customers spread more equally over the market, the probability of finding a really big firm, and *a fortiori* the probability to find a really big firm on the verge of bankruptcy, is lower.

In addition to great depressions, the growth path of aggregate output is characterized by fluctuations resembling business cycles. The model is able to generate an alternation of aggregate booms and recessions as a non-linear combination of idiosyncratic shocks affecting individual decision-making processes. The account of business cycles offered by the C@S model thus contrasts sharply with DSGE theory, according to which fluctuations in aggregate activity are explained by random variations in aggregate TFP growth.

Even though no serious attempt to calibrate the model has been made, our model does not display pathological phenomena, nor degenerate dynamics. The unemployment rate ranges between 1 and 15 percent, while the yearly rate of inflation is on average equal to 3 percent, reaches a high at around 16 percent, and turns occasionally into moderate deflationary episodes. As shown in panel (d), real wages and productivity follow a similar pattern. Since we do not impose any aggregate equilibrium relationship between the two variables, the (on average) constancy of income shares over time is just an emerging feature of a self-organizing system of heterogeneous interacting agents.

Some other interesting stylized facts emerging from simulated decentralized interactions are depicted in Figure 2. In panel (a) a weak, although statistically

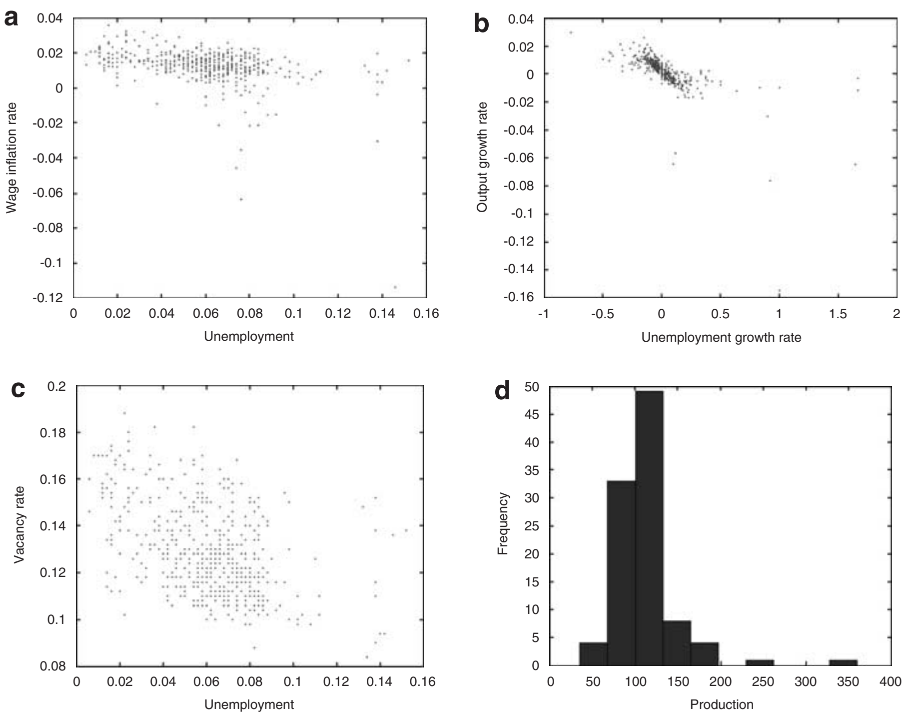

Figure 2. Phillips (a), Okun (b) and Beveridge (c) curves, and the firms' size distribution (d) generated by simulations.

significant, negative relationship between the rate of wage inflation and the rate of unemployment — that is, a standard Phillips curve — can be detected. Panel (b) shows that a negative relationship between the output growth rate and the unemployment growth rate — that is, an Okun curve — characterizes the system dynamics. A third emerging regularity regarding the labor market is the Beveridge curve reported in panel (c), showing a negative relationship between the rate of vacancies (here proxied by the ratio between the number of job openings and the labor force at the beginning of a period) and the rate of unemployment. Finally, panel (d) shows the firms' size distribution, with size measured by production. As in real industrialized economies, the distribution is highly skewed to the right: firms with small and medium size dominate the economy; large firms are relatively rare, but they represent a large part of total supply. When the firms' size distribution is skewed, the mean firm size is larger than the median one, and both are larger than the modal firm size. Clearly, in this case the very notion of a representative firm is meaningless.

As reported above, for reasons of space a proper robustness check via Monte Carlo explorations of the parameter space is left for further research. Nevertheless, we believe that the evidence reported here is sufficient to convey the idea that identifiable aggregate regularities may easily appear from the complex interactions of heterogeneous adaptive adjustments on different margins, technological innovation, limited searches, and out-of-equilibrium decentralized transactions on three interrelated markets. Mainstream economic theory, with its emphasis on equilibrium outcomes from hyper-rational representative households and firms, encounters enormous difficulties in jointly explaining such a rich list of phenomena.

For instance, basically all modern theories that attempt to explain the great depression that hit the world economy during 1929–1939 treat this episode as an outlier, and rely on a rather ad hoc combination of severe frictions, technological, and policy shocks [Chari et al. 2002]. ACE models, on the contrary, can naturally accommodate the alternation of phases of smooth growth and sudden crisis as instances of the same underlying dynamical process.

An obvious criticism of our conclusions is that an appropriate comparison between the C@S family and more traditional DSGE models can be made only if the same testing methodology is used. According to DSGE scholars, the performance of models of the business cycle has to be measured in terms of their ability to replicate aggregate phenomena at cyclical frequencies along three dimensions: persistence, volatility, and comovements of key variables with output. In this paper we start to explore the ability of our ACE virtual economy to challenge DSGE models by mainly focusing on the latter dimension.

The results are reported in Figure 3, where we plot the cross-correlations with output at four leads and lags of employment (a), productivity (b), the price index (c), the interest rate on loans (d), and the real wage (e). Each panel is completed by

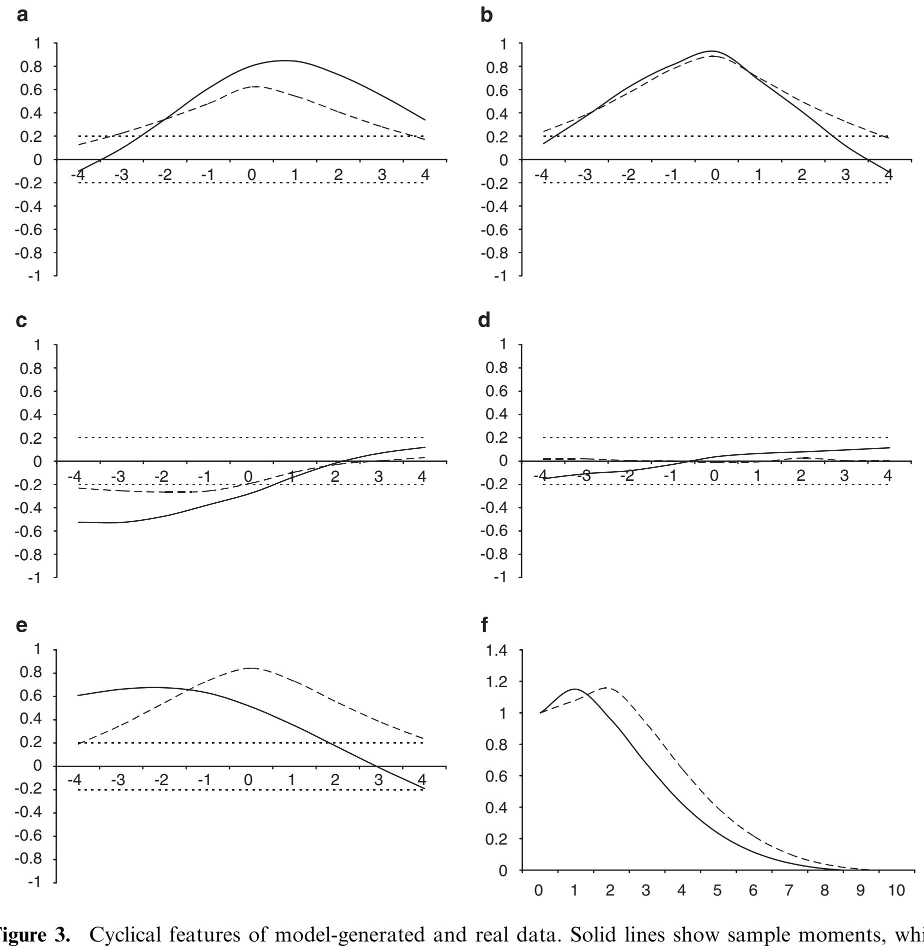

Figure 3. Cyclical features of model-generated and real data. Solid lines show sample moments, while dashed lines show moments generated by simulations. (a) Employment, (b) productivity, (c) price index, (d) interest rate, (e) real wage, (f) GDP transitory impulse–response function.

the corresponding function calculated from real data and a ± 20 percent band, which is conventionally assumed as signaling a lack of correlation.

The model of the third section does a good job in four cases out of five. From simulations we find that employment and productivity are highly correlated with contemporaneous output; prices are slightly negatively correlated and anticipate output, while the interest rate is a-cyclical. All these patterns mimic remarkably well the evidence for the US economy. The simulated real wage turns out to be pro-cyclical, as in real data, but fails to anticipate cyclical movements of aggregate activity by two to three quarters.

Finally, panel (f) of Figure 3 presents the transitory impulse–response functions, calculated by means of an AR(2) estimate for the actual (solid line) and the model-generated (dashed line) output, respectively. The simulated model can mimic the hump-shaped response of cyclical output to transitory shocks — a feature that first-generation RBC models failed to capture [Cogley and Nason 1995] — though the peak in real data precedes the simulated one by one-quarter. The trend-reverting dynamics is nevertheless very similar.

While reminding the reader that all these results have been obtained without any serious effort to calibrate the model, we argue that the C@S basic setup displays rich and interesting aggregate and disaggregated dynamics under rather general conditions on the one hand, and that it can also successfully challenge the explanatory power of neoclassical models when confined to their same ground, on the other.

CONCLUSIONS

In this paper we sketch the basics of a research program aimed at providing microfoundations to macroeconomics, moving from premises dissimilar to the *rationality-cum-equilibrium* methodology followed by the neoclassical mainstream theory. Although the perspective we offer — that is, one based on heterogeneity, adaptation, bounded rationality, and an explicit analysis of decentralized market processes — can be firmly rooted in the history of economic thought, its full disclosure requires the development of new analytical and computable tools. Among them, we argue that the ACE approach is particularly promising, for at least three reasons. First, agent-based simulations allow a remarkable degree of flexibility in modeling human behavior. Instead of deducing aggregate relationships from the maximization problem of a fully rational representative individual and the imposition of general market clearing, artificial agents can be instructed to behave in accordance with the evidence coming from experimental research and econometric work using field data. Second, artificial markets and institutional settings can be constructed by imposing a pre-ordered structure of interactions or, alternatively, the latter can be allowed to spontaneously emerge from the algorithmic description of simple searching heuristics. In both cases, the net of incentives and constraints that feed back and forth between individual and social behavior shapes demand, supply, and price formation, as well as the relationships between growth and business cycles. Third, the ACE approach allows researchers to easily keep track of individual and aggregate outcomes as the simulation goes on, and to assess the sensibility of these outcomes to changes in the environment. Once built, an ACE model becomes a computational laboratory in which several experiments can be made with negligible marginal costs.

Moving from these premises, we introduce a prototypical member of a class of computational agent-based macroeconomic models, the so-called C@S family. We show that the system dynamics generated during simulations can accommodate a large set of stylized facts regarding the long-run and medium-run performance of industrialized countries. In particular, we take up the gauntlet flung down by the neoclassical school, according to whom models of the business cycle should be assessed in terms of their ability to mimic correlations of aggregate variables. In fact, when tested against US data our model can challenge DSGE models in their aptitude to account for business cycle stylized facts.

Beyond a mere ability to match selected statistical regularities, the model we present is aimed at joining those proposed among the others by Clower and Howitt [2000] and LeBaron [2001], to demonstrate that ACE may represent a practical and effective substantiation of the post-Walrasian approach to macroeconomics [Colander 1996; 2006]. In particular, we argue that the methodology discussed in the previous sections of this paper can eventually lead us to successfully tackle several macroeconomic issues that have remained so far largely unsolved. An example we are planning to address in the near future is the following. According to Leijonuhfvud [1986], in properly modeling economies with increasing returns one should abandon the reduced-form externality view proposed by the neoclassical endogenous growth theory, and rediscover instead the time-honored Smithian pin factory parable. According to this view, the economy is conceived as a non-linear input–output system of production, in which firms show increasing returns to scale and every firm uses intermediate inputs that are produced by others. Such a system of interrelated firms turns out to display increasing returns in the aggregate if, and only if, firms overcome coordination failures due to opportunistic hold-ups. In fact, the hold-up of just one input or output can cascade through the system, leaving many firms without an essential input, who in turn fail to deliver their output to still other, and so on. An implementable research agenda consists in setting up an ACE laboratory along these lines, in order to study causal relationships between the design of contracts and procurement processes on the one hand, and the emergence of recessions, bubbles, liquidity constraints, supply–demand disequilibria, and pathological price dynamics on the other.

Acknowledgements

We are indebted to three anonymous referees for helpful comments on an earlier draft of this paper.

Notes

1. The attempt by Lucas to build a monetary theory of business cycles in terms of informational asymmetries and misperceptions in a Walrasian framework [Lucas 1972; 1975] was discarded as logically inconsistent by Okun [1980] and Tobin [1980], in the same issue of the *Journal of Money, Credit and Banking* hosting the piece by Lucas cited in the main text. Lucas himself implicitly recognized it 5 years later, when he focused his 1985 Yrjö Jahnsson lectures on business cycles entirely on the RBC approach of Kydland and Prescott [Lucas 1987].
2. Fixed-point theorems are also at the root of some impossibility results in computable economics. We will briefly touch on this point later on.

3. A possible way to define Knightian uncertainty is that the potential outcomes of an action are identified by two or more distributions at one time, and that these distributions are overlapping.
4. Several interpretations of the acronym KISS circulate, most of them overlapping. The one we prefer is *keep it short and simple*.
5. In simulations, we fixed the duration of contracts to 8 periods, while the minimum wage is revised every 4 periods. If we assume that one simulation period corresponds to a quarter, this means that labor contracts last two years, while the minimum wage is revised annually.
6. Examples of degenerate dynamics we want to avoid are extremely unstable aggregate GDP paths, average rates of bankruptcy and unemployment over 50 percent, and average rates of annualized inflation out of the interval (-100 percent, $+1{,}000$ percent).
7. We use the Hodrick–Prescott filter with the smoothing parameter λ set at 1,400.

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