Agent-based economic modelling in EURACE

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Summary

- Introduction to the ACE approach
- Key features of EURACE
- Agents
- Timing
- Markets
- The balance sheet approach
- Concluding remarks

A snapshot of EURACE

- The EURACE model is by far the largest and most complete agent-based model developed in the world to date.
- It represents a fully integrated macroeconomy consisting of:
  - the **real sector** (production of consumption and capital goods with labor, capital goods and energy as factors of production and relative markets; technological innovation);
  - the **credit sector** (financing production plans of firms);
  - the **financial sector** (exchange of claims on the equity capital of producers as well as of governments liabilities);
  - the **public sector** (polcy making, i.e., fiscal policy made by Governments and monetary policy set by the Central Bank).

Main objectives of EURACE

- Scientific objectives:
  - Establishing an innovative framework for the study of the macroeconomy according to the agent-based computational approach.
  - Providing new insights on the emergence of global regularities in the aggregation of heterogeneous interacting agents.
- Technological objective:
  - Development of new software methodologies for implementing, designing and validating large-scale agent-based economic simulations.
- Societal objective:
  - Development of an agent-based software platform to perform simulation experiments on economic policy design for the European Union.

Why EURACE ?

- In 2005, when the proposal was presented to EU, we were unsatisfied about the present state of mainstream economic theory (representative agents, rational expectations, perfect asset markets, market clearing, ...)
- 2009: what about now?

2009: the state of the mainstream approach :-)

The day after the crisis.....

- The current financial and banking crisis and the subsequent severe economic recessions have caused a crisis of confidence in the science of Economics.
- Most economists have been unable to forecast timely the crisis and even to devise helpful policies at its beginning.
- The Nobel Laureate Paul Krugman recently feared that most macroeconomics of the past 30 years was "spectacularly useless at best, and positively harmful at worst" (The Economist, July 16^{th} 2009).
- "Economics needs a scientific revolution" by J.-P. Bouchaud (Nature, October 30^{th}, 2008)

Why mainstream failed to predict the crisis?

- According to mainstream approaches to economics, e.g. DSGE models, the structure of financial liabilities in the economy only has limited influence on the aggregate economic activity.
- Capitalist economies are viewed as essentially stable and tending towards steady growth; and the investment-finance linkage is considered at the most as amplifying mechanism of exogenous shocks.
- On the contrary, a different, unduly neglected strand of research emphasizes the role of the investment-finance link not just as a propagator of exogenous shocks but as the main source of financial instability and business cycles. (H. Minsky, Stabilizing an Unstable Economy, 1986).

The ACE approach

- Simulating artificial economies on the computer is becoming a promising approach to the study of economic systems, able to overcome the limitations of elegant, yet unrealistic, mainstream analytical economic models (Nature vol 460, August 2009).
- The study of the economy by means of agent-based computational models is a relatively new field and dates back to the 90s.
- The increasing availability of cheap computing power made possible to undertake the computationally expensive experiments required to model the interactions of large numbers of bounded rational, heterogeneous agents.

The ACE approach and the credit crisis

- The agent-based methodology fully addresses the interaction and the coordination processes of heterogeneous economic agents by considering both individual and social learning behaviours.
- It allows the study of the emergent aggregate statistical regularities in the economy, which cannot be originated by the behaviour of a "typical" or "average" individual (Kirman J. Econ Perspectives 1992), but is the result of agents' behaviour and interaction.
- It takes into account the complex pattern of interactions in the credit markets, like networks topologies, credit rationing, bankruptcy waves and cascade effects, which are very important issues for the present state of the economy.

Example: financial fragility under the ACE approach

- Relevant examples today are the studies about the relationship between financial fragility of firms and business fluctuations (Delli Gatti et al. JEBO 2005).
- If firms are heterogeneous (also) in terms of degree of financial fragility, this type of heterogeneity plays a crucial role in the evolution over time of aggregate variables such as production and unemployment.
- In this context, small idiosyncratic shocks at firm-level may generate single firm bankruptcies, which cause credit rationing by banks and so waves of bankruptcies among firms, then inducing large aggregate fluctuations in the economy.
- Furthermore, an endogenous credit bubble and then a boom-bust cycle caused by overlending during good times may be created and studied.

The ACE approach for policy design

- Multi-agent economic systems are gaining more and more attention for the purpose of policy analysis.
- An agent-based simulator is a powerful computational facility where to perform large-scale experiments on complex and realistic economic environments and to test different issues of policy design.
- It offers a realistic environment that is well suited for studying the out-of-equilibrium transitory dynamics of the economy caused by changes of policy parameters.

See e.g., two special issues: Dawid and Fagiolo, eds, 2008 and LeBaron and Winker, eds, 2008). Some studies are focused on the design of regulatory policies for financial markets (Mannaro et al. 2008, Westerhoof et al. 2008), other on the design of appropriate fiscal and monetary policies. (Russo et al. 2007; Haber 2008, Raberto et al. 2006, Raberto et al. 2008)

Key features of EURACE

- Technology (FLAME, GUIs, parallelization).
- Spatial structure and local interactions.
- Realistic time scales and asynchronous interactions.
- Decentralized markets (Walasian auctioneer banned expect for the financial market):
  - market clearing is not for granted
  - no law of one price
- Adaptive and empirically grounded behavioral rules (optimization banned).
- Balance sheet approach in modeling agents.
- Validation based on the reproducibility of well-known empirical regularities and the consistency of balance sheets.

Agents (I)

The EURACE model is characterized by a set of agents' typologies with proper balance sheets and behavioral features:

- Households
- Consumption goods producing firms
- Investment goods producing firms
- Commercial Banks
- Governments
- Central bank

Agents (II)

Besides the agents presented before, the simulator is populated by a number of agents for the purpose of facilitating market exchanges and statistical computation:

- Malls
- Eurostat
- Clearing House

Households

They have the role of:

- consumers
- workers
- firms' equity and governments' debt holders
- financial traders

Firms

- Consumption Goods Producers
  - Employ labor and capital goods to produce consumption goods
  - They sell consumption goods to households
  - Take loans from commercial banks to finance their production plans
  - Distribute dividends to shareholders (households)
- Investment Goods Producers
  - Employ labor and energy to produce capital goods
  - They sell capital goods to consumption goods producers
  - Distribute dividends to shareholders (households)

Commercial banks

- Collect cash deposits from households and firms
- Give loans to firms
- Access the standing facility of the the central bank
- Distribute dividends to shareholders (households)

Policy makers: Governments and the Central Bank

- Governments:
  - Decide fiscal policies (set tax rates)
  - Collect taxes
  - Pay unemployment benefits, transfer and subsidies
  - Issue bonds to finance budget deficit
- Central Bank:
  - Decide monetary policies (set interest rates and eventually implement quantitative easing by means of government bonds purchase)
  - Provide temporary liquidity if needed to Governments and Commercial Banks (standing facility)

Timing

- The choice of time scales for the agents decision making has been made in order to reflect the real time scales in economic activities
- The agents financial decisions are made on a shorter time scale (day) than the economic decision making, e.g., consumption and production, where the proper time horizon can be a week, a month, or a quarter.
- Central bank sets its monetary policy on a monthly basis.
- Governments decide fiscal policy on a yearly basis.

Asynchronous interactions

- In reality, most human decision-making and interaction is asynchronous, due to the autonomous decisions of the agents.
- We model this asynchronous decision making by letting agents have different activation days.
- This means that on a single market different agents are active on different days
- Some activities, however, are synchronized. This is in particular the case when they are institutionally initiated (e.g., tax and wage payments).

Markets

- Consumption goods market
- Investment goods market
- Credit market
- Financial market (stock and government bonds)
- Labor market

Except for the financial market, the other markets are all decentralized.

Consumption goods market

- Consumption goods producers offer (and store) goods at selected geographically distributed local market outlets (malls).
- Consumers visit their local mall and make purchasing decisions based on price/quality information they collect about the goods offered at the mall.
- Suppliers on the consumption goods market act globally (without spatial frictions) whereas consumers buy locally.
- Timing: asynchronous

Credit market

- Firms ask for credit to banks to finance their production plan.
- Banks offer loans to firms with a related interest rate. Based on firms financial fragility, credit rationing may occur.
- Firms accept loan offers according to the interest rate.
- Timing: asynchronous.

Financial market

- Households form beliefs about expected assets total returns.
- Households compute a desired portfolio allocation according to their preference structure.
- Firms may issue new stocks to finance their production plans.
- Governments may issue new bonds to finance the budget deficit.
- A centralized mechanism (clearing house) collect all orders, match demands and supply curves for each assets, and clear the market.
- Timing: day

Labor market

- Firms post job vacancies based on planned output.
- Searching workers send applications based on posted salaries.
- Firms rank applications based on skills and make offers.
- Workers rank offers (wage - commuting costs), compare best offer to their reservation wage and accept/reject.
- Labor Market is global with spatial frictions.
- Timing: asynchronous.

Examples of decision rules

- Firms and Households act rule-based using backward looking expectations
- Households decisions in the financial market are based on prospect theory
- Operational decisions of firms are modelled using standard decision rules from the Operations Management literature:
  - Pricing (markup)
  - Inventory and Production Planing
- Savings/consumption decisions of household are based on empirically-founded rules derived from the buffer-stock theory of consumption, see Deaton (1991) and Carrol (1993)
- Purchasing decisions of households are modelled using standard logit-models from the Marketing literature

The balance sheet approach

- A double-entry balance sheet with a detailed account of all monetary and real assets as well as monetary liabilities is defined for each agent.
- Monetary and real flows given by agents' behaviors and interactions determine the period by period balance sheet dynamics.
- A stock-flow model is then created and used to check that all monetary and real flows are accounted for, and that all changes to stock variables are consistent with these flows.
- This provides us with a solid and economically well-founded methodology to test the consistency of the model and it increases the credibility that can be attached to the model's results.

Monetary and financial assets

- cash holdings in the form of commercial bank or central bank deposits. There is no cash hoarding since all money is held inside the banking sector;
- bank loans
- central bank standing facility
- government bonds
- equity shares (issued by firms and banks)

Real assets

- firms inventories
- physical capital
- human capital

Household (H): balance sheet overview

Assets	**Liabilities**
M^h: liquidity deposited at a given *bank*	
n_g^h: government bonds holdings	(nome)
n_f^h, n_b^h: equity shares holdings of firm f and bank b	

- Financial wealth:

$$W = M^h + \sum_{f \in \{firms\}} n_f^h p_f + \sum_{b \in \{banks\}} n_b^h p_b + \sum_{g \in \{governments\}} n_g^h p_g$$

- p_f, p_b: daily price of equity shares issued by firm f and bank b, respectively
- p_g: daily price of the bond issued by government g

Firm (f): balance sheet overview (I)

Assets	**Liabilities**
M^f: liquidity deposited at a given *bank*	D_b^f: debts to *banks*
I_m^f: inventories at *malls*	E^f: equity
K^f: physical capital	

- M^f, I_m^f updated daily following firms' cash flows and sales
- K^f, and D_b^f updated updated monthly (at the first day of the month to act)

Firm (f): balance sheet overview (II)

- E^f: equity updated monthly (at the last day of the month to act) according to:

$$E^f = M^f + p_C \sum_{m \in \{malls\}} I_m^f + p_K K^f - \sum_{b \in \{banks\}} D_b^f$$

- p_C: average price level of consumption goods
- p_K: price of capital goods

Bank (b): balance sheet overview (I)

Assets	**Liabilities**
M^b: liquidity (reserves) deposited at the *central bank*	D^b: standing facility (debts to the *central bank*)
L_f^b: loans to firms	M_h^b: households' deposits at the bank
	M_f^b: firms' deposits at the bank
	E^b: equity

Bank (b): balance sheet overview (II)

- M_h^b, M_f^b, L_f^b updated daily following the private sector deposits changes and the credit market outcomes
- M^b, E^b updated daily following banks cash flows and also:

$$M^b = D^b + \sum_{h \in \{households\}} M_h^b + \sum_{f \in \{firms\}} M_f^b + E^b - \sum_{f \in \{firms\}} L_f^b$$

- if M^b becomes negative D^b is increased to set $M^b = 0$
- if both M^b and D^b are positive, D^b is partially or totally repaid

Government (g)

Assets	**Liabilities**
M^g: liquidity deposited at the central bank	D^g: standing facility with the central bank n^g: number of outstanding bonds

Government budget:

- Revenues: taxes on corporate profits and household labor and capital income;
- Expenses: unemployment benefits, transfer and subsidies.

Central Bank (c): balance sheet overview (I)

Assets	**Liabilities**
n_g^c: Government bonds (QE)	M^c: fiat money due to QE
M^c: liquidity	M_g^c: Governments liquidity
L_b^c: loans to banks	M_b^c: banks reserves
L_g^c: loans to governments	E^c: equity

- With quantitative easing (QE), the central bank purchases government bonds using money it creates from nothing (fiat money), and so expands its balance sheets.

Central Bank (c): balance sheet overview (II)

- Since the Central Bank is not allowed to make a profit, its revenues from government bonds and bank advances are distributed to the government in the form of a dividend.
- In case of multiple governments, the total dividend payment is equally divided among the governments.

Validation rules

- Balance sheet accounting identities can be devised across agents and used to validate the model.
- Examples:

$$\sum_f \sum_b L_f^b = \sum_f \sum_b D_b^f$$

$$\sum_h M^h = \sum_b \sum_h M_h^b$$

$$n^g = \sum_h n_g^h$$

Monetary aggregates and invariants

- In the EURACE model we have a key monetary invariant:

$$\Delta\Big(\sum_h M^h + \sum_f M^f\Big) + \Delta\Big(\sum_b E^b\Big) + \Delta\Big(\sum_g M^g + M^c\Big)$$

private sector deposits + banks' equity + public sector deposits

$$=$$

$$\Delta\Big(M^c + \sum_b L^c_b + \sum_g L^c_g\Big) + \Delta\Big(\sum_b \sum_f L^b_f\Big)$$

fiat money + credit money

Monetary aggregates and policy considerations

- For policy considerations, it is clearly important to consider the monetary endowment of agents in the private sector, i.e.,

$$\sum_h M^h + \sum_f M^f + \sum_b E^b$$

- An higher monetary endowment due, e.g., to a loose fiscal policy and QE, leads to a higher nominal demand that not necessarily translates into a higher real demand. It depends on the behavior of prices.

Validation in EURACE

Besides the stock-flow consistency checks, we have pursued:

- Calibration
- Purely qualitative theorizing e.g. by means of parameters sensitivity analysis.
- Empirical validation, based on the reproduction of the stylized facts drawn from empirical research.

Concluding remarks

Besides the stock-flow consistency checks, we have pursued:

- The ACE approach is a promising methodology for economic modeling and policy design. Understanding and proposing valuable solutions will be a key test in this respect.
- EURACE is the most complete and sophisticate agent-based model and simulator of the macroeconomy.
- The EURACE development technology (FLAME, GUIs, and parallelization) plays a central role in deploying a viable simulator.
- The balance sheet approach is a distinctive features in the modelling of EURACE agents and a powerful validation technique.