Large-Scale Modeling of Economic Systems

[a]**Mike Holcombe, Simon Coakley, Mariam Kiran**
[b]**Shawn Chin, Chris Greenough, David Worth**
[c]**Silvano Cincotti, M. Raberto**
[d]**Andrea Teglio**
[e]**Christophe Deissenberg**
[f]**Sander van der Hoog, Herbert Dawid, Simon Gemkow, Philipp Harting**
[g]**Michael Neugart**

[a]*Department of Computer Science, University of Sheffield*

[b]*Software Engineering Group, Rutherford Appleton Laboratory, STFC*

[c]*DIME-CINEF, University of Genoa*

[d]*Department of Economics, Universitat Jaume I*

[e]*Faculty of Economics, Université de la Méditerranée (Aix-Marseille II)*

[f]*Department of Economics, Bielefeld University*

[g]*Fachgebiet Finanzwissenschaft und Wirtschaftspolitik, Technische Universität Darmstadt*

Following the events of the credit crunch and the onset of a global recession, alternative ways of modeling modern economies and mechanisms for carrying out policy analysis are now an urgent priority. Traditional mathematical economics is widely viewed to have been compromised through gross simplifications with many assumptions that are now seen to be unjustified. New ways of looking at economics that are more grounded in reality are required, and agent-based computational economics is now receiving a lot of attention. Although the ideas are not new, the previous attempts to use this approach have been largely limited by the inability to model realistically large systems with millions of complex agents. Without this capability, the usefulness of the approach is limited. The EU–STREP project EURACE brought together a consortium of leading economists, experts in parallel supercomputing, and the designers of the FLAME framework to build the largest and most complete model of the European Union economy ever built.

1. The EURACE Model

The EURACE economic model [1] is probably the first detailed description of the entire European Union (EU) economy created using the agent-based modeling technique. It makes no assumptions about the rationality and homogeneity of market participants and the inherent stability of markets. Instead, it begins by considering each individ-

ual player—household/individual, firm, bank, government, or other—and models its behavior in a realistic way. The complete system then comprises hundreds of thousands of interacting components involved in several markets simultaneously.

For example, the consumption goods market involves the interactions between retail outlets selling goods produced by consumption goods producers and households that represent the consumers. For this to work, the firms making the goods engage in planning production levels of their goods or services, identifying their financial needs—which may be using their own cash reserves or other sorts of financial input, such as releasing equity, borrowing on the credit market, or labor force needs—and then hiring staff as required. To achieve some production objectives, the firm may thus need to invest in new production equipment or software, which is purchased from other firms—the investment goods producers. These connections are illustrated in Figure 1.

The labor market is illustrated in Figure 2.

An idea of the complete integrated EURACE model is shown in Figure 3.
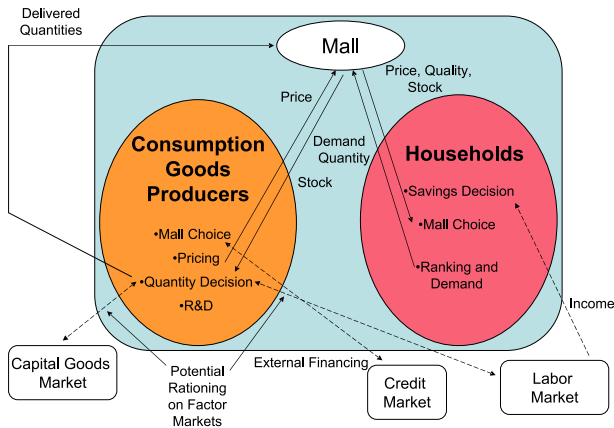
Figure 1. Consumption goods market.

2. The Agents in EURACE

The different markets are modeled in great detail with, for example, the labor market firms seeking credit, buying capital goods, deciding production levels, advertising and appointing staff, and selling consumption goods, and households applying for jobs, deciding on
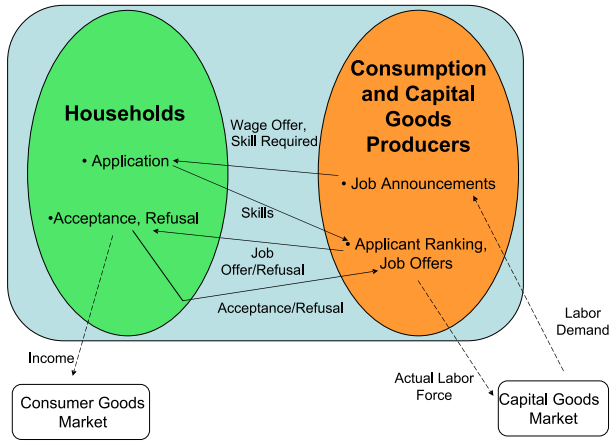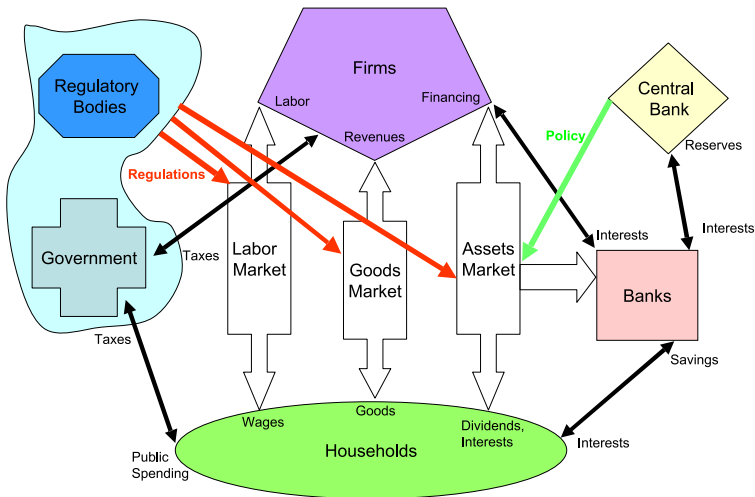
Figure 2. Labor market.

Figure 3. Integrated EURACE model, including the credit (assets) market and the regulatory authorities.

offers, commuting to work, buying goods, saving with banks, and seeking credit. Thus, an agent is active in many different markets and contexts, which was a key aspect of the construction of the integrated economy model that combined all of these markets into a single coherent whole.

Here is the full list of agent types:

- Firms (consumption goods producers)

- Households (workers and consumers)

- Investment goods producers

- Malls (retail outlets selling consumption goods)

- Banks (providing credit and taking savings and investments)

- Clearing house (managing the market and buying and selling of equity—shares, bonds, etc.)

- Government (setting fiscal, labor, and other policy and collecting taxes, offering subsidies, etc.)

- Central Bank (managing money supply, interest rates, etc.)

- Eurostat (collecting and reporting economic statistics)

Each agent type is active in different markets, and these markets interact with each other. There are 159 functions using 55 message types (see Figure 4).
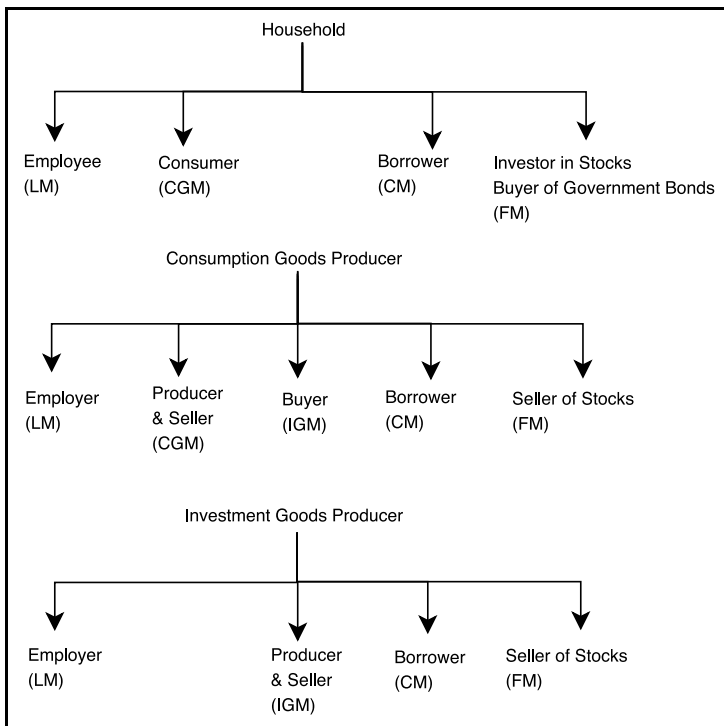
Figure 4. Some agent hierarchies.

The complete set of agents and their interactions and behaviors is plotted on a very large state diagram available online [2]; the different markets are color-coded and the vertical flows indicate the orders of the state transitions that the different agent types can experience, with the communication links shown in green. Figure 5 shows a small section of the graph (FLAME generates these graphs from the specification) [3].
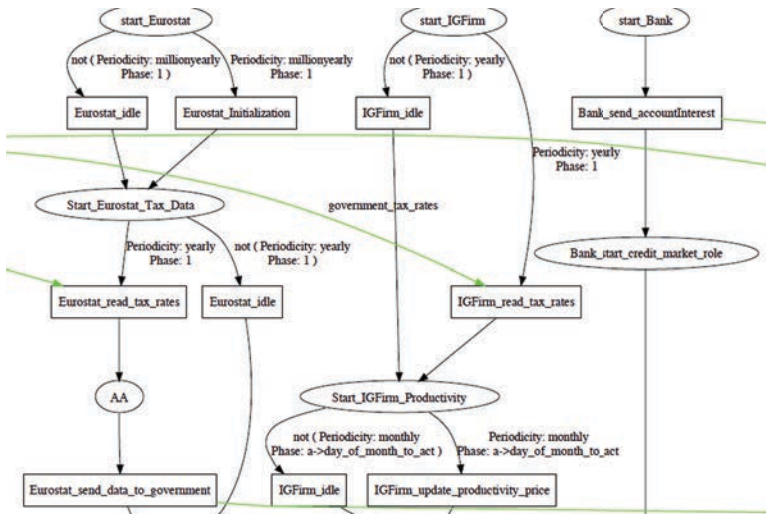
Figure 5. A section of the EURACE stategraph [2].

For each type of agent it is specified what it does and when. Agents communicate through sending and receiving messages. Each agent can be in a number of different states and has an internal memory containing, for example, its location and assets. What it does at any moment depends on these.

▌ 2.1 How the Model Works

The system is both event-driven, with agents responding to the particular situation at the time of each interaction, and calendar-driven, whereby certain events are triggered at a given time, for example, firms calculating monthly balance sheets.

Each month, all firms go through a standard routine in which they determine monthly production output, vacancies and redundancies, investment goods needed, and dividends to be paid.

- Financial planning routine: a firm computes all commitments and liquidity needs, decides on the use of internal/external funds, and goes to the credit market seeking bank loans or other external financing.

- Financial market routine: a firm raises capital through equity release if needed.

- Production routine: a firm calculates desired production capacity using new investment goods purchased with the new credit/finance, calculates labor needs for production, employs/fires labor, confirms contracts, and so forth.

- Accounting routine: a firm updates income statements based on sales and outgoings, creates balance sheets, and calculates cash flows.

- A bankruptcy routine is applied where necessary; this is based on the financial picture and involves several possibilities, including ceasing trading if necessary.

As part of the labor market, activity firms may decide to hire workers. This is done by functions that may send out messages to potential workers and may go through a number of state-based functions.

- A firm announces vacancies if additional workers are needed. The firm's vacancy messages describe the different wage offers for the different general skill groups.

- A firm reads the applications, ranks the applicants according to their general and specific skills, and sends as many job offers to the first-ranked applicants as the firm has vacancies to fill. The other applicants are refused.

- A firm reads job responses. The firm reads the responses to their job offers and updates the number of employees and the number of vacancies.

Alternatively:

- A firm sends redundancy messages to selected workers if the firm wants to decrease the workforce.

- A firm is idle (the firm does nothing).

The households respond appropriately, deciding to accept offers on the basis of a value calculation, for example, choosing a better salary if not accompanied by excessive commuting costs.

These definitions are encoded in a simple XML language using suitable software and then fed into the FLAME program generator that produces a full program in C that will run on any computer, including parallel supercomputers.

The model is then initialized by specifying what state each agent is in at the start of the simulation, what its location is, what its current assets are, and other parameters.

The initialization files for each agent are generated using a suitable interface, as shown in Figure 6.

Figure 6. An example of the initialization interface [1].

This allows for populations of different agents to be automatically generated to fit given statistical distributions based on the available economic data (stylized facts). Large simulations involving hundreds of thousands of agents are run and all the data about their behavior is collected and analyzed.

3. Policy Experiments

A number of policy experiments have been carried out to demonstrate the capabilities of the complete model.

3.1 An Analysis of the Impact of Fiscal Tightening Compared with Quantitative Easing in Economic Performance

In the fiscal tightening policy (FT) scenario [2], the government pursues the objective of zero government budget deficit by increasing tax rates and reducing public spending as necessary. Both the increase of taxes and the issuing of new government bonds that are sold in the market fund the budget deficit. The government thus issues new bonds on a monthly basis to increase its liquidity if this is negative. The government also raises the tax rates on a yearly basis if its present liquidity summed to the past year budget deficit is negative.

Under the quantitative easing policy (QE), the zero government budget deficit is not an issue and tax rates are then maintained at a constant level [3]. New government bonds are sold in the market, and these fund the budget deficit. If market demand is insufficient to match the supply of new bonds and the present market price, the central bank buys the unsold bonds from the government. Equivalently, the government provides the funds for banks to purchase these bonds.

Government revenues include taxes on corporate profits, household labor, and capital income. Expenses include, for example, unemployment benefits. Government liquidity is defined as the cumulated budget surplus.

The result of a QE policy is that a larger amount of government bonds must be issued to fund the deficit; this further depresses the bond market price with respect to the FT policy case. For the FT policy, government liquidity is generally higher because fiscal policy is calculated on a yearly basis and so is less flexible (Figure 7).
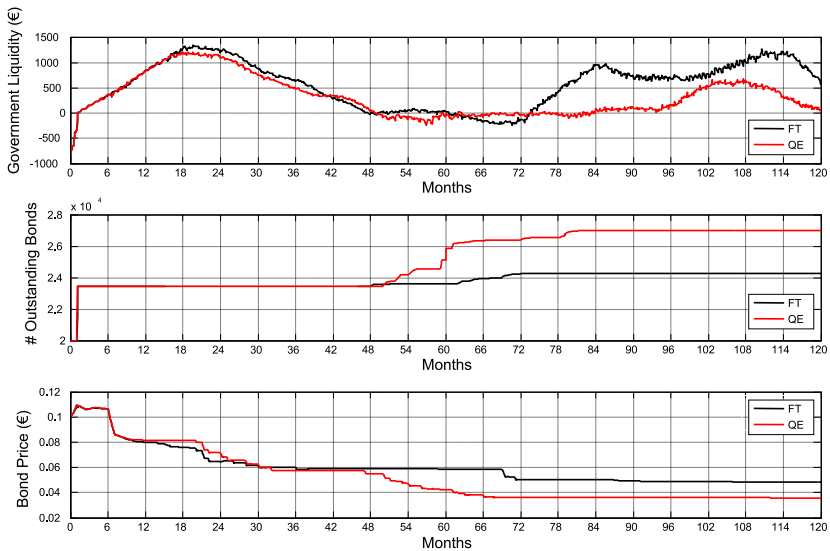

Figure 7. Simulation results of government liquidity and bonds.

Now we examine the policy outcomes. The QE policy results in the injection of new fiat money into the economy; agents in the private sector, that is, households, consumption goods firms, the investment goods firm, and banks (their reserves), are characterized by higher monetary endowments. There is no government fiscal intervention producing a movement of liquid resources from the payment accounts of the private sector to the public treasury, unlike the FT policy case.

For the FT policy, the total amount of loans (credit money created by the banking system) is higher; it emerges that the banking system partially substitutes the role of the central bank in creating money for the economy (credit money versus fiat money). There is a propensity to consume and to invest that is more or less constant in the two policies considered; firms' positive cash flows are lower in the FT policy case. Consequently, firms are forced to rely heavily on external funding in order to finance their production plans.

The quantitative easing policy provides better macroeconomic performance but does not stimulate more lending from the banking sector (Figure 8). The QE policy produces higher levels of output and lower levels of unemployment; this leads to higher endowment of the stock of physical capital, thus indicating that QE policy may outperform FT policy even in the long run.
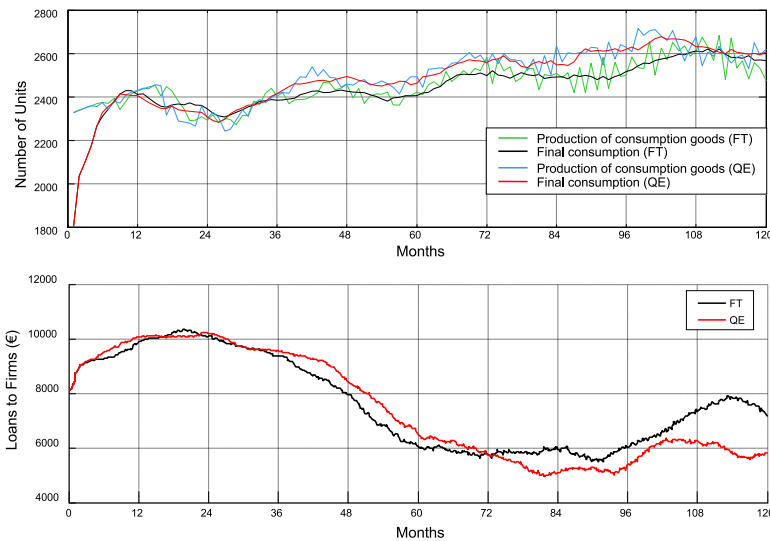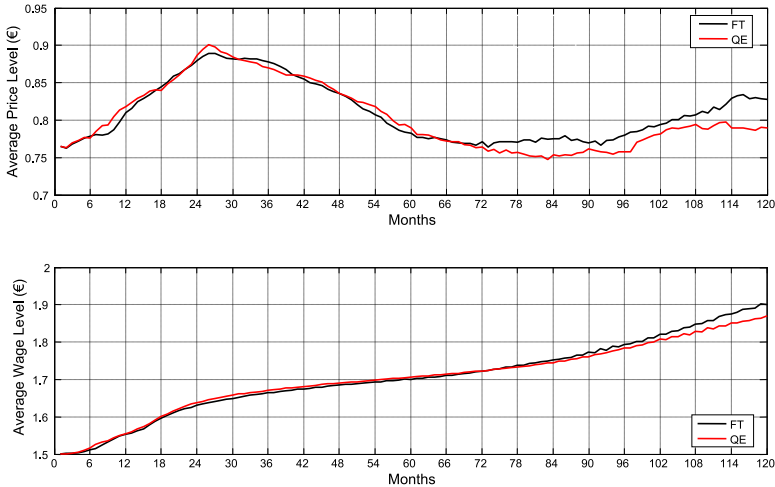

Figure 8. Simulation results of (top) production and consumption levels and (bottom) total loans.

The FT policy produces a higher level of credit money in the economy. Even if it partially works as a substitute for the lack of creation of new money, it is unable to provide a macroeconomic performance similar to QE.

Under a QE policy, the level of prices and wages is generally lower (Figure 9). Given the higher level of monetary aggregates, the opposite could have been expected (at least this will happen in a general equilibrium framework without nominal rigidities). Regarding the

price level, an explanation may be based on the pricing mechanism of
firms, which is based on a fixed markup on costs. The amount of
loans and the loans interests directly affect prices. In the QE case, the
amount of loans is generally lower.

Figure 9. Simulation results of (top) prices and (bottom) wages.

The quantitative easing policy provides better macroeconomic per-
formance than fiscal tightening. This can be explained by the fact that
private sector agents, being endowed with higher monetary resources,
are more able and willing to consume and invest. The higher mone-
tary endowment is not offset by higher prices. Quantitative easing,
however, does not stimulate more lending from the banking sector, as
it has been claimed recently. Indeed, the opposite is true. Quantitative
easing, being a lender of a last-resort mechanism to the government,
provides a better macroeconomic performance by reducing the crowd-
ing out effect on the demand side of the economy that may be caused
by the financing of public debt.

The model has produced useful insights into the management of
quantitative easing as a policy to address the current financial crisis.
Note that the pricing mechanism may limit the generality of the
study. This is an initial analysis of the EURACE model.

3.2 The Effect of Open Migration within the European Union on the Economies of the Member Countries

In this scenario there are two countries: country 1 is an old EU mem-
ber with high technology industries and a skilled workforce, and coun-

try 2 is a new EU member with low technology industries and skills [4–7].

Four policies were considered:

- no migration permitted between regions 2 and 1;

- migration permitted after 1000 days;

- open migration permitted with commuting costs; and

- open migration permitted without considering commuting costs.

Firms seek credit, purchase capital goods, plan production, assess workforce needs, advertise for staff, sell goods in malls, and so on. Governments provide skills training. Individuals have a level of general skills and can develop special skills at different levels.

Several different key economic variables highlighting the differences between a typical old member state (Germany) and a new member (Poland) are captured. Workers have both general skill distributions (level 5 of the International Adult Literacy Survey), which reflect school attainment, as well as possibly more advanced or specific skill levels.

Other factors in the model are:

- Quality of physical capital stock

- Size of per capita physical capital stock

- Public transfer payments, for example, wage replacement rate

This implies a number of issues that are important:

- Different distances of firms and regions to the technological frontier

- Different initial wages, per capita income, and so on

- Homogeneous consumption goods produced using (vertically differentiated) capital and labor

There is a complementarity between the quality of investment goods and the level of specific skills of workers; in other words, more productive and sophisticated factory machinery requires more skilled workers. The productivity of a given technology level is only fully exploited if workers in the firm have sufficiently high specific skills.

The general skill levels are assumed to be heterogeneous within and across regions. The specific skills are attained during employment in firms. Higher general skills improve the speed of attaining specific skills. Specific skills of workers increase due to learning by doing while they are employed. The speed by which specific skills increase depends on the general skill level of the worker and the quality of the capital stock of his or her employer. Potential knowledge flows and

spill-overs are achieved through the dynamics of the labor market: workers transfer specific skills when changing employers.

Consumption goods producers offer (and store) goods at selected geographically distributed local market outlets (malls). These firms post the prices of their goods in all the malls they serve. Suppliers on the consumption goods market act globally (without spatial frictions) whereas consumers buy locally.

When visiting a mall, a consumer collects randomly selected information about prices and inventories of producers serving that mall. A purchasing decision is modeled using a *logit* approach.

Investment goods are supplied globally to consumption goods producers by an investment goods producer.

The quality of supplied investment goods increases stochastically over time according to the dynamics of the technological frontier. The average quality of the capital stock of a consumption goods producer is updated as old capital is replaced by new investments. Diffusion of technologies is driven by investment decisions of firms and is therefore affected by demand effects.

Firms post job vacancies based on planned output. The offered wage depends on the current base wage offer of the firm and the general skill level of the applicant. Applicants rank offers (wage versus commuting costs), compare the best offer to their reservation wage, and accept or reject it. If a firm is rationed on the labor market, it increases its base wage offer.

The two main policy questions were:

- How does the timing of the opening up of labor flows between old and new members affect growth and technological development in both regions?

- Should producers and households in a region have different preferences concerning slow/fast opening of labor markets?

The simulation analysis looked at the issues of innovation and skill development in the two regions, as well as the overall economic performance (Figure 10).

In conclusion, the simulations indicate that the free migration of workers from a new accession country to an established country brings considerable economic benefits to the receiving country. The downside is that the contributing country suffers an economic penalty. This should be seen in the light of the recent UK policy to free migration from the new EU countries in contrast to the policy of some other countries, for example, Germany (Figure 11).

(a) (b)
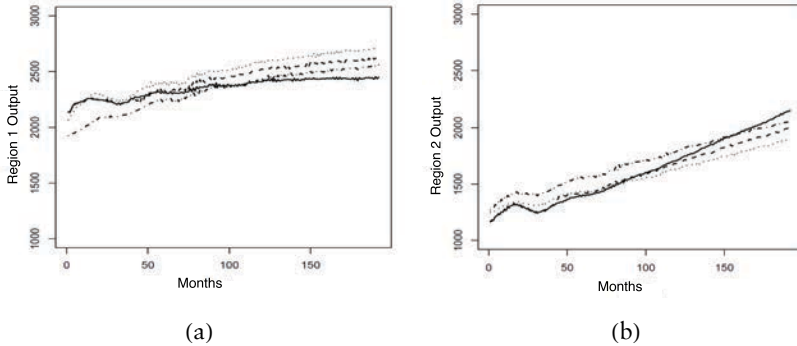
Figure 10. Dynamics of output in (a) region 1 and (b) region 2 for the following scenarios: closed (solid line), closed-open-1000-c (dashed line), open-c (dotted line), and open (dashed-dotted line).
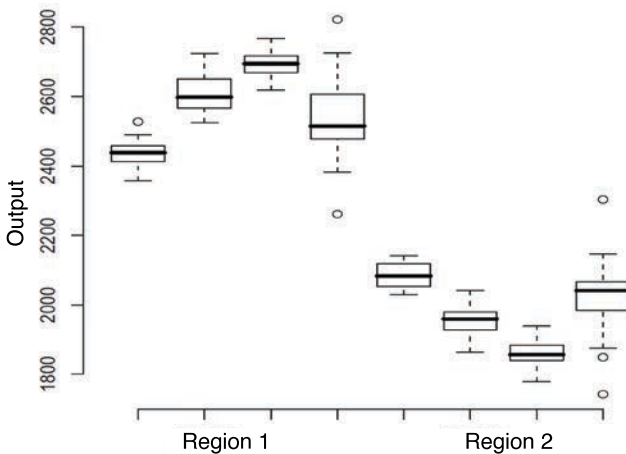
Figure 11. Output by regions (from left to right within high-income region 1 and low-income region 2, respectively) for the following scenarios: closed, closed-open-1000-c, open-c, and open.

3.3 The Effects of a Policy of Household Subsidies in Dealing with an Exogenous Oil Price Shock

The impact of a sudden rise in a key commodity such as oil can be highly damaging to an economy [8–10]. This can be shown using the model (Figure 12). By incorporating energy prices into the capital goods prices and using an energy price markup, we have shown how a prolonged energy crisis may affect gross domestic product (GDP) growth negatively.
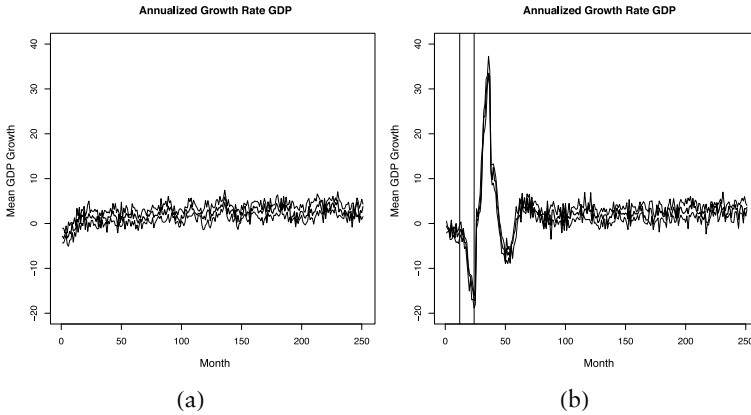
Figure 12. The impact of an oil price shock on economic activity: (a) no shock and (b) effects of a shock.

There are a number of policies that can be adopted by governments to ameliorate this impact. The main aim of such a portfolio of stabilization policies could be a focus on the use of household subsidies to counteract the negative effects on GDP growth rate, unemployment, and inflation by directly stimulating consumption, employment, and investment.

Each household receives a subsidy as a percentage of its total monthly consumption expenditure. The consumer subsidy is meant to compensate for the loss in purchasing power of the households. The main objective is to support the demand side of the economy.

Implementing household consumption subsidies helps to "shoot out" of a recession in the short run (Figure 13). In the long run, the growth rate is the same due to the absence of real investment.
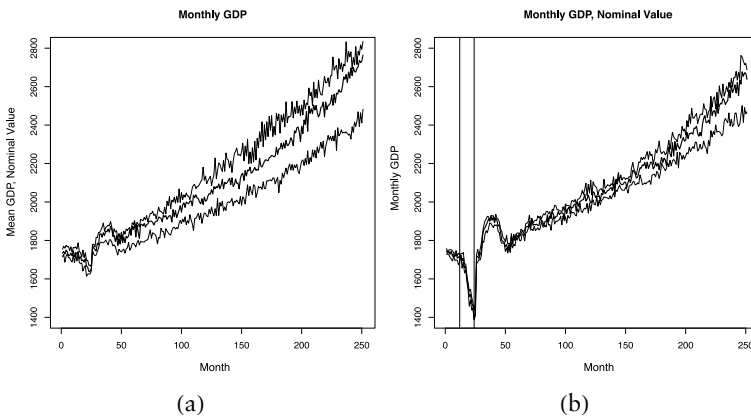
Figure 13. Price shock effects on GDP (a) without subsidies and (b) with subsidies.

4. Conclusions

The EURACE model, built using the FLAME environment and run on supercomputers [11], has demonstrated that agent-based modeling of large-scale economic systems is both possible and useful. Although the full EURACE model was only available toward the end of 2009, enough detailed policy experiments have been carried out to demonstrate this. Most of these experiments involve a relatively small number of agents—around tens of thousands. The running of the model with a large number of agents, say in the millions, has not been done yet due to lack of time. However, the model is ready for this, and more comprehensive experiments can be expected in the near future. These will be reported in the economics literature.

Details of the FLAME environment and how to download it are given in [12].

Details of the EURACE project can be found in [1, 13, 14]. The main stategraph of the original EURACE model, which describes how all the components interact, can be found in [15].

Access to the model—which is under continuous improvement—can be arranged by the first author. The code of the model is available on request under a confidential disclosure agreement.

Acknowledgments

References

[1] "The EURACE Project." (Apr 12, 2013) http://www.eurace.org.

[2] S. Cincotti, M. Raberto, and A. Teglio, "Credit Money and Macroeconomic Instability in the Agent-Based Model and Simulator EURACE," *Economics*, Discussion Paper No. 2010-4, 2010. http://www.economics-ejournal.org/economics/discussionpapers/2010-4.

[3] A. Teglio, M. Raberto, and S. Cincotti, "Explaining Equity Excess Return by Means of an Agent-Based Financial Market," in *Artificial Economics: The Generative Method in Economics* (C. Hernandez, M. Posada, and A. Lopez-Paredes, eds.), Berlin: Springer-Verlag, 2009 pp. 145–156.

[4] H. Dawid, S. Gemkow, P. Harting, K. Kabus, K. Wersching, and M. Neugart, "Skills, Innovation, and Growth: An Agent-Based Policy Analysis," *Journal of Economics and Statistics*, **228**(2–3), 2008 pp. 251–275.

[5] H. Dawid, S. Gemkow, P. Harting, and M. Neugart, "On the Effects of Skill Upgrading in the Presence of Spatial Labor Market Frictions: An Agent-Based Policy Analysis of Spatial Policy Design," *Journal of Artificial Societies and Social Simulation*, **12**(4), 2009 p. 5.

[6] H. Dawid, "Agent-Based Models of Innovation and Technological Change," in *Handbook of Computational Economics, Volume 2: Agent-Based Computational Economics* (L. Tesfatsion and K. L. Judd, eds.), Oxford, UK: North-Holland, 2006 pp. 1235–1272.

[7] H. Dawid, S. Gemkow, P. Harting, and M. Neugart, "Labor Market Integration Policies and the Convergence of Regions: The Role of Skills and Technology Diffusion," *Journal of Evolutionary Economics*, **22**(3), 2012 pp. 543–562. doi:10.1007/s00191-011-0245-1.

[8] S. van der Hoog, C. Deissenberg, and H. Dawid, "Production and Finance in EURACE," in *Complexity and Artificial Markets*, Vol. 614 of Lecture Notes in Economics and Mathematical Systems (K. Schredelseker and F. Hauser, eds.), Berlin: Springer, 2008 pp. 147–158. doi:10.1007/978-3-540-70556-7_12.

[9] C. Deissenberg, S. van der Hoog, and H. Dawid, "EURACE: A Massively Parallel Agent-Based Model of the European Economy," *Applied Mathematics and Computation*, **204**(2), 2008 pp. 541–552. doi:10.1016/j.amc.2008.05.116.

[10] S. van der Hoog and C. Deissenberg, "Energy Shocks and Macroeconomic Stabilization Policies in an Agent-Based Macro Model," in *Computational Methods in Economic Dynamics* (H. Dawid and W. Semmler, eds.), New York: Springer, 2011 pp. 159–181.

[11] S. Coakley, M. Gheorghe, M. Holcombe, S. Chin, D. Worth, and C. Greenough, "Exploitation of High Performance Computing in the FLAME Agent-Based Simulation Framework," in *Proceedings of the 14th International Conference on High Performance Computing and Communications (HPCC2012)*, Liverpool, UK, New York: IEEE, 2012 pp. 538–545. doi:10.1109/HPCC.2012.79.

[12] "FLAME: Flexible Large-Scale Agent Modelling Environment." (Apr 12, 2013) http://www.flame.ac.uk.

[13] "EURACE at the University of Sheffield." (Apr 12, 2013) http://www.eurace.group.shef.ac.uk.

[14] "Fakultät für Wirtschaftswissenschaften." (Mar 11, 2013) http://www.wiwi.uni-bielefeld.de/vpl1/projects/eurace.html.

[15] "EURACE Stategraph." (Apr 12, 2013) http://www.dcs.shef.ac.uk/~wmlh/stategraph.pdf.