Agent-Based Macroeconomic Modeling and Policy Analysis: The Eurace@Unibi Model*

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May 2014

Contents

Abstract

Agent-based simulation models are a relatively new addition to the tool-box of macroeconomists. In this chapter we introduce the Eurace@Unibi model and the research that has been done within this framework. We show how an agent-based model can be used to identify economic mechanisms and how it can be applied to spatial policy analysis. Our assessment is that agent-based models in economics have passed the proof-of-concept phase and it is now time to move beyond that stage. It has been shown that new kinds of insights can be obtained that complement established modeling approaches. We conclude by pointing towards some potentially fruitful areas of agent-based macroeconomic research.

*We are grateful to Shu-Heng Chen and two anonymous referees for helpful comments on a previous version of the manuscript.

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1 Introduction

Predicting short and long-run effects of economic policy measures and of institutional changes in an economy is a challenging task. The difficulties of this task are largely amplified by the close linkages between the dynamics of financial markets, credit markets, and the real side of the economy as well as by the growing interrelation between developments in different regions of a globalized world economy. Ideally, predictions about policy effects and the design of policy measures should be informed by rigorous analyses based on calibrated economic models. But capturing the main aspects of the different linkages mentioned above is often beyond the scope of standard economic models. During the financial and economic crises which started in 2008 several policy makers have voiced concerns that it is hard for them to base their decisions on existing often very simple policy models, which might not be able to capture the mechanisms that seem to be mainly responsible for the problems. To quote former ECB President Jean-Claude Trichet:[1] *'When the crisis came, the serious limitations of existing economic and financial models immediately became apparent.[...] Macro models failed to predict the crisis and seemed incapable of explaining what was happening to the economy in a convincing manner. As a policy-maker during the crisis, I found the available models of limited help. In fact, I would go further: in the face of the crisis, we felt abandoned by conventional tools.* Jean-Claude Trichet also sketches properties of economic models that would make them in his opinion more suitable to capture crucial properties of economic systems and make them more appealing to policy makers: *'We need to deal better with heterogeneity across agents and the interaction among those heterogeneous agents. We need to entertain alternative motivations for economic choices. [...] Agent-based modelling dispenses with the optimization assumption and allows for more complex interactions between agents. Such approaches are worthy of our attention.'*

The aim of this chapter is to describe the Eurace@Unibi agent-based macroeconomic model and review research that has been carried out within this framework in recent years in order to develop a useful tool for the rigorous analysis of economic policy measures. Agent-based simulation models are a relatively new addition to the tool-box of economists, and in spite of the growing effort that has been invested in developing this research area, the field is still in its adolescence. However, the research reported here highlights that new kinds of questions can be asked and new kinds of insights can be obtained using such an approach, thereby showing the potential of agent-based modeling as an instrument complementing established modeling approaches. This potential has also been demonstrated by a number of other agent-based macroeconomic models that have been developed in recent years. Although space constraints prevents us from discussing this research in great detail, we briefly review it in Section 2.

Agent-based analyses have been carried out for numerous policy areas, where issues related to financial market dynamics, banking regulation, credit linkages or monetary policy have attracted considerable attention. In this chapter we concentrate on research that is concerned with the facilitation of economic growth on a local and global scale in an economy consisting of different regions with (potentially) heterogeneous characteristics. Understanding how different policy measures affect the economic dynamics in different regions of an integrated economic area is not only crucial for proper design of cohesion policies, but is also an important contribution to the prevention of deep economic crises. For example, the government debt crisis in the Euro area was not only due to the excessive spending. One of the major underlying causes was the

[1] Quoted from the speech 'Reflections on the nature of monetary policy non-standard measures and finance theory' by Jean-Claude Trichet, President of the ECB given as opening address at the ECB Central Banking Conference Frankfurt, 18 November 2010. The text of the full speech is available at http://www.ecb.int/press/key/date/2010/html/sp101118.en.html.

persistent gap in terms of economic competitiveness between the central European economies and the countries in the Southern periphery. As a result, a sustainable solution to such a crisis should not only entail cuts in government spending; rather there has to be a coordinated and specifically targeted policy that increases the competitiveness of the lagging countries and fosters economic convergence. One keystone of the Economic and Monetary Union (EMU) is, however, the integration of the European economies where integration is associated with a reduction of barriers for a free flow of goods, labor, and capital. But this might imply that it is almost impossible to isolate the effects of an economic policy only in the target region. In fact, it is often ex ante not clear how a policy affects the economic performance of neighboring regions and whether or not there are also feedback effects, either positive or negative, on the target region itself.

This chapter presents research addressing these important issues based on simulations with an agent-based macroeconomic model with spatial structure called the Eurace@Unibi model. The model has been developed with the particular aim to gain a better understanding of the processes that foster the development and diffusion of new technologies in an economy, of the interplay between industrial dynamics and the development of the workforce, and the contribution of these dynamics to economic growth and business cycles. It provides a general framework for the examination of economic mechanisms and policy effects on labor, goods and credit markets. The underlying modeling philosophy is to generate economic dynamics on the industry and macroeconomic level as the aggregate outcome of interactions on the micro-level that are modeled with recourse to strong empirical foundations.

To put this work into perspective we first present in Section 2 a brief overview of recent research on agent-based macroeconomics. In Section 3 we provide a brief description of the Eurace@Unibi model and discuss some of its properties. Section 4 demonstrates the kind of economic mechanisms that can be identified by careful consideration of simulation results by considering the dynamics of technological diffusion in the Eurace@Unibi economy. Several spatial policy analyses that have been carried out using (previous versions of) the model are discussed in Section 5. The value-added of the proposed framework and the results that can be derived from it is discussed in more general terms in Section 6.We conclude in Section 7 with an outlook on high-potential research areas for the application of agent-based policy models.

2 Recent Developments in Agent-Based Macroeconomic Modeling

In the last ten years a number of projects have been initiated that aim at the development of closed macroeconomic models using an agent-based approach. Although these different models share the general approach to describe macroeconomic dynamics as the outcome of aggregation of (local) interaction on the micro-level, their focus differs quite significantly. This difference in focus implies that the care and detail with which certain markets and institutions are modeled varies between these models. At this point no generic standard agent-based macroeconomic modeling framework has evolved, which can be used as a starting point for more specific models aiming at certain areas of policy analysis. Nevertheless, a number of common denominators can be identified in the modeling choices and also a number of qualitative features of simulation results, which also match empirical stylized facts, are generated in several of the models described below. Many of these models are able to replicate the main stylized facts concerning business cycle fluctuations and to highlight the economic processes that generate these fluctuations. At the same time they attempt to match the micro-dynamics to reproduce the heterogeneity in firm investment behavior, firm distributions, and income distributions.

The model which is perhaps closest to Eurace@Unibi has been developed by Giovanni Dosi, Gorgio Fagiolo, Mauro Napoletano, and Andrea Roventini, and has been documented in a series of recent papers (Dosi et al., 2006, 2008, 2010, 2013). Their model consists of two sectors, in one of which firms perform R&D producing a heterogenous capital good which is used together with labor input for the production of a homogenous consumption good. A government levies wage and profit taxes to finance an unemployment benefit system. Overall the model can replicate an impressively large set of empirical stylized facts such as typical growth paths, business cycle properties, macroeconomic correlates, and cross-sectional distributions. Using this model the authors have analyzed the (long run) effects of policies aimed at the strengthening of demand and of policies that facilitate the speed of technical change as well the interaction of these polices. In Dosi et al. (2013) a more explicit representation of the credit market and of bank behavior is added to the model with the aim of exploring the interactions between the functional income distribution and monetary and fiscal policies. They find that fiscal policies are becoming more effective as the income distribution is more skewed towards profits. Moreover, there appears to be an interaction between monetary policies and income distribution in a sense that a change in the interest rate does not affect macroeconomic variables that strongly when profit rates are higher.

Domenico Delli Gatti, Mauro Gallegatti and colleagues have been working on agent-based macro models with a particular emphasis on the role of credit markets for aggregate fluctuations (see, e.g., Delli Gatti et al., 2007; Gaffeo et al., 2008; Delli Gatti et al., 2008, 2010; Assenza and Delli Gatti, 2013). This line of research has been heavily influenced by the work of Greenwald and Stiglitz (1993). At their core these models typically feature a credit market and a goods market in which a homogenous good is produced. Firms are heterogeneous with respect to their financial robustness captured by firm-specific equity-ratios. They adjust their capital stock by maximizing expected profits. Credit supply is mostly rule-based mimicking capital requirement regulations. Typical simulations reveal clustered volatility of output growth rates and various other variables show distributional properties similar to empirical findings. Among these are skewed firm size distributions with power law properties. An important aspect of several of these researchers' models is that they capture the linkages based on credit relationships between firms and banks, among firms, and among banks. These properties allow to gain important insights into relevant mechanisms responsible for default avalanches and to explore implications of different types of bank and credit market regulations.

The exploration of the effects of bank regulation is also an important aim of Ashraf et al. (2011). Their agent-based macroeconomic model puts strong emphasis on the institutional role of banks in a market economy as the provider of liquidity. Behavior of agents is determined by simple rules and market interactions are governed by search and matching processes. The authors provide a careful calibration of the model using U.S. data and based on this calibration examine in detail the role of banks in the economy in normal times as well as in times of crisis. They show that banking regulation in normal times hardly affects macroeconomic stability while in bad times more stringent regulation has an effect on the economy as it suppresses lending to firms in need.

The focus of the agent-based macroeconomic model by Gintis (2007) is less policy-oriented and no particular empirical regularities or policy issues are addressed. Rather, the main concern is to investigate (disequilibrium) dynamics in a standard Walrasian economy under the assumption that a certain fraction of the agents uses private prices. The model has several sectors, where different consumption goods are produced using labor and capital. Consumers have heterogeneous utility functions and make their consumption decisions in accordance with utility maximization based on price information about a (random) subset of producers in each sector. Firms alter their behavior due to imitation and mutation as well as to myopic adjustment dynamics. It is shown that with private prices the dynamics of the economy is overall stable with persistent small volatility. Neither shocks nor structural changes induce a loss of these stability properties. However, if a certain fraction of agents use public prices for their trades the price dynamics becomes less stable and if this fraction is sufficiently large the dynamics exhibits price explosions in which prices deviate from their equilibrium values.

The Lagom model (Mandel et al., 2010; Wolf et al., 2012) extended the Gintis model to include capital accumulation, inter-industry trade, and life-cycle saving behavior. A monetary authority lends money to new firms and poorly performing firms until they go bankrupt. Additionally the same agent (called monetary authority) takes over government activities. It levies profit and wage taxes in order to finance unemployment benefits. In the Lagom model, technology choice, household consumption, firms' mark-ups, and wages are determined using genetic algorithms. The different sectors of the model are linked by input-output tables, which are initialized based on real world data. Additionally, some of the agents' production and investment decisions are rule-based. The authors of the Lagom model see their first main contribution in providing a "proof of concept" that large-scale agent-based macro-models are feasible. However, the authors also have more policy oriented applications of the model in mind. In particular, there is a spatial version of the model, which, among other aspects, includes a representation of local emissions induced by economic activity. This opens up the possibility to consider different types of economic policy measures also from an environmental perspective. As pointed out in Wolf et al. (2012) a systematic calibration of the model using data from European and Mediterranean countries is on the research agenda of the authors.

Apart from these contributions several other agent-based macroeconomic models have been developed more recently. For example, Lengnick (2013) presents a more minimalistic agent-based macroeconomic model than the previously introduced ones. It consists of firms and households that are connected by temporarily fixed networks. Wages and prices adjust according to a stochastic process. Firms produce with labor input only and the production technology is fixed. No government agencies are modeled as the main purpose of the contribution is to demonstrate that major stylized facts can be replicated with a bottom-up approach of interacting agents. Further, more policy-oriented contributions include Oeffner (2009), Greiff et al. (2011) or the research by Cincotti et al. (2010) and Teglio et al. (2012) that also originates from the Eurace project and mainly focuses on the macroeconomic effects of financial regulations. Space constraints do not allow us to discuss all these contributions in more detail here.

3 A Sketch of the Eurace@Unibi Model

The Eurace@Unibi model is based on the agent-based macroeconomic simulation platform developed within the Eurace project.[2] After the completion of the Eurace project in 2009 the authors of this chapter have extended and altered the model substantially in numerous directions leading to the current version of the model. In particular, substantial changes and extensions have been made to the production technology, to the model of the decision processes of consumption good producers, to the investment goods production sector and to the bankruptcy procedures of

[2]The EU-funded project was carried out by a consortium lead by Silvano Cincotti (University of Genova, Italy), Herbert Dawid (University of Bielefeld, Germany), Christophe Deissenberg (Universit de la Mediterrane, France), Kaan Erkan (TUBITAK National Research Institute of Electronics and Cryptology, Turkey), Mauro Gallegati (Universit Politecnica delle Marche, Italy), Mike Holcombe (University of Sheffield, UK), Michele Marchesi (Universit di Cagliari, Italy), and Christopher Greenough (STFC - Rutherford Appleton Laboratory, UK).

firms. Furthermore, interest payments of banks have been introduced on the credit market and the structure of the balance sheets has been completely overhauled. Finally, the financial market of the original Eurace model has been replaced by a much simpler model following a slightly different approach than the original one.

The policy orientation and the specific interest in the spatial dimension of policy effects imply a partly different focus of our model when compared to the agent-based macroeconomic models reviewed in the previous section. As the Eurace@Unibi model features regions it allows for the analysis of regionally differentiated policies and interactions arising through goods and factor flows between the entities. These flows include the movement of labor which made it necessary to impose more structure on modeling the labor market. The interaction protocol between workers and firms features a frictional labor market with adapting wage offers of firms and adapting reservation wages of workers rendering labor supply endogenous. Besides the spatial dimension of policies, the interest has been in the policy effects arising from subsidies to firms purchasing capital goods and human capital policies. To this end, a more distinct production technology is implemented as compared to other agent-based macroeconomic models. This allows for an interplay between a firm's vintage structure and the skill endowment of its workers. Moreover, the detailed modeling of agents' behavior entails to find meaningful decision rules. There, the Eurace@Unibi model relies on rules with strong empirical micro-foundations, as explained below. Finally, the Eurace@Unibi model is a closed model and a balance-sheet approach is systematically used making all flows in the modeled economy transparent and ensuring stock-flow consistency. These features highlight the main difference of this approach to other models in this literature. We will now explain the set-up of the Eurace@Unibi model in more detail.

3.1 Overall Structure

The model describes an economy with markets for labor, consumption goods, investment goods, financial assets and a credit market. It is possible to specify a geography with multiple regions. The economy is populated by firms (consumption goods producers and investment goods producers), households and banks. For each of these agent types there are multiple instances. Each of these agents is located in one of the regions. Additionally, there is a single central bank and a government that collects taxes and finances social benefits as well as, potentially, economic policy measures that might differ between regions. Finally, there is a statistical office (Eurostat) that collects data from all individual agents in the economy and generates aggregate indicators according to standard procedures. These indicators are communicated to the agents in the economy (who might use them as input for their decision rules) and also stored in order to facilitate the analysis of the simulation results. An illustration of the crucial parts of the model is given in Figure 1.

Investment goods of different quality (*i.e.*, potential productivity) are provided by investment goods producers with infinite supply. The technological frontier (i.e. the quality of the best currently available investment good) improves over time, where technological change is driven by a stochastic (innovation) process. Firms in the consumption goods sector use investment goods combined with labor input to produce consumption goods. The labor market is populated with workers that have a distinct general skill level. Additionally, they acquire specific skills on-the-job, which they need to fully exploit the technological advantages of the capital employed in the production process. Each time a consumption goods producer invests in new investment goods he decides which quality of investment goods to select. The quality (or vintage) determines the diffusion speed by which new technologies spread throughout the economy. Consumption goods are sold at local market platforms (called malls), where firms store and offer their products

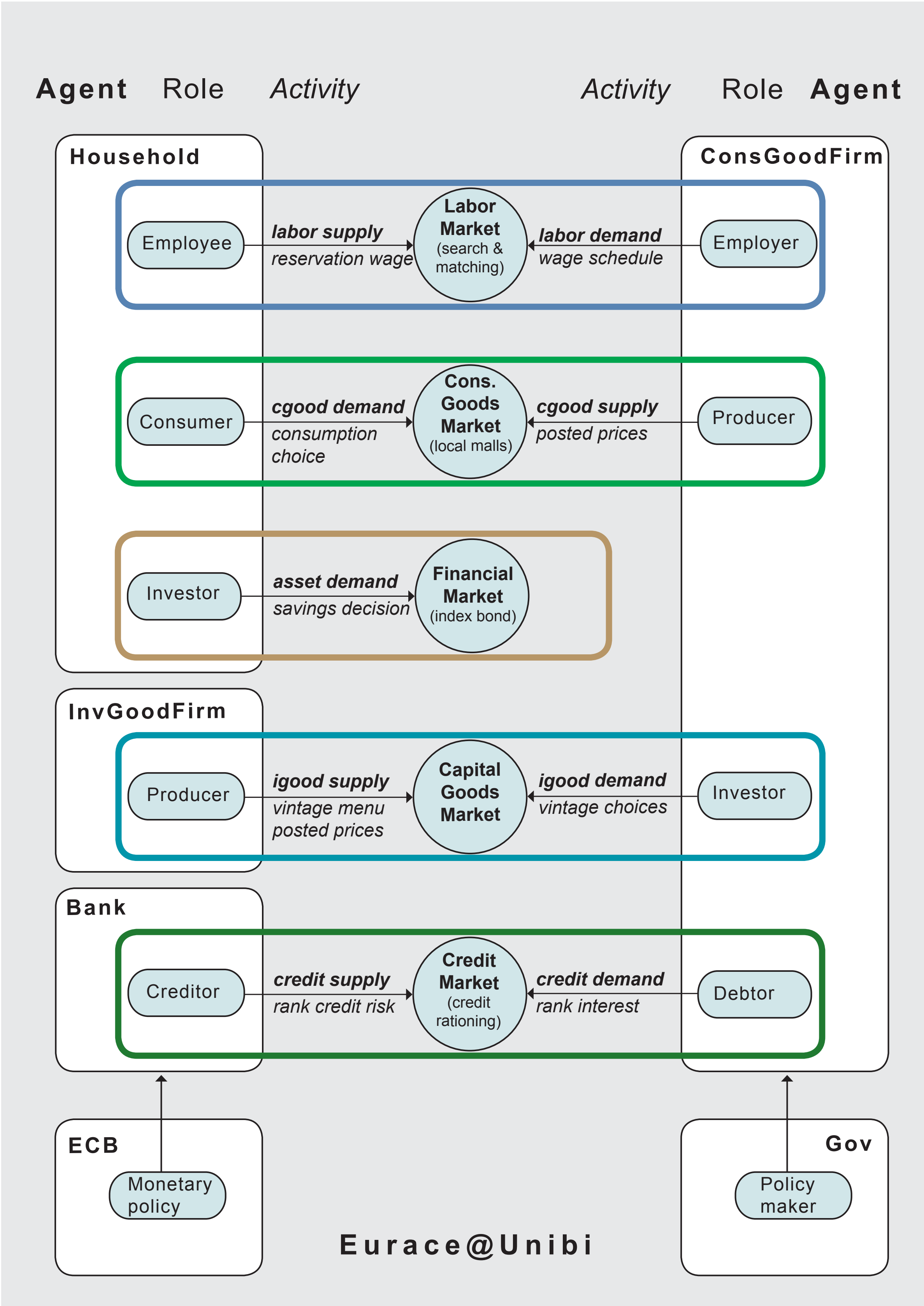

Figure 1: Overview of the Eurace@Unibi model.

and consumers come to buy goods at posted prices. Labor market interaction is described by a simple multi-round search-and-matching procedure where firms post vacancies, searching workers apply, firms make offers and workers accept/reject. Wages of workers are determined, on the one hand, by the expectation the employer has at the time of hiring about the level of specific skills of the worker, and, on the other hand, by a base wage variable, which is influenced by the (past) tightness of the labor market and determines the overall level of wages paid by a particular employer. Banks collect deposits from households and firms, and supply credit to firms. The interest depends on the financial health of the firm and the size of the loan might depend on the bank's liquidity and risk exposure. Firms can be credit rationed in which case they need to re-plan their original investments and production plans and rescale the level of output. There is a financial market where shares of a single asset are traded, namely an index bond representing all firms in the economy. The dividend is determined by the total dividends currently paid by all firms, divided by the total number of index bonds outstanding. This simple representation of a financial market is not meant to be suitable to describe speculative bubbles in the financial market, but captures potentially important feedback effects between firms' profits and households' wealth dynamics.

The central bank provides overdraft and emergency liquidity facilities for the banks at a given base rate. It pays interest on banks' overnight deposits and might provide fiat money to the government.

Firms that are not able to pay their financial commitments declare to be illiquid and enter into an illiquidity bankruptcy procedure. Furthermore, if at the end of the production cycle the firm has negative net worth, the firm is declared insolvent and enters into a bankruptcy procedure. In both cases it goes out of business, stops all productive activities and all employees loose their jobs. The firm writes off a fraction of its debt with all banks with which it has a loan and stays idle for a certain period before it becomes active again.

The spatial extensions of the markets differ depending on the type of goods traded. The investment goods market is global, that is, firms in all regions buy from the same global investment goods producer. Therefore every consumption goods firm has access to the same production technology. On the consumption goods market demand is determined locally in the sense that all consumers buy at a local mall that is located in their region. Supply of consumption goods is global, each firm can sell its product in every regional mall. Labor markets are characterized by spatial frictions determined by commuting costs that arise if workers accept jobs outside of their own region. It is assumed that firms have access to all banks in the economy and, therefore, that credit markets operate globally. Firms select banks ranked on the lowest interest rate offered, whereas banks select firms ranked on the lowest risk exposure. Rationing is possible on all markets except on the investment goods market where the supply is fully elastic.

3.2 Decision Making and Sequence of Activities

In contrast to dynamic equilibrium models — where it is assumed that the behavior of all actors is determined by the maximization of the own (inter-temporal) objective function using correct expectations about the behavior of all others — in an ABM the model description needs to provide explicit rules that describe how different agents build expectations and take decisions based on the available (local, private) information.

To explicitly specify these rules for all agents and decisions is an important modeling decision. As put forward by Sims (1980) the 'Wilderness of Bounded Rationality' is a serious concern since a large number of different approaches to model boundedly rational behavior and its adaptation have been put forward in the literature. At this point there is little indication for the emergence of a widely accepted consensus that provides empirically or theoretically well-founded concepts for tackling this issue.

The choice of decision rules in the Eurace@Unibi model is based on a systematic attempt to incorporate rules that resemble empirically observable behavior documented in the relevant literature. Concerning households, this means that empirically identified rules for consumption and savings behavior are used. Purchasing choices are described by models from the Marketing literature that have a strong empirical support. Regarding firm behavior we follow the 'Management Science Approach' that implements relatively simple decision rules matching standard procedures of real-world firms. There is a rich literature on (heuristic) managerial decision rules in many areas of management science. This includes pricing (see, e.g., Nagle and Hogan, 2006), production planning (see, e.g., Silver et al., 1998) or market selection (see, e.g., Wind and Mahajan, 1981, Kotler and Keller, 2009). Although it certainly cannot be assumed that all firms in the economy rely on such standard managerial heuristics, capturing the main features of such heuristics when modeling the firm adds a strong empirical micro-foundation to the agent-based modelling approach.

Cyert and March's *A Behavioral Theory of the Firm* (Cyert and March, 1963) could be considered a precursor to the Management Science Approach. In this seminal work many operating procedures of firm decision making are detailed.[3] For an assessment of the impact of *A Behavioral Theory of the Firm* and its methodological stance, see Argote and Greve (2007, p.339):

> "The general methodological point was that theory should model organizational processes, and should be generated through systematic observation of processes in actual organizations. One component of this point is that organizational theory should not oversimplify. Although parsimony is needed in theory building, parsimony that throws out basic insights – like replacing a process model with a maximization assumption – can be harmful."

Generally speaking, the Management Science Approach implies that a parametrized decision rule is developed for each decision an agent makes. Whereas the parameter values that determine the exact form of the rule might differ between individuals and might change over time, it is assumed that all individuals share the same (empirically motivated) structure for every rule and that this structure is time-invariant. A more extensive discussion of the Management Science Approach can be found in Dawid and Harting (2012).

Concerning the activation of agents, the actions can be calendar-based (time-driven) or event-based, where the former can follow either subjective or objective time schedules (agent-time vs. clock-time). Furthermore, the economic activities take place on a hierarchy of time-scales: yearly, monthly, weekly and daily activities all take place following the calendar-time or subjective agent-time. Agents are activated asynchronously according to their subjective time schedules that are anchored on an individual activation day. These activation days are uniformly and randomly distributed among the agents at the start of the simulation but may change endogenously.

For example, an employee of a firm is paid on the day the firm starts its production but each firm starts production on a different day of the month. This induces a heterogeneous schedule of activities on all input markets. When the employee is fired it receives unemployment benefits on the same day of the month as it received its salary. However, when it is re-employed by a different firm, its subjective monthly time schedule is synchronized with the activation day of its new employer due to the wage payments. Now, the employee receives its salary on a different day of the calendar month and shifts its consumption accordingly. This modeling approach is

[3] Besides the emphasis on organizational processes and decision making routines, a further aim of the theory was to link empirical data to the models by considering results from case studies of real firms.

supposed to capture the decentralized and typically asynchronous nature of decision making processes and activities of economic agents. It should avoid artificial lock-in and overshooting effects which quite naturally arise in many purely clock-driven simulation models.

In Tables 1 and 2 we provide an overview of the decisions, activities and their frequencies of firms and households. A more extensive discussion can be found in Dawid et al. (2012b) and a full description of the C code is available online as a User Manual (Dawid et al., 2011).

Table 1: Consumption goods producers: sequence of economic activities.

Time scale	Activity
Yearly	
	determine retail price
Monthly	
	production planning: decide planned output
	determine input demand for capital and labor
	financial management
	credit market interaction
	investment goods market interaction
	labor market interaction
	production of output and distribution to malls
	accounting: revenues, income statement and balance sheet
	pay taxes, dividends
Event-based	
	bankruptcy protocol: entry and exit (if equity < 0)

Table 2: Households: sequence of economic activities.

Time scale	Activity
Monthly	
	receive labor income (unemployment benefits if unemployed)
	receive capital income (dividends)
	pay taxes
	consumption/savings decision for upcoming month
	financial market trading
Weekly	
	consumption goods market interaction
Event-based	
	labor market interaction (if unemployed)

3.3 Parametrization, Baseline Scenario and Sensitivity Analysis

Given the complexity of agent-based macroeconomic simulation models, the induced large number of modeling choices and the typically large set of model parameters[4], it is important to provide empirical and conceptual arguments for the usefulness of the developed model for economic analysis. In accordance with the recent literature on the empirical grounding of agent-based models in the social sciences (see, e.g., Windrum et al., 2007 and Poteete et al., 2010) we follow an approach that can be characterized as follows:

i) Incorporate empirical and experimental evidence about the principles underlying real-world behavior of the agents.

ii) Identify a set of stylized facts to be reproduced/explained at the industry or macro level.

iii) Restrict the parameter space and initial conditions to sets where the simulation output matches the stylized facts.

iv) Deepen the understanding of the causal mechanisms that underlie the selected stylized facts.

Following this approach parameter constellations have been identified where a large set of stylized facts can be reproduced. In Figure 2, panel (a) shows the annual GDP growth rate with an approximate mean of 1.5 percent. Panel (b) features the unemployment rate and panels (c) and (d) contain band-pass filtered time series.[5] As can be seen in panel (c), investment is more volatile than consumption. Moreover, consumption and investment are pro-cyclical. Panel (d) presents the counter-cyclical movement of unemployment and firms' price mark-ups. All these features are typically brought forward as the stylized facts describing business cycles. Moreover, the relative size of the amplitudes qualitatively matches those reported, e.g., in Stock and Watson (1999).

It should be pointed out that stochastic productivity shocks are not the driving force of the business cycles generated by the model. However, the GDP growth rate can be steered by setting the rate of technological change. Detailed analysis of the dynamics of micro-level variables like demand expectations, investments, costs, prices, household income and consumption budgets show that the cycles are generated by the interplay of optimistic demand estimations of firms in the upswing, the resulting investment patterns, the induced cost- and price effects, the implications of these effects on sales, mark-ups and firm earnings and the reinforcement of such implications through the demand channel due to changes in the real consumption budget of households.

As can be seen in Figure 3 (panels a and b) the model is also able to generate persistent heterogeneity in firm sizes as documented, for example, in Dosi et al. (1997) and substantial persistence in firm market shares. Finally, we show a Beveridge curve derived from the time series data on vacancies and unemployment rates that resembles real-world data. It should also be noted that several of the stylized facts, in particular all the distributional ones, are reproduced by the model, although the reproduction of these empirical patterns has not been targeted when determining the parameter settings used.[6]

In addition to the variables shown here, the model also reproduces other empirical findings, see Dawid et al. (2012b) for an overview. Rather than going through a long list of simulation variables, in this chapter we would like to illustrate how economic mechanisms can be identified,

[4]In the Eurace@Unibi model overall about 40 parameters have to be determined, where for some the values can be heterogeneous across agents. The exact number of parameters depends on the setting considered in the

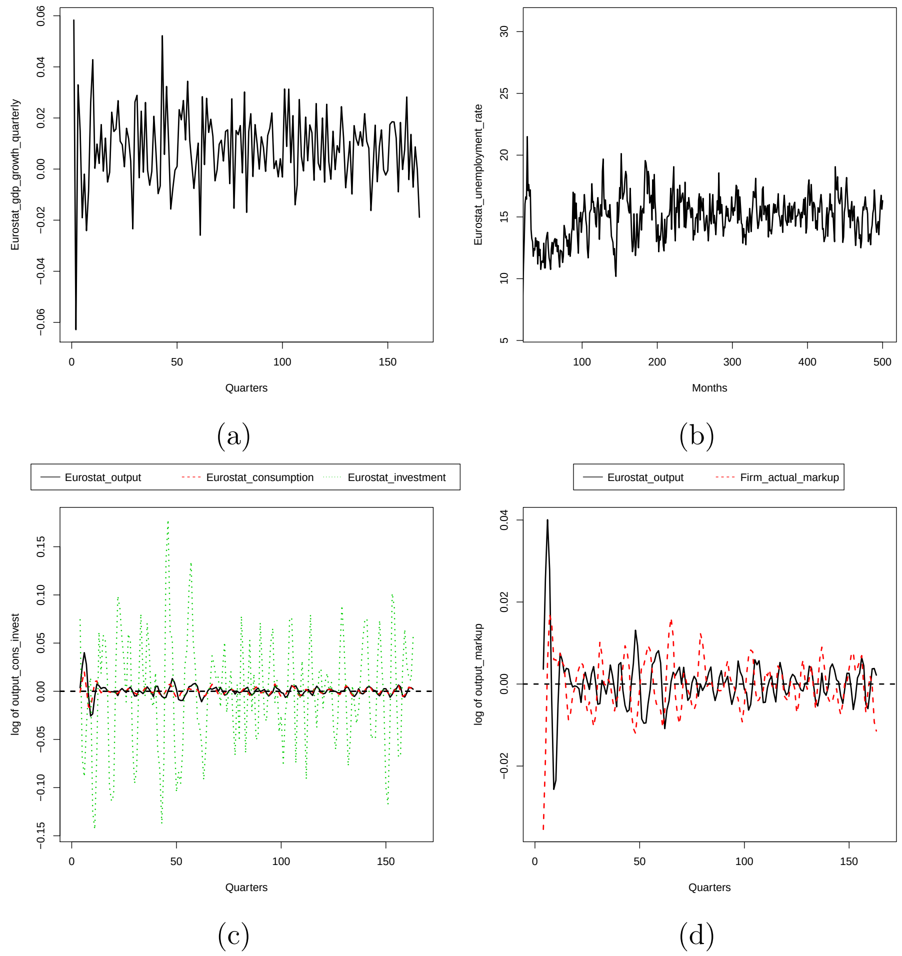

Figure 2: Time series of macroeconomic variables. (a) annual GDP growth rate (quarter-on-quarter); (b) unemployment rate; (c) band-passed filtered time series for output, consumption and investment; (d) band-passed filtered time series for output and average price mark-ups.

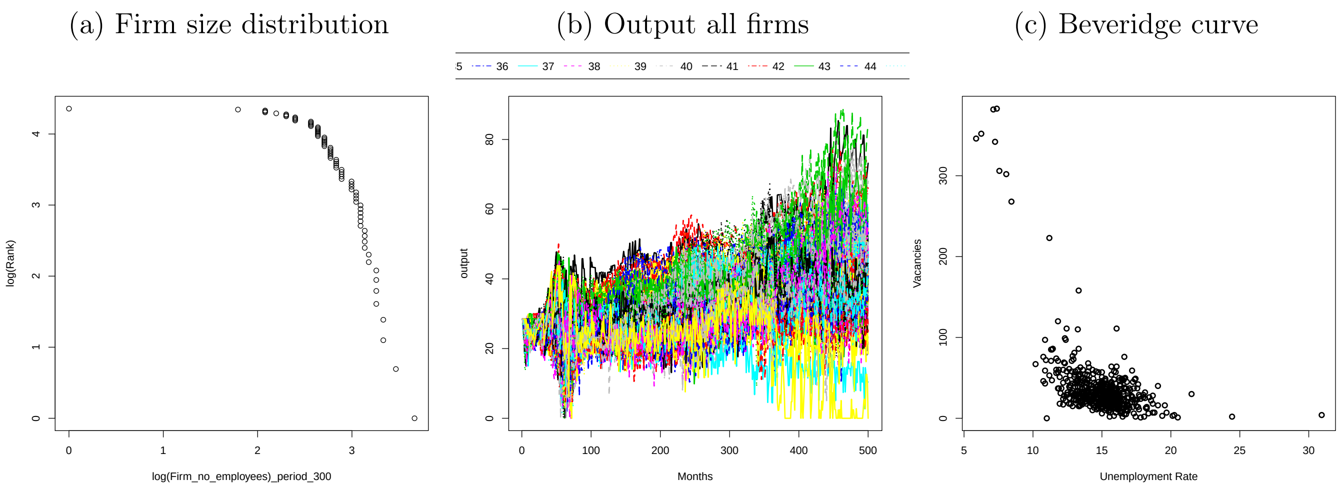

Figure 3: Stylized facts wrt. firm heterogeneity. (a) Firm size distribution (measured as no. of employees) after 300 months; (b) Time series of output for all 80 firms. (c) Beveridge curve.

and how to interpret the results of the model in an economical plausible fashion. Adding to the credibility of the model and the trust that it is based on plausible and empirically relevant economic mechanisms is in our understanding the main reason to check how the model output compares to stylized facts. Given this goal of gaining a qualitative understanding of economic mechanisms driving dynamics and policy effects, no attempt has been made to calibrate the model more precisely to specific regions or sectors and to quantitatively target certain time series data. Nevertheless, in different papers based on this model parameter settings have been identified to distinguish e.g. between technologically more and less advanced regions (see Dawid et al., 2012a, 2014).

For observations at the aggregate level to be useful it is crucial to gain an understanding of the (dynamic) mechanisms at the micro- and industry level that are responsible for the observed changes in the aggregate dynamics. Gaining such an understanding is also of particular importance for the analysis of the implications of economic policy measures in different economic environments and in different time windows. In the next section we illustrate one such economic mechanism by considering in more detail the driving forces of technology diffusion and productivity change.

4 Identifying Economic Mechanisms

As alluded to above, persistent heterogeneity of firms with respect to a number of key variables is an empirical stylized fact in many industries. In Figure 4 we show heat-maps depicting the dynamics of the evolution of population distributions of prices, total units of capital stock, earnings per unit of capital for a single run of the model with the standard parameter constellation.

It can be clearly seen that the model indeed generates persistent heterogeneity. The shape of the distributions seems to be quite robust over time, although for prices and earnings the concentration of the distribution is slightly decreasing. More detailed analyses of the dynamics of these variables for single firms, not shown here, furthermore highlight that not only the population distributions exhibit persistent heterogeneity, but also the position of individual firms within the distribution changes only slowly over time (compare Figure 3b).These observations are appealing from an empirical perspective, but from a more theoretical point of view raise the question how such heterogeneity can survive in the long run and in how far such persistent heterogeneity influences the aggregate economic dynamics.

Our discussion here focuses on the role of heterogeneity in the mechanisms driving the diffusion of new technologies and thereby the dynamics of technological change in the economy. Figure 5 shows the evolution of the relationship between firm size (measured by units of capital stock) and the average quality of the capital stock as well as the actual productivity of a firm. Firm size is measured on the vertical axis and at each point in time the color of the block at a certain firm size indicates the average quality of the capital stock. It can be clearly seen that on average larger firms have capital stocks of higher quality and that new technologies diffuse into the economy in waves starting at the large firms and then moving to the smaller ones. On the other hand, actual productivity seems to be largely independent of firm size.

particular policy analysis under consideration.

[5]Since we are using quarterly data, we use a band-pass filter which admits frequency components between 8 and 36 quarters.

[6]In a recent paper based on a two-region version of the model it has also been demonstrated that the model in its standard calibration reproduces typical patterns of income inequality dynamics across regions with different technological levels although such patterns have never been targeted at the parameter determination, see Dawid et al. (2013).

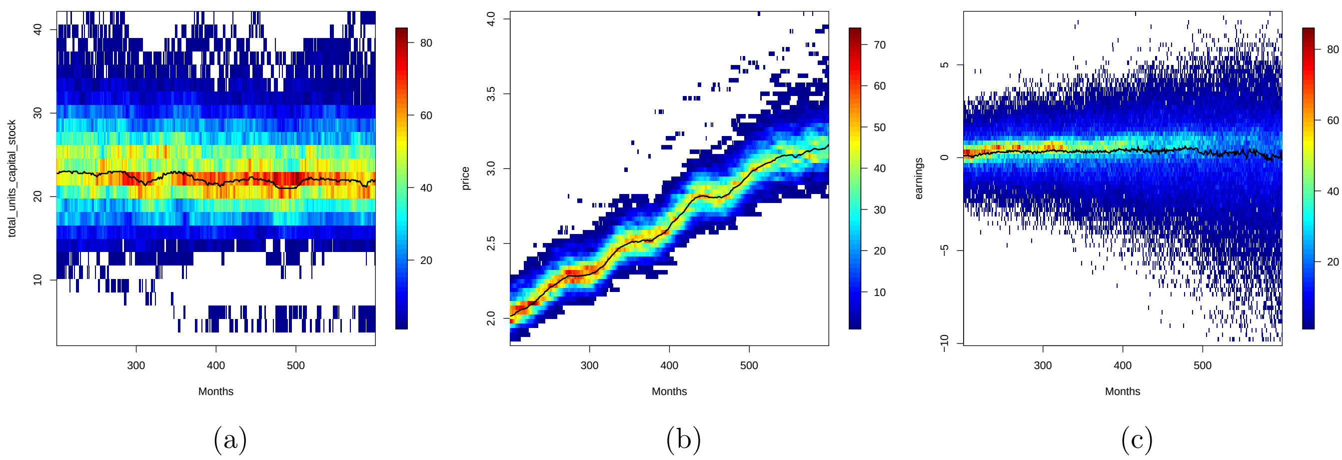

Figure 4: Evolution of population distributions after an initial transient phase (500 months) of (a) units of capital stock, (b) prices, (c) earnings per unit of capital stock in a single simulation run. The color code indicates the density of the population distribution in the considered range of the depicted variable. The black line shows the median of the population distribution.

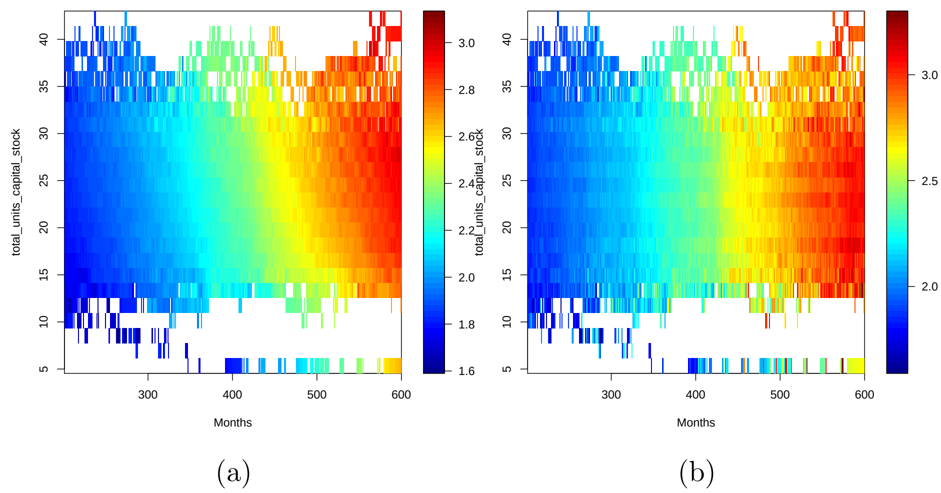

Figure 5: Time evolution of (a) average quality of capital stock, (b) output per worker sorted by firm size (measured as total units of capital stock).

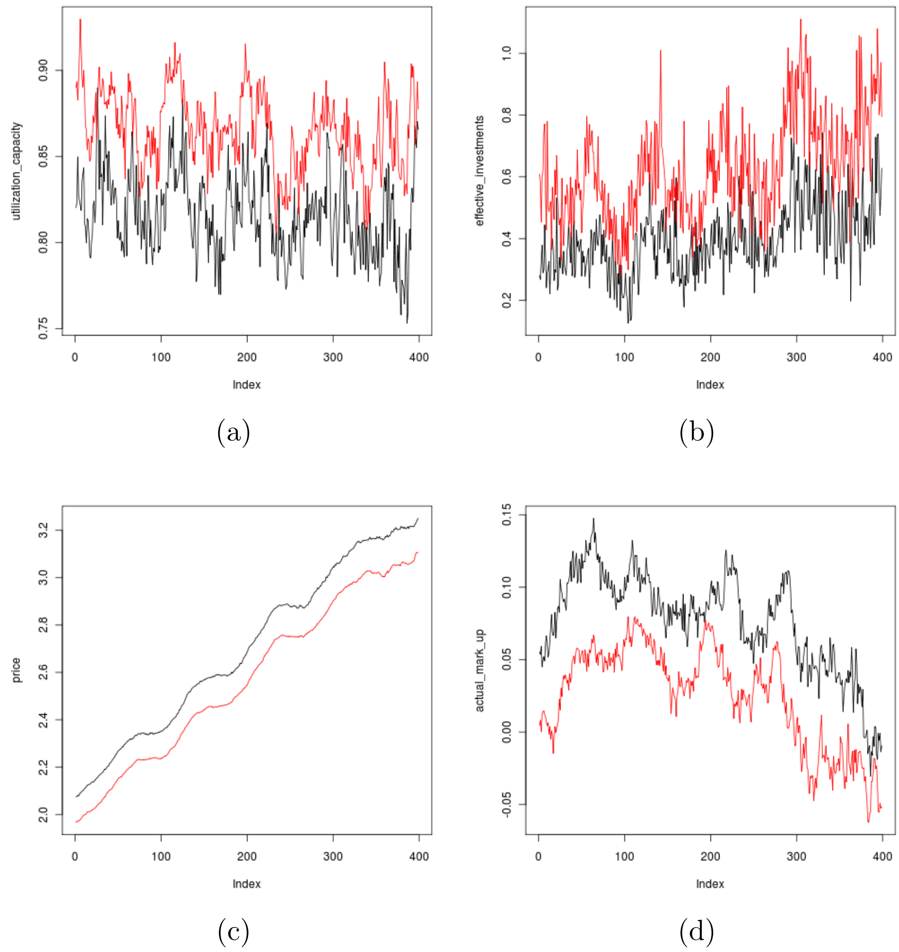

Figure 6: Comparison of time-evolution of the means of key economic variables of large (red line) and small (black line) firms, where the group of large firms consists of all firms whose size (measured in units of capital stock) is above the population median: (a) capacity utilization; (b) investment measured in quality units; (c) price of consumption good; (d) mark-up.

In order to understand this pattern one first has to take into account that actual productivity of a firm depends not only on the average quality of its capital stock, but also on the degree of capital utilization (because firms first use their best vintages and then have to move down to older and worse ones) and the skills of its employees. Indeed, as can be seen in panel (a) of Figure 6 the degree of capacity utilization of large firms is persistently higher than for small firms. Intuitively both size and degree of capacity utilization is driven by the relative competitiveness of firms. Those firms that charge the lowest prices tend to expand over time in the presence of demand increases. Expansion is triggered if firms hit their capacity contraints, which implies that the most competitive firms are on average characterized by large size (as explained below) and high capacity utilization. The correlation between size and capacity utilization explains, on the one hand, the observation that there is no systematic relationship between actual productivity and firm size despite of the systematic difference in average capital stock quality. On the other hand, it makes clear why the diffusion of new capital vintages tends to start at large firms. Due to the lower average amount of unused capacity, it is more likely that single large firms hit their capacity constraints and decide to expand their capital stock by investing in new investment goods. As can be seen in Figure 6 (panel b), the average investment (measured in terms of quality units) by firms whose size is above the population median is in fact almost twice as large as the average investment by small firms with size below the population median. Despite these systematic differences in firm behavior and characteristics between large and small firms, actual labor productivity and unit costs (not depicted here) do not differ between these groups. The reason for the persistence of differences in firm sizes and market shares is a systematic difference in prices – large firms charge lower prices (see Figure 6c) – which is due to differences in mark-ups (see Figure 6d), rather than in costs. Note that, similar to empirical studies, we define mark-ups here relative to observable *unit costs* rather than to *marginal costs* as is typically done in the theoretical industrial organization literature. To understand these price differences it is important to realize that the pricing rules used by firms in the Eurace@Unibi model – which according to the Management Science Approach resemble real-world pricing procedures in simplified form – take into account estimations of both demand elasticities and cost functions. The estimated (marginal) cost curves of firms with large capital stocks are much flatter than those of their smaller competitors,[7] which by standard economic arguments implies that these firms choose lower prices. The fact that profit-oriented pricing rules are considered, rather than for example fixed mark-ups, is crucial for the emergence of this phenomenon and highlights the more general point that considering forward-looking and goal-oriented behavior of agents enhances the richness of economic insights that can be obtained from agent-based models.

Overall, this brief discussion shows that due to path dependencies firms persistently differ in their investment and pricing behavior. Moreover, due to these differences a certain class of firms (namely, the large firms that charge lower prices) is of particular importance for the dispersion of new capital vintages, and therefore accelerates the speed of diffusion of new technologies in the economy. Insights of this kind are highly useful when considering the effect of policy measures on the aggregate dynamics and on the behavior and performance of different groups of agents. One might, for example, infer from our discussion that fiscal policy measures, which try to foster technological change by providing subsidies for investment in new vintages, should have a redistribution bias towards large firms.

Although a good understanding of the different forces at work at the different levels of aggregation is very useful to develop such intuition for the implications of different policies, a rigorous statistical analysis of the effect of a policy measure on key economic variables and a

[7] This holds in particular in the high-output regions, where small firms would have to invest heavily in order to generate the necessary capacities.

careful examination of the induced economic mechanisms is needed to confirm such conjectures. For a given parameter constellation and a given policy environment the time series observed in a simulation is a realization of a stochastic process whose exact properties typically are not fully understood. Hence, statistical methods are appropriate to evaluate the effects of changes in the policy environment on the properties of the time series under consideration. Particularly challenging in this respect is to evaluate in a statistically rigorous way the evolution of policy effects over time.

In Dawid et al. (2014) and Dawid et al. (2013) we have introduced a penalized spline approach as a tool to unravel the dynamic effects of policies on the economic variables of interest. According to this approach the time series resulting from batch runs with different policy settings are pooled and based on this data a non-parametric model using penalized spline functions is estimated. For each of the considered policy options a spline function is associated with a dummy variable indicating whether the policy has been used in a particular run. These spline functions then capture the dynamic effects of the corresponding policy measure. Standard techniques allow the derivation of confidence intervals for those spline functions and therefore insights about the statistical significance of policy effects at a given point in time can be obtained. We refer to Kauermann et al. (2009) for a more extensive treatment of penalized spline methods.

In the following section, we briefly discuss several examples of policy analyses, which have been carried out using (previous versions of) the Eurace@Unibi model. Several of these analyses rely on the penalized spline method described above.

5 Spatial Policy Analysis

Explicit consideration of heterogeneity is not only important on an individual level but also on more aggregated levels like regions or nations. Macroeconomic processes are characterized by the aggregation of economic interactions which to a large degree take place on a local level, where local economic environments and properties of individual agents might differ significantly between regions. Such regional differences are of particular importance if it is taken into account that the flow of goods and production factors between regions is affected by spatial frictions that hinder equilibrating forces between different local markets. Such considerations have important normative implications since they suggest that policy makers should not only care about the type and dose of policy interventions but also about the spatial distribution of the measures taken. Agent-based models are particularly well-suited to explore the implications of (local) policy measures in economies consisting of regions with different characteristics because they allow to understand how individuals with different characteristics (e.g. skills for workers, capital endowment for firms) in different regions are affected over time by the policy and how the resulting varying reactions of these individuals influence regional and aggregate economic dynamics. Detailed analyses of the evolution of the population distributions of key economic variables, similar to the one sketched in the previous section, are an important instrument for policy studies of this kind. They should complement statistical tests on the implications of policy measures on simulation results.

The Eurace@Unibi model has been used to examine in a multi-region setting the design of economic policy measures that facilitate technical change and economic growth. In the political debate the balance between policies fostering the catch-up of weaker regions and the reinforcement of strengths of advanced regions is a recurrent theme, not in the least in the context of policy design for the European Union. However, theoretical studies of the effects of different spatial distributions of policy measures, that also take into account the interplay of local dynamics and cross-regional flows of factors and goods, are limited. In particular, careful consideration of the implications of spatial frictions on different markets for the effects of different policy measures are rare. This seems to be mainly due to the fact that most theoretical policy models do not explicitly take into account heterogeneity on the individual *and* regional levels.

The analysis in Dawid et al. (2008) contributes to the debate whether activities to strengthen technological change should be targetted on stronger regions, weaker regions, or whether it should be uniformly distributed. The concrete policy measure under consideration is an increase in the level of general skills of workers in a region. Our interest in the effects of skill improving policies was driven by two main motivations. First, there is strong empirical evidence that the skill distribution of the workforce has substantial influence on the speed of technological change, the employment and wage dynamics, and growth in the economy (e.g. Bassanini and Scarpetta, 2002). In order to efficiently use new technologies the workforce of the industrial firms has to be able to build up the required level of specific skills and the ability to do so depends on the general skill levels of the employees. Therefore, policies that aim at a change in the local skill distribution may play an important role in fostering technological change and growth. Furthermore, we observe that high-skill employees are in many instances strongly concentrated in a few areas. The Eurace@Unibi model is capable to capture these aspects and is therefore well-suited to explore the different implications of the described policy variants.

Under the assumption that the flow of workers between regions is hindered by substantial spatial frictions (which might be due to commuting costs or legal restrictions) the simulation experiments show that the concentration of policy measures in one region in the short run triggers stronger overall growth in the economy compared to a uniform allocation of policy measures across both regions. However, a policy maker with a long run growth perspective in mind should refrain from such spatial concentration of the policy effort since the uniform policy shows better performance on the long run.

The economic mechanisms behind the results are intricate and serve to underline the valuable insights that can be gained from an agent-based approach. The finding is driven by the relatively low mobility of labor compared to that of consumption goods which in the long run leads to an incomplete substitution of production in the low skill (less supported) region with the production in the high skill (more supported) region. In the case of a concentration of the skill-upgrading in one region (the high-skill region) in the short run this region gains a competitive advantage due to faster productivity increases, which induces a shift of demand towards this region. This shift has a moderate overall growth enhancing effect in the economy since production is shifted towards the firms where productivity increases fastest. However, eventually the additional demand cannot be covered with the available workforce in the high-skill region. This leads to rationing of firms on the labor market with associated wage increases that open a gap between wages and productivity of labor. The combination of these frictions and wage distortions, which do not occur in case of a uniform application of the policy in both regions, are the main reason for the lower long run growth effects of the spatially concentrated policy. Furthermore, the falling demand for goods of producers in the low-skill region and labor mobility costs prevent these firms from hiring high-skilled workers from the other region. Consequently, no technological spillovers from the high- to the low-skill region emerge which also contributes to the observation that the geographically focused policy is less effective.

This policy analysis is developed further in Dawid et al. (2009) where the role of labor market frictions is analyzed more deeply. Again we compare policies that moderately increase general skill levels of workers uniformly across regions with an alternative approach where all efforts are concentrated in one region. Contrary to Dawid et al. (2008), however, we look into the opposite case of low spatial frictions. It turns out that the size of the commuting costs indeed has a crucial impact on the relative performance of the different policy types. In the empirically hardly relevant benchmark case of zero commuting costs (i.e. workers are completely indifferent between working in their own or some other region as long as the same wage is offered), no significant differences between the effects of the policy types emerge. However for small frictions in labor mobility the performance of the spatially concentrated policy is better than that of the uniform one. With positive but low commuting costs, contrary to the previous findings, a self-reinforcing cycle of capital and labor investments emerges which leads to faster overall growth. The origin of this cycle is an initial asymmetry in labor costs and prices induced by the combination of a geographically concentrated skill-upgrading policy and (small) spatial labor market frictions. The price asymmetry leads to demand asymmetry, which in case of low commuting costs induces spatial worker flows rather than local wage increases. Therefore, firms facing the increased demand in this scenario are not rationed on the labor market and therefore are able to expand their production and have incentives to invest in additional physical capital. The additional investment induced by this demand shift leads to a faster diffusion of technology. This faster diffusion, together with the policy-induced improvement in workers' ability to acquire the specific skills needed to work with the new machines, leads to a speedup of productivity and output growth.

In Dawid et al. (2012a) the relationship between spatial labor market frictions and (regional) economic growth is considered from a slightly different policy angle. The main question addressed in this paper is to which extent different policies of opening up labor markets that accompany an integration process of goods markets affect output and consumption dynamics in regions that start from different levels of economic development. This policy question has clear real-world relevance. For example, for countries which became part of the EU in May 2004, during a transition phase of up to seven years restrictions on labor mobility of workers could be imposed. Along the "2+3+2" formula restrictions had to be reviewed after two- and another three years. In fact, these policies raise important and so far not well understood research questions. In particular, it is an unresolved issue to which extent spatial frictions with respect to labor mobility may have positive or detrimental effects on overall and region-specific variables related to the well-being of their citizens in the medium and long run. It is a complex task to understand the most likely consequences of various labor market integration policies in a world where regions differ with respect to distributions of skills and the endowments of firms' physical capital and where productivity dynamics are influenced by complementarities between skill adjustments, investment dynamics and potentially skill-selected labor flows. Moreover, the mobility of workers interacts with: (1) important feedback effects through the wage dynamics (accompanying productivity growth), (2) demand shifts, that are driven by changes in households' consumption, and (3) the investment behavior of firms.

The policy experiments on labor market integration conducted with the Eurace@Unibi model indeed yield strikingly different outcomes depending on the variable of interest (regional output or consumption), the regional level of analysis, and the time horizon. Total output is lowest for closed regional labor markets and equally higher for all policies that mimick an opening up of the labor markets. Regional output, however, differs along all four policies.

Thus, when the objective is to maximize overall output the policy advice would be to choose either of the policies that at least gradually opens up labor markets. The advice to a policymaker who cares about convergence of regions would go differently. A policymaker that is willing to trade-off some output on the aggregate for more convergence should rather not integrate labor markets. If, however, a policymaker is not willing to give up overall output, then the advice is to fully open up labor markets as among all the policies that promote labor market integration, this was the policy which resulted in the least inequality between regions with respect to output levels.

Furthermore, in a world in which there are considerable flows of workers who work abroad but still consume in their domestic region, results in terms of convergence effects of the various labor market integration policies differ, and so would the policy advice if a policymaker's objective is to reduce inequality between regions regarding per-capita consumption. In this case, no trade-off between convergence of the regions and overall performance arises. Consequently, it is advisable to open up labor markets as this policy yields better results in terms of overall consumption and convergence of regions than not allowing workers to commute between regions. A detailed discussion of the dynamic mechanisms yielding these policy implications can be found in Dawid et al. (2012a).

In Dawid et al. (2014) we again analyze a concrete European regional policy issue using the Eurace@Unibi model. The focus of the paper is on the effectiveness of different types of cohesion policies with respect to convergence of regions. In particular, two types of policies are considered, which in a stylized form represent two main instruments of the EU cohesion policy.

The first is a technology policy, which resembles activities under the European Fund for Regional Development (ERDF), that provides subsidies to firms in an economically lagging region in order to invest in technologies at the technological frontier. Thereby, the incentive for firms in that region to acquire the latest available vintages of physical capital increases. This should lead not only to an increase in the quality of the physical capital in that region, but – due to the learning-by-doing effect captured in the Eurace@Unibi model – also to an improvement of the specific skills of the workers.

The second policy is a human capital policy, which represents measures within the European Social Fund (ESF), that induces an improvement of the distribution of general skills in the workforce in the target region. This improvement implies that on average workers in the target region acquire specific skills more quickly and, since the technology choice of firms is influenced by the skills of their workforce, it should further be expected that this policy also leads to an increase in the general skills and to an improvement of the quality of physical capital.

The dynamic implications of these two types of policies are studied in a two-region version of the Eurace@Unibi model, where firms in region 1 (the high-tech region) are initially endowed with a capital stock whose technological level is close to the frontier, while the capital in region 2 (the low-tech region) shows a considerable gap. The human capital differs in that the labor force in the first region is better educated and, by working with the most recent technology, has acquired higher specific skills than workers in the other region. Two different setups are considered. In the first setup the labor markets are fully integrated such that there are small frictions and all workers have almost unhindered access to both local labor markets. In the other setup the labor markets are completely separated and workers can only work in their home region. These are two extremes where the former may be seen as the political aim of an integrated European labor market, whereas the second is close to the current status quo in the EU, where actual labor mobility across larger distances and language barriers is still relatively small.

The main results of the analysis are that the human capital policy is only effective in terms of fostering cohesion if labor markets are separated. If labor markets are integrated, output actually falls in the lagging region at which the policy is targeted. Technology policies speed up convergence for integrated and separated labor markets and their effect is substantially stronger if they are specified such that they incentivize firms to purchase the newest vintages.

In summary, these findings strongly make the point that the spatial distribution of policy measures matters and the degree of frictions in labor mobility are crucial for the convergence patterns to appear. This inherently relates to the regional differences of the interaction patterns between the agents, that leads to macroscopic outcomes, and that again feed back on the individual and firm choices. The Eurace@Unibi model has proven to be a useful tool to capture various aspects that are relevant for spatial policy design. However, the structure of the model also allows to use it to gain insights into issues that are not directly related to spatial policy questions. For example, the explicit representations of the processes generating heterogeneity of firms as well as of workers makes the model suitable for the examination of dynamic mechanisms influencing (income) inequality in an economy. An example in this respect is Dawid and Gemkow (2014), where the impact of labor market characteristics, in particular the importance of social networks and referral hiring, on wage inequality is studied.

6 How Much Complexity for Policy Analysis?

Macroeconomic policy issues, including questions related to the policy studies described above, have of course been analyzed extensively using macroeconomic models of different types. In particular, in recent work Dynamic Stochastic General Equilibrium (DSGE) models have been frequently used to address such issues. Hence, it is important to understand how the agent-based approach and the policy analyses carried out using this approach relate to DSGE-based studies. The overall structure of the Eurace@Unibi model is in fact quite similar to that of typical dynamic equilibrium models that capture (endogenous) processes of technical change (see, e.g., Acemoglu, 2008).[8] In particular, there is a consumption goods sector producing a final consumption good using labor input provided by households and there is physical capital (machinery) provided by upstream firms in an investment goods sector. The driver of economic growth is the growing quality of the physical capital employed in production. Also similar to general equilibrium models, the Eurace@Unibi model is a closed macroeconomic model in the sense that there are no monetary- or real flows into and out of the economy. Both types of models are parametrized to replicate the empirical stylized facts of the macroeconomy.

In contrast to their DSGE counterparts however, in agent-based models the agents' decisions do not follow from the assumption of a representative agent who is intertemporally optimizing an objective function under rational expectations. Rather, the behavior of the agents is modeled using rules that have well-established (empirical) foundations. The microbehavior may differ between agents and they do not fully foresee all the consequences of their own actions and that of the other agents. While this exposes agent-based models to the Lucas Critique, it seems a more appropriate assumption on firm and household behavior within the context of a complex dynamic economy (*cf.* Cyert and March, 1963). Heterogeneity is allowed to a large degree and there is an explicit aggregation of individual behavior. One could even go further, and claim that the agent-based models are truly micro-founded as aggregation is not achieved by adopting the simplifying and possibly even erroneous assumption of a representative agent. The aggregation of individual decisions could end up in situations were markets do not clear. Therefore, contrary to the equilibrium-based DSGE framework, agent-based models capture economic frictions that result from the fact that actual economic agents are not fully coordinated in their (market-) actions. Agent-based models are able to address how such frictions affect the aggregate economic dynamics or the effects of policy measures. With that said, we refrain from discussing in more detail the motivations and merits for those differences in modeling philosophy (see Fagiolo and Roventini, 2012 for an extensive discussion on DSGE- versus agent-based modeling).

In terms of economic policy analysis the agent-based approach provides possibilities for analysis that do not seem feasible in a DSGE framework. We illustrate this point with the policy experiments discussed in the previous section. As pointed out, the mechanisms responsible for the effects of the policies rely on the interaction of distinct actions by agents, exposed to hetero-

[8] Similar statements hold true for other agent-based macroeconomic models.

geneous market situations. Path dependencies might emerge as a result of these heterogeneous actions, or from the (selected) factor flows across regions, and from the frictions arising in markets due to the explicit interaction protocols. In a representative agent equilibrium framework it is not possible to capture policy effects that are associated with such phenomena. It is our conviction that the effects of actual policy measures are strongly influenced by such path dependencies, heterogeneities and market frictions. Hence, in many policy domains it seems essential to work with models that are able to capture these effects.

Moreover, our analyses highlight the ability to rigorously study the effects of policy measures at different time scales. This is something that is very difficult (if not impossible) to do in a dynamic general equilibrium framework where the transitional dynamics inbetween equilibria – that arises after an (unanticipated) shock to the economic environment – typically cannot be characterized. Hence, such transient effects after a policy shock are subsequently ignored in the DSGE framework, while the ABM approach takes full account of such rippling effects.

A challenge of working with agent-based macroeconomic models is the complexity of interrelated effects and dynamics that result from the explicit modelling of interactions on different markets and the representation of (heterogeneous) rules to determine the behavior of agents. For an economic analysis carried out within an agent-based model the question can be raised whether the mechanisms in focus could not be represented in a more parsimonious, analytical model. The approach taken in the development and analysis of the Eurace@Unibi model is to build a framework that captures main (empirically motivated) factors that are responsible for technological change and associated skill dynamics on the micro-level of an economy. Hence, the model exhibits complementarities between the skill levels of workers and the quality of the capital stock inside the firms, and both variables are determined endogenously and influenced by the emerging patterns of the matching between workers and firms. Furthermore, the modeling approach integrates the dynamics of labor, consumption and investment goods markets in order to capture the feedbacks between technology choices by firms, the skill acquisition by workers and the evolution of demand for consumption goods. These aspects seem crucial to understand the (regional) technological change and related policy issues and therefore have been modelled with considerable micro structure. The parts of the model which are not crucial for the issues we are focusing on, in particular the financial- and credit markets, as well as the interactions between consumers and producers on the consumption goods market, are kept as simple as possible and are mainly used for model closure.

For several features of the model, like the endogenous determination of firm mark-ups or the vintage choice of firms, simplified alternatives, like e.g. fixed constant mark-ups, have been tested during the development of Eurace@Unibi and then dismissed because they generated economically implausible dynamics either on the micro or the macro level. So, also in this respect the development of the model is based on the intention to avoid complexity which is not essential for a sound understanding of the economic mechanisms under consideration.

As has been shown above, the developed framework is sufficiently general to be used to address different policy issues in our focus area. A common modelling strategy is to develop a separate (partial) model for each of the issues, capturing a single economic mechanism that seems especially important to the investigator. In contrast, our approach has been to analyze in a full-fledged model what are the linkages between different agents and markets that turn out to be of particular relevance to understanding the effects of a certain policy.

7 Concluding Remarks

There have been convincing attempts in terms of proof-of-concept to use agent-based models for macroeconomic research. These models are often simultaneously reproducing a large set of empirical stylized facts including correlations and lag structures between macroeconomic variables or distributions.

The Eurace@Unibi model and other contributions in this field have gone well beyond showing that stylized macro features can be replicated by agent-based models. Standard macroeconomic models such as RBC models and new-Keynesian DSGE models require a continuous stream of exogenous shocks to produce business cycle fluctuations. Agent-based models on the other hand produce self-sustaining business cycle fluctuations by relying on the endogenous generation of shocks at the microlevel. Additionally, there have been insightful contributions using agent-based macroeconomic models in the area of ex-ante policy simulations. It has been shown how policy measures, related to the improvement of the quality of human capital or to the flow of production factors change the behavior of firms and workers in a spatial context, and how the interaction of agents unfolds at the more aggregated level. Non-trivial improvements have been achieved in terms of the technical implementation of such large-scale simulation models. In terms of reliability of the results, stock-flow consistent (SFC) models have been an important step forward.[9]

Besides these very promising steps forward, many things remain to be done or are currently at an unsatisfactory stage. In particular, the patchwork of decision rules that we typically find across variants of agent-based macroeconomic models and sometimes even within a single model is not a convincing approach to model agent behavior. Also, the development of feasible techniques for systematic calibration or estimation of agent-based models is to a large extend still an open issue. Furthermore, the way simulation output is analyzed and policy experiments are carried out should be made more rigorous and unified across the various agent-based analyses to allow for a better comparison of model properties and results.

We see various possibilities to build on existing work in the area of agent-based macro. One route for future research is the inclusion and analysis of the role and consequences of networks in agent-based models. There have been various attempts to build into agent-based macroeconomic models networks with regard to the credit and financial sector (e.g., Battiston et al., 2007 and Battiston et al., 2012). What has been neglected so far are labor market networks where the links between workers and firms evolve endogenously, and where the links between workers vary along different characteristics with varying degrees. Similarly, the role of firm networks or sectoral networks such as production chains, which are typically at the center of empirical studies such as input-output analysis, are not included in (agent-based) macroeconomic models as far as we know. We know little about how network characteristics between suppliers of investment goods or other input factors and downstream firms would alter the diffusion of new technologies, business cycle characteristics, or the efficacy of policies in general.

Another route is to study in much more detail the effects of particular policies on the interaction between the real and financial economy. Interesting questions here focus on the transmission channels of risk, e.g. through the financial accelerator mechanism. We see in particular the strength of agent-based models in linking short run policy analyses on the business cycle with the longer run as policy measures may involve trade-offs along the time dimension. For example, policies that lead to the expansion of the financial system may lead on the short run to allow more innovative projects to be financed, and hence may increase the speed of technological

[9]For early statements on the importance of Stock-Flow Consistency, see Lavoie and Godley (2006) and Lavoie (2001).

change and technological diffusion. In itself, from a partial model point of view, this would enchance long-run growth. However, it also leads to more risky financial positions of firms, opening up the possibility for endogenous crises through increased financial fragility, firm bankruptcy and debt write-offs. Banking regulations aimed at preventing such endogenous increases of risk may dampen the short-run volatility, but could also reduce the speed of technological change and thereby depress long-run growth. It is only in models where the real and financial markets are sufficiently detailed and integrated that such second-order effects of policies can be studied. As such, agent-based macroeconomic models could form a bridge between the literature on financial fragility and endogenous growth models by using integrated models instead of partial market models.

As a final hint towards future directions of research we would like to emphasize that by its very strong micro-foundations, that stress heterogeneity at the agent-level, agent-based models open-up more interesting ways to study the distributional outcomes of policy that go beyond pre-existing research. With agent-based models we have the possibility to study income distributions across agents or groups of agents as well as along the spatial dimension or the time dimension (see, e.g., Dosi et al., 2013, Dawid and Gemkow, 2014). All these topics are exciting areas for future research with agent-based macroeconomic models and we are looking forward to more interesting insights produced by a steadily growing community of researchers in the future.

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