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ORIGINAL PAPER

Multi-agent modeling of economic innovation dynamics and its implications for analyzing emission impacts

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Abstract In this elaboration we focus on the role of multi-agent systems as a tool for modeling economic dynamics. Hence, at the beginning the specific features of this tool are considered. Taking the example of explaining the relationship between innovations and economic growth it will be shown after that how the tool of multi-agent modeling can be used for the following purposes: (1) for explaining the occurrence of innovations, (2) for specifying the effects these innovations have on economic growth, (3) for linking emission impacts to this growth and finally (4) for exemplarily assessing political options to reduce these impacts.

Keywords Innovation · Economic growth · Simulation · Multi-agent model · Rebound effect · Emission abatement

1 Introduction

Undoubtedly many of the observable impacts on ecological systems (e.g. depletion of minerals and species, emissions and waste) can be derived from economic activities. But the relationship between the two is far from being fully clarified in scientific analysis. Either the focus on this impact perspective and/or lack of economic knowledge often leads to a specific framing of economic analysis in this environmental context: *Firstly*, only economic aggregates (like gross domestic product) and their dynamics are considered; *secondly*, this analysis is normally carried out by using computable modeling frame works (like computable general equilibrium models). What is missing in such a framework is a realistic

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consideration of the microeconomic foundation for the driving forces of economic processes. To assume a representative optimizing agency is not sufficient in this context because neither behavioral constraints (in terms of information processing and knowledge acquisition) nor non-linear interaction effects between economic actors can be taken into account by making this assumption. A realistic view on the microeconomic background of observable economic aggregates is not only important for explaining the (aggregate) economic output itself, it is also essential for assessing the possibilities and constraints for political regulation.

The problem at stake here can be illustrated by referring to the endeavor to model the climate change. Obviously there is a dichotomy between the model compartments related to the natural and ecological components of the climate change on one side and the model compartment portraying the economic dynamics on the other side. Whereas the former is usually conceptualized as a complex adaptive system the latter is framed as a more or less straight-forward optimization machine (e.g. IPCC 2007; Rayner and Malone 1998; Janssen 1998; McGuffie and Henderson-Sellers 1997; Walker and Steffen 1996; Nordhaus 1992). Hence, there is a complexity gap between these two model compartments raising the question of their general compatibility. Furthermore concepts of aggregated growth play an essential role in the architecture of the economic modeling compartment. Due to the requirement of prognosis computable general equilibrium models are the most preferred model designs in this domain of economic research (e.g. Nordhaus and Bojer 2000). A meaningful access to evaluating political regulation cannot be given in such a context because there is no possibility to relate political measures to the action of individuals, organizations or groups of both.[1]

We are suggesting to fill this gap of micro-foundation in economic analysis by using a multi-agent framework. In such a framework there is no necessity to confine the analysis to economic aggregates and to a corresponding stylized micro-foundation. Rather different types of agents as well as their interaction can be conceptualized as the driving forces for the (aggregate) economic dynamics without missing the property of computability. At the same time by referring to agents (and their interactions) the addressees of political regulation are explicitly taken into account. Hence, assessing political options from an agent-based perspective is possible in such a framework.

In what follows the main focus is on methodological issues. It will be shown how aggregate economic dynamics can be (re-)constructed by using such a multi-agent framework. Therefore we will not deal with the problem of empirical calibration of multi-agent models.[2] For demonstrating the importance of such an agent-based approach we will take the example of innovation induced market dynamics. Looking at modern theories of growth there seems to be a consensus that innovation is of

[1] This problem is often circumvented by postulating targets (e.g. in terms of reducing emissions) without showing by means of which transitions agents can meet these targets and how these transitions can be triggered. If this would be specified the uncertainty with regard to emission scenarios could be reduced (cf. IPCC 2007; Pielke et al. 2008).

[2] Depending on data availability there are generally two different ways to calibrate the initial values of the state variables and the parameters of the model: either indirectly by postulating the reproduction of given data time series or directly by doing behavioral observations (cf. Beckenbach et al. 2009; Beckenbach and Daskalakis 2008; Windrum et al. 2007; Edmonds 2001).

utmost importance for explaining the dynamics of economic growth and—as one has to add by encompassing latest developments in the real economy—stagnation. The implication such an approach has for the dynamics of ecological impacts is demonstrated by taking an exemplary emission related to economic activity (e.g. CO_2) into account.[3] Such a methodological reflection can be considered as a first step for conceptualizing a more realistic economic compartment in combined modeling of climate change. It is only in such a broadened perspective that the ecological boundary conditions for economic activities as well as the influence of impacts generated by economic activities on the ecological dynamics itself can be analyzed more closely.

2 What multi-agent modeling is about

Multi-agent systems are the appropriate modeling framework if the focus of the analysis is on a property of the system encompassing all its elements (macro-property) not simply derivable from analyzing singular elements or by aggregating the elements. Rather this macro-property is shown to result from the interaction of the elements which are autonomous in that they have a certain degree of freedom in what they can do. Neither the way they are acting nor what they are doing is therefore predetermined by general or situational conditions. Hence, these elements—the agents—have the possibility to adapt their states according to different conditions for action they can observe (e.g. social results from individual actions like prices). Furthermore the autonomy of the agents includes a variable way of interaction with other agents: according to the experience they face agents can select different ways to coordinate their own action with others. Even if everything else (e.g. initial endowments) should be the same for all agents this autonomy of agents makes them heterogeneous in the course of time due to the different way they are adapting and coordinating their activities. In short, multi-agent modeling is an adequate tool if a "complex adaptive system" is under consideration having emergent properties derivable from interacting autonomous and heterogeneous agents (cf. Holland 1996, 1998).

This modeling tool is originated in artificial intelligence research in that it is a radical way to portray the potentials of distributed intelligence in contradistinction to expert systems (cf. Russell and Norvig 1995). Agents are then mapped as (parts of) computer programs interacting with each other. Taking into account the well-known intricacies of modeling social interaction in general and especially market interaction (cf. e.g. Lee and Keen 2004) it is almost natural to apply multi-agent models in this context and considering agents as a representation of human beings.[4] Then the limited capability of agents to generate and to perceive information as a background for their way to act is considered as a partial representation of the

[3] Hence, due to methodological reasons we will neither deal with interacting emissions, nor with impacts related to the extraction side, nor with the effects all these impacts have on the state and dynamics of the various parts of the ecological system.

[4] This could be either a single human being in its essential properties or a group of human beings having at least one common property being essential for their way to act.

cognitive processes accrued to real human beings. This necessitates to enrich this modeling of human cognitive processes by picking up insights from sciences investigating the behavior of real human beings like modern (cognitive) psychology, neuroscience as well as experimental economics. According to the findings in these behavioral sciences limited short-term memory capacities, patterns of perception and understanding (like frames, schemata, scripts, mental maps etc.) as well as the cognitive economizing included therein (manifest in the prominent role of routines and habits), different types of learning as well as the process of selecting and weighing goals seem to be an essential part of the (limited) capabilities of human beings to act (cf. Camerer et al. 2005; Gintis 2000). Multi-agent models are on one side a framework predestined for incorporating these insights (cf. Sun 2001, 2006); on the other side there is a constraint in that these insights have to be translated into a computable framework and in that incorporating the above mentioned insights should contribute to the emergent property at stake. Hence, the problems of arbitrariness arising if Pandora's box of bounded rationality (Simon 2000) is opened can at least be constrained in a multi-agent modeling framework: there is *firstly* a need of computability and *secondly* a need for plausibility of the assumptions borrowed from the modern behavioral sciences for the given modeling context.

According to this strand of thought agent-based modeling has been applied to a lot of phenomena belonging to the realm of economics (cf. the overview in Tesfatsion 2002; Tesfatsion and Judd 2006), especially market processes (Kirman and Vriend 2001; Farmer 2001; Luna and Stefansson 2000), technological change (Dawid 2006; Fagiolo and Dosi 2003), network dynamics (Wilhite 2001) and organizations (Chung and Harrington 2006; Klos and Nooteboom 2001; Prietula et al. 1998). The same is true for ecological phenomena resulting from human impacts. Here a special emphasis has been laid on common pool resources and land use patterns (cf. the overview in Janssen 2002, 2004). Only recently the question has been raised if agent-based modeling is an appropriate tool for analyzing climate change adaptation and sustainability issues (cf. Balbi and Giupponi 2009 for a survey). These studies are a starting point for revealing the potential of multi-agent modeling related to real human beings. Especially with regards to economic phenomena there are still multiple opportunities to unfold and to incorporate ideas about bounded rationality, non-linear interaction in markets and 'far-from-equilibrium'-regularities on the macro-level into a multi-agent framework. In the following section we will demonstrate how the dynamics of economic aggregates can be explained by agents and their interaction both being based on modern behavioral insights.

3 Agent-based analysis of innovation dynamics

In this context economic *growth* (in aggregated monetary terms) is conceptualized as an *emergent property* (as explained in section 2). That means growth cannot be derived by simply analyzing a representative economic entity or by only aggregating all entities of an economy under investigation. Hence, there is no simple functional relationship between economic inputs (like 'capital', 'labor' etc) and outputs (like the produced amount of commodities and services expressed in monetary terms).[5] As already mentioned in section 1 there are (at least) two basic reasons for being skeptical about such a simple production equation: the behavioral complexity of individuals (or agents) investing capital, labor etc. and the non-linear interaction effects between these agents. The *agents* we will focus on are *firms*. Undoubtedly they play the most important part for generating growth in the economy. In the case of firms the adaptive capacity required for the agents in a multi-agent framework (cf. section 2) is given in terms of endowments (finance, knowledge) and different modes of action (like routines, choices etc.). The latter circumscribe different in-house capacities to perceive a situation, to use information as well as knowledge and to select an activity. Furthermore firms have an adaptive potential in determining their way of interaction with other firms (indirect market interaction, direct cooperation or loose network relations). Due to empirical evidence on one side and the corresponding shortcomings in modern economic growth theory on the other side we will confine ourselves to analyze the *creation of novelties* (innovation and imitation) by firms as a *driver for economic growth*. Creating novelties is a temporary (very resource-consuming) activity of firms involving a high risk of failure. Accordingly novelty creating activities of firms are triggered by specific behavioral and competitive conditions.[6] If it is successful a novelty will generate additional activities; at the same token a devaluation or substitution of old activities will take place.[7] Hence, the overall effect of novelties for aggregates of economic activities is by no means trivial.

For grasping the relationship between novelty creating activities of agents and the growth of economic aggregates a *multi-level approach* is suggested (cf. Fig. 1). The *first* level specifies the triggering conditions for novelty creating activities for the agents i.e. firms. Here the behavioral elements and the modes of actions for the firms are portrayed by using an agent-based approach. On the *second* level the consequences of successful innovations and imitations in a given sector of economic activities are dealt with. This depends on the frequency of successful novelties and on the way they diffuse in that sector. We use an agent-related functional approach applying difference equations for depicting the stylized facts of the diffusion dynamics. Finally on the *third* level sectoral interdependencies are taken into account. By referring to an accounting approach (input/output-table) the diffusion effects of novelties in one sector for other sectors can be traced. Only if these different levels of economic dynamics are separated as well as related to each other it is possible to derive aggregate effects of novelties for the whole economy. This

[5] To assume one or several simple relations (e.g. as aggregated equations or as production functions) is still the state of the art in modern growth theory (cf. e.g. Fine 2000). No attempt has been made to show that these are empirically and methodologically legitimate assumptions. Using evolutionary methodologies allowing disaggregate defines an alternative path for conceptualizing growth in general and especially environmental innovation (cf. Frenken and Faber 2009). In the sequel we will follow this path of economic thinking.

[6] This essential feature of novelty creation is ignored in theories of 'endogenous growth' (e.g. Romer 1990) where r&d is a continuous and riskless activity separated from other firm activities.

[7] To ignore this (non-linear) interdependency of new and old activities (and of their outcomes respectively) is another failure of most contributions to 'endogenous growth theory': here every innovation is immediately patented and the new activity is simply an add-on for total production (cf. Romer 1990).

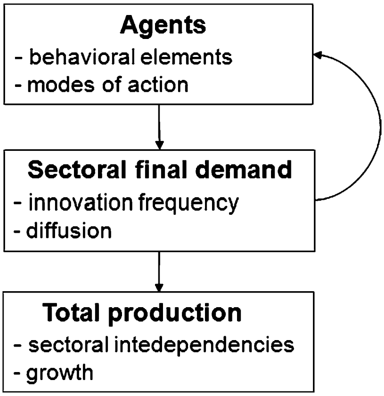

Fig. 1 Overview of multi-level approach

procedure manifests the importance of the multi-scale property for analyzing the economy as a 'complex adaptive system' (cf. Arthur et al. 1997).

On the first *agent-related level* the question to answer is: Under what conditions and how do agents create novelties or—in knowledge related terms—under what conditions do agents search for new knowledge? Letting a principal methodological caveat against this question apart[8] there are two types of answers to it. In the 'functional approach' (mainly originated in the work of Hayek) a strategic (first mover) advantage for successful creators of novelties is derived from competition. From this assertion it is directly concluded that there is a person/an agent who makes use of this advantage. In the 'personal approach' (mainly originated in the work of Schumpeter) it is assumed that there simply is a specific type of agents whose main profession is to innovate, i.e. the entrepreneurs. Both approaches are not sufficient in explanatory terms. In the personal approach it is neglected that innovation is a temporary activity which can be attributed in principle to every economic agent; in the functional approach no explanation is given why only a part of a whole population linked by a competitive process is in fact innovating and what kind of motives these innovating agents have.

To avoid these shortcomings in explaining the novelty creation by firm agents it is necessary to take up insights of modern behavioural research. There exist a lot of conceptual ideas about a behavioral foundation of economic activities in the literature.[9] But most of them are not related to novelty creation or not even oriented towards including different modes of activities. Hence, in this literature, empirical evidence, if given at all, is only related to parts of a behavioral framework needed here. Therefore it is necessary to include behavioral evidence as a criterion for selecting *conceptual* ideas. For elaborating a behavioral synthesis we combine the

[8] According to this caveat the novelty creating process is totally conjectural without anything to generalize. Due to the idiosyncratic nature of the processes as well as of the persons involved in innovations there is seen only a limited possibility for some after-the-fact analysis on an aggregated level (cf. e.g. Vromen 2001).

[9] Most prominent in this respect are revisions of the expected utility theory (e.g. prospect theory; cf. Kahneman and Tversky 1979) and enhancements of game theory (cf. Gintis 2003).

approaches of Ajzen (1991) and the Carnegie School (March and Simon 1993; Cyert and March 1992) both of which have been tested and approved empirically. According to this behavioral synthesis (cf. Beckenbach et al. 2007) the traditional microeconomic approach (focusing mainly on preferences and constraints) is reshaped and enhanced. The major behavioral explanantia are attitudes (instead of preferences), endowments as well as control abilities (instead of constraints) and norms (reflecting a minimum of social embeddedness). Instead of the unrealistic optimization rule a satisficing rule (related to an aspiration level) in pursuing and balancing different goals is assumed as the central mechanism of cognitive control. As already mentioned in section 2 the agent's ability to act is given in terms of different modes of action which are selected according to time-dependent constellations of the behavioral explanantia.[10] Corresponding to the multiple-self nature of economic actors these behavioral elements are feeding different cognitive forces each of which is directed in favor of a possible mode of action.[11] The strongest force determines which mode of action will be pursued by the agent. Hence, the formation of patterns (routines) as well as erosion of patterns (novelty creation) can be explained on the individual level. A graphical overview for this behavioral architecture is given in Fig. 2.

Taking routines as the default mode of action we define the *preservation force* related to it simply as:

$$\mathrm{F}_0 = 1 \tag{1}$$

The force to overcome this routine mode of action is further differentiated in the force directed to imitation (F_1) and the force directed to innovation (F_2). Formalizing these forces necessitates to distinguish sub-forces or force components (f_i) picking up the different traits and state variables characterizing the agents.

The first force component to consider here is curiosity which is strongly related to the phenomenon of 'slack', i.e. the reserve capacities in terms of knowledge (kr) and finance (fr). In any given time step this slack is tantamount to balancing the given state of knowledge and finance on one side and the amount of these resources needed for a given mode of action on the other side. Again, the intensity of curiosity triggered by this slack is depending on a personal trait, the exploration drive (w_0). Hence, curiosity is formally defined as

$$\mathrm{f}_0(\mathrm{t}) = \mathrm{w}_0(\mathrm{kr}(\mathrm{t}) + \mathrm{fr}(\mathrm{t})). \tag{2}$$

The other two force components to take into account here are related to the goals of the agent: profit (p) and market share (m). They formalize the degree of satisfaction of the goal attainment indicated by the relationship of the aspiration level for profits (asp) and the aspiration level for market share (asm) to the actual degree

[10] These explanantia—in model terms: variables—are moderated by behavioral traits (e.g. risk attitude, curiosity)—in model terms: parameters.

[11] In the present context only routine, innovation and imitation are taken into account.

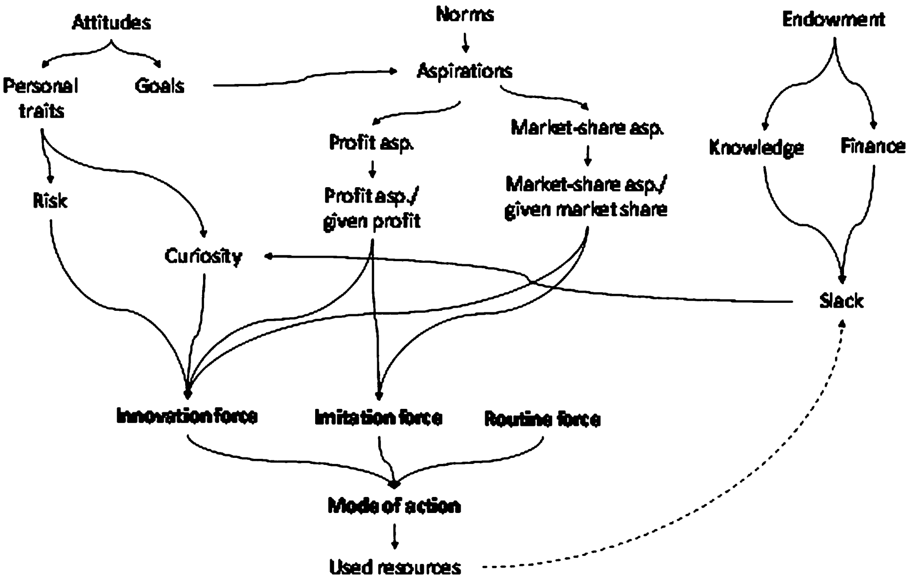

Fig. 2 Specification of agent's behavior

of goal attainment in a given time step. For each of these goal components parameters in terms of weight (w_1, w_2) and elasticity (ε_1, ε_2) are given. The force components for profit aspiration and market share aspiration can be formalized as:

$$f_1(t) = w_1 \left(\frac{asp(t)}{p(t)}\right)^{\varepsilon_1} \quad (3)$$

$$f_2(t) = w_2 \left(\frac{asm(t)}{m(t)}\right)^{\varepsilon_2}. \quad (4)$$

The aspiration levels included in these force components are updated at the end of each time step. For the profit aspiration this updating formally means:

$$asp(t+1) = (1-\phi)\, asp(t) + \phi p(t) \quad (5)$$

(and analogously for asm) where ϕ is the flexibility of adaptation, which is another personal trait ($0 \leq \phi \leq 1$).

Then the *force directed to imitation* can be formalized as:

$$F_1 = \frac{f_1 + f_2}{cim} \quad (6)$$

with *cim* as the parameter for the expected costs of an imitation.

The *force directed to innovation* also includes the essential force components f_1 and f_2. But it has three features making it different from the imitation force: *Firstly*, due to the nature of the innovation process curiosity (f_0) has to be included.

Secondly, there is a comparative difference in expected costs: the expected costs for innovation projects (cin) are higher than the expected cost for imitation projects. *Thirdly*, the innovation force contains a parameter (α) indicating the role of risk acceptance. Then the force directed to innovation can be formalized as:

$$F_2 = \alpha \frac{f_0 + f_1 + f_2}{cin} \tag{7}$$

Given the time-dependent amount for F_0, F_1 and F_2, the agent will activate that mode of action for which the corresponding force is highest. If this mode of action is 'imitation' or 'innovation' it will be pursued by the agent in addition to its ongoing routine activity, i.e. they will start new novelty creating projects. If F_1 or F_2 remain higher than F_0 after these projects have been finished, new projects will be started. If this is not the case the agent will only pursue routine behavior. Hence, it is respected in the simulation model that innovation as well as imitation are specific temporary modes of action.

On the second *sectoral level* we refer to the stylized facts of diffusion analysis: A critical mass has to overcome for initiating a self-feeding diffusion process up to a maximum level where all needs are satisfied. Furthermore according to the dominance of retarding effects at the beginning of this diffusion process and due to the dominance of the promoting effects at later stages of the diffusion process an S-shaped time-dependent diffusion curve is assumed (cf. Rogers 1995). Finally, the shortcomings of economic growth theory (cf. section 2) necessitate to give innovation a twofold effect: a growing of the demand for the products of an innovating firm and a substitution for old products. These stylized features of the diffusion dynamics are summarized in Fig. 3.

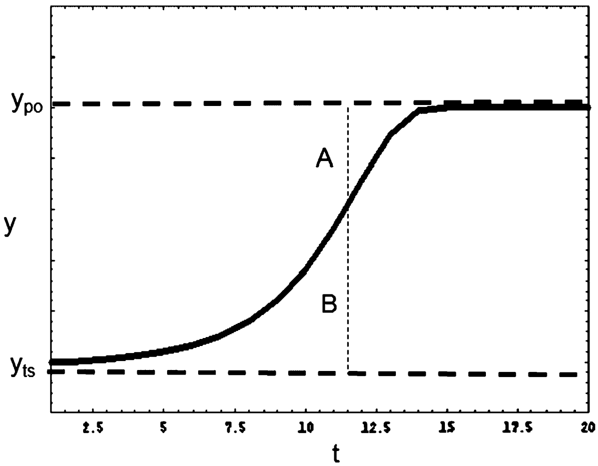

Fig. 3 Specification of sectoral diffusion dynamics

A newly created innovative product (independently of whether it is created individually or cooperatively) is characterized by the following parameters which are determined randomly but influenced by endogenours variables:

- demand potential (y_{po}),
- initial value of demand (y(t0)) (at the time when the new product is put on the market),
- threshold value for diffusion, the 'critical mass' (y_{ts}), and
- velocity of diffusion (v).

The expectation value for the demand potential is set proportionally to the turnover of the firm and to a certain power of the amount of declarative knowledge of the firm(s) that has (have) created the new product (more precisely: to the number of knowledge domains where the firm has got knowledge).[12] The expectation values for the initial value of demand and for the critical mass are set proportionally to the demand potential. The expectation value for the diffusion velocity depends linearly on an indicator of the intensity of competition in the corresponding production sector.

The dynamics of final demand for an innovative product follows a stylized diffusion model. The final demand for this product of a given firm at the next time step $y(t+1)$ is calculated via the following difference equations that leads to a logistic increase (resp. decrease) of demand if and only if the current demand y(t) is greater (resp. smaller) than the threshold value y_{ts}:

$$y(t+1) = y(t) + v \; \frac{(y(t)-y_{ts})(y_{po}-y(t)}{y_{po}-y_{ts}} \quad \text{if } y(t) \geq y_{ts}, \tag{8}$$

$$y(t+1) = y(t) + v \; \frac{y(t)\ (y(t)-y_{ts})}{y_{ts}} \quad \text{if } y(t) y_{ts}\,. \tag{9}$$

Obviously it holds:

$$\lim_{t\to\infty} y(t) = y_{po} \quad \text{if } y(t_0) > y_{ts}\,,$$

$$\lim_{t\to\infty} y(t) = y_{ts} \quad \text{if } y(t_0) = y_{ts}\,,$$

$$\lim_{t\to\infty} y(t) = 0 \quad \text{if } y(t_0) < y_{ts}\,.$$

If a firm imitates an existing innovative product, the part of the demand potential that has not yet been exhausted at that point in time (distance A in Fig. 3) is shared equally among the imitating firm and the original innovator(s) (and previous imitators if existing).

After having been adopted by a certain fraction of all consumers and thus having reached a certain amount of demand, an innovative product may be devaluated by

[12] The background for this assumption is the positive relation between the broadness of knowledge and the firm's flexibility as regards to the demand side.

further technological process and substituted by newer innovative products (innovation vintage model). Therefore the total final demand Y(t+1) for products of the sector where innovations have been brought to the market[13] is rescaled in such a way that it grows only by a certain proportion of the total increase of demand for the current innovations. Formally, if there are r innovations in a given sector, the total increase of demand for all these innovations is

$$w(t+1) = \sum_{k=1}^{r} (y_k(t+1) - y_k(t)). \tag{10}$$

If we denote by *su* the substitution factor (a model parameter measuring the degree by which conventional products are substituted by innovative products; $0 \leq su \leq 1$), we can now define the time-dependent scaling factor sf(t) by

$$sf(t) = \frac{Y(t) + (1 - su)\, w(t+1)}{Y(t) + w(t+1)}. \tag{11}$$

Rescaling then means that the demand that each firm of this sector faces is multiplied by this same factor sf. This leads to an endogenous growth of total final demand, which is damped by a partial substitution of demand for conventional (or older innovative) products by demand for new innovative products in the same sector amounting to (1-sf)Y(t). The growth rate of final demand then comes to

$$\frac{Y(t+1) - Y(t)}{Y(t)} = \frac{(1 - su) w(t+1)}{Y(t)}. \tag{12}$$

The *inter-sectoral effects* of the diffusion of innovations are the subject matter of the third level. The sectoral final demand derived from the innovation activities in a given sector is enhanced by the intermediary commodities and services delivered by that sector to other sectors.[14] The relation between the final demand component and its intermediary components in a given sector are assumed to remain constant.[15] Hence, if there is an increase in the final demand component of that sector a proportional increase is necessary for its intermediary components. Consequently further growth is induced in sectors in which these components are produced, which in turn induces further growth (in diminishing amount) in other sectors etc.. This mechanism is an important part of the growth dynamics being effective in modern market economies.

For calculating this intersectoral dynamics we use input-/output tables (cf. Leontief 1991). These are well-known statistical accounting schemes being an obligatory part for the System of National Accounts (SNA). In such a table sectoral activities are differentiated between an intermediary component and a value added

[13] The subscript for the sector is skipped here.

[14] In developed market economies this intermediary part of the sectoral production is on average about 2/3 of the total sectoral production.

[15] How these coefficients of intermediary production can be conceptualized dynamically is an intricate question which is beyond the scope of this elaboration (cf. Pan 2006).

component. Furthermore two perspectives on the sectoral activities are integrated: the perspective of ordering (buying) and delivering (selling). For each sector the ordering and delivering activities are balanced to the same amount. The basic structure of an input/output table is depicted in Fig. 4.

4 Linking innovation dynamics and growth

The emergence of economic growth can now be explained by using this 3-level approach. In each sector a multitude of agents is adapting (in different ways) to the market competition which in turn is generated by the agents themselves. In the given context the most important option for an agent to improve his competitive position is to create novelties. Depending on the frequency of successful innovations and imitations a different diffusion dynamics in terms of increase of total demand and substitution of the demand for old products will result in each sector. Summing up the time-dependent sectoral final demand components in each time step ($Y_i(t)$) is tantamount to the total net production (net value or value added).

$$\mathrm{Y}(\mathrm{t}) = \sum_{\mathrm{i}=1}^{\mathrm{n}} \mathrm{Y}_{\mathrm{i}}(\mathrm{t}). \tag{13}$$

The gross production in each sector can be calculated by taking into account the constant structure of the intermediary production. Denoting the corresponding coefficients (i.e. the total production share of the intermediary commodity j in a given sector i) by $\mathbf{A}(\mathbf{t}) = \{a_{ij}(t)\}$ the Leontief inverse multiplied by the vector of sectoral net productions $\mathbf{Y}(\mathbf{t}) = \{Y_i(t)\}$ comes to the vector of sectoral gross production (I being the unit matrix):

$$\mathbf{X}(\mathrm{t}) = (\mathrm{I} - \mathbf{A}(\mathrm{t}))^{-1}\mathrm{Y}(\mathrm{t}). \tag{14}$$

Summing up the time dependent components of X(t) is tantamount to total gross production.

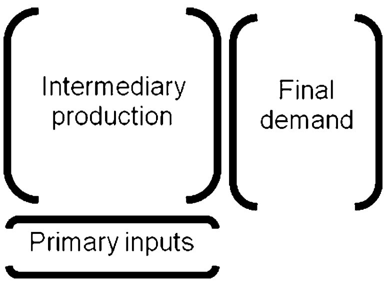

Fig. 4 Specification of inter-sectoral diffusion dynamics

In Figs. 5 and 6 the results of an exemplary run of the simulation model are shown. Here we assume an optimistic scenario leading to an increase of total production by 300% in 120 time steps (30 years) (Fig. 5, left part). In the right part of Fig. 5 the amounts for intermediary and final production as well as primary inputs of the input/out-table (cf. Fig. 4) are represented by columns. What is clearly understandable in this example is that in t=120 only about one third of total production is net production (value added). That the modes of actions (and their frequencies) at the agent level play an essential role for the growth of total production can be verified by looking at Fig. 6. In terms of the frequencies of the modes of action the system passes through a transition phase (up to about t=50) after which a pattern of moderate irregular fluctuations around an average level occur for all modes of action (routine, imitation and innovation). It is only in this second phase in which the share of firms pursuing only routines and the share of firms additionally creating novelties follows a cyclical pattern that the growth of total production increases significantly (cf. Fig. 5, left part).

To sum up, the link between novelty creation and growth is not trivial: First of all the innovation activity itself has to be triggered and has to be successful. If so, it has a primary growth effect in terms of an increased value added (final demand) in the same sector. Furthermore, the secondary effect constituted by substitution and devaluation of old products has to be included. Finally the inter-sectoral (tertiary) effects of the primary and secondary effect have to be considered for getting a comprehensive picture of the dynamics in the whole economy.

5 Driving forces and dynamics of emission impacts

The multi-level model developed in section 3 and 4 is now enhanced by including emissions. Because the main purpose here is to demonstrate the applicability of such an approach for analyzing the dynamics of environmental impacts only one exemplary emission (e.g. CO_2) is assumed. This emission is related to the level of

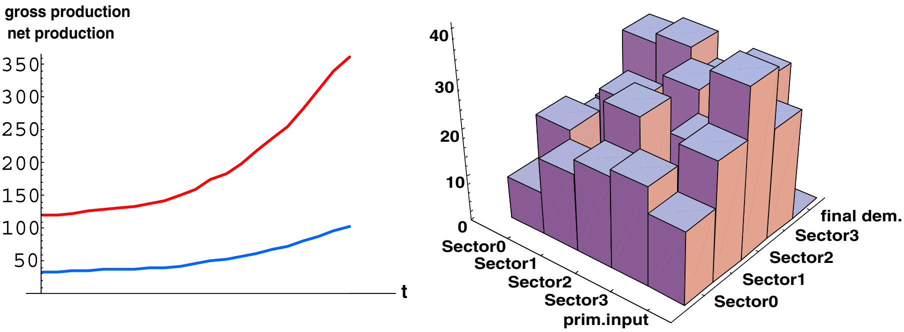

Fig. 5 Gross production over time (left) and sectoral production (input/output-table) in t=120 (right)

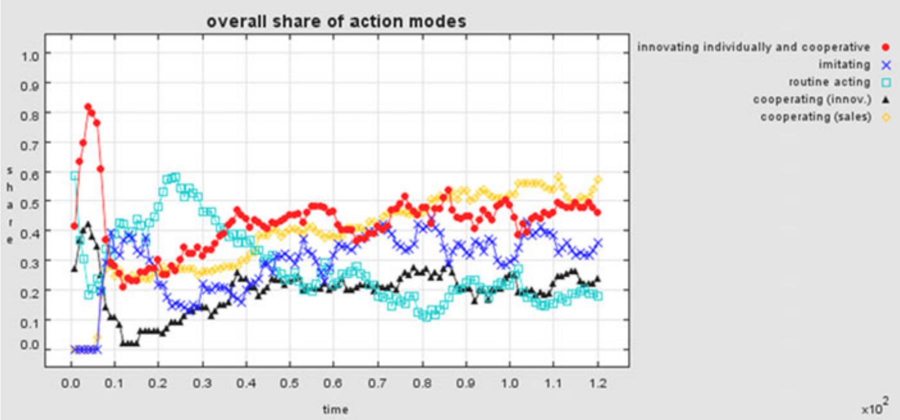

Fig. 6 Modes of action (agent-level) over time

production activity of agents.[16] To begin with, the vintage structure of our innovation model has to be explained briefly: The production activities of firm agents consist of innovative products generated by previous innovation activities in different time steps during the simulation and activities related to conventional (or old) products. This vintage structure is of importance for the dynamics of final demand as well as for the emission coefficients related to the various innovative products (see the next paragraph).

The driving forces for the internal emission dynamics can be decomposed in four different effects. *Firstly* and most importantly the type of innovation as regards emission has to be taken into account. Generally the emissions may increase or decrease as a result of innovation. This can be expressed by the time dependent development of the emission coefficient, relating the emission and amount of output in every time step. For getting an adequate idea about the internal dynamics of generating emissions the initial emission coefficient is set on an equal level for all products in all sectors. To each newly created innovative product j in some sector i, a product specific emission coefficient ($em_{i,j}$) is associated which is calculated on the basis of the current mean emission coefficient of all products in the corresponding sector and the emission reducing or increasing effect of innovation. Given this emission-increasing or emission-decreasing nature of innovation, the overall effect of innovation *secondly* depends on the speed of diffusion for the innovated product under consideration. This diffusion effect is tantamount to the time-dependent increase in the share of the innovated product on the corresponding market. Closely related to this growth effect of diffusion is *thirdly* the substitution effect, i.e. the replacement of old products by new ones[17] on the level of final demand. *Fourthly*, every sector is producing intermediary commodities, i.e. commodities not determined to meet the final demand but to be an input for production in other sectors. That part of the intermediary commodities delivered by innovating firms is also shaped by the vintage structure: It is assumed that

[16] This activity level is measured in value terms because price fluctuations are not dealt with in the model.
[17] This means that conventional products as well as older innovative products are substituted by newer innovative products.

the emission coefficients for these intermediary commodities follow the same dynamics as the mean emission coefficient for all final products; in other words, the same emission coefficient is valid for the total gross production in the sector and not only for the mean of innovative products for the consumer market.

The total emission in a given time step and a given sector and of the economy can be determined by taking these four effects into account and summing up over all innovative and conventional[18] products:

$$\mathrm{em_i(t)} = \frac{\mathrm{em_i(t-1)Y_{i,old}} + \sum_{j=1}^{P_i(t)} \mathrm{em_{i,j}\ Y_{i,j}(t)}}{\mathrm{Y_{i,total}}} \tag{15}$$

where $P_j(t)$ denotes the number of innovative products in sector i that are on the market in time step t.

The overall emission in the time step and sector under consideration then amounts to:

$$\mathrm{Em_i(t) = em_i(t)X_i(t).} \tag{16}$$

Two of these effects shall be considered more closely: the type of innovation and the velocity of the diffusion v (a model parameter, cf. section 3 (4)) of given innovations. The former is determined by the model parameter M (change factor of emission coefficient) which co-determines the emission coefficient for an innovative product created in time step t:[19]

$$\mathrm{em_{i,j}(t) = M\, em_i(t-1).} \tag{17}$$

In order to illustrate the influence of these two crucial parameters, we are going to analyze the dynamics of the emissions for three exemplary cases: (i) the overall growth case (M>1, v is high), (ii) the case with decreasing emission and fast diffusion (M<1, v is high), and (iii) the case with decreasing emission and slow diffusion (M<1, v is low).

From an environmental point of view *case (i)* is the worst case. It may represent all economic constellations related to a narrow-minded promotion of economic growth by supporting innovation. Figure 7 depicts a simulation result for such a case. It is assumed that M=1,15 i.e. if an innovation is triggered on the agent level (cf. section 2 (3)) the amount of emissions (related to the same amount of output) is increasing by 15%. Due to the strong innovation dynamics documented in the upper left part of Fig. 7 in about 100 time steps almost all initial products are substituted by products derived from innovations. Hence, generally the emission coefficients are increasing in all sectors although the spreading of this increase among sectors indicates a comparatively different innovation dynamics in the different sectors

[18] The final demand for conventional products is treated 'amorphously' in our model, i.e. we do not distinguish single conventional products; rather we treat this part of final demand as if there is only one conventional product in each sector.

[19] In the debate on decarbonisation the reduction of emissions is only dealt with in terms of technological potentials. How these potentials are transformed into technologies of market agents by means of competition and environmental instruments remains rather vague in this analysis. But even given these instruments the overall effect on emissions depends on the assumption about the growth of GDP which is treated as a separated issue (cf. Green et al. 2007).

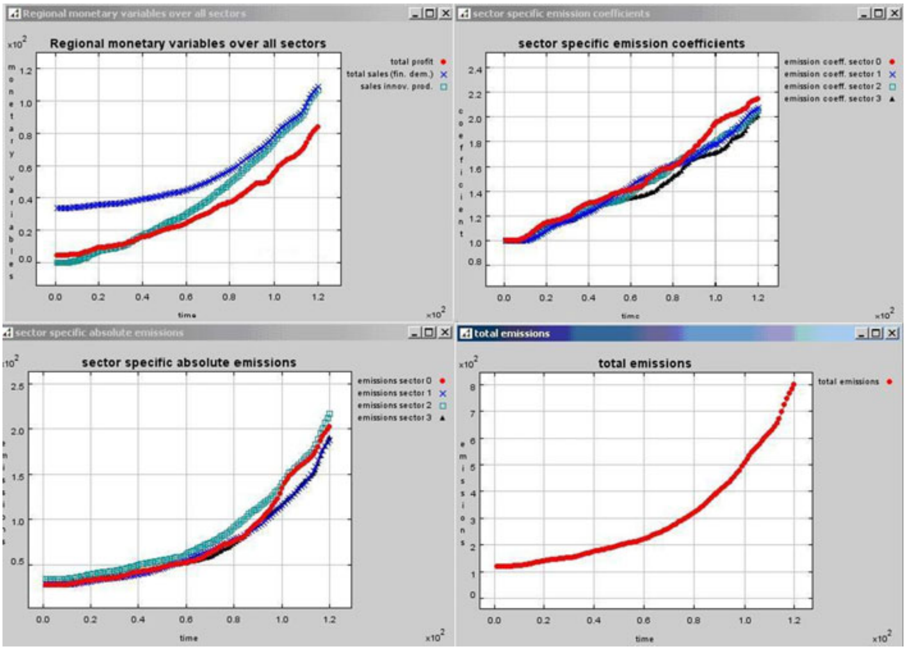

Fig. 7 Case (i) for growth dynamics

(upper right part of Fig. 7). Due to the time-dependent intersectoral effects determining the size of a given sector, the innovation frequency and its effect on final demand alone is not sufficient for deriving the relative share of the sectoral contributions to the emissions. As can be seen from the lower left part of Fig. 7 sector 1 being dominant in terms of innovation frequency almost for the whole time span is only in the last third part of the time span increasing its relative share of emissions. The lower right part of Fig. 7 depicts the time-dependent development of the overall emissions. Not surprisingly they are increasing in an exponential manner (increase of about 800% in 120 time steps, i.e. 30 years).

More representative for the developed market economies might be *case (ii)*. Whereas the optimistic assumptions about the diffusion dynamics remained unchanged compared with case (i), it is assumed now that M=0.85. This means that there are boundary conditions given, guaranteeing that in the case of an innovation the level of emissions is reduced by 15% (i.e. to 85% of the previous level). What is interesting in simulating this case is *firstly* an almost stable difference in terms of emissions in the different sectors (cf. lower left part of Fig. 8). *Secondly*, and even more important is that the sectoral as well as the total emission development has essentially two phases: In the first phase (from $t=11$ to $t=45$) after the initial (transient) phase,[20] the emissions are slightly decreasing. This is

[20] In the initial phase (until about $t=10$) the model is swinging in: The first innovative products have to be developed (which is time-consuming) before they can be put on the market, and their diffusion starts only slowly. Therefore the nearly constant level of final demand and emissions in this transient phase rather constitutes an artefact of the model.

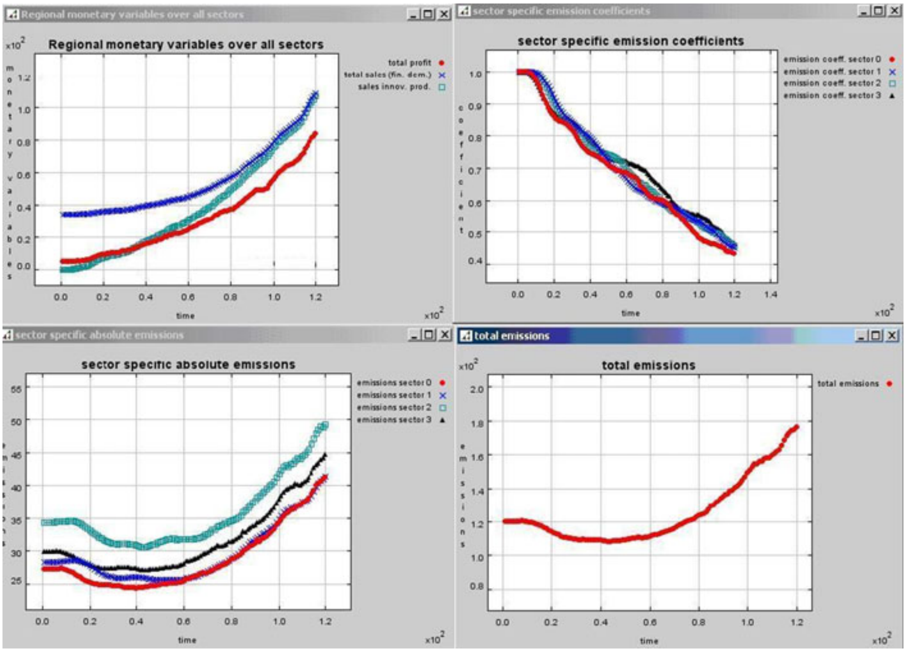

Fig. 8 Case (ii) for growth dynamics

tantamount to a dominating innovation effect and the corresponding substitution processes of new for old products. Contrary to that, in the second phase (*t*>45) of the emission dynamics things are reversing in that now the growth effect of innovation and the corresponding intersectoral effects are becoming superior (cf. lower parts of Fig. 8). This is a specific variant of the so-called rebound effect often observable in modern market economies (cf. Sorrell 2007).[21] Hence, it may be concluded that in the long run the rate of emission abatement on the agent level mentioned above is not sufficient for guaranteeing a sustainable reduction of the total amount of emissions.

Finally *case (iii)* might be used as an approach to the effect of economic crisis and stagnation. It is assumed that the boundary conditions in favor of emission abatement still persist but that the diffusion dynamics is hampered due to a catastrophic jump in the critical mass the overcoming of which is necessary for a successful (self-enforcing) diffusion of new commodities.[22] Considering the monetary aggregates (upper left part of Fig. 9) there are three phases: moderate growth dynamics until the crisis is occurring (*t*<60), the stagnation after the blocking of diffusion and finally—due to a massive exit of firms suffering from their bad economic performance—the crisis manifesting itself as a reduction of final demand and correspondingly as the stagnating share of innovative commodities. Due

[21] In the given case the rebound effect has a direct component resulting from the increasing attractiveness of innovative products for their appliers and an indirect component resulting from intersectoral interdependencies. These two components are normally not taken into account because the focus is on cost reduction in a given sector.

[22] y_{ts} is increased from 0.02 to 0.5 for *t*>60 (Cf. section 3 (4)).

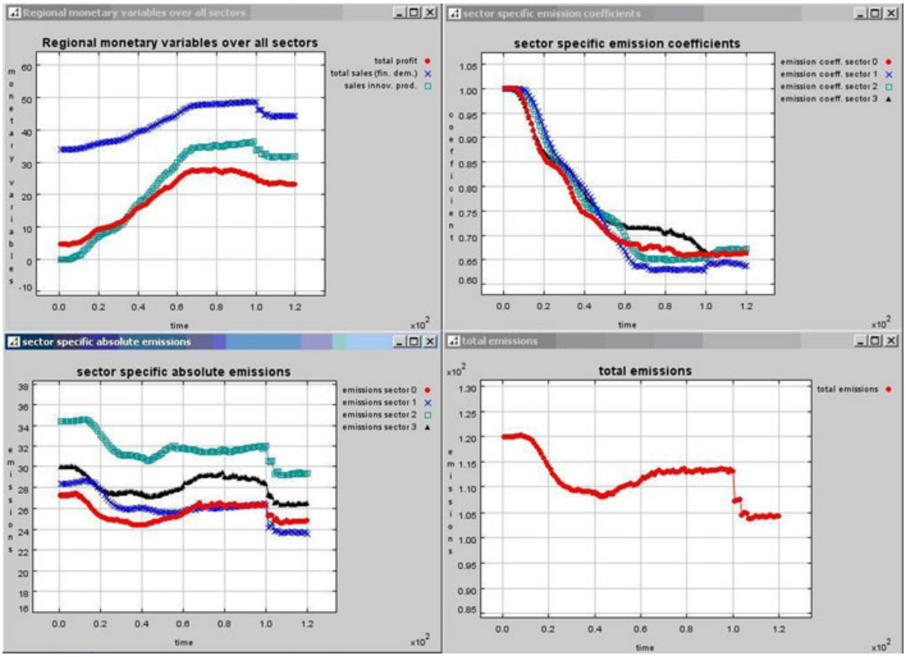

Fig. 9 Case (iv) for growth dynamics

to moderate growth effects in the first phase on one side and the ongoing of abatement activities on the other side the substitution effect of innovations dominates the growth effect and the emissions in all sectors are decreasing. Before this is reversed and the rebound effect can become effective (as in case (ii) above) the stagnation occurs and due to the blocked growth dynamics as well as due to the negative feedback of the economic performance on further innovation activities the amount of emissions remains about constant in all sectors (cf. lower left part of Fig. 9). Corresponding to that the innovation-dependent abatement activities are abruptly reduced in all sectors (though they differ in the starting point and the speed of this reduction) (cf. upper right part of Fig. 9). Finally, innovation activities come to a halt, firms are exiting and the total amount of emissions is drastically reduced in the crisis proper ($t > 100$; cf. lower left part of Fig. 9). Hence, our simulation results indicate that even in a regime of abatement activities of firms economic stagnation and crisis are the only self-organized mechanism to circumvent the rebound effect by stabilizing or even lowering emissions.

6 Redirecting innovations as a regulatory option?

The simulations in the previous section manifest that the emission dynamics is strongly influenced by a market induced innovation dynamics which is more or less given in all developed market economies. The core of this dynamics is determined by a self-organized process in which behavioral states and constellations of market competition are related to each other triggering different modes of action one of which is novelty creation. Due to the difficulty to anticipate the time dependent frequency of these modes of action, due to the unpredictable outcome of individual novelty creating endeavors, and due to unknown social acceptance of these outcomes (in terms of diffusion) there is no possibility to assess or even to plan such a process in advance. Rather it necessitates to confine political influence or regulation to a trial and error perspective.[23] Nevertheless the exemplary simulation analysis given above shows that any kind of political regulation has to face an innovation dilemma: If innovation is successful on the individual as well as on the social level there is a high probability that it generates growth and if it generates growth, it generates additional emissions. The only self-organized way to circumvent this dilemma seems to be economic stagnation and crisis.

Against this background three general options for regulation can be distinguished: (i) blocking the core of the innovation dynamics, (ii) fostering differentiation in favor of establishing environmental benign technologies as well as products and (iii) redirecting the innovation dynamics. Option (i) seems to be unfeasible in that it is incompatible with a given market and competition environment. Option (ii) is often pursued by political authorities but faces the problem of establishing and protecting a niche or—to take it the other way round—it is confronted with the constraints of path dependencies (cf. Nill 2009). Due to these constraints for options (i) and (ii) the following discussion focuses on option (iii). Without going into the details of an instrumental debate it is assumed that regulatory authorities are willing and firms are able to implement a predefined path of reducing emissions. This is more specific than the usual framing of the problem to reduce emissions (e.g. in the debate about climate research) in that economic agents as the main subject of these policy options are explicitly taken into account.

The first regulatory regime to analyze more closely is a short term dynamic *incremental dynamic abatement* of emissions. Setting the initial change factor of emission coefficient to 95% (i.e. in the beginning of the simulation, when creating an innovative product, a firm has to reduce the emissions per produced unit by 5% compared to the mean emission factor of the branch) the innovating firms have to comply with the obligation of reducing this change factor of emission coefficient (model parameter M; cf. section 5 (2)) by further 5% every 20 time steps (5 years). This means that the speed of technological progress in terms of the reduction of emission factors is accelerated more and more over the whole simulation. This regime is depicted in Fig. 10.

In formal terms this means

$$\mathrm{M(t) = 0.95\ for\ t < 20, M(t+20) = M(t) - 0.05\ for\ all\ t.} \qquad (18)$$

Figure 11 indicates that it is not before $t=100$ (i.e. only after 5 regulation periods) that the emissions in two of the four sectors start to be reduced leading to an overall

[23] For a specification of this perspective of political regulation cf. Kemp and Zundel 2007 and Beckenbach 2007.

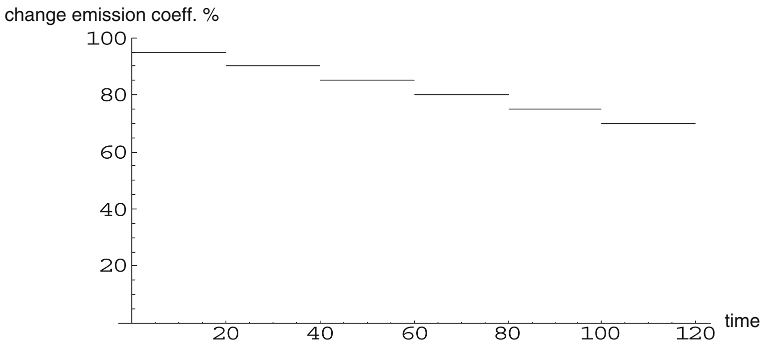

Fig. 10 Incremental dynamic abatement regime

stagnation of the emissions (cf. Fig. 11, lower part). Hence, it can be concluded that this incremental dynamic abatement regime is inappropriate for meeting emission reducing targets. Therefore it seems necessary to take more *radical dynamic abatement* regimes into account. Because the firms need at least more time for conforming to this more ambitious target the regulatory time span has to be longer than in the case of incremental dynamic abatement.

In the second regulatory regime the obligation for innovating firms is to reduce the change factor of emission coefficient by 15% every 40 time

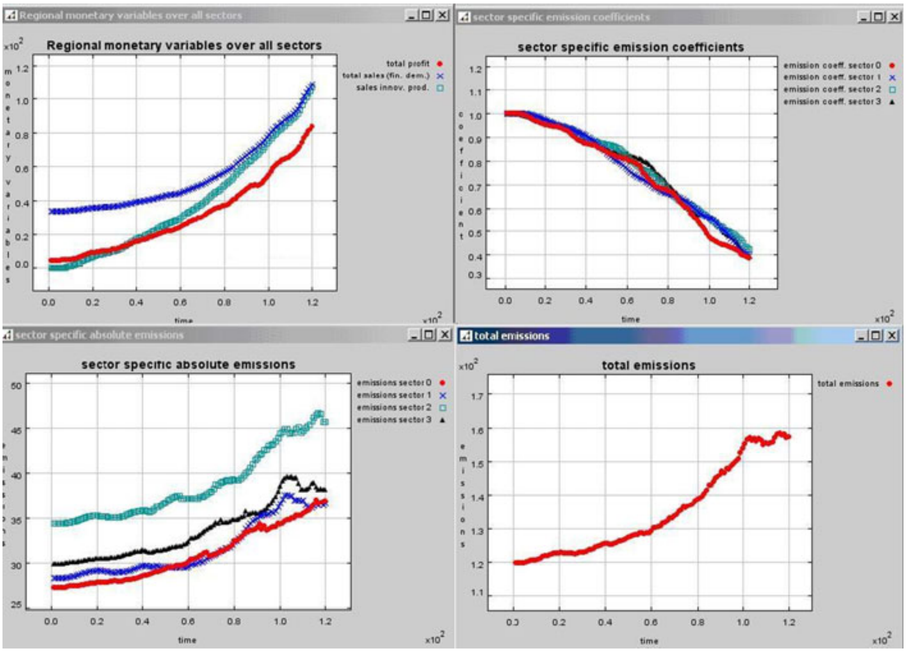

Fig. 11 Growth dynamics with incremental dynamic abatement regime

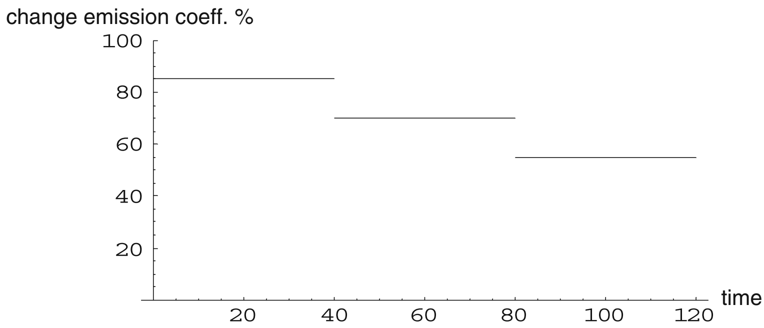

Fig. 12 Radical dynamic abatement regime

steps, i.e. 10 years (cf. Fig. 12), beginning with 85%. In formal terms this means:

$$\mathrm{M(t) = 0.85\ for\ t < 20, M(t + 20) = M(t) - 0.15\ for\ all\ t.} \tag{19}$$

As can be seen from Fig. 13 it is only in this strong abatement regime that emission targets similar to those politically defined in the climate change debate can be met (25% reduction of absolute emissions in 30 years). Comparing the upper right part with the lower left part of Fig. 13 it can be deduced that not only the

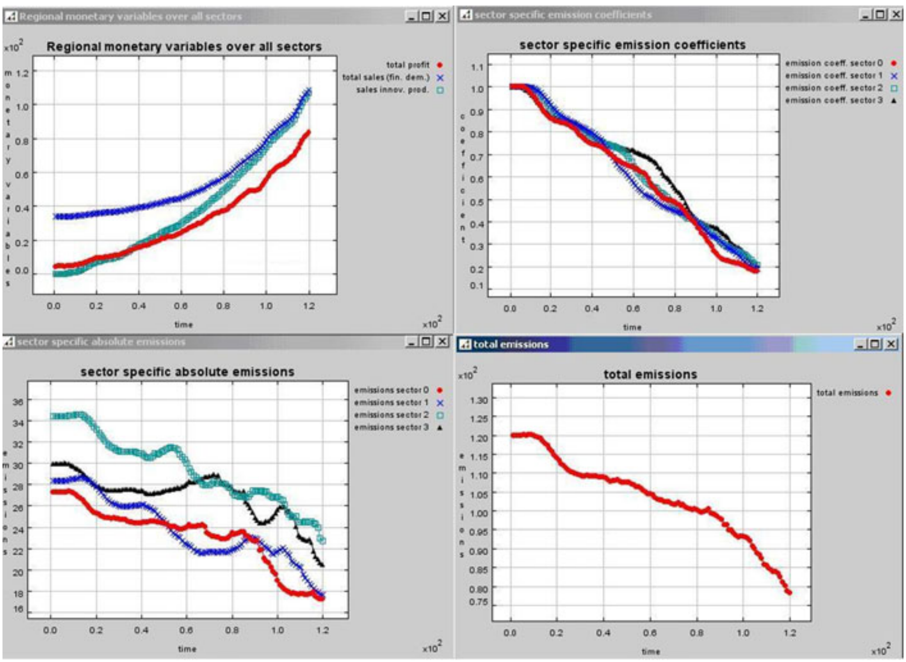

Fig. 13 Growth dynamics with radical abatement regime

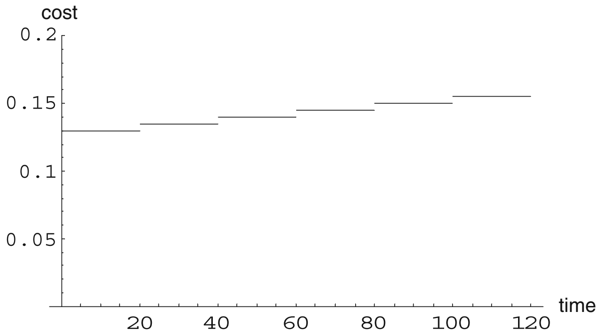

Fig. 14 Costs of innovation in the incremental dynamic abatement regime

innovation dynamics is influencing the sectoral amount of emissions but also the intersectoral dynamics modifying the emission related ranking of the sectors as regards emission coefficients.

This clear-cut picture of needing a radical abatement regime for innovating agents to comply with given social emission targets is modified if the implicit assumption so far that the abatement comes as a free joint product of innovation is given up. Picking up the case of incremental dynamic abatement again it is now additionally assumed that the *costs of abatement* are increasing linearly with the amount of reduced emissions (starting from the default level of 0.125 there is an increase of 0.005 in every regulation period; cf. Fig. 14). These costs are considered as a part of the innovation costs.

What is obvious from Fig. 15 is *firstly*, that the frequency of innovations is reduced[24] and therefore the growth of final demand is damped (cf. Fig. 15, upper left part). *Secondly*, the spreading of the innovation frequencies between sectors in $t>40$ is more distinct than in the case without cost increase (cf. Fig. 11, right upper part in comparison to Fig. 15, right upper part). *Thirdly*, the higher volatility of the behavioral innovation force (cf. above) opens up the possibility for synchronous jumps in innovation activities in different sectors (as it is the case in $t>70$) leading to a temporary abrupt reduction of emissions before the growth effect is dominating again (cf. Fig. 15, lower part). Here again the innovation dilemma mentioned above becomes obvious: it is only if the innovation dynamics is effectively damped by cost effects that the occurrence of the emission increasing rebound effect can be avoided.

The simulation runs suggest that only a radical abatement regime with moderate additional costs is appropriate to meet emission targets as proposed in the debate on climate change. Looking at the reality of technological development on one side and of the slow dynamics of environmental policy on the other side one has to be skeptical about the technological as well as political feasibility of such a radical regime. In both cases the problem of path-dependency will be an important issue. Hence, a more realistic alternative seems to be either to face significant abatement costs (in economic as well as political terms) bearing the risk of letting the innovation process stagnate or to confine oneself to an incremental dynamic abatement regime being in danger of not meeting required emission targets. What is

[24] The reason fort hat is that the increase of innovation costs is reducing the relative force toward innovation on the agent level (cf. above) Eq. 7.

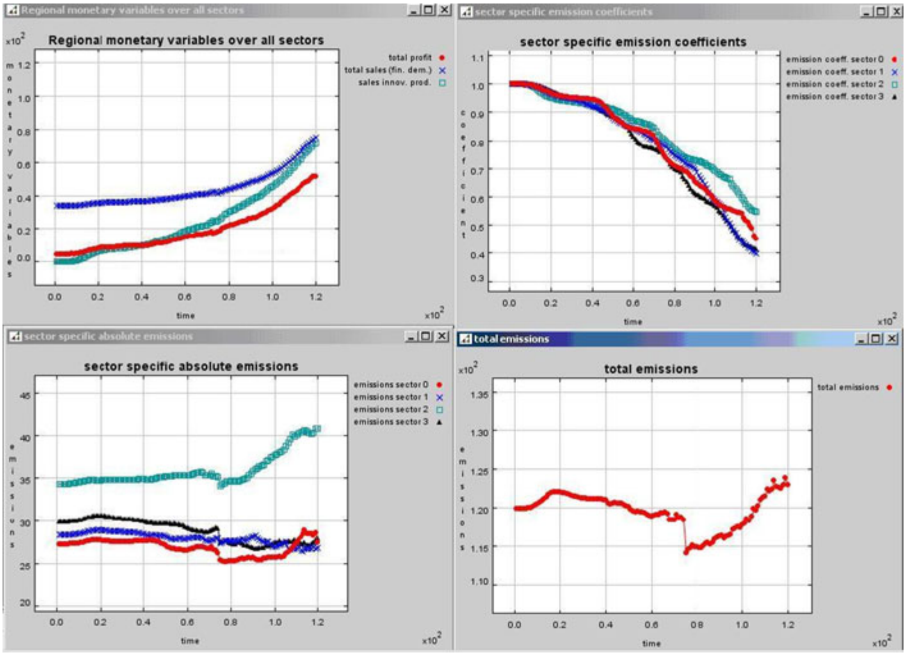

Fig. 15 Growth dynamics with incremental abatement regime and increasing abatement costs

obvious here is a double regulation dilemma: Implementing innovation and generating growth are features of a self-organized economic process which cannot be predicted and influenced precisely; but if regulation does not prescribe ambitious emission reduction targets, innovation will imply growth which could overcompensate emission reductions associated with the single innovation project.

Whatever the regulatory options are, the multi-agent model indicates that only imposing emission targets is not sufficient. Rather it is necessary to figure out abatement paths by taking into account the agents, the context they are operating in, and the time scale for regulations. Furthermore: because there are different paths for fulfilling (or missing) a target it is necessary to select a path, to update the achievements, and—if necessary—to adapt the path features to the new experience. In this sense policy should be conceptualized as a part of a broader complex adaptive system.

7 Conclusions

Emissions are coupled to innovation and growth in a complicated manner. The direction of innovation, the velocity of diffusion and the dependencies between sectors have been shown as the main sources for this complication. For shedding light on these relations the economy was conceptualized a ‘complex adaptive system’ having diffusion, growth and emissions as ‘emergent properties’. To distinguish different but related levels of activities and especially to include an agent-based analysis of the dynamics on the micro-level are essential features of such an approach.

By using such a framework it is possible to bring more conceptual realism into economic models without losing the required property of computability. In this contribution it is suggested to specify bounded rational agents by picking up insights of modern behavioral research. The agent's ability to act is given in terms of different modes of action the selection of which depends on behavioral and competitive conditions the agents themselves are generating. Novelty creation (i.e. innovation and imitation) is one mode of action being triggered endogenously in the model. Hence, innovation and imitation are explained endogenously. This is the basis for reconstructing the dynamics of economic aggregates without referring to representative agencies and optimizing activities.

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