Interacting with complex systems: models and games for a sustainable economy

Background Studies

Netherlands Environmental Assessment Agency

Interacting with complex systems: models and games for a sustainable economy

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Interacting with complex systems: models and games for a sustainable economy

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Contents

Summary

This Report is one of the deliverables of the Global System Dynamics and Policies (GSD) Project (www.globalsystemdynamics.eu) which is coordinated and funded by the Future & Emerging Technologies Division of the European Commission (Work Package 3: Appendix A). Chapter 1 provides an introduction to economic growth models in the context of macro problems such as resource depletion and ecosystem degradation. The first Chapter examines the standard 'textbook' models within the larger framework of different worldviews and the various ways in which these models can be improved.

In Chapter 2 we provide the reader with an overview of the literature on Complex Systems Science (CSS) in the search for better 'elementary models for a sustainable economy' – which was the title used for a workshop held in Utrecht in January 2010 (Appendix B). This overview is in fact biased as it is largely based on the contributions of workshop participants. It contains brief descriptions of economic growth engine models, supply-demand mechanisms at micro-level, evolutionary economics models, generalised utility function formulations, income distribution mechanisms, agent-based models of economic behaviour, energy and knowledge as production factors and the incorporation of catastrophic regime shifts and provision of services in ecosystems. The description of this rapidly growing field is, of course, incomplete.

In subsequent chapters we describe some research done in the context of the GSD project. We first report on the SusClime model, which has been used to explore the role of decision making rules in the transition to renewable (non-carbon) energy sources to offset natural resource depletion and climate change. This has led to the use of a model in which utility-maximising strategies are simulated in a world of finite oil reserves and climate change. The utility loss for a competitive strategy (where each region optimises for itself) is compared against a cooperative strategy (where a central planner optimises) and is shown for a set of modelling experiments. Strengthening the science-policy interface is partly a matter of legitimacy – hence the importance of simple, interactive models and simulation games about (the perception of) macro-problems. In the last chapter a brief description is given of an MSc research project done on the perception and behaviour of climate change risks under uncertainty.

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Although contributions have come from many sides, the final responsibility of this Report is mine. The views and insights presented are mine and are not those of any of the supporting institutes. I have not been meticulous in the use of *I* or *we*, as the reader may notice, but I have been careful in proper referencing. I hope that this Report will be a contribution to this topic and that the complex world around you may never be the same again after reading it.

Bert de Vries

1

Modelling economic growth

'Society currently faces a set of new challenges that are both global in scale and highly dynamic. Examples are: climate change, energy security, globalisation of the economy and communication, living standard inequalities with associated potential for conflicts, and the spread of new diseases such as HIV.' (GSD, 2008:3)

1.1 Introduction

'The modern economy is structurally reliant on economic growth for its stability.' (Jackson 2008:14).

Recently, an editorial comment in a Dutch newspaper stated that *'Healthy economic growth is the best way to relieve the debt burden. Whatever the other considerations are, this should be a short-term priority.'*. I have frequently heard the argument that the unemployment rate is related to economic growth. Now, in spring 2010, the debts which result from the pro-growth financial policies of the last decade have become the argument. The same newspaper had as its headline on 2 february 2007: the Dutch Central Bureau of Statistics (CBS) announced that 2006 had been an excellent year for the economy *"... with a growth of 2,9%...The growth in 2006 is however smaller than the 3,25% which the cabinet used as its starting point in its Miljoenennota... Germany announced this morning 2,7% over 2006 and France 2%. The Dutch economy may in the fourth quarter have been affected negatively by the very mild autumn. This caused a lower demand for natural gas by consumers and the energy sector therefore contributed less to the growth."* This article highlights at least three phenomena: the government (always) expects higher growth, a country sees itself in competition with others, and less energy use is bad for economic growth. As a third example: numerous are the newspaper items which state *"economic growth is good for the environment"* – as if growth-enhancing expenditures to combat pollution among the rich and more physical production to satisfy basic needs of the poorest are comparable.

All these are symptoms of the fundamental dilemma which is aptly described by Tim Jackson in his book *Prosperity without Growth* (2008): with growth there are boundaries and feedback of a finite earth, without growth there are risks of social instability – this represents a genuine quandary for governments. Or, as explained by one of the pioneers of complex systems thinking, Jantsch, in his book *The Self-Organising Universe* (1980): human social and economic systems are like *'somebody who is struggling not to fall forward and can only prevent this by walking forward'*[i]. Whatever the arguments are, the word 'crisis' has become closely intertwined with the issues of economic prosperity and growth.

Reading a textbook on economic growth gives us a very contrasting impression. *'Over the past two decades, Economic Growth has re-emerged as an independent field'* writes the author David Weil in the preface of one of the more recent, better-known economic textbooks on the subject[ii]. In line with scientific specialisation – and fragmentation – this branch of economic science focuses on why some countries are richer than others, and why some countries grow more quickly than others. This book makes it clear that 'modern economic growth theory' as usually explained in textbooks, is weak in concept, and does not provide strong links with observed and constructed 'data'.[iii]

In essence, the standard economic growth model consists of two positive feedback loops – in population and capital – and substitution between factors of production. Usually, the production factors are capital (K) and labour (L). To increase the explanatory power of the model at the level of country output and income (growth) data, corrections are made to the statistically constructed values of K and L. Innovation is incorporated into the model as an exogenous increase of factor productivity and of trade and knowledge transfer between countries. The outcome is a set of highly aggregate equations which correlate with important and well-known economic indicators such as output and income (growth).

However, it is difficult to find good descriptions and explanations of many of the real world phenomena. What about the financial crisis, the risks of climate change and epidemics, the resource scarcity conflicts, the income gap, the 'failed state' and corruption, the globalising crime and illegal trade? They are not part of the theory, it may be argued, because these phenomena are mere ripples on the continuation of the post-war path of exponential growth in output and income[iv]. Is it possible to abstract away from such phenomena. This is obviously incorrect for relatively slow and long-term processes such as climate change and resource depletion. But it may also be incorrect for many of the relatively fast and short-term processes, such as water use conflicts or institutional failures, because these may be connected in complex ways to the long-term as cause and consequence. And it obscures the analysis of the role of technology, with stochastic and irreversible events leading to contingent pathways: *'history matters'*.

1.2 The mystery of economic growth

'It is not self-evident that economists should construct models of economic growth; far less that they should construct more and more complicated models of economic growth.' (Mirrlees, quoted in Jones 1976:9).

The dynamics of human populations are relatively well understood (e.g. the demographic PHOENIX-model: http://www.pbl.nl/en/themasites/phoenix/index.html). There are of course still unresolved issues, for which adequate mechanisms and data are lacking – for instance, the drivers of urban-rural and international migration. Population dynamics is fairly well described and modelled as compared to the dynamics of economic growth, although interactions between demographic and economic processes are still not well understood (see e.g. GISMO-model: http://www.pbl.nl/en/themasites/gismo/index.html). A good example is the linkages between fertility and mortality, and expenditure on, and organisation of, health and educational services. In this chapter, our focus is on the theories and models of economic growth and development *per se*.

The economist Helpman in his book *The Mystery of Economic Growth* (2004) addresses the issues that make some countries rich and others poor, by summarising what economists have come up with in the form of hypotheses and explanations. In the twentieth century, economists have identified the *accumulation of physical capital* as the major force behind income growth, while technological change was considered to be an exogenous process. According to the neo-classical growth model, the economic growth rate should in the long term converge to the rate of technological progress and, secondly, the per capita income growth rate should be lower for higher capital-labour ratios. There is no doubt that capital accumulation and capital-labour substitution has played an important role in economic growth. In agriculture, for instance, it was one of the dynamic factors behind expanding output and trade – and it is still an important mechanism in low-income regions. Unfortunately, time-series and cross-country analyses for economic growth in the industrial economies of the twentieth century suggest that the observed accumulation of physical capital (a rising capital-labour ratio k=K/L) can only explain half or less of the observed output growth. Similarly global income convergence is not borne out by the facts. These shortcomings have been acknowledged for half a century, with 'technology' appearing as the explanatory *deus ex machina*.

It is customary to equate technological progress to the change in *total factor productivity* (TFP), assuming no corrections for factor productivity. Almost two-thirds of income variation is explained by differences in TFP. What drives TFP? Several determinants are involved: investments in education which affect labour skills and productivity, research and development (R&D) expenditures etc. If we include the factors which augment productivity, such as education of labourers and quality improvement in capital goods for example, there is still a significant part of economic growth and the income gap which remains unexplained (Helpman 2004). It may well be that – hardly predictable – long waves of general purpose technologies (GPT) are more important for long-term TFP changes than the processes of incremental innovations.

As mentioned earlier, the empirical finding is that more than half of the variations in income (growth) across countries must be assigned to changes in TFP. Since the 1980s there has been much interest in the role of *science-based technology*. Using data from the 1800s onwards, it has been shown that the accumulation of knowledge has important positive externalities for an economy. This occurs in various forms, represented by for instance a learning-by-doing mechanism and an average *human capital* stock of aggregate skills. The latter has been correlated to education levels, but this suggests an upper limit and thus cannot feed long-term growth. The focus subsequently shifted to innovation, in particular investments into R&D, scale effects and GPT such as the steam engine, electricity and the computer. Patenting is an important channel of technological diffusion. Scale effects tend to be positive despite the risk of crowding into R&D activity, and improvement in products along quality ladders and GPTs explain part of the cycles in GDP growth. Yet there are still no definitive answers for the large variation and divergence in the levels of income and growth globally.

The economic literature indicates trade, inequality, and institutions and politics as alternative possible explanations for output growth. *Trade* flows have increased with successive waves of globalisation and have become more complex. A review of the findings on the role of trade suggests that the terms of trade adjustments may stimulate convergence when it reflects diminishing returns in large countries – but it may be only one of several mechanisms. Aggregate analyses suggest that more open economies tend to have higher growth rates – and rich countries appear to benefit most (Helpman 2004:85). Another important transmission channel for economic growth is the international spillover of R&D investments through learning-by-doing. The actual outcome depends on the size of countries and their intrinsic productivity levels and learning speeds, with the possibility of lock-in from initial conditions. In the 'new' growth theory, this has been elaborated with concepts such as the impact of R&D on a range of products and on the stock of knowledge. Again, there are several simultaneous forces at work the net effect of which may be a divergence in income. *'In theory, trade can encourage or discourage the growth of income per capita.'* is a summary conclusion (Helpman 2004:69).

There are indications that protectionism played a role in promoting economic growth before World War I, while protection resulted in decreased growth rates after World War II. In addition it was found that the size of the R&D capital stocks of trade partners tended to impact positively on a country's TFP – this is one of the mechanisms behind growth in low-income countries *and* behind the widening North-South income gap. Such econometric findings only represent average impacts across countries, not particular mechanisms. Evidently, trade flows represent a series of other post-World War II trends, such as:

- continuous decline of transport cost per unit value;
- increasing mobility and transfer of capital and knowledge as well as labour;
- shifting resource supply-demand patterns and technologies;
- a structural shift in economies away from agriculture towards industrial and manufacturing and at higher incomes, towards formal service sector activities.

Economic growth theory and models have little to say about *income inequality*, either as a cause or as a consequence of economic growth. The conventional view was that wealth would 'trickle down' from the richer to the poorer strata of society, in line with the 'Kuznets curve' which suggests an inverted U-shape of inequality as a function of income (Kuznets 1955). However, the measured effects of growth on the poorest segments of society are controversial. Many results seem to confirm the adage 'the winner takes it all'. Most people would agree that there is an 'optimum' income inequality, when the incentive to take risks and create wealth is in balance with the fairness needed for citizens' compliance.

One of the other, less tangible phenomena is *institutions and politics* – can it explain the growing income and wealth differences within and between countries? Economic historians have recently emphasised the role of efficient institutions, such as legal protection of property and transparency in markets in the onset of economic growth in Europe[v]. The functioning of producers and consumers in markets is only possible if a government provides certain goods and services, such as defence against enemies and civil rights and their protection ('public goods'). Adequate provision of education and health services require (public) institutions. All of these are part of a society's infrastructure in a broad sense.

Another determinant of economic growth is *infrastructure*. The construction and maintenance of canals, railways and roads, and the provision of public utilities such as electricity and water are considered 'natural monopolies'. For reasons of fairness or cost, they use to be provided by governments– but the neo-liberal trend of the last decades has led to deregulation and privatisation in the public domain, with the argument that competition would lead to more efficiency and lower costs. Infrastructure in the form of public goods and services is essential for economic prosperity – and is present only in highly abstract form or absent altogether in most macro-economic models[vi].

Whereas the positive externalities (or 'economies') of science and innovation are widely acknowledged and used in formal growth models, negative externalities (or 'diseconomies') also need attention. Some of these are gradually incorporated in formal growth models, notably the dynamics of *resource depletion* and *environmental degradation*. Indeed, incorporating such externalities into macro-economic models and policies is at the core of resource and environmental economics.

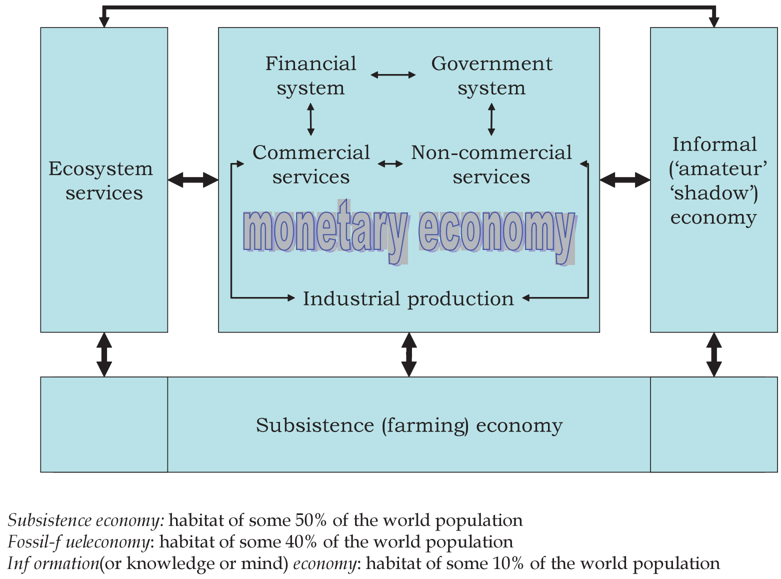
Nevertheless, most aspects of depletion and degradation are absent in macro-economic growth models, and usually only the increasing cost of resource exploitation and pollution abatement are considered.

According to the behavioural economist Day, the increasing *complexity* of planning, communicating and coordinating is another 'internal diseconomy' which yields diminishing returns to the population within an economy in absolute terms (Day 2004:182). A corollary to this observation is that 'an economy's technology can only be effective if a part of the population forms a social infrastructure upon which the use of a given technology depends' (Day 2004:183). In other words, a viable economy is based on a strong infrastructure and the associated administrative technology. Unfortunately, these questions far exceed the realm of economic science. The answers are mostly stylised fact type correlations, hypotheses, speculations and anecdotes, and there is no theoretical basis for their incorporation in formal models[vii].

The overall impression is that mainstream economic science, despite all the impressive formulae, is unable to provide 'laws' which explain or 'models' which incorporate the key determinants of economic activity and growth. A lot of improvements have been proposed within the neo-classical framework, such as the New Growth Theory (NGT-technical change, increasing returns) and the Real Business Cycle (RBC-external technical change shocks). Most of these are not based on mainstream economic science – see for instance Barro and Sala-i-Martin (2003), Aghion and Durlauf (2005), Greiner *et al.* (2006) and Scrieciu (2007). In this Report I will neither discuss nor judge these theories. Instead, I will focus on the growing amount of interdisciplinary research which examines the foundations of micro- and macro-economic theory and on new concepts, theories and models which are closer to observations and facts in an increasingly complex and global network of interactions. Of course, many of these emerged because of discontent with prevailing mainstream theory, and in particular with the invocation of equilibrium states and the isolated and rational *homo economicus*.

Some shortcomings of prevailing theories and models at the level of everyday phenomena can indicate in which direction we should search for improvements:

- lack of short-term dynamic processes (e.g. stock markets, innovation processes, media influences) and their potential impact on long-term system dynamics;
- no proper account of the role of ICT and the emergence of commercial and non-commercial services as the major source of employment[viii];
- almost exclusively market-based activities, hence there is not much to say about informal activities (e.g. in subsistence settlements and voluntary and illegal activities) and government regulations and interventions;
- lack of long-term infrastructure investments (rail, road, electricity/gas networks, internet) and their role in economic dynamics (inertia);
- lack of explicit consideration of institutions such as (inter) national governments, the (global) financial sector, non-governmental organisations (NGOs), and their role in the pursuit of economic growth;



Scheme of mainstream economic theory and its peripheries.

- weak or absence of coupling of economic with ecosystem dynamics and the complex responses (thresholds, cusps) of resource exploitation that result.

The quest for improvements is urgent because these shortcomings are present in many of the economic forecast models used in government and business, including macro-economic models to assess climate change impacts (Appendix D). Some authors have already discussed these shortcomings and proposed complex system insights as a complementary or alternative theory (see e.g. Ormerod 1998, Beinhocker 2005).

The scheme in Figure 1.1 is an attempt to sketch the full arena of economic activities. The lower part of the central box represents macro-economic theories and models of the motenid economy and the upper part represents governments and financial and other institutions, which is hardly dealt with other than as part of the monetary service economy. The bottom box represents the 2 to 3 billion people who still live in poverty; they tend to be neglected because their role in the monetary economy is relatively minor. The box to the right indicates the informal economy, where a variety of (legal and illegal) activities take place, but which is not usually considered in economic statistics. It is also neglected as a potential reservoir of meaningful employment. Finally, the box to the left encompasses all the other blocks as it is society's life-support system. In the economic context, it represents the resources in the broadest sense. In other words it provides the necessary ecosystem services without which the subsistence and the monetary and informal economies would not survive.

1.3 Economic theory through the lens of worldviews

These issues have several basic features in common. They involve resources and impacts which no single group in society controls, but which affect all people worldwide. They require the allocation of significant resources to the preservation or development of 'public goods', such as the earth's climate, security or public health. The problems are highly dynamic, the relevant global systems changing rapidly relative to a reference undisturbed state. They are also novel: the prediction and confirmation of anthropogenic climate change, or the appearance and then widespread diffusion of HIV are issues that have arisen only in very recent history. (GSD, 2008:4)

'The human mind is built to think in terms of narratives, of sequences of events with an internal logic and dynamic that appear as a unified whole...It is generally considered unprofessional for economists to base their analyses on stories. On the contrary, we are supposed to stick to the quantitative facts and theory – a theory that is based on optimisation, especially optimisation of economic variables.' (Akerlof and Shiller 2009:51-54)

1.3.1 Scenarios, stories and worldviews

I was involved in the SRES-IPCC *scenarios*, using with our team the IMAGE-TIMER modelling platform (Nakicenovic et al. 2000; de Vries et al. 2000). Working with several teams of environmental scientists, energy modellers and economists, I participated in discussions on the driving forces behind the greenhouse gas emissions in the course of the twenty-first century. It is then that I became interested in macro-economic models and their strengths and weaknesses. Many economists considered it irresponsible to apply these models in forward calculations of more than five to ten years ahead. Yet, a number of them – belonging to the family of Integrated Assessment Models (IAMs) – were used for the period 1971-2100, in line with the IPCC mandate for emission scenarios.

As it turned out, the SRES scenario team agreed on two axes in order to classify future world developments in four quadrants. In shorthand notation, the first axis denoted the dimension of globalisation versus regionalisation and the second axis the dimension of market versus government[ix] . For each quadrant, a *storyline* (or narrative) was developed which was a plausible development path of the world system (population, economic activity, energy use). Such a storyline needed a *logical framework* (or logic) which was derived from aggregate 'stylised fact' hypotheses. Some important hypotheses are as follows:

- more room for market forces will give higher economic growth;
- higher income will cause a more rapid stabilisation of population growth;
- protectionism would hinder trade and therefore economic growth (de Vries 2006, Riahi et al. 2007).

The economic and energy models were subsequently run with assumptions which were thought to be more or less consistent with the storylines and their logic.

The shorthand names for the four (caricature) worlds have become rather familiar (Figure 1.1): A1 for the market-oriented globalising world (Global Market); B2 its opposite: the community-oriented regionalising world (Caring Region); A2 the market-oriented protectionist world (Safe Region); and B1 the government-oriented globalising world (Global Solidarity). The names in brackets are the ones I will use here; the SRES IPCC team did not use these names but many other scenarios have been constructed with names which fit into the SRES IPCC scheme (de Vries 2006).

The *Market Forces* logic in the *A1 world* is that material wealth is an essential part of a good quality of life; that it can be acquired by specialised skills and a competitive and risk-taking attitude. It is ensured by market-driven economic efficiency and government regulation and barriers to trade – goods, services, capital, labour, resources – should be minimal. The benefits may accrue to a small part of the population, but the poor people will benefit also in the future when wealth 'trickles down'. Post-war performance of the USA is the most visible proof of the correctness of this view. The enormous achievements of current global high-tech multinational corporations have only been possible because of the hard work, ingenuity, creativity and adventurism of entrepreneurs and business people. If these values and qualities are lacking or obstructed, society will become stagnant and backward.

Not everyone will adhere to this view – other people may value very different aspects of life: leisure time, small-scale enterprises, social and cultural traditions, community, nature (MNP 2004). They will express these values by protecting their small and local world by cooperation, solidarity, enclosure and fencing off intruders. In this *B2 world*, citizens may acquire an identity by cherishing what is local, be it their vernacular, the village church or a nearby forest. Their focus is on local needs and livelihoods, to which technology and governance should be geared. Protectionism is not a bad thing for them, as it may be the only survival option for their socio-economic as well as cultural way of life. However, their *Civic Society* ideal often clashes with the Market Logic, where large-scale and high-speed operations are appreciated for their competitive edge.

They may clash in another direction as well. The B2 citizens cherish autonomy, but they cannot avoid a growing myriad of links with the outside world. Much to their discomfort, they are confronted with alarming stories about dwindling fish stocks, water pollution and the threat of climate change, displacement of local jobs, increased immigration rates and the threat of famine. Blaming the A1 and A2 achievers and consumers is not a solution. Hence, many of them would be interested in the *B1 vision* of *Global Governance*, where international cooperation and solidarity are needed in order to solve the large-scale and long-term social and environmental problems the world is facing. People who adhere to the B1 vision support values of a more universal nature, such as the enlightenment of science and achieving global solidarity and peace. There is a genuine concern about universal human rights and the global commons. The Millennium Development Goals (MDGs) are a typical expression of this worldview.

Many people will dismiss the B1 logic as a hierarchical utopia – citing the political quarrels, fraud and mismanagement prevalent in the UN organisation. Not being able to join the 'famous and wealthy' in the consumer paradise of the A1 world, they may resort to a kind of realism which is a strange mix of clientelism, nationalism and fatalism. Protectionism, opportunism and bilateralism will characterise trade and an inward orientation may emphasise military power. Excessive consumerism spur innovations as well as envy and conflict and semi-criminal organisations may penetrate regional government business networks. This *Fortress World* logic of the *A2 world* is fed by beliefs such as: governments are not to be trusted, they waste your tax money; worldwide poverty is largely caused by overpopulation; global firms overpower local and regional firms; nothing can be done against climate change, we are powerless to curb the huge carbon emissions in China and India. There is a continuous crisis of legitimacy of political and financial elites, unless or until a military elite takes over. Yet, as in each narrative, this world too has a lot to offer to certain sectors of the population – it provides opportunities for local/regional politicians and entrepreneurs and recognition and security for those who cherish traditional and religious values, practices and cultures.

In their book *Animal Spirits*, Akerlof and Shiller assert that traditional economics fails to consider the extent to which people are guided by noneconomic motivation. It ignores animal spirits: *'The economics of the textbooks seeks to minimise as much as possible departures from pure economic motivation and from rationality.'* (2009:5). They propose a remedy in the form of theoretical fragments dealing with confidence (and 'confidence multipliers'), fairness, corruption and bad faith, money illusion, and stories. In their view, stories or narratives, as sequences of events with an internal logic and dynamic that appear as a unified whole, are crucial for economics: they may not merely explain the facts, sometimes they *are* the facts. Is it possible to examine mainstream economic growth theory and the necessary extensions in the scenario framework presented above?

1.3.2 Stories and worldviews

It can be argued that prevailing macro-economic theories and models, with smooth market-clearing processes and *homo economicus* type agents as micro-economic foundations, fit well into the *A1 world*. It is the world of Adam Smith's invisible hand, which has become the credo of modern free market capitalism. It has become a powerful ideology: markets know best and governments or the state should be as small as possible. Of course, in the real world there are no 'free' markets: there are monopolies, trade secrets and barriers, restriction on the movement of capital and labour, government regulations and interventions etc. All these 'imperfections' may overwhelm the balance of supply and demand mechanisms and cause continuous disequilibria and fluctuations. In a way, the strength of economic growth theory is that it abstracts from these real world phenomena, which makes it a strong ideology of powerful economic interest groups.

Of course, modern neoclassical economic (growth) theory has been criticised from many different angles. Its reductionist formal modelling approach, developed over the twentieth century at a great cost to real world relevance (see Hodgson 2005), can be explained in various ways. *'Economists insist on rationality because they do not like the alternatives… [this is why] economists adopt a concept of rationality that reduces to self-interest. It seems to offer an anchor in an ocean of otherwise unpredictable human behaviour. The assumption of rationality gives economics rigor that distinguishes it from other social sciences …self-regarding, materialistic behaviour would be the norm because no other behaviour could persist in a market economy'* (Kay 2001:212). The model's abstract theoretical content and weak empirical validation has evoked criticisms from within the same A1 paradigm. All these criticisms have to do with the way in which humans are represented in economic growth theory: as atomistic, narrowly rational and perfectly informed entities.

Nelson and Winter (1982), no longer satisfied with the aggregate approach of technological and innovation dynamics, laid the foundation for evolutionary economics. Many others have built on this, replacing the nineteeth century metaphors of classical thermodynamics and mechanics with another set of – also nineteeth century – metaphors from Darwinian biology (Döpfer 2005). The *homo economicus* is replaced by a pragmatic and adaptive individual or organisation, who is in constant search for achieving his goals in competition with other individuals/organisations and the environment. Authors such as Beinhocker (2005) have developed a new theoretical blend of technocratic 'evolutionarism' which fits well into the competition-oriented A1 world[x].

Another group of authors' criticise the absence of cognitive and social capabilities in the *homo economicus*. In the 1960s Simon stressed that a genuine theory of human motivation was needed in order to understand human individuals and/in organisations better than prevailing (market) theories offer. In the 1970s Forrester introduced notions of information delays, misperceptions and goal-oriented behaviour in system dynamics models to explain real world fluctuations in economic variables[xi]. Schelling (1978) and Kirman (1993) criticised the agents of economic theory for their lack of interaction with others. Ormerod (1998) criticised the notion of a welfare-maximising agent with fixed preferences – as if advertising efforts were all in vain and as if business people really thought there is such as thing as the best plan[xii]. A similar critique, though more qualitative and not phrased in agent terminology, is given by Akerlof and Shiller (2009) in their book *Animal Spirits*. If the *homo economicus* is equipped with the new features of pragmatism, interaction, adaptiveness etc., the new theory might still fit within the A1 worldview. In combination with powerful electronic media under corporate control, it may even strengthen the global capitalist system (Capra 2002).

An important characteristic of the other worldviews outlined above is that the underlying values and interpretations differ from those in the A1 world. For instance, in the diametrically opposed *B2 worldview*, people are focused on community and cooperation, on sharing and caring, on the social and environmental qualities of their life. An important contribution to economic science is the work by Ostrom (1990) and colleagues about the diverse management schemes for local resources and the role of institutions in such schemes[xiii]. Another contribution is Jackson's book *Prosperity without Growth – Economics for a Finite Planet* (2008). He asks if dematerialised growth is an option, questions the role of the informal 'amateur' economy, and explore how to green and localise the economy. He states that these and other issues must be addressed by adequate and transparent models apart from the multitude of real-world experiments.

The network society with distributed dynamics[xiv] is another development which may fit nicely into a B2 world. A new wave of technologies set the trend towards decentralised provision of information, energy and other services, which would have an inherent tendency to unite consumers (as local producers) and producers (with system responsibilities) and a mediating role for (local) governments[xv]. It would require quite new economic concepts, reinforcing changes which are already apparent in the more advanced service-oriented societies and rapidly influencing emerging economies. However, it is difficult to predict if such decentralising tendencies will get the upper hand – the forces behind the networks of global capitalism are centralising and strong. At the same time, the legitimacy and authority of nation states is being eroded under the pressures of competition between global players (multinational corporations, authoritarian regimes, criminal organisations). This may induce widespread return to, and support for, 'power of identity' movements (Castells 1996) and fuel resistance from the population against the homogenising tendencies of globalisation from states or markets (Scott 1998). Possibly one of the most interesting and strongest expressions of these trends is the movement for a basic income (see for instance www.grundeinkommen.de and www.basicincome.org/bien/).

The *B1 worldview* too will favour theories and models different to those in an A1 world.. Followers of the B1 worldview will insist on strong governments and institutions; on commitment to and targets for basic needs provision in health and education; and on mechanisms for fair distribution of benefits and costs, including aid and fair trade. The institutions and diplomacy of the European Union and the

United Nations are their only hope for the future. It reflects the world of bureaucratic organisations, in international government and NGOs as well as in multinational corporations (MNCs). All this should be part of economic models … but can it?

The welfare-optimising technocrat would fit nicely in this world as planning is an integral part of his conviction and endeavour. However, their rationality is primarily procedural and their objectives are more broad and systemic than individual material welfare ('consumption') – for instance, they worry about social instability as a consequence of large income disparities, about the threats of disease epidemics due to complex chains or about the prospect of geopolitically-driven energy shortages.

The B1 perspective is naturally associated with the social planning ideologies of the twentieth century, founded on a combination of 'the greatest happiness for the greatest number' (Bentham's utilitarianism), state communism and engineering technocracy. The World3 model in the Report to the Club of Rome (Meadows et al. 1971) which warned for the overshoot-and-collapse future of mankind if exponential growth in population and resource use could not be controlled, also had a characteristic B1 outlook. Similarly, national planning models were a cornerstone of economic policy, before the neo-liberal waves of the 1980s turned them into the suspect tools of intellectual elites[xvi]. International B1 examples are the Global Environmental Outlook (GEO) by UNEP and the World Development Reports (WDR) by the World Bank.

The Intergovernmental Panel on Climate Change (IPCC) is a good example of the procedural rationality in the B1 worldview and the problems it faces. It makes painstaking efforts to adhere to the universalism which many scientists claim for modern science. It takes the global perspective as an undisputable starting point in its investigations and communications – and yet, now that the potential consequences of a stringent climate policy become clear, it is confronted with quite different views on what is true and what deserves priority. Concern about the global commons and the failure of the existing institutions to manage them adequately is also eloquently expressed within this worldview and with extensive scientific research and models (Rockström et al. 2009, Walker et al. 2009). Interestingly, there is a keen awareness here that the agents and processes are in many ways contingent upon local situations – possibly because the ecologists and social scientists involved are more familiar with 'real world' fieldwork.

Finally, the values and interpretations in the *A2 world* are different again. One interpretation is that it represents the conservative groups in society which tend to loose their privileges to global financial and business elites (A1), international bureaucratic elites (B1) or citizens (B2). They often position themselves against those forces by fostering nationalism and fundamentalism, finding loopholes, resorting to crime and corruption etc. They do not see any need for formal models – their mental maps rely on metaphors such as 'survival of the fittest' or on kinship relationships and historical heroism. The A2 forces and views are not to be underestimated. They are manifest in resource related wars[xvii], failed states; drug and weapon trade in the shadow economy and so on. As in the B2 world, there is a populist streak in it; it is the legitimacy of government that is at stake.

The colonial past, cultural traditions, growing populations and rising expectations – excited by the fast dissemination of images and information across the world – make governance in many countries a very difficult task. In some places it is part of the longer term transition from tribal-oriented governance to 'modern' forms of the nation state and the welfare state. In other countries the emergence of 'westernised' elites leads to a variety of conflicts with the more traditionally oriented parts of the population – as is splendidly described by Castells (1996). So far, these complex socio-political and socio-cultural processes have escaped formal modelling – although some attempts are now being made (Modelski 2007).

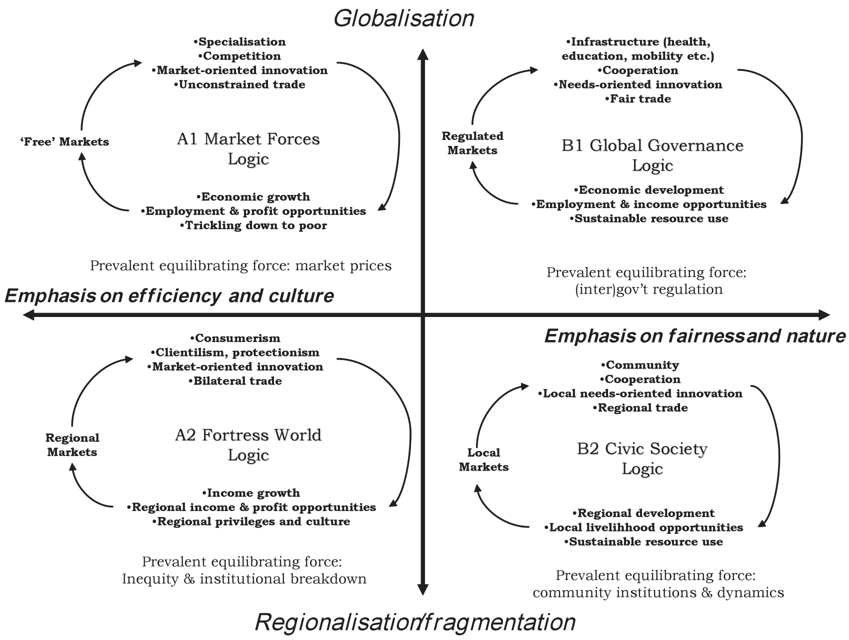
The scheme in Figure 1.2 sketches in a simplified way a characteristic mental map for each of the four worldviews. Value orientations and dominant actors accompany underlying mental maps. The economic elites of the corporate world, representing such values as adventurism and competitiveness, inhabit the A1 world. The less profit and achievement-oriented B1 world is the domain of the 'enlightened' international political elites, with their emphasis on social welfare and control. If such elites, either economic or political, loose legitimacy or simply deny its validity, they may be backed up by nationalist and military elites – the A2 world. The individual citizen in the B2 world, with his immaterial as well as material needs and disillusioned by the promises of the elites, try to organise their own life…

A diagram such as that shown in Figure 1.2 can provide a basic logic for a person's perceptions of problems and preferred solutions. Everyday information and experiences are framed within such elementary maps. But most people are not simply the victims of rigid reasoning and judging, but adhere to somewhat consistent storylines to make sense of a bewilderingly complex world. It is also a 'battle of perspectives' (Janssen and De Vries 1998), in the sense that the different worldviews are in permanent flux, and interactions with one view dominating parts of the world while the seeds of the opposing worldview are growing silently somewhere else. The challenging question with regard to sustainable development pathways for humankind is how this dynamic interplay can, and should, evolve over the decades to come in the face of an increasing human footprint on the world.

1.4 Summary

Current mainstream economic concepts and theories are largely representative of the industrial era, in which material growth and progress through applied science and capitalist arrangements brought great benefits to many. This era is over. The side effects and hidden costs of this form of growth and progress have become so intense as to essentially change it completely.

Figure 1.2



Four worldviews and a sketch of (part of) their logic (De Vries and Petersen 2009).

New concepts and theories are now needed. Since the 1960s economic science has seen the birth of subdisciplines such as resource and environmental economics, ecological economics, institutional economics, amongst others. Their practitioners acknowledged resource depletion, environmental (air, water, soil) pollution, ecosystem degradation, community destruction and human destitution as phenomena which were aspects inherent to the industrial era growth model. They often advocated adjustments, with some success.

Yet, many of these aspects are still poorly understood and are not well represented in mainstream economic thinking and modelling. 'Modern' economic growth theory does not explain key positive feedback mechanisms such as innovation dynamics. It also fails to provide satisfactory mechanisms which explain the lack of income convergence, trade disadvantages, resource mismanagement, the role of institutions (governments, finance) – all increasingly important features of a world which is now heading for a population of 9 billion people and increasing resource scarcity.

A natural consequence has been that mainstream economic theory, although taught in schools in its original form, is not relevant to the real world or, worse, is outright misleading. In other words, many relevant stories about the world are not told and cannot be told. One approach in the search for updated concepts and theories is to tell divergent relevant stories (scenarios) and consider the implication for (economic) models. In this chapter we have done this exercise for the four SRES IPCC scenarios.

In recent decades, the ingredients for twenty-first century concepts and theories have been emerging – often denoted by the term 'complexity science'. Can they be of any help, and if so, how? The next chapter addresses this question.

2

Contributions from complex systems science[xviii]

'Currently, most natural and social science models dealing with the emerging global challenges represent strenuous attempts to reproduce the complicated nature of the relevant problems, with multiple causes and physical processes describing the response to mankind's interventions in often very complex ways. However, the very complexity of these models has limited their use in decision making and policy making. This is caused by two main factors. Firstly, the models require large quantities of data and assumptions about policy etc. and then require a lot of effort to run. … The time-scales of model development are … in strong contrast to the timescales of political and industrial decision making which, although striving to look forwards far into the future using painstaking processes of policy development, often requires answers in the process of policy formulation in a very short timescale, even in almost real time. Secondly, the information provided by these complex models does not always address the actual questions that decision makers have, and the information that the models do provide is often too complex to be understood in the very short timescales in which decisions are often made.' (GSD, 2008:6)

'In terms of systems analysis, environmental issues represent a higher order of parameters which set the constraints for macro-economic modelling. They constitute a 'tube' of sustainability within which all dependent sub-systems must be contained. Macro-economics still relies on crude equilibrium models, and should move towards non-equilibrium dynamic models inspired by developments in the physical sciences. This would be especially beneficial in the assessment of the likely effects of system disruptions, which depend critically on the point in the dynamic cycle at which the disruption occurs. Mathematical techniques emerging in the physical sciences could contribute significantly to the reduction in uncertainty in complex systems modelling, but are not being taken up and applied as they should be.' (CEC, 2006a:4).

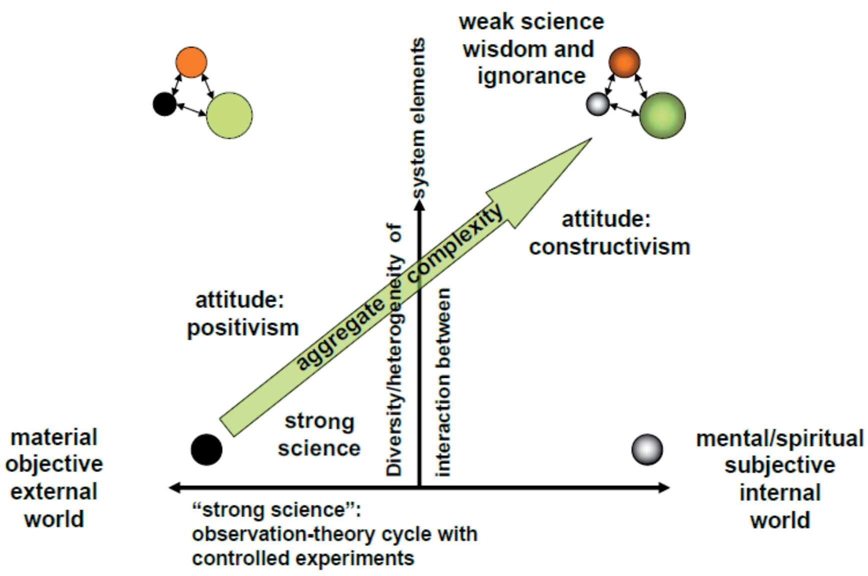
'…economic models need to improve…The field could benefit from lessons learned in the large-scale modelling of other complex phenomena, such as climate change and epidemics. Those lessons…suggest an ambitious research agenda – not just for economists, but for psychologists, political and social scientists, computer researchers and more.' (Nature Editorial 6 august 2009)

2.1 Complex systems (or complexity) science and its tools

What is complexity? Without attempting to come up with final definitions, it makes sense to reflect a moment on the notion of complexity from an epistemological perspective. One approach is to distinguish two dimensions of complexity. The first refers to complexity, in terms of the number, diversity and heterogeneity of the elements of the system under consideration and of their interactions – the vertical axis in Figure 2.1. The second is about the extent to which knowledge concerns the external, material world versus the internal, mental/spiritual world – the horizontal axis in Figure 2.1. The first, vertical axis is rather widely considered a determinant of complexity and is associated with phenomena, such as self-organisation and self-emergence (e.g., see Nicolis and Prigogine, 1989; Kauffman, 1995). One major impediment to making strong statements about such systems is the difficulty of performing controlled experiments – as the case of climate science is showing us, all too well. The second, horizontal axis of the external/objective versus the internal/subjective is an essential aspect of cognitive psychology and evolutionary economics and is also an ingredient in the formulation of agents in simulation models (Döpfer, 2005; Ferber, 2007; Hollis, 2007). It is less common in discussions on complexity, although here, the tension between the natural and the social sciences is most intense.

An increase in aggregated complexity of a system is a movement along the arrow from the lower left to the upper right, in Figure 2.1. The lower left represents the world of the natural sciences and its engineering applications. Knowledge is acquired in observation and description and strengthened and made 'objective' in controlled experiments open to reproduction and falsification. The tools of mathematics – such as differential calculus – have been and still are essential in this process. In going to the upper right, new ways are needed to acquire knowledge about the more complex

Figure 2.1



The direction of aggregate complexity (De Vries and Petersen 2009)

systems, such as social-ecological systems. This is the field of Complex Systems Science (CSS).

What are the tools of Complex Systems Science? With the advent of ever faster computers, mathematics has evolved into a large array of new tools with which scientists look at the phenomena of their interest. It's not unlike the 17th century period when the construction of telescope and microscope opened up new, previously unknown and unsuspected vistas. It was the beginning of a paradigm shift for which not yet a definite name has settled, but it is often associated with the shift from modernism to postmodernism (Toulmin 1990, Jones 2005).

Until the 1980s most people engaged in economic and social policy analysis/making would rely on qualitative methods. Some ventured into quantitative methods and applied the techniques of operations research, among them for instance linear programming optimisation and feedback control stabilisation (Richardson 1991). It fitted with the prevailing engineering paradigm: society could and should be managed as a machine, a factory. Characteristic was the title of a 1990 issue of Scientific American: *Managing Planet Earth*.

However, the question what could sensibly be modeled mathematically remained controversial. Many in the life sciences and social sciences, not in the least the empirically-minded, were aware of the extreme simplifications most models forced upon reality. One argument: it's always better to use an explicit and formal too-simple model than an implicit and ambiguous one. Thus, the simplistic models borrowed from ninetenth century physics and chemistry to describe and explain phenomena in ecosystems and economic and social systems were the best one could get – and therefore good enough. It is this context that economic science heavily borrowed from classical thermodynamics and geography from classical mechanics, to mention a few cases (Döpfer 2005).

Was it bad that such far-too-simple models were used to manage resources, to regulate economies, to govern states? Generally speaking: probably not. The models represented the understanding and control of the material world which made possible enormous advances in *la condition humaine*, in one word: progress[xix]. The surely played an important role in making the world more comprehensible for large parts of the population – in this sense they can be called archetypical models[xx]. They were part of modernism and the *Entzauberung der Welt*, even if at best partly correct. Yet, two phenomena have changed this situation – and make the use of obsolete models a more serious error.

First, some of the far-too-simple models became a creed which was no longer open to scientific examination – which is how certain models of man and society turned into stalemate ideologies (capitalism, communism). This still remains a threat, because falling back on far-too-simple models is one way of responding to one's fear and impotence in the face of a complex and ill-understood world. Secondly, modernity has launched technological developments which accelerate the system dynamics to ever higher magnitudes and rates of change (e.g. Costanza et al. 2007). This is evident in the physical flows of human persons and material goods (e.g. Steffen et al. 2005), but also in the financial and informational flows (e.g. Castells 1998). It implies a rise in complexity: more diverse and more intense interactions.

In other words: now that human interventions increase exponentially in extent and frequency, management has to be founded on more adequate models, at all levels of scale in space and time[xxi]. Having wrong representations (or models) of the system becomes increasingly dangerous, because change itself accelerates. Mixing up the accelerator and the

Methods and tools and application fields along the complexity dimension (De Vries 2009) Table 2.1

Methodology	Sustainable Development related modelling approaches and applications
Integral-differential equations	Physical and engineering sciences; pollutant dispersion
Optimisation and control theory, linear/dynamic programming	Physical and engineering sciences; resource depletion; least-cost abatement strategies
Systems science, systems dynamics, cybernetics	Resource systems; environmental economics and management
Catastrophe theory	Ecosystem dynamics; social [r]evolution
Network (graph, neural) theory	Foodwebs; economic input-output theory; social and information networks
Game theory	Common property resource management; social dilemmas
Cellular Automata (CA)	Land-use and land-cover dynamics (geography)
Genetic Algorithms (GA)	Optimal strategy search in complex systems
Multi-Agent Simulation (MAS)	Systems science and ecology; resource and ecosystem management
Complex Adaptive Systems (CAS)	Ecosystem dynamics; socio-natural system [co-]evolution (archaeology)
Scenario analysis	Connecting qualitative story-telling and quantitative modelling (management science; futurology)
Simulation gaming and policy exercises	Resource management

brake pedal due to a faulty 'model' can be accommodated at low speed – it's a way of learning – but may cause serious trouble on a highway at 100 km/h. Science is easily discredited in this situation: the old models fail, the new models offer mostly post-modern uncertainty and complexity.

Many of the pioneers who proposed far-too-simple models were well aware of the shortcomings of the models – but they did the mathematically best possible, tempted by the inventory of mathematical equations and techniques used to describe and explain phenomena inside the laboratory and often in conjunction with or guided by analogs and metaphors. Validation on the basis of empirical data was often an ambiguous if not impossible affair[xxii]. Those pioneers were also aware, usually, that the existing scientific insights from observations and common sense would require much more sophisticated models – but the mathematical tools to solve them in the abstract and the data to link them to observations in the concrete were missing. That's how economists came to talk about 'stylised facts': a mixture of observing, styling and explaining.

What has Complex Systems Science to offer? To bring some order in the diverse contributions from complexity science, Table 2.1 gives some of the methods and applications relevant in the present context. It is not easy to construct a genealogy or taxonomy of the different methods which have emerged in the last decades. They have a few common origins, but in each field of application specific approaches have unfolded – an evolutionary process, indeed[xxiii]. An important root is evolutionary biology, which has provided a new guiding metaphor for dynamic systems (see e.g. Döpfer 2005). Another root is graph (or network) theory, which has permitted new ways of looking at stability of dynamic systems – in close connection with the traditional integral-differential calculus (see e.g. Buchanan 2006). A related method is Cellular Automata, which considers interaction in a discrete lattice and got widespread application in geography (see e.g. Batten 2005). It has its roots in certain physical theories about particle interaction. A related strand of developments emphasises the heterogeneity in the system elements as much as the interactions, and is denoted with agent-based models (ABM) or multi-agent simulation (MAS) models (see e.g. Holland 1995, Bergh et al. 2000, Perez 2005, Phan and Amblard 2007). More realistic representation of (human) agents – behaviour, memory etc. – is the kernel of the approach.

In the next paragraph we will examine a couple of complex system applications which might contribute to an economic theory for a sustainable world. The criterium is whether a method/application can enrich mainstream thinking about the economic system within one of the four worldview quadrants (discussed in Section 1.3). Can it explain the fluctuations and cycles in the open, global capitalist system (A1)? Does it lead to more adequate understanding and management of sustainable resource management at the community level; does it indicate new directions for enhancing social capital, for novel arrangements in work and leisure time; can it provide a better model for the provision of public goods (B2)? Does it deepen our insights in the causes of the poverty trap and the income gap; can it present an adequate model for the sound management of the global commons (B1)? And, finally, will it clarify part of the dynamics of 'failed states' and of squandering resources; can it if not explain then at least incorporate the dynamics of militarism and crime (A2)? Clearly, an ambitious agenda – yet the task science has to face in my view.

Of course, this is not the first attempt in this direction. Complex Systems Science (CSS) methods are increasingly used in economic science in interaction with other disciplines in order to deepen understanding of micro-economic fundamentals (see e.g. CREED at http://www.csca.nl/research/institutes/creed/ on experimental economics and TIBER at http://www.tilburguniversity.nl/tiber/ on behavioural economics). Several good reviews have been written about the prospects and problems of using novel methods such as agent-based moling in economics (see e.g. LeBaron and Tesfatsion 2008). Unnecessary to say that the examples chosen are in no way covering this large and rapidly growing field[xxiv].

Macro-economic [growth] models

(source: http://en.wikipedia.org/wiki/Macroeconomic_model)

A macro-economic model is an analytical tool designed to describe the operation of the economy of a country or a region. These models are usually designed to examine the dynamics of aggregate quantities such as the total amount of goods and services produced, total income earned, the level of employment of productive resources, and the level of prices.

Macro-economic models may be logical, mathematical, and/or computational; the different types of macroeconomic models serve different purposes and have different advantages and disadvantages. Macro-economics models may be used to clarify and illustrate basic theoretical principles, they may be used to test, compare, and quantify different macroeconomic theories, they may be used to produce 'what if' scenarios (usually to evaluate the possible effects of changes in monetary, fiscal, or other macroeconomic policies), and they may be used to generate economic forecasts. Thus, macroeconomic models are widely used in academia, teaching and research, and are also widely used by international organisations, national governments and larger corporations, as well as by economics consultants and think tanks.

General equilibrium theory is a branch of theoretical neoclassical economics. It seeks to explain the behavior of supply, demand and prices in a whole economy with several or many markets, by seeking to prove that equilibrium prices for goods exist and that all prices are at equilibrium, hence general *equilibrium, in contrast to* partial *equilibrium. As with all models, this is an abstraction from a real economy, but is proposed as being a useful model, both by considering equilibrium prices as long-term prices, and by considering actual prices as deviations from equilibrium.*

Computable general equilibrium (CGE) models are often microfounded on assumptions about preferences, technology, and budget constraints… and focus mostly on long-run relationships, making them most suited to studying the long-run impact of permanent policies like the tax system or the openness of the economy to international trade. Economists of the 1980s and 1990s began to construct microfounded macroeconomic models based on rational choice, which have come to be called dynamic stochastic general equilibrium (DSGE) models. These models begin by specifying the set of agents active in the economy, such as households, firms, and governments in one or more countries, as well as the preferences, technology, and budget constraint of each one. Each agent is assumed to make an optimal choice, taking into account prices and the strategies of other agents, both in the current period and in the future. Summing up the decisions of the different types of agents, it is possible to find the prices that equate supply with demand in every market. Thus these models embody a type of equilibrium self-consistency: agents choose optimally given the prices, while prices must be consistent with agents' supplies and demands. DSGE models emphasise the dynamics of the economy over time (often at a quarterly frequency), making them suited for studying business cycles and the cyclical effects of monetary and fiscal policy.

Another modelling methodology which has developed at the same time as DSGE models is that of Agent-based computational economics (ACE). Like the DSGE methodology, ACE seeks to break down aggregate macroeconomic relationships into microeconomic decisions of individual agents. ACE models also begin by defining the set of agents that make up the economy, and specify the types of interactions individual agents can have with each other or with the market as a whole. Instead of defining the preferences of those agents, ACE models often jump directly to specifying their strategies. Or sometimes, preferences are specified, together with an initial strategy and a learning rule whereby the strategy is adjusted according to its past success. Given these strategies, the interaction of large numbers of individual agents (who may be very heterogeneous) can be simulated on a computer, and then the aggregate, macroeconomic relationships that arise from those individual actions can be studied.

Strengths and weaknesses of DSGE and ACE models. DSGE and ACE models have different advantages and disadvantages due to their different underlying structures. DSGE models may exaggerate individual rationality and foresight, and understate the importance of heterogeneity, since the rational expectations, representative agent *case remains the simplest and thus the most common type of DSGE model to solve. Also, unlike ACE models, it is typically very difficult to study* local interactions *between individual agents in DSGE models, which instead focus mostly on the way agents interact through aggregate prices. On the other hand, ACE models may exaggerate errors in individual decision-making, since the strategies assumed in ACE models may be very far from optimal choices unless the modeler is very careful. A related issue is that ACE models which start from* strategies *instead of* preferences *may remain vulnerable to the* Lucas critique: *a changed policy regime should generally give rise to changed strategies.*

2.2 Economic system modelling: what can complex systems science contribute?

'Modern macroeconomic theory is largely founded on assumptions of perfect competition, driven to this modelling strategy not so much by empirical evidence as by considerations of analytical tractability.' (LeBaron and Tesfatsion 2008:248)

2.2.1 Introduction: forces and mechanisms in the economic system

Economic development in most of the presently 'high-income' (OECD) countries of the world has been characterised by a number of quantified, stylised facts about *la longue durée*, such as:

- the declining fraction of agriculture and the increasing fraction of service activities as fraction of GDP;
- the continuous rise in tax revenues as fraction of GDP, reflecting the rise of the welfare state with its collective organisation of health and education, infrastructure, social security etc.; and
- the halving of the working week since the mid-nineteeth century and a growing fraction of women working in the formal economy[xxv]

These long-term trends are associated with the process of 'modernisation' and 'westernisation'. They occurred against the background of exponential growth in population, in novel manufacturing processes and consumer products and in throughput of energy and materials. Other less tangible forces were at work in the last decades to keep economic activities (and GDP) growing:

- the inherent sense of ambition, excitement and entrepreneurship caused (young) (parts of) populations to develop *new desires and needs* and aspire to satisfy these; this process has been reinforced by applied and commercially driven science and technology;
- *capital* and the financial elites behind it are roaming around the world in search for high returns and are as such a, if not the, major force behind economic expansion; the resulting imbalances pose risks to financial, economic and social stability;
- the rise of global ('casino') capitalism has made if difficult to sustain *employment* in (OECD-)countries in a situation of increasing competition from and outmigration to low-wage areas; the associated social risks are an important political drive to compensate increasing labour productivity with higher output;
- *political elites* have become dependent on economic growth as their spending power is directly related to it via taxation; it also explains to some extent their desire to bring the informal parts of the (national) economies under government control.

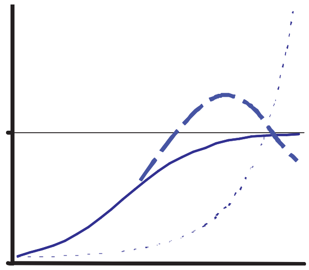
These trends coincide with other trends which may strengthen the aspiration for growth in monetary flows cq. GDP. For instance: the growing *financial and social insecurity* of citizens may intensify the desire for (individual) wealth as a source of independence, and the rise in income inequality may produce a *'bottomless barrel' of desires* heralded as innovations[xxvi]. It is as yet unclear whether and how the welfare state, being under threat, can fulfill these desires e.g. via *income (re)distribution*.

There are also forces at work which tend to slow down the process of (economic) development and prowth. *Saturation* in the sense of 'having enough' or not being able in terms of skills or time to consume more, is one of those forces – as advertisement companies know in their attempts to annul it. Sometimes, as consumers become more aware and critical, there may be the realisation that (part of the) *consumer desires* are (increasingly) activated by media and by comparison, status and competition, and will therefore by their very nature never be (fully) satisfied (Hirsch 1977, Layard 2005, Jackson 2009). One empirical indicator of these trends is the trade-off people make between work and leisure – it was found, for instance, for Denmark that the percentage of the population opting for 'same pay, less work' increased from 43% in 1964 to 72% in 2007, whereas a roughly constant proportion (25-30%) preferred 'more pay, same work' (Norgard, personal communication 2009).

Other developments may further constrain and slow down or even halt the growth process:

- system aspects: although one would like to have the good or service, the system to deliver it is deficient, expensive or absent due to the 'law of increasing complexity' (Tainter 2000, Day 2004) in the private as well as the public domain;
- social and psychological constraints: stress due to ever larger emphasis on efficiency and productivity in work and household and due to a culture of excessive desires and communication (advertisements, ICT), increasing lack of adequate education and sense of insecurity among parts of the population (job insecurity, crime, immigrants) (see e.g. Wachtel 1991);
- spatial/environmental/ecological constraints: traffic congestion, declining air quality and high costs/efforts for experiencing nature, and in the longer term resource-scarcity and climate change related (geo)political conflicts (see e.g. Wenzel 2008).

Many policies of governments and business lobbyists are aimed at overcoming these obstacles. Whether this results in a continuing growth of GDP and net disposable income, as assumed in almost any official scenario, is unclear[xxvii]. For instance, the push for liberalisation has induced enormous growth in ICT-business and legal services and has recreated regulatory bureaucracies. These become part of GDP but whether such a growth of GDP enhances the experience of well-being is equally if not more uncertain. Most governments forecast on the basis of macro-economic models a continuous growth in labour productivity ('efficiency') while at the same time claiming a substantial reduction in relative use of natural resources. Whether such a decoupling of economic growth and energy and material flows in absolute terms is possible is also uncertain (see e.g. Jackson 2009, Polimeni et al. 2009).



In this chapter we present mechanisms and models which may enrich the way in which we think and discuss the economic prospects for the world. The idea is not to imagine building a new and comprehensive theory and/or model, but to collect different pieces which provide new perspectives and possibly become building blocks for larger ensembles (Hasselmann 2009). In view of the inevitable growth of the world population with another 2-3 billion human beings over the next decades and the serious limits to be faced as a consequence (see e.g. PBL 2009), the task is urgent. What we present here is an incomplete attempt at synthesis and is meant as an invitation to contribute. Against the background of standard neo-classsical growth models, we have grouped the various contributions from Complex Systems Science (CSS) in a couple of clusters:

1. Engine of growth: capital, labourers and customers
2. Supply-demand dynamics and commodity and business cycles
3. Co-evolution of producers and consumers
4. Generalised utility functions
5. Income distribution mechanisms
6. Technology and behaviour diffusion in transitions
7. Models of interaction: on predators and arms
8. Agents in social networks
9. Agent and land use dynamics
10. Factors of production in the production function
11. Economy-environment interface: renewable resources and ecosystem services
12. Non-renewable resources
13. Managing the commons: the challenge of cooperation.

As one can see the list is a mix of concepts and topics. Appendix C lists a number of elementary models using CSS methods. It is a list, a catalog, not (yet) a genealogy or taxonomy. It serves as a background to the applications discussed in this chapter. Not everyone will agree with the heading complex systems science – but we have no intention to be argumentative about this at the moment.

2.2.2 Engines of growth: capital, labour and customers

'It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth.' (Jevons, in: The Coal Question, 1865)

It is important to get a more systemic insight into the process of economic growth if one wishes to construct and implement policies dealing with complex issues such as climate change – but is it possible? Numerous books and papers have been written about it, theories and hypotheses abound. Here, we are interested in non-mainstream approaches and select a few of these for discussion. Sterman (2000:364) presents a detailed *system dynamics model* on the engine of corporate growth, distinguishing a series of feedback structures:

- product awareness: firms will use advertising and sales efforts to promote its products. In combination with word of mouth and media attention this may create a positive feedback towards ever larger sales cq. market share;
- unit production cost: there is continuous drive to lower unit cost (see above and Figure 2.2) through R&D. Traditionally, the ways to reduce costs are through economies of scale, economies of scope and learning-by-doing. All three can work as positive feedback loops through which unit cost declines;
- unit development cost: in many modern knowledge-intensive industries the upfront development cost are a large fraction of total cost: the actual production cost are small or negligible (chips, software, music…). Once underway, there is an enormous drive to create large sales to recover the upfront cost.

He lists a couple of other mechanisms which may contribute to the growth of firms (or, if absent, to their decline) such as: new product development; acquiring mono/oligopolistic market power; mergers and acquisitions; promoting workforce quality and loyalty; and access to cheap capital by high profits and growth rates. One particularly important mechanism are the increasing returns (i.e. positive feedback) from interaction synergies and network effects, which can create significant path dependencies (Appendix C.4). We come back to this.

At a more aggregate level, as shown in the scheme in Figure 2.2 suggests, two basic loops drive economic growth (see e.g. Ayres and Warr 2005, Warr et al. 2002)[xxviii].

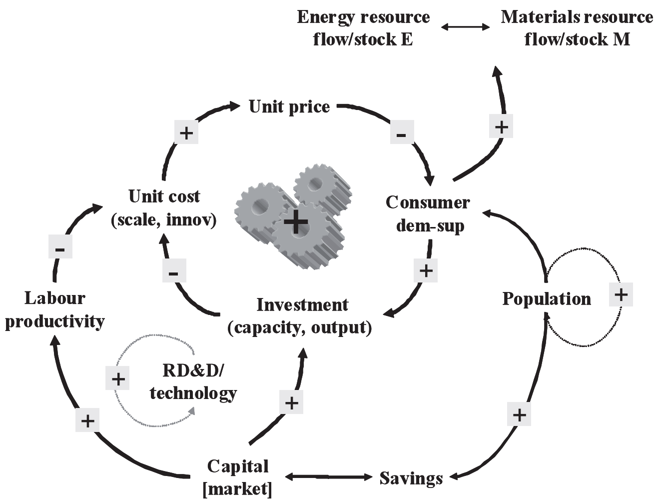
- population growth, with an associated demand for goods; and
- increase in knowledge (RD&D): incremental and breakthrough innovation which causes a continuous increase in labour productivity.

As a result, the unit cost c tend to go down and, with fluctuations, the price too. This induces an increase in demand, at times spurred by advertisements by the producers who prefer growing markets over a competitive struggle for market share. Rising demand will lead to expansion investments, which tend to bring costs further down with economies of scale and mass production. The cycle presumes sufficient savings to provide capital at a sufficiently high reward. In the process, the natural resource base will be degraded, but the subsequent inefficiency and cost increase has been largely offset by RD&D. As a consequence, resource prices have been in decline for most of the twentieth century – and absolute resource use has increased. As far as sustainability is concerned, the feedback loops suggest that any gain in resource efficiency will, in combination with rising labour productivity, partly or wholly undo the decline in absolute resource use – the *rebound effect* (Polimeni et al. 2009).

The rising labour productivity has at least three important consequences. The first one is rising demand as wages go up. Secondly, an increase in capital per unit of good and its usual complement, energy, as these are substituted for labour. Thirdly, a lower demand for labour – except for high-skilled labour in the RD&D – and hence rising unemployment in the 'standard' economy. In a wider system context, the population is involved in several indirect and longer-term ways:

- as a political force to promote economic growth in order to maintain a desired level of (formal) employment; this can lead to a 'race to the bottom' with regard to perceived barriers to growth such as social security and environmental regulation; and
- as 'small capitalists' in order to assure a high return on their savings; this may actually reduce employment as capital can be drawn to other high-growth high-profit regions in the world and/or accelerate the call

Figure 2.2



A schematic view of the 'engine of economic growth'.

for economic rationalisation in the form of rising labour-productivity.

This description is largely in line with a more qualitative analysis given by Jackson (2009). Introducing Baumol's book *Good Capitalism, Bad Capitalism* which defines capitalism as private ownership of the means of production, he extracts as the mainstream view that 'good' capitalism is entrepreneurial capitalism with a dose of big-firm capitalism thrown in. At the core of this growth-oriented 'good' capitalism is the well-known 'circular flow' model of the economy, where households offer labour and capital (savings) in exchange for income, which is spent on goods and services produced by firms who employ labour (people) and capital (buildings and machinery) to this purpose. Households offer their capital in the hope to get a 'healthy return' on it. Firms – say: corporations – need the capital as working capital to invest in cost reduction and innovation. The former is mostly done by reducing labour costs i.e. increasing labour productivity, and this form of 'efficiency' creates downward pressure on employment which can only be relieved if output goes up (Figure 2.2). The latter is a continuous process of 'creative destruction', to use Schumpeter's famous expression. Both cost minimisation and innovation are driven by competition and are, in turn, driving economic growth.

Notoriously absent in most schemes is the finance sector. The 2008 financial crisis has awakened economists to the insights that a macro-economic model without the (global) financial sector may miss out on major crucial economic events. A large number of agent-based models have been constructed over the years to understand the workings of stock markets. Here we do not consider this part of the economic system, but we would like to alert the reader to presentations on this topic in other GSD-workshops (see e.g. the presentations by Boucheaud and Pietronero in the BIG STEP event in Brussels 14-15 april 2010 and the ECF / GSD Conference: Beyond the Financial Crisis – Globalisation at the Crossroads event in Berlin 5-6 november 2009 (www.globalsystemdynamics.eu).

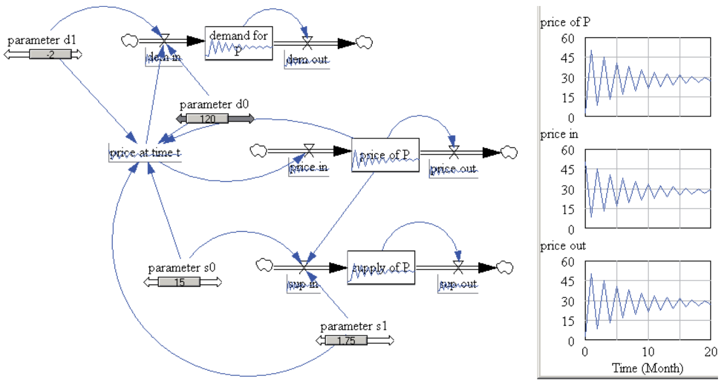
2.2.3 Supply-demand dynamics and commodity and business cycles

'[Equilibrium thinking has] so permeated economics that very few attempts have been made to follow in the tradition of the early economists and to develop theories in which the existence of cycles is an integral feature of the economy.' (Ormerod 1998:107).

Dozens of positive feedback loops are at work at the firm level – what does this mean for the aggregate economy? Neoclassical economic thinking is dominated by the notion of decreasing returns (i.e. negative feedback): if a firm is successful and gets above-average profits, other firms will enter the market and competition will lower prices and profits. Investigation of the past century of firms and industries in the USA and the UK, however, suggest that such equilibrating processes may happen with significant delays because of the strengths and duration of virtuous cycles of several positive feedbacks. In other words: one should expect fluctuations in key aggregate economic variables. At this point, it is appropriate to wonder whether evolution provides a better metaphor than the physico-chemical analogs which inspired neo-classical economic science. Let us first have a closer look at the supply-demand dynamics.

It is well-known that economic output in countries shows long-term fluctuations – called Kondratiev-waves after the Russian economist who detected them – and short-term fluctuations – called business cycles[xxix]. Both phenomena cannot be understood satisfactorily from a neo-classical macro-economic growth theory perspective. Yet, the occurrence of fluctuations in economic variables may have consequences for the degree to which an economy is vulnerable for and can cope with external shocks such as weather extremes as part of climate change (Hallegatte and

Figure 2.3



The simple cobweb demand-supply model in a Vensim ® representation.

Ghil 2008). Short-term fluctuations also tend to overwhelm policies aimed at longer-term transitions such as the energy transition, by absorbing all resources and efforts towards tinkering with short-term phenomena. If the fluctuations are at least partly understood and communicated, the risk of volatile and therefore ineffective policies diminishes. Which theories are around?

In his book *Culture and Prosperity* (2004) Kay explains how the market creates spontaneous order: *'the disciplined and effective matching of buyers and sellers that emerges from the apparent chaos of the [flower] market.'* (2004:152). In a perfectly competitive market, no trader can influence the price[xxx]. The well-known cobweb model is based on a time lag between supply and demand decisions in such a perfect market. An equilibrium will be reached if the demand curve is flatter than the supply curve. The basic equations are simple: $D(t) = f\left[p(t)\right]$ and $S(t) = g\left[p(t-1)\right]$. If these non-linear functions f and g are linearised: $D(t) = d_0 + d_1\left[p(t)\right]$ and $S(t) = s_0 + s_1\left[p(t)\right]$, one can calculate the price p_{eq} at which demand and supply are in equilibrium. The price change necessary to let supply satisfy demand follows from equating D(t) and S(t):

$$p(t) = \frac{s_0 - d_0}{d_1} + \frac{s_1}{d_1}\,p(t-1)$$

This will for some parameter settings give oscillations, either convergent or divergent – a cobweblike figure in phase space. Figure 2.3 gives a simple Vensim-model representation. In the simple cobweb model, agents have myopic expectations. Much research in behavioural and experimental economics explores price formation in markets where the agents are much more sophisticated, e.g. forward looking and learning (see e.g. Hommes et al. 2007).

Several extensions of the cobweb model have been proposed. In an attempt to understand price formation, Gintis (2007) constructed an agent-based model with workers, consumers and firms and replicator dynamics (Appendix C.10). The simulations suggest that when price information is shared even among a small fraction of the agents, the price system becomes highly volatile. Such sharing of information is highly probable, given the tendency of people to imitate others in situations of incomplete information (uncertainty). In other words: the existence of 'public prices' – which destroys the disorganised nature of 'private prices' – induces correlated behaviour by the economic agents with subsequent price fluctuations. Such extensions introduce more realistic ways of interaction among market agents: not immediate and throughout, but delayed and locally dispersed[xxxi].

Although the simple cobweb model captures the core structure of the commodity cycle, Sterman (2000) considers it unsuitable for serious modelling of market dynamics. In *system dynamics* advanced models of demand and supply processes have been constructed. Sterman (2000:798) mentions a couple of principal feedbacks which operate in the real world to equilibrate demand and supply:

- Substitution: if the price goes up and/or a new product at a competitive price enters the market, demand will fall – usually in some combination with income and other trends. Sometimes, customers can adjust quickly but often the old product is tied up with capital stocks and habits and will be substituted for only slowly;
- Utilisation: if prices go up, producers will in first instance react with higher utilisation rates if the profit outweighs the additional operational cost. This can be rather quickly;
- New capacity: if prices are expected to remain high, producers will consider to add new capacity to the existing one. This is a longer-term process, in which quite different factors are considered e.g. new technology and interest rates;
- Customer and producer are connected via a series of operations, such as transport from the factory to the wholesale company and on to the retailer. Inventory management is often another source of fluctuations.

Together these mechanisms make fluctuations in commodity systems almost inevitable[xxxii]. At the more aggregate level of sectors and economies, there may be more equilibrating and damping mechanisms at work – but not necessarily and not always. What is clear, however, is that bottom-up 'prediction' of business cycles is a hazardous affair, more than ever in the internet-economy[xxxiii].

Can the long-run dynamics of science, technology and innovations, in combination with capital stock characteristics and trade patterns, cause fluctuations? Sterman (1986) found from simulations with a large macro-economic model that the long Kondratiev-type of wave may arise from the interaction of two fundamental facets of modern industrial economies: the inherently oscillatory structures of firms and self-reinforcing processes which amplify the instability. Köhler (2003) proposed to incorporate dynamic input-output coefficients in a CGE-model in order to explore long-run fluctuations of the Kondratiev-type. Crassous (2008) combines in the IMACLIM-R model an input-output matrix with a simple neoclassical growth model; this permits periodic updating of the technical coefficients on the basis of exogenous expert views and/or innovation models (Appendix D). A more qualitative, technology-oriented perspective would emphasise the interaction with energy and the associated scientific discoveries and technical innovations: 4 out of the 5 large Kondratiev waves are directly linked with energy, namely: hydropower, steam power, electrical power and motorisation based on oil[xxxiv]. To judge from the suspiciously smooth exponentially growing variables in almost all macro-economic forward projections, there isn't much effort to incorporate the phenomena causing fluctuations into official forecasting models – at least not explicitly (see Box). Yet, it is a necessity in any serious exploration of a sustainable economy.

2.2.4 Co-evolution of producers and consumers

'It is the peculiar characteristic of the human race that it set in process a vast evolutionary dynamic of production of its own artifacts, with species more numerous than the insects, ranging in size from the microscopic transistor circuit to thousands of miles of thruways and skyscrapers.' (Boulding 1978:121)

Business cycles have been explained in economic literature on the basis of external shocks[xxxv]. However, Ormerod (1998) convincingly argues, using three-dimensional phase plots, that there is not much hope to discover a structure in the macro-economic data which would explain business cycles. Economic processes may resemble more the decisions of ants as described by Kirman (1993) than the Lorenz equations from meteorology with a clear deep structure. It seems we have to look anew at the microfoundations of economic fluctuations. It also seems that *interaction* is then the keyword.

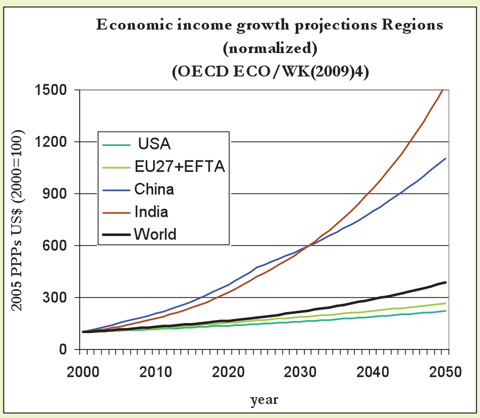
Ormerod (1998:200) has suggested a very simple model: firms base their decisions on the expected growth which in turn is based on past growth, and on the general mood which depends on the past and on the average growth rate. The introduction of slight differences in the perception of the general mood among firms is enough to create a growth rate distribution similar to the historical one. Dosi et al.

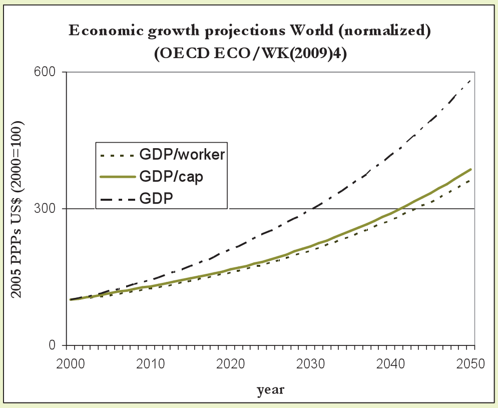
An example of the – rather rare – long-term model-based projections of world economic growth is the OECD-report ECO/WKP(2009)4 by Duval and De la Maisonneuve. which is '… based on a standard aggregate Cobb-Douglas production function with physical capital, human capital, and labour as production factors and labour-augmenting technological progress, and [assumes] that production function is invariant both across countries and over time, GDP per capita can be decomposed as follows:

$$\frac{Y_t}{Pop_t} = \left(\frac{K_t}{Y_t}\right)^{\frac{\alpha}{1-\alpha}} A_t h_t \left(\frac{L_t}{Pop_t}\right)$$

where K_t/Y_t, A_t, h_t, and L_t/Pop_t denote the capital/output ratio, TFP, human capital per worker and the employment rate (defined here as the ratio of employment to total population at time t), respectively, and α is the capital share in aggregate output. From the graphs below, it is seen that official forward projections like these indicate exponential growth in economic activity measured as GDP and GDP/cap until 2050 – even for the richest regions in the world.

(http://www.olis.oecd.org/olis/2009doc.nsf/LinkTo/NT00000AE2/$FILE/JT03260306.PDF)





(2008) share Ormerod's skepticism about the conventional explanations of business cycles and they have constructed an evolutionary economics model, in which continuous entry and exit of firms is at the heart of the model – and which reproduces several aggregate economic statistics fairly well. Let us have a closer look.

Dosi et al. (2008) attempt an explanation on the basis of an evolutionary, multi-agent model of an economy. It is in line with the foundational work of Nelson and Winter (1982). There are F firms and L workers/consumers. The firms belong to either consumption-good firms F_1 or machine-tool firms F_2. The consumption-good firms (F_1) plan investment decisions, i.e. orders for the machine-tool firms, on expected demand, desired inventories and desired capacity utilisation. The key equations describing investment behaviour of firm j are:

- the desired production level Q in period t: $Q_{jt}^{des} = D_{jt}^{exp} + \left(N_{jt}^{des} - N_{j,t-1}\right)$ with D (expected) demand and N (desired) inventory;
- the desired capital stock K in period t: $K_{jt}^{des} = Q_{jt}^{des} / u^{des}$ with u the (desired) level of capacity utilisation;
- with $A_{i\tau t}$ indicating the labour productivity of machine tool producer/type i of generation τ, which makes up a fraction g_{ij} of the total capital stock of firm j, the unit labour cost c is calculated as: $c_{i\tau t} = w_t / A_{i\tau}$ with w the nominal wage.

The actual investment only takes place above a certain trigger. A crucial part is that new capital stock has a higher labour productivity and thus lower product cost.

A firm decides to scrap old capital according to a simple payback criterium and orders new capital from a subset of suppliers (F_2). Which machine-tools are bought depends on the price and productivity of this subset of suppliers. As a consequence of expectations and imperfect information, firms will perform differently in the consumption-good market. This is simulated on the basis of the replicator dynamics (Appendix C.5). There will be dynamic evolution of market shares with a continuous entry and exit of firms. Machine-tool firms (F_2) are supposed to employ labour only, under constant returns to scale. They plan the level of production and the hiring of workers accordingly on the orders they expect from the consumption-good firms. Labour productivity in these firms differs among firms and over time.

The authors then identify a dozen of macro and micro empirical regularities ('stylised facts') about modern economies and distill from their model a number of variables/distributions for comparison with macro-statistics. The comparison is done, with a set of initial conditions and benchmark parameterisations, for a *work-or-die scenario* in which only employed workers earn an income and consume it completely, and for a *social-security scenario* in which part of the market wage is redistributed to unemployed workers.

If technical change is completely turned off, the economy is in a steady-state with zero growth. If it is turned on, the simulated economy starts to evolve in a permanent disequilibrium. It is found that the model results do reflect most of the empirical regularities and generate fluctuations in investment, consumption, employment etc. in line with empirical counterparts. It is concluded that *'evolutionary microfoundations are shown to exhibit a macro-dynamics with strong Keynesian features. Indeed, investment and production decisions induce in the model demand propagation effects much alike Keynesian 'multiplier' effects. Conversely, adaptive expectations on demand drive investments in ways closely resembling the Keynesian 'accelerator'. The resulting aggregate demand fluctuations endogenously give rise to business cycles. '* (Dosi et al. 2008:431). Although the vocabulary is different, several features (for instance, desired or anticipated vs. actual) in the model resemble elements of the system dynamics models of Sterman and others – and, not surprisingly, so do the conclusions.

So far, the consumer has hardly been part of the models. Apparently, under the pressure of advertising and sales efforts, customers become all-devouring consumers. Is this correct, and if so why? Jackson (2009) introduces at this point the desire for *novelty* as the consumer complement to the competitive drive for innovation among firms[xxxvi]. Consumption of goods and services is much more than satisfying basic material needs for food, shelter and so on. *'Material things offer the ability to facilitate our participation in the life of society…our attachment to material things can sometimes be so strong that we even feel a sense of bereavement and loss when they are taken from us…Novelty plays an absolutely central role in all this.'* (Jackson 2009:98-99). Following this psychological argument, key elements in understanding consumers are the longing for social distinction and social comparison. Consumption is partly a substitute for religious consolation, a filling up of the 'empty self' and combating a sense of meaninglessness (Handy 2000). This restless desire of the consumer merges with the restless innovation drive of the entrepreneur – voilà the root forces of growth in consumer capitalism.

These considerations, albeit in different interpretations, have also led to a series of models in which the social logic of the consumer is central. Much of this work has been induced by dissatisfaction with the representation of agents in standard economic theory. We come back to this later. Let us first look at another *evolutionary economics model* which, like the one by Dosi et al. (2008), simulates producers but also consumers and the interaction between the two.

This model has been constructed by Safarzynska and Van den Bergh (2010) and explores the probability of technical lock-ins in a situation of multiple positive feedbacks. The *production* side of the economy is simulated as firms which set the desired production level for the next period, invest in capital expansion, invest (remaining) profits in advertising and R&D activities towards quality improvements, and, if sales are insufficient, can carry out marketing research and consider radical innovations. There is only one factor of production: $y_{jt} = k_{jt}^{\beta}$ with y output and k the (depreciating) capital stock for firm j at time t. The good produced has a certain quality level x_{jt}, which is initially assigned randomly but which can be improved towards a maximum by R&D-investments. If the desired target level of output $y_{j,t+1}$, which is a combination of sales and demand, exceeds current output y_{jt}, the firm will invest in capital expansion within the constraint of profits. If profits are zero or negative for some consecutive periods, the firm is replaced by a new one with a random chosen quality level. If profits exceed needed investments, the remainder is invested in R&D (i.e. improvement of the quality level x_{jt}) and advertising. Whether an innovation ($x_{j,t+1} > x_{jt}$) is actually introduced is based on a market research among a subset of customers. The cost (and price) will decrease inverse proportionately with output, but will increase exponentially with increasing quality level. Given the initial random assignment, one may expect an evolutionary path during which the most wanted quality products are produced by firms with varying profit levels. There are some interesting differences with the model of Dosi et al. (2008), which would make a confrontation with statistical data an interesting one.

The *consumers* are divided into a rich and a poor class, each individual i aspiring for a product j with the highest utility u_{it}:

$$u_{it} = \frac{x_{jt}^{\alpha_i} n_{jt}^{\varsigma} f_{jt}^{\varpi} b_{jt}^{\varpi}}{p_{jt}^{0.5-\alpha_i} l_{jt}^{\kappa}}$$

with x product quality, p product price, f advertising effort being a function of a firm's spending on it, and b a public campaign effect most of the time set at one. The term l_{jt}^{k} with l_{jt} the number of poor class consumers purchasing the good j in period t represents the snob effect. Increasing quality, more advertising efforts and lower prices lead to higher utility and to larger sales for producer j. The model introduces three network effects:

- The usual assumption that market share is a proxy for popularity: m ($n_{jt}=m_{j,t-1}$);
- A positional good effect: a good is preferred if its quality exceeds the quality of the most frequently purchased product in the social network in the previous period ($n_{jt}=x_{jt}-x_{avg,t-1}$ for $x_{jt}-x_{avg,t-1}>1$);
- A conformity effect: a good is preferred the closer it is to the quality adopted by the majority of the consumers in the social network in the previous period ($n_{jt}=x_{maxatt} - |x_{jt}-x_{avg,t-1}|$).

The model thus incorporates some important phenomena observed in consumer behaviour and denoted as bandwagon and snob effects. They represent important feedback mechanisms, which can either be positive (as with positional and snob) or negative (as with conformity).

It is not easy to summarise the outcomes of the model experiments. Thousand simulations across parameter space suggest that the snob effect is crucial in preventing or undoing lock-in and that the need for distinction and conformity between members of the rich and the poor class generates distinct market niches. A couple of other stylised facts are more or less confirmed by the model results, although more systematic and rigorous experimentation is needed for further conclusions. The model does indicate novel ways to simulate the complex interactions – co-evolution – between producers and consumers, given the existence of increasing returns among firms (learning-by-doing, economies of scale, innovations) and among their customers (network, snob and advertising effects). It will help to understand how to make a transition away from environmentally unsustainable activities to sustainable ones, notably in agriculture, energy and transport sectors and overcome the lock-in of the dominant, unsustainable technology.

The evolutionary economics model experiments indicate good prospects for a more dynamic and in-depth representation of two of the major groups of actors in an economy: producers and consumers. At the meso-level the models are in various ways connecting the findings of behavioural scientists with the observations on aggregate economic system performance. It will be interesting to explore the relation between the positive feedbacks and the mechanisms of economic growth. A limited segment of society may 'drive' the system to ever newer forms of production and consumption, due to e.g. the snob effect (desire for 'novelty') and other incentives within their subsystem (rewards for speculative behaviour, competitive desire for sales growth etc.). Can we identify and understand the drive for new drugs, new health treatments, new weapons in this context? Can the role of the advertisement industry and the resistance against less working-hours be understood in more depth?

Another avenue for research is the inclusion of the financial sector as an important factor in producer and consumer behaviour. There is clear evidence that the role of financial institutions and stock markets on the behavioural rules and incentives of corporate executives has led to a decoupling of the financial and the physical economy, feeding a temporary growth illusion and a spending and debt boom with dire consequences for large parts of the population.

There are still a couple of epistemological issues to be dealt with. To what extent are evolutionary mechanisms indeed dominating the dynamics of economic agents? Could the profit- and/or utility-maximising agent formulation be a modelling lock-in? Which recipes are to be followed in model construction and which criteria are to be used in model validation? Another important issue is how the evolutionary micro-foundation can be constrained by mechanisms which are known and dealt with in macro-economics, such as structural changes in demand, export competitiveness, balance-of-payment constraints and innovations as outcome of cumulative experience rather than random search. Whatever the answers, there can be no doubt that the quest for a sustainable economy will have to follow this path, amongst others, to explore the dynamics of the transitions ahead.

2.2.5 Generalised utility functions

'Social sciences dealing with needs and wants remain firmly bound to the individualist tradition, thus weakening the analysis... unlike current theorising, the social and cultural dimensions of human needs and wants must be included... Human needs and wants are generated, articulated, and satisfied in an institutionalised feedback system. They do not appear from thin air but are created by the social interactions that comprise the civic community.' (Douglas 1998:259).

Mainstream economic theory postulates the representative agent: rationally maximising, isolated and with perfect foresight, also denoted as *homo economicus*. The standard way in which this is formalised is maximisation of a concave utility function u=u(c) under a budget constraint. The functional u is supposed to represent a set of ordered, fixed preferences, with $du/dc>0$ and $d^2u/dc^2<0$. In most macro-economic models dealing with climate change, for instance, an aggregate 'national' utility function U is maximised across generations applying a discount rate (Chapter 3; Appendix D). Foremost among the criticisms of such a presentation of the consumer (individual, household) is the lack of interaction with others. Indeed, not only the presumed rationality but also the individual-in-isolation is a serious flaw in the way humans decisions are represented in textbook micro- and macro-economic theory. As we have seen, interaction and associated feedbacks are crucial elements in system dynamics and evolutionary models.

The idea that consumption is intrinsically social is neither new nor solely theoretical. Empirical surveys indicate that at higher income levels it is not (absolute) income ('GDP/cap') but (relative) income position that is the driving force behind (the desire for) growth in itself[xxxvii]. The phenomena of habit formation, imitation and social comparison have been suggested as social mechanisms (Jager et al. 2000, Jackson 2009). This area is partly covered in behavioural economics, where the focus is largely on the presumed irrationality of economic agents or, in other words, on the many deviations from the representative homo economicus. There is evidence that the degree of (in)equity is related to people's (dis) satisfaction/(un)happiness as well as to social (in)stability. To incorporate these findings into models, one should explicitly include heterogeneity in income, values, beliefs etc. of people (MNP 2004). Will an extended formulation of the utility function be of any help?

Modelling social interactions in economics, sociology and social psychology have been so far developed to a large extent in isolation. However, it has been shown recently that these efforts can be used to broaden the concept of *utility function*. The traditional utility function postulates that individual agents experience utility as smoothly increasing with income – but declining at the margin. There is a built-in saturation, in the sense that a 100€ increase for a rich person has lower utility than for a poor person. It is unclear whether this is correct for the average person: the level of satisfaction ('enough is enough') may vary a lot within a population. Here we will focus on the *utility of discrete choices*. To make analysis even easier we will conceptualise agents making binary choices.

Let us suppose an agent is facing a discrete, binary choice: either +1 or -1. For instance: buy this car or don't buy this car. The approach is similar to models in statistical mechanics (Appendix C.1-2). An extended utility function for individual i can be represented as a decision rule D

$$\sigma_i^{t+1} = D\left(\sigma_i^{t+1}, \sigma_i^t, h_i, \mathbf{N_i}, \varepsilon_i\right)$$

with h_i the individual preferences, N_i the individual's social environment and ε_i random factors affecting the individual in its choice at time t+1. The introduction of the social environment has to be based on some kind of individual decision rule. One of the early solutions has been proposed by Granovetter (1979):

$$\sigma_i^{t+1} = \begin{cases} +1 & \text{if } m > \sigma_i^{Th} \\ -1 & \text{if } m < \sigma_i^{Th} \end{cases}$$ with m the mean choice: $$m \equiv \frac{1}{N}\sum_j \sigma_j$$

and σ_i^{Thr} the threshold i.e the number of agents in i's social environment which choose +1. Small changes in distributions of the threshold levels may, in combination with random influences, give radically different aggregate outcomes. The structure of the social network also plays a role. Like Schelling's segregation model, these models are known as *threshold models* (Appendix C.5-6).

A number of such models have been applied to understand the dynamics of attitude and opinion formation. Social interactions have been studied intensively in social psychology. One notable line of models was developed using social impact theory by Nowak, Szamrej and Latane (Nowak et al. 1990), (Appendix C.7). Social impact theory (Latane 1981), formulated initially in the static setting of a group impact on an individual, is backed by considerable empirical evidence. The theory states that social impact exerted by the group on an individual is proportional to the 'strength' of interaction, social distance and number of group members. Application of the theory to the group setting using computer models (Latane and Nowak 1994) led to interesting results. In particular, the model was able to reproduce the survival of minority clusters in equilibrium. Another interesting feature of this model is inclusion of 'self-support' – a tendency of an individual to sustain her/his opinion. This means that an agent's choice depends on a choice she/he formerly made, which produces a certain inertia in the agent's behavior resulting from the psychological tendency toward consistent (Festinger 1957) or habitual behavior (it can also be interpreted as an agent's susceptibility to outside influence).

Although economic mainstream models do not include social interactions, there are already successful pioneering efforts to incorporate this feature into the utility function. One increasingly popular approach in this direction is based on an analogy with interacting particles using methods of statistical mechanics. It was initiated by Folmer (1974), but it proliferated in the 1990s with the models belonging to the class of *Random Utility Models* (Brock and Durlauf 2001) (Appendix C.7).

There is a close relationship between utility-function models, impact function models and threshold models. Actually the first two of them are equivalent (Ostasiewicz et al. 2008). In the mean field approximation, assuming certain properties of the utility function, they can be reformulated as the threshold model. This equivalence allows us to use insights from both economics and social psychology to develop models applicable to a wider range of situations. Economic models with social interactions already expanded the limited *homo economicus* assumptions of neoclassical theory. Utility of agents is not only based on economic benefits and costs but also includes gains and losses related to conforming with others' choices. Moreover psychological perspectives add inertia to agents' decisions, in the form of a tendency to follow the last choice.

It is possible to formulate a *generalised utility function* for the binary choice problem (Appendix C.8). Such generalised utility takes form of an additive function of individual preferences, inter-personal influences, randomness and 'self-supportiveness' (individuals' inertia). It has been shown that a wide class of these models may exhibit multi-stability that is often exploited in resilience theory (Ostasiewicz et al. 2008). This means that a whole system can be in one of two stable states, usually one of them being socially undesirable. This explains the existence of some kind of social traps where rational individual decisions lead eventually to the situation where everyone is worse off. Transitions between these equilibria can be abrupt and have certain similarities to phase transitions studied in statistical mechanics.

It is important to introduce these more advanced, generalised notions of what makes individuals decide into models of economic growth and resource transitions. It provides a link between people's values and interactions as studied in social science and marketing research on the one hand, and the long-term dynamics of adjustment processes like the energy transition and climate change adaptation on the other. Clearly, using these expanded concepts, one can then tell some of the plausible stories about the future more convincingly (Chapter 2).

2.2.6 Income distribution mechanisms

'Capitalism thrives on inequality. Markets separate out the successful from the less successful in a very thorough way. This competitive process creates wealth for the country as a whole, but it doesn't spread it around.' (Handy 1998:229)

What are the data about and the mechanisms behind income and wealth distribution? Income and wealth distribution have important impacts on aggregate consumption and investment patterns – what are those impacts? There is some evidence that wealth inequality may be bad for growth, in particular when capital markets are imperfect and agents are heterogeneous (Aghion et al. 1999). It has also been shown that income differences more than income levels play a role in people's satisfaction with life and that income equality is correlated with a good quality of life (Layard 2005, Wilkinson and Picket 2009). Large income and wealth inequality also enhances risks of social conflicts. Given the welfare state aspiration to sustain an acceptable level of equality, it is important to introduce such mechanisms and impacts into the long-run economic growth models.

Pareto suggested more than a century ago that income distribution is governed by a simple law: for any income limit I_r, the fraction F_r of the population with an income I> I_r is equals F_r =F c I_r^{α} with α≈-1.5. Recent research of data for industrialised countries suggests that such a power-law relationship only holds for the upper (1-3%) tail of the income distribution, whereas for the low-middle part a two-parameter lognormal distribution is found which also turn out to differ for countries and change over time (Clementi and Gallegati 2005). It is possible to explain a Boltzman distribution of wealth for the majority of the population and a Pareto distribution for the superrich from different assumptions on what is supposedly maximised in the system (Mimkes and Willis 2005).

In the econophysics literature, quite some mechanisms for income/wealth distributions have been proposed. Ipolatov et al. (1998) used a simple model, in which two persons exchange either a fixed (additive) or a proportional (multiplicative) amount of capital (both with a random and a greedy version: the richer only take). They found a power-law distribution for the multiplicative 'greedy' exchange. Wright (2005) presents a model of employers and employees which self-organise on the basis of a small set of rules (hiring/firing, expenditures etc.) and which, he claims, reproduces rather well a series of distributions found for developed capitalist economies.

In a similar vein Boucheaud and Mézard (2000) apply the 'directed polymer' problem in physics to economics. They assume that there is an exchange of wealth through trading and that the amount of money earned or spent by an agent is proportional to his wealth, which gives the stochastic dynamic equation for the wealth $W_i(t)$ of agent I at time t:

$$\frac{dW_i(t)}{dt} = \eta_i(t)W_i(t) + \sum_{j(j\neq i)} J_{ij}W_j(t) - \sum_{j(j\neq i)} J_{ji}W_i(t)$$

with η a random factor and J an asymmetric matrix. It can be shown that for a 'mean-field' model assumption that all agents exchange with all others at the same rate (J_{ij}=J/N), the system equilibrates to a Pareto power-law tails for large w's. The authors explore the effects of income and capital tax, showing that the former may decrease and the latter may increase income inequality. They also examine the evolution for the assumption that agents have exchanges according to some network configuration. Again a Pareto distribution is found. The authors conclude that *'The important conclusion of the above model is that the distribution of wealth tends to be very broadly distributed when exchanges are limited. Favouring exchanges (and, less surprisingly, increasing taxes) seems to be an efficient way to reduce inequalities'* (2000:544).

Di Matteo et al. (2004) explore the evolution of wealth if agents exchange in a network in the presence of noise. They find a power-law distribution when the network connecting the agents is scale-free. Campanale (2007) explains that household wealth distribution is much more concentrated than income distribution by using the fact that there is a systematic positive relationship between asset holdings and the return on these holdings. In other words: assuming that economic agents get a return on their savings that increases with the size of the assets they hold explains most of the wealth inequality. The existence of some extremely wealthy households may need another explanation, such as the disproportionate large number of entrepreneurs in the top income class. One of the weaknesses of these models is the use of an extremely simplified model of economic agents: only transfers and no heterogeneity. We come back to this.

A deeper understanding of the mechanisms of income and wealth distribution, within and between countries, may clarify some of the mechanisms of economic growth. Some scholars have observed that income distribution influences growth (i.e. that Gini coefficients on income predict growth rates). Others see a clear link between income inequality and the level of violence and social erosion, hypothesising that social status competition is an important driver behind the desire for ever more consumption (Frank 1999). Reversely, pro-growth advocates claim that a certain degree of income inequality is needed to make an economy grow – indeed, regional income gradients do play an important role in migration and travel flows. Is it possible to model these forces and simulate how the leading richest groups drive the system upwards? Can it be upscaled in order to understand that a pro-growth (government) policy is driven by concerns about social instability as soon as growth falters?

2.2.7 Technology and behaviour diffusion in transitions

Only if we can link collective behaviour to the trade-offs and decisions of individuals can we understand the possible behavioural responses that might follow the implementation of some new technology. (Allen and Strathern 2000:83)

One area of special interest to (evolutionary) economists has been the dynamics of innovations and, in the broader perspective of transitions towards a sustainable society/economy, of particular technological transitions. Initially, this has been studied as the subsequent market penetration of new products/processes along an S-shaped (logistic) curve. Marchetti et al. (1979) have analyzed long-term dynamics based on the Fisher-Pry substitution model and found an almost law-like dynamics[xxxviii]. Although this *logistic substitution model* is interesting in its claim that economic forces are apparently subservient to technological ones, it is too aggregate to provide reliable guidance for the future.

We briefly present here a selection from the many analyses of market penetration and, relatedly, transition dynamics (see e.g. Köhler et al. 2009, Los and Verspagen 2009, Alkemade et al. 2009). The examples suggest that the methods applied may vary from parameterised equations rooted in statistical physics to elaborate rules for simulated agents. They also indicate the important role of psychology in understanding the role of agent behaviour and interaction in a technological transition.

Many agent-based models to simulate innovation processes have been constructed in the last couple of years. However, as Weisbuch et al. (2007) note, the *adoption of 'green' technologies* is a complex socio-economic process and it is hard to model agent behaviour without loosing track of the full scope of model outcomes and of the links with empirical data. For this reason they have proposed a simple analytical model, the essence of it being the Willingness To Pay (WTP) function. It represents the fraction f_i of the consumer population willing to pay above a certain price p_i for the product – say, a car. The more expensive option is assumed to be the 'greener' one. It is also assumed that each option has a maximum cost P_{0i} at zero market share, which declines linearly with the market share. The resulting model is similar to some models in physics. It can be solved analytically and produces 'phase' or 'regime' transitions for variations in the value of the ratio of w/k with w the width of the WTP distribution and k the linear increasing-returns (or learning) coefficient. Thus, such a simple model exhibits multiple attractors and hence complex competition dynamics from the simple assumptions of consumer heterogeneity in willingness to pay and product cost decline upon market gains. It is a reminder not to write off the benefits of analytical models too easily, once user-friendly software for system dynamics and agent-based models is available.

Weisbuch (2000) gives two concrete examples of how a bottom-up approach to emergence can deal with uncertainty and (lack of) cooperation in environmental innovation issues. Individual agents are given partial knowledge of their environment and endowed with motivations and an internal representation (incl. learning and adapting). The first model simulates the spread of environment-friendly innovations in a population of farmers in analogy with epidemiological models: individuals have random encounters which for a potential adopter (of the presumedly beneficial innovation) lead to 'infection'. Additional features are then introduced: encounters happen across a social network and agents are inhomogeneous with regard to the (relative) attractiveness of the innovation. The approach is based on percolation theory – in technical terms: networks of threshold automata, with Bayesian updating and coupled map lattices (Appendix C.2).

Given a social network and a priori utilities for the standard option and the environment-friendly option, what fraction of farmers F_{eq} will adopt the latter? It turns out that with full rationality – the usual assumption – exact prediction of F_{eq} is possible and may have any value between 0 and 1. With social networks and agent heterogeneity, i.e. a form of bounded rationality, herd behaviour occurs and prediction is difficult, with a tendency for F_{eq} to be near 1 or 0 (cf. evolutionary selection). Thus, outcomes may significantly differ from standard economic models.

In a second model, the extent to which car drivers will adopt anti-pollution equipment as a function of the direct (air quality) and indirect (information from neighbours) feedback is examined. This model explicitly links the air pollution dynamics to the social dynamics. The simulation results suggest rather complex patterns of polluting and non-polluting equipment adoption in the (physical) space.

Another interesting sequel of models about product market penetration has been constructed by Jager et al. (2000) and Janssen and Jager (2003): the *consumat model*. The first element is the explicit modelling of cognitive processing. It is assumed that people engage in different cognitive processes depending on the degree of their needs satisfaction and their uncertainty. *Needs satisfaction* is expressed as an expected utility $E[U_{ij}]$ for individual I from consuming product j:

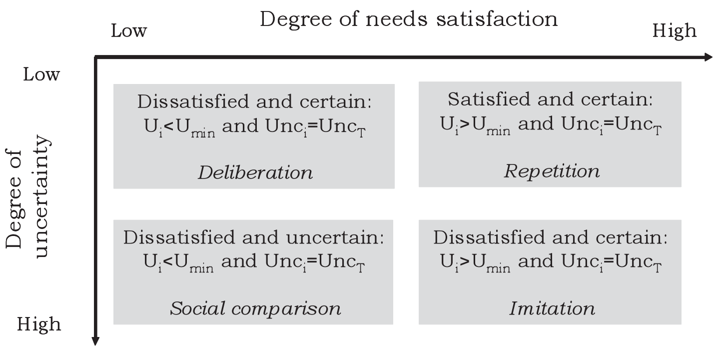
$$E[U_{ij}] = \beta_i \cdot (1 - |d_j - p_i|) + (1 - \beta_i) \cdot x_j$$

This utility function some of the previously discussed. The first term is the individual part and measures the distance between the personal preference p_i ($0<p_i<1$) and the product dimension d_j ($0<d_j<1$). The second term represents a social effect, with x_j the fraction of the friends of individual i who consume product j. The expected uncertainty $E[Unc_{ij}]$ is thought to increase with more sensitivity for social effects (small β) and more isolated in the use of the particular product. Hence:

$$E[Unc_{ij}] = (1 - \beta_i)(1 - x_j)$$

The social effects are investigated for two different types of networks (small-world and scale-free) and with and without random contacts. The resulting framework is shown in Figure

Figure 2.4



The consumat model framework.

2.4. The concrete rules are based on thresholds for the needs satisfaction (U_{min}) and uncertainty (Unc_T). In this way, the model incorporates an interesting mix of agent sophistication and connectedness.

In the simulation experiments, Janssen and Jager (2003) use the degree of dominance of a product on the market and the rate at which consumers change choice, called turbulence, as two indicators to characterise the manifold outcome space. Using N=1000 agents and M=10 products, these two indicators are investigated for divergent values of the satisfaction per unit of consumption ('product attractiveness' α in $U_{ij}=\alpha\, E[U_{ij}]$). Some of the results are:

- At low levels of satisfaction one can expect a higher level of turbulence on the market, because agents engage in deliberation and social comparison and therefore frequently change choice;
- Turbulence also remains high if agents attach much value to their social needs satisfaction (low β) and are uncertain;
- Visibility, measured as the extent to which a network is searched for imitation or comparison, also affects turbulence: high visibility has a stabilising effect;
- The shape of the network has serious consequences for the number of products that dominate the market; investigating the network features for particular products appears useful and promising.

This kind of models may refine our understanding in market dynamics and improve policies aiming at faster penetration of certain goods and services, as in the energy transition. The models discussed in this chapter are still experimental 'toy models'. However, they are not (yet) part of the large AIMs used to explore long-term transitions, although these models do incorporate a manifold of technological transitions (Appendix D). Usually such transitions are simulated with a discrete choice model which takes some relative cost measure as the driving force for substitution[xxxix]. There are attempts to introduce behavioural dynamics into the discrete choice formulation. For instance, Mau et al. (2008) add an intangible cost element into the multinomial logit equation.

Another trend is to introduce more sophisticated behavioural dynamics into theme-specific models, for instance by Verhoef and Rouwendal (2004) in a cost-minimisation traffic congestion model, by Sterman (2000) in a system dynamics private vs. public transport model, and by Safarzynski (2010) in an evolutionary economics simulation of electric power investment strategies. A recently published network model of the diffusion of novel technologies combines contagion among consumers with heterogeneity of agent characteristics – such combination of diverse elements may well be the way forward (Cantono and Silverberg 2009). The relevance of these models is that they analyze the mechanisms behind technological transitions, e.g. differences between a patenting or a freeware strategy, and that they may give clues for effective (government) policies to steer the transitions.

2.2.8 Models of interaction: on predators and arms

'Could it really be the case, as The Economist suggests [in November 2008], that we are still behaving like hunted animals, even in the 21st century, driven by the fine distinction between predator and prey? If we are, it would be good to recognise it. And to understand why.' (Jackson 2009:87).

When Georgescu-Roegen was drawing economists's attention to their neglect of the Second Law of Thermodynamics, Boulding proposed A New Theory of Societal Evolution in his book *Ecodynamics* (1978). It was rooted in the theory of ecological interaction, which distinguishes cooperative, competitive and independent interactions between (two) species. The resulting schemes of mutual cooperation, parasitism, predation, mutual competition, dominant-cooperative and dominant-competitive and mutual independence, provide a context far richer than the conventional economic framework. Boulding used it to sketch the threat system, the exchange (trade) system and the integrative ('love') system as the three elements of human evolution. Boulding formalised his ideas with a set of differential equations of the form:

$$dX/dt = a_{11}X + a_{12}Y + c_1$$

$$dY/dt = a_{21}X + a_{22}Y + c_2$$

with which he explored the equilibrium of predation or parasitism, the (un)stable mutually competitive equilibrium and the equilibria of mutual cooperation and of dominant species. The apparent simplicity of the ecological theory of the 1970s vanished with the advent of novel methods and insights of complexity science and exponentially growing computing power. New approaches, such as network dynamics, take over – but they are still rooted in these same analytical equations. These simple equations provide still a strong metaphor or analog of what is going on in a world where competition for money, power and resources are still major driving forces – be it economic, military or political.

At least two important, widely used analogs relevant for economic dynamics are in this set: the predator-prey model (in its simplest Lotka-Volterra form) and the arms race model (in its original form proposed by Richardson in 1918). The *predator-prey model*, which offers a telling metaphor for much of what is happening between firms and nations in the world, rests on the following observations and insights:

- if one species is food for the other, the prey population is part of the carrying capacity of the predator;
- more predators increase the prey death rate (prey-death-per-predator relation) and the amount of prey affect the predator death rate (predator-death-rate-from-prey-shortage relation).

For X=prey and Y=predator, one has $a_{12} < 0$ and $a_{21} > 0$. The a_{11} and a_{22} are the species-specific net growth rate. Under certain conditions the system may exhibit a neutral oscillation, well-known from mechanical analogs, or an unstable spiral. Of course, this model is an extreme simplification. In the course of the years, numerous multi-population models have been proposed and analyzed – most of them being refinements of the Lotka-Volterra model.

Another model which provides a metaphor for economic life is the *arms race model*, which has only one interaction term: arms expenditures of nation X depend on the perceived expenditures on arms of nation Y. The diagonal elements a_{11} and a_{22} will be negative and represent the 'pacifist' tendency to spend on butter not arms, counteracting the reinforcing spiral of armaments expenditures ($a_{12} > 0$ and $a_{21} > 0$). This model has been tested for several historical situations – no evidence of an arms race was found for the Greece-Turkey conflict but the India-Pakistan interaction suggests an arms race (Dunne et al. 1999). Here, too, extensions of this overly simplistic model have been proposed. As a metaphor for corporate business in capitalist economies, it has heuristic value. For instance, an extensive review of McKinsey & Company of pharmaceutical sales force effectiveness stated (In Vivo, October 2001:74): *'the leading pharmaceutical companies have driven that [phenomenal] growth by engaging in an increasingly intense commercial 'arms race' to shift share to new, more efficacious therapies.'* Recently, a British journalist called the last decade one of 'a consumption arms race'. Is it possible to incorporate these interaction mechanisms in the representation of agents in economic models?

2.2.9 Agents in networks

'As a network becomes more connected, its average fitness rises, so that it becomes more robust with respect to shocks. Yet, at the same time, the proportion of extinction events which are very large, on a near-global scale across the system, increases. The probability of such an event is still very low, but it is considerably greater than in a very weakly connected system. So fragility increases as the connectivity of the network increases.' (Ormerod and Colbaugh 2005:3)

The examples of interaction in models in the previous paragraph are in the differential-integral calculus tradition. Extensions into higher-order, non-linear sets of equations abound in almost all the sciences. They are useful for stability analysis, as abundantly shown in the ecological literature, but the limitations are that they often cannot analytically be solved and that they can hardly deal with discrete heterogeneous objects and informational delays and feedbacks. It is not impossible – but the interpretation becomes often too strenuous to be successfully communicable.

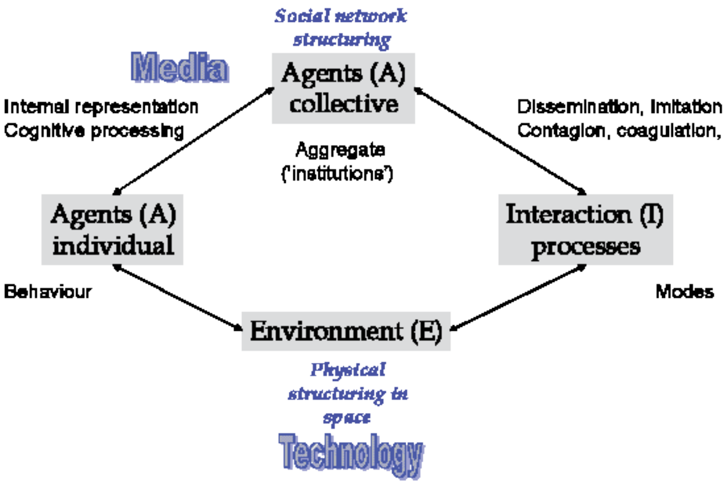
Some of the models previously discussed – system dynamics, evolutionary economics – do rely on simulation techniques and languages. In essence, these models try to improve upon the isolated economic agent with fixed preferences and a maximising utility rule by introducing a) heterogeneity among the agents, and b) interaction between the agents – in other words: by introducing complexity (Figure 2.1). We will now turn to some other methods which pursue the same goal and which were already part of applications discussed so far: evolutionary game theory, network models, and agent-based (or multi-agent) simulation models.

It is not the intention here to summarise what is going on in this vast and growing field. The field is still rather fragmented and attempts at establishing 'community standards' are most welcome (Janssen et al. 2008). The scheme in Figure 2.5 sketches the different roads taken. There is a difference in emphasis: some researchers wish to improve the 'inner' representation of agents (e.g. memory, choice criteria etc.), while others focus on the interactions between agents in networks or as part of larger entities (clubs, tribes, institutions etc.). We have already seen this difference in previous applications: the econophysics wealth distribution models focus almost exclusively on interactions with agent behaviour implicit in the model parameters, whereas agents in evolutionary economics have explicit behavioural rules and distributed characteristics. Here, we present a few more examples in order to illustrate the possible role of the novel methods in economic modelling (see also Appendix E).

A first model is a simulation based on *evolutionary game theory* (Lindgren 1997). It is meant as a framework for studying the evolution of cooperative behaviour using evolution of finite state strategies. In essence it is a repeated prisoner's dilemma (PD) with risks for mistakes. The author has performed a basic and systematic set of experiments with agents who interact with each other, memorise the outcomes and adjust their strategies.

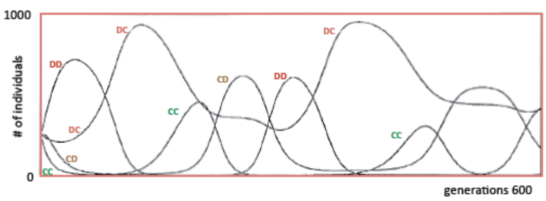
An agent can initially only apply 4 strategies (always defect, always cooperate, tit-for-tat and anti-tit-for-tat) but mutations or 'innovations' may lead to new strategic behaviour involving a larger memory. Replicator dynamics (Appendix C.10) leads to changing patterns of winning and losing strategies, sometimes yielding an evolutionary stable strategy (ESS).

Figure 2.5



Scheme of the ways in which agent-based modelling is applied

Figure 2.6



Initial population, 250 each of memory 1 strategies:
CC — Always Cooperate
DD — Always Defect
DC — Tit-for-tat
CD — Anti-Tit-for-tat

Trajectory of subpopulations (Lindgren 1997)

Given mutation and mistakes/errors, an evolutionary path will unfold in which different strategies are competing for dominance. In the actual model experiments, one thousand players interact with everyone else. Figure 2.6 shows the number of individuals following different, simple strategies over time. The Nash-equilibrium D[effect]D[effect] strategy gives way after some time to other strategies – first DC, then CC and so on. More complex cooperative strategies emerge, which maximise an expected long-term payoff for both players but with a punishment in case one of the players defects. An interesting finding is that the introduction of mistakes makes the game strategies more difficult but also more cooperative. The model is a nice example of building an ecology from agents applying strategies in an evolutionary frame and this kind of fundamental and systematic research is, or should be, at the basis of much work in e.g. evolutionary economics. A next step is to introduce a form of cognitive processing in the agents which permits the exploration of the role of interpretations of the actions of other agents (Eriksson and Lindgren 2002).

Payoff matrix:

		Action for player B	
		Cooperate	Defect
Action for player A	Cooperate	(3,3)	(0,5)
	Defect	(5,0)	(1,1)

One can draw far-reaching conclusions from such findings: *'In an evolutionary system…there is no single winner, no optimal, no best strategy. Rather, anyone who is alive at a particular point in time, is in effect a winner, because everyone else is dead. To be alive at all, an agent must have a strategy with something going for it, some way of making a living, defending against competitors, and dealing with the vagaries of its environment.'* (Beinhocker 2006:230). Although simulation models like these are still far from the multi-faceted ways in which human beings interact and form coherent higher-level units (institutions, nations, corporations), they suggest conditions under which certain strategies (policies) might be (in)effective.

There is an interesting issue here regarding the *validity of thinking in equilibria*. In the finitely repeated PD when the number of rounds is known, backward induction, as a basis for reasoning, leads to defection in last rounds being rational – going backwards step by step one can conclude that defection from the very beginning is the only Nash equilibrium. There are also other game-theoretic and economic situations which share the same payoff structure, and they do not necessarily have a time component like the repeated rounds. There are situations where this 'only' rational Nash-equilibrium is the worst outcome – think of overexploiting the commons. We also know, both from experiments and from 'rational reasoning' when we come into similar situations, that humans would reason and act in a different way.

The backward induction builds on the idea that both players are reasoning 'rationally' step by step as described above. But, if the joint result of such a reasoning and procedure is the worst outcome, then one may draw the conclusion that a different approach would be better. For, example, by cooperating in the first round one actually signals to the other player that one uses another way of reasoning. And then it is clear, especially when the game is repeated for a long time, that there are huge potentials for a joint profit from cooperation. One only has to decide to cooperate 'long enough'. But there is no way to find an optimum here and, in a way, that is the point: the vagueness of the reasoning makes it difficult to exploit. Both will gain and the ambiguity will lead to one of the players getting a little more, but both of them gain a lot from cooperating. If game theory and economic theory fail so radically to explain such simple situations, then why should we trust equilibrium analysis in more complex situations?

A formal way to deal with interactions between (simple) agents is a rather old mathematical technique: *network (or graph) theory* (Appendix C.3). The theorems from network theory have many applications. Several of these have their roots in physical models, such as the Ising-model (spin-interaction on a lattice) and the percolator-model (Appendix C.1-2). What can network theory contribute to understanding complex (economic) phenomena?

One can think of two alternative pathways to improve the realism of low-dimensional (or aggregated) illustrative agent-based models: (i) increasing the complexity of of the internal representation of the agents and thus, e.g. accounting for the complexity of real-world decision-making processes or actions and (ii) improving the realisation of the topology of agent interactions in the model. The approaches (i) and (ii) do not necessarily have to be exclusive, however, studying them separately is in the tradition of model reductionism and allows for a controlled build-up of a complex model from simpler building blocks.

In this paragraph the emphasis is on the influence of a systems interaction topology on its function. Every distributed complex systems that consists of many interacting elementary units can be described as network: nodes represent the elementary units and links describe the topology of the interactions. A motivation for such a general discussion of the influence of a systems interaction topology on its function is the relatively recent finding that a striking number of complex systems has interaction structures that fall into a number of broad classes: scale-free networks or small-world networks are the most prominent hallmarks. Moreover, a number of recent studies has shown that differences in system structure lead to profound differences in system function.

We illustrate this point by a simple *model of consensus formation* in heterogeneous populations of agents. In its basic structure the model is similar to models discussed in previous paragraphs. However, the emphasis of our analysis here is on the role of the interaction topology and its interplay with agent heterogeneity on consensus formation and not on the mean-field picture as above. The aspect of agent and interaction heterogeneity is of great importance for real-world social systems, since a variety of recent studies has shown that social interaction networks are typically very heterogeneous. Further, people with similar traits are often clustered, i.e. people with similar ethnical or social backgrounds tend to live in the same suburbs, thus also tending to have interactions preferably with each other.

Consider agents with a continuum of opinions (which may be preferences to buy a somewhat green car in the model of section 2.2.7) represented as the time derivative of some continuous number φ>0 and a natural bias towards a native opinion w. In the absence of interactions with other agents an agent sticks to its own opinion, i.e. d φ/dt=w, the agent's opinion is constant. Interactions are introduced via the influence of the opinions of the neighbours of an agent on its opinion. If the matrix A describes the adjancy structure (i.e. Aij=1 if i is a neighbour of j and Aij=0 otherwise) we write:

$$\frac{d\phi_i}{dt} = w_i + \sigma \sum_j A_{ij} \sin(\phi_j - \phi_i)$$

In the above, sigma gives the strength of the influence of neighbours of i on i and the term $\sin(\varphi_j-\varphi_i)$ expresses that the influence of neighbours is the stronger the stronger the deviation of their opinion from the opinion of i, but the influence is bounded (by the inclusion of the sine function in the interaction term). This model basically represents an extension of the well-known Kuramoto model for phase synchronisation to networks and has found quite a lot of attention in the recent literature on synchronisation phenomena on complex networks.

Studying the model for just two coupled interacting agents with different opinions reveals a number of different solutions for the stationary state: agents might basically stick to their respective opinions when the coupling is low or their opinions will converge when the coupling is larger than some threshold value. For larger systems the model exhibits a very rich behaviour: depending on the interaction structure (the matrix A) and the coupling strength possible solutions are: (i) no consensus, when the coupling is very low, (corresponding to the desynchronised state) (ii) a partial consensus for intermediate coupling (corresponding to partial synchronisation) or, possibly, (iii) a full consensus (corresponding to full synchronisation) among all agents for large coupling.

How does topology of the interaction network influence this dynamics? Generally, a more heterogeneous network allows for the onset the regime that allows for a partial consensus for lower coupling, while a full consensus is impossible or only achievable when the coupling is very large. Contrariwise, in very homogeneous networks a partial consensus may only be possible for relatively large coupling, but one does not need that much more coupling than for a partial consensus to reach a full consensus.

These results have recently been augmented by studies of the influence of correlations between the native opinions on the chances of consensus formation (Brede 2008a, 2008b, 2008c, 2010). So, imagine that people with similar preferred opinions preferably interact with each other: Will this make it easier or harder to achieve a consensus among all? The answer is simple: It won't. The more positively correlated the preferred opinions of people that interact with each other, the harder it becomes to even achieve a partial (but macroscopic in the sense that a finite fraction of the whole population must share it) consensus. Even more: even if the consensus is possible, it will take a very long time to achieve it and the time grows with the strength of the correlations between the preferred opinions of people that interact with each other.

The basic explanation for this phenomenon is simple. If like people interact, they will quickly form a micro-consensus among a group of their neighbours. Henceforth they will mutually reinforce themselves in their consensus opinion and thus make it very hard to find a consensus with any other (group of) agents in the population. In contrast, if different people interact preferably, it is very difficult for micro-consensuses to emerge and if they are formed, they tend to be 'weak' and easily destroyed by the influence of other members of the population.

The above cautions us in a number of ways about the use of mean-field approaches (like that of the omniscient representative agent in economics) and the necessary level of detail that needs to be included when modelling agent utilities and agent interactions. First, it becomes apparent that a careful model of real-world social interactions is quite crucial for a realistic model of consumer choices. Not only this, such a model will also require a data-driven approach that utilises information about mixing patterns and segregation to allow for realistic projections. Both conclusions put a big question mark behind the RARE-agent hypothesis in traditional economics.

Of course, a crucial component in real-world dynamics is the emergence of larger social units, say: institutions, which are in complex interactions with the (sub)systems below and above them. For instance, governments have in most OECD-countries gotten important roles in redistribution and public goods provision. Their development has not been subject to the same evolutionary pressures as individuals and firms. What are the mechanisms in the way governments fulfill their role? Has the ICT-revolution / globalisation led to important novel dynamics of comparison and imitation and new forms of strategic behaviour in international arena's? The finance sector has a special role, because not only is it subject to competitive pressures (like other productive firms) but also it plays such a central role in the allocation of resources to other firms. Clearly good allocation decisions are important to growth, but the sector also engages in redistributive (rent-seeking) activity that may be counterproductive or at best neutral. Also, it is the focus, if not the sole generator, of bubbles and crashes. Its deregulation, concentration and globalisation has made these features more outspoken and influential. In short: our agent-based models have a long way to go and are therefore not a substitute for good political economy and common sence.

2.2.10 Agents and land use dynamics

'Agent-based modelling is effective in solving problems involving complex nonlinear dynamics that cannot be handled through standard optimisation techniques.' (Gintis 2007:1281).

Much of the CSS-approaches are about introducing heterogeneity among the (model) entities. This can be done in the form of distributions of one or two key features of an agent or a node, such as a strategy (in evolutionary game theory), a link-plus-rule (in network theory) or a location-plus-rule (in cellular automata). Not surprisingly, the Cellular Automata approach has become most prominent in the area of land use and land cover change (often denoted as: LUCC) in which the automat interact with their neighbours in physical space. Initial applications were abstract in the sense that physical gradients rather than agents were driving the dynamics (see e.g. IMAGE-model, Appendix D). In the last decade many applications of *Cellular Automata* (CA) *models* in geography have been published (Batty 2005). The approach is encroaching on economic issues – a few examples clarify the approach.

We first have a look at observed *regularities in space* (Andersson et al. 2003). The fact that geography forces the economy to distribute itself in on a surface may offer a window to understand not just urban growth but also economic processes. Indeed, economic geography is full of regularities and most notably approximate *power law distributions* that turn up in statistics over both cluster shapes and sizes (population, land value, area etc.). Regardless of details about these distributions, what can be said with confidence is that there is a clear stationary hierarchisation in economic geography. These patterns are furthermore curiously persistent geographically as well as historically. Hence, they are unlikely to be caused by idiosyncratic details of some economies, but should be due to quite fundamental, likely essential, properties of economies operating over a geographical space. Hence, these regularities may well be able to reveal fundamental things about economics in general.

CA models typically do not include economic models, and neither do they reproduce these regularities. In summary, the problem is that, although power laws in cities and economics have been addressed, one should bring these things together in a reasonably simple model: the shapes, geographical distribution and statistics of activities and their clusters. Andersson et al. (2003, 2005, 2006) has attempted to design a model of this by combining the CA approach with a complex network model. The CA governs local considerations about proximity to infrastructure. The complex network model is founded in one fundamental assumption about economics: value arises in exchange between activities. Briefly: connections form by two mechanisms – additive and multiplicative growth – and the proportion between them is controlled by a parameter. Both are also bias by distance so that short connections appear more frequently than long connections. Using a handful of parameters, many of which can be calculated empirically, the model generates results in agreement between simulated and empirical data (land value and population aggregated to 100X100 meter cell for Sweden in year 2000) on several unrelated regularities at the same time.

Another approach in economic geography has been the construction of an agent-based *land market model* (ALMA) grounded in urban economics (Parker and Filatova 2008). The conventional monocentric urban model was modified in an agent-based computational economics tradition (Tesfatsion and Judd 2006). Specifically, a) the equilibrium price determination mechanism was replaced by a set of bilateral distributed trades between buyer and sellers of land; b) representative agent was replaced by a population of heterogeneous ones. The ALMA model shows evolution of the spatial structure of land prices and the division of gains from trade under different scenarios of market power of agents and their adaptation to the competition in a land market (Filatova et al. 2009). Moreover, model runs with heterogeneous agents (e.g. in location preferences, incomes or risk perceptions) produce qualitatively different results from a model with representative agent, even if the former are in average the same as the latter. This has important policy implication since majority of policy decision-support systems use a representative economic agent. In particular, if individual heterogeneity in flood risk perceptions among agents is assumed, then urban development expands into the flood zone that a representative agent considers economically inefficient. Thus, potential damage from natural hazards in coastal town will grow beyond the level anticipated by policy makers (Filatova et al. 2009).

There are many more examples of agent-based models of processes in real-estate and finance, in agriculture and in other fields such as water and energy management. One next and promising step for these models is to reproduce empirical data and observations – for instance, in the form of reproduction of 'stylised facts' and system distributions (Dosi et al. 2007, LeBaron and Tesfations 2008). Such a link between data and observations on the one hand and theoretical models of agents on the other is what is needed now. Indeed, agent-based modelling may herald a new era in social science scientific method, because it makes participatory research .... data gathering a natural if not mandatory approach (Appendix E-F). At the moment the accessible agent-based models can roughly be categorised as:

- Toy models, with demos available on platform websites such as NetLogo: http://ccl.northwestern.edu/netlogo/;
- Applications as part of participatory policy exercises and games, notably the companion modelling approach developed at CIRAD: http://cormas.cirad.fr/indexeng.htm; and
- Add-on to engineering models on energy, water, traffic and other areas, where decision rules are gradually introduced to simulate human behaviour in a technology context.

Examples of the last category have already been given in previous paragraphs. In many scientific disciplines, agent-based models are being developed and published as open-source in combination with a couple of modelling platforms (see Appendix E and F).

2.2.11 Factors of production in the production function: energy, knowledge

'You cannot permanently pit an absurd human convention, such as the spontaneous increment of debt [compound interest], against the natural law of the spontaneous decrement of wealth [entropy].' (Soddy, in Cartesian Economics 1922:30)

Energy as an input is in most economic analyses considered as one of the subordinate production factors, labour and capital being the more important ones. After all, the coal and later the oil and gas which fuelled the industrialisation process were becoming more abundant and cheaper and considered to be available 'for free' – unlike in pre-industrial societies where people were and are well aware of the time needed to gather fuel wood, or of the land required to feed animals or of the human (slave) labour to drive processes. In the second half of the twentieth century, the appreciation of fossil fuel changed. As discussed before, capital accumulation and substitution between labour and capital explains at most half of historical growth in GDP, with the residue to be ascribed to 'technological change'. But what has been the role of energy? It has been argued since the 1930s that energy inputs, if properly measured, are the key explanatory factor behind economic growth. In response to the oil crises in the 1970s, it was proposed to expand the K-L production function with energy and materials: K-L-E-M.

Ayres and colleagues have taken up this issue and done careful data analyses. For the USA, for instance, the input of energy in the form of useful work ('exergy services') yields an almost perfect explanation of GDP-growth for the period 1900-1975 on the basis of the so-called LINEX production function (Warr et al. 2002; Kümmel et al. 2002, Ayres and Warr 2009):

$$Y = A \cdot U \cdot \exp\left(\frac{aL}{U} - \frac{b(U+L)}{K}\right)$$

with labour input L, capital input K, useful work input U and A, a and b parameters. If commercial energy use is used for U instead of useful work, the correlation with empirical data is much weaker. It highlights the important role of electric power. Two points are remarkable. First, useful work may well be a *sine qua non* for the kind of GDP-growth the high-income regions have realised in the past. Secondly, after 1975 the US-economy has experienced another source of value added - possible candidates are the oil price hike induced efforts to increase energy productivity and the rise of ICT. This suggests that GDP-growth in the low-income regions of the world will inevitably concur with an increase in the use of exergy services - notably of the high-quality carrier electricity. Or, stated differently, it suggests a clear lower bound on the energy-intensity defined as useful work per unit of value added (GJ/€).

One characteristic of high-income regions is the large and still growing fraction of employment and GDP of the *services sector*. This structural change process is the outcome of a complex interplay of factors: manufacturing and 'traditional' services have become ever more knowledge-intensive in interaction with IC-technology developments, simultaneously new manufacturing and consumer services have emerged, and globalisation has increased specialisation and information flows. This has been acknowledged long ago and incorporated in some macro-economic models by distinguishing different skill-levels in the labour force and introducing endogenous R&D-expenditures. But the basic production function framework has never been adjusted.

In manufacturing energy is a complement and a substitute ('mechanisation') for labour, while enhancing the productivity of capital. In service production (banking, insurance, administration etc.) labour routine operations can also be replaced by computer-based information processing ('automation') – but labour cannot be substituted for completely. Automation is accompanied by additional inputs of energy (mostly electricity) and capital (mostly information-processing). Along the lines of the LINEX production function described above, Lindenberger (2003) has proposed a maximum level of automation, which is associated with decreasing returns to energy utilisation. Assuming constant returns to scale and a boundary condition on the output elasticity of capital, he suggests a service production function of the form:

$$Y = Y_0 L \cdot \exp\left\{ a_0 \left(3 - 2\frac{L}{K} - \frac{L \cdot E}{K^2} \right) + a_0 c_m{}^2 \left(1 - \frac{L}{E} \right) \right\}$$

with variables as above and E the energy input, Y_0 and a_0 constants and $c_m = F\ e_m/k_m$ a measure of energy-intensity of the capital stock. Without going into any more detail here, it will be interesting to see if introduction of physical boundary conditions can yield more realistic production functions and, for some service sectors in particular, represent the limited potential for an increase of labour productivity ('Baumol's law').

Knowledge as an important factor of production has been introduced into macro-economic models in the form of endogenous (or new) growth theory. It is not discussed here. A rigorous way in which knowledge can be introduced in the economic dynamics is incorporated in the MADIAM-model (Weber 2004, Weber et al. 2005, Hasselmann 2009).

2.2.12 Economy-environment: renewable resources and ecosystem services

"It is becoming increasingly clear that many complex systems have critical thresholds – so-called tipping points – at which the system shifts from one state to another…it now appears that certain generic symptoms may occur in a wide class of systems as they approach a critical point. " (Scheffer *et al.* 2009:53).

Since the 1960s economic theory has started to (re) consider physical resources and constraints. New branches in economics have emerged as a result: environmental and resource economics, ecological economics. These subdisciplines are now well-established domains of education and research – see for instance the textbooks by Common and Stagl (2005) and Perman *et al.* (2003). Mainstream thinking in these subdisciplines is centered around ideas such as price mediated equilibria in natural resource and pollutant markets, factor substitution between manufactured and natural capital, long-term supply cost curves, optimum utility trajectories, the balance between taxation and regulation etc. (Van den Bergh 2002). Is 'getting the prices right' an adequate answer to shortcomings in theory and models? Clearly, solid answers to these questions are important – but there remain other urgent questions to be posed at the interface between economics and ecology.

The role of human behaviour in renewable resource exploitation. It is widely recognized nowadays that humans are overexploiting many of the resources which sustain human society in its present form – not only non-renewable ('finite') ones such as oil and mineral deposits but also renewable ones such as fish, forests and soils. Many resource-economic models have been proposed, mostly from a (maximum) extraction perspective. Such models were developed by high-level 'predatory' groups in society, whether governments or business – and the scientific reductionism served their interests (Scott 1998)[xl]. The big failure was the exclusion of human behaviour.

Most conventional renewable resource use models are inadequate to explain real-world behaviour – a point cogently made by Allen and McGlade (1987) in the case of the Nova Scotia Groundfish Fisheries. For instance, only for one of three fish species – haddock – a relation between catch and effort has been observed. The (only) explanation is that for haddock prices were responding to demand-supply dynamics, whereas this appeared to be absent for the other two species – cod and pollock. Specifying a three age-cohort haddock fisheries model with logistic growth dynamics, it is also found that inclusion of a well-known fact: the extremely variable birth rate of the haddock, suddenly shifts the smooth equilibrium behaviour of the deterministic simulation into wild fluctuations. The explanation here is that the *human exploitation responses can amplify the natural fast fluctuations*, inducing Lotka-Volterra type oscillations. A natural 'background noise' can suddenly show up during human interference and such a fluctuating resource can probably never yield a constant and satisfactory economic return – an important conclusion and a caveat for simplistic ideas about sustainable management.

Using the *logistic growth model* for (three, competing) species, the authors simulate the distribution of fishing boats in space using two terms for fishing strategy. The first one is: if revenues exceed costs in a zone, fishing effort is directed to that area – and if they don't, effort will decrease. The second one is: there is an exchange of information within and between fleets, which causes spatial migration on the basis of 'expected profits'. The latter term is modelled as a probability, with a behavioural factor I between 0 and 1: for I=0 the available information on other boats is disregarded and the skipper is a randomly operating *stochast*, whereas for I=1 any difference in expected profitability leads to behavioural change and the 'ultra rationalist' skipper is called a *cartesian*. This still rather simple model gives some interesting results about the actual and possible complexity of renewable resource exploitation.

The non-risk-taking cartesians go fishing where they know it to be profitable – and then deplete the zone and move on. The risk-taking stochasts, on the other hand, exploit in a stochastic fashion also what is knew – and in the process map the resource more quickly and completely. Thus, the behavioural parameter I represents the trade-off between cartesian *efficiency and stochastic innovation*, with a hierarchical and anarchic organizational structure respectively. If both strategies are permitted, the stochasts will outcompete the cartesians. But – the cartesians may develop novel strategies, for instance, becoming stochasts themselves or get information from stochast explorers (spying, stealing, buying). Simulations indicate that with a complete information exchange the cartesians outcompete the stochasts and the latter only survive if they manage to form alliances.

Thus, the model shows the role of *behavioural variety*; it indicates the importance of invading new strategies; and it suggests the potential for complexity in real-world situations. From a sustainable development point-of-view, the relevant lesson is that any real-world situation will fluctuate between random behaviour with long-term benefits (knowledge, innovations) and efficient behaviour with short-term gains (profits, stability). Both sides are needed and will show up in the cycles of real-world exploitation history. Besides, *"the model shows the opposition between short and long term decision making... in order to escape from the destructive circle of increasing competition, we see the importance of management principles which would maintain diversity, and explore alternatives beyond the present 'rationale'...If we are to avoid a future of ferocious and ever growing competition, in a shrinking world with a single perspective and the common values of a single culture, then we must encourage 'stochasts', and the diversity and expansion which only they can bring."* (Allen and McGlade 1987:165-166). Similar research on fishermen's strategies suggests that, indeed, the role of humans as predator is a key determinant and has an inherent logic in the long-term evolution of the resource (Brede and De Vries 2009).

Increasingly it is acknowledged that the exploitation of renewable resources is taking place within a complex web of ecosystem relationships and that those ecosystems provide many more functions than the one singled out by traditional and commercial users. This idea is expressed in the notion of *ecosystem services*. The number of papers and books on these phenomena is growing rapidly and once again we do not aim for completeness. Instead, I focus on what these insights might mean for economic modeling.

In the last decade, attention has been drawn to the more general and widespread effects of economic growth on natural systems in the form of degradation and loss of *ecosystem services* (www.millenniumassessment.org). The role of ecosystems in providing necessary but often non-priced inputs for economic processes is becoming more clear, now that productive soils, unpolluted water flows and clean air become more scarce. Yet, it is not easy to assess their role as they are in multiple ways connected to human activities. Their valuation is also contentious, not in the least because it usually is a common resource for which adequate exploitation regimes have to be established lest they are not degraded or even destroyed. A major topic in environmental and ecological economics is at which level the quality of ecosystem services should be sustained. This, of course, depends not only on the 'utility' in a broad sense derived from it but also on the effort, or 'utility' forgone, by maintaining the quality.

One approach is to assess the economic value of the ecosystem services lost. A practical solution is to count the inputs needed to restore the environmental quality c.q. ecosystem services to the desired level as the value added which should be assigned at the very beginning to the natural resources, together with the lost resource value due to size and quality decline. Of course, there will never be an absolute reference point in complex socio-ecological systems: humans have been altering many ecosystems already for centuries or even millennia. This has intensified in recent times – as exemplified, for instance, in a model on the co-evolution between the biological species and the agricultural practices in the form of pesticide resistance (Noailly 2008). In its most simplistic form the issue solved with (marginal) abatement cost curves and the various methods to evaluate the (implied, long-term, discounted) costs of ecosystem damage against the (short-term, discounted) costs of reducing ecosystem interference. As has been argued in the Sustainability Outlook (MNP 2004, 2007) a more strategic and comprehensive approach is to use cultural perspectives and value orientations. For instance, one can distinguish the extremes of a risk-taking entrepreneurial attitude ('nature robust', risk of lost business opportunities) and of a risk-averse conservationist attitude ('nature fragile', risk of irreversible loss) (de Vries 2001a). Recently, the notion of synergy or co-benefits, that is: of policy measures which simultaneously support the quality of various sources and sinks, is gaining prominence.

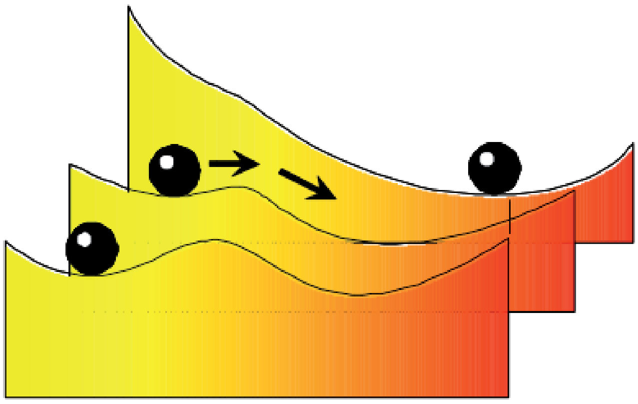
2.2.13 Economy-environment: catastrophic change

It has been known for quite some time that ecosystems occasionally experience sudden, discontinuous change (partly) as a consequence of human interference (exploitation, pollution). Such non-linear complex behaviour has been studied in the last decades with help of formal models, in order to understand such behaviour and use it for adaptive resource management. The existence of more than one basin of attraction may cause a sudden shift in system structure and behaviour – a so-called *regime shift*. A class of nonlinear equations which have been proposed to analyze this phenomenon is a third order equation (Appendix C.11):

$$dX/dt = -X(X^2 - \alpha)$$

This equation was at the basis of *catastrophe theory* as developed in the 1960s and 1970s by Thom and Zeeman. The essential point is that a change in the slow parameter α influences the behaviour of the fast changing state variable X. Figure 2.7 is the iconic representation of such a dynamic: it shows how the position of a system (the ball) may gradually shift to another attractor due to slow changes (α) in the landscape.

Figure 2.7



Graphic representation of a system's dynamics for a change in slow variables.

There are now several real-world phenomena which suggest the existence of such regimes shifts. Gordon *et al.* (2008) examine how agricultural changes across the whole hydrological cycle can produce regime shifts. They have identified three categories of agriculture – water regime shifts which do with more or less evidence occur. The first group are in agriculture – aquatic systems, including changes in runoff quality and quantity that lead to regime shifts in downstream aquatic systems; the second one are in agriculture - soil, in which changes in infiltration and soil moisture result in terrestrial regime shifts; and the third one agriculture - atmosphere, in which changes in evapotranspiration result in regime shifts in terrestrial ecosystems and the climatic system.

A classical example is the *Spruce budworm and forest* which is about the interactive dynamics between the spruce budworm, its predators and the boreal forest (Holling 1986; Meadows 2008:92). One of the lessons was that the budworms are crucial in maintaining forest diversity. It has important consequences for forest management: interference by spraying insecticides kept the budworm population under control but it also kept the budworm food stock (balsam fir) at a high level and killed off the natural predators. In Holling's words: the forest managers set-up a situation of 'persistent semi-outbreak'. A similar cycle has been observed with regard to budworms, tree foliage and predators (birds).

Another situation of nonlinear regime shifts in response to external and associated internal ecosystem variables may occur when there is a positive feedback between consumers (e.g. plants) in combination with limiting resources (e.g. water, nutrients). Such a regime shift might happen in *semi-arid regions* if grazing pressure exceeds a critical threshold – with possibly catastrophic consequences indeed (Rietkerk et al. 2004, Kefi et al. 2007). It was found that the patch-size distribution of the vegetation follows a power law and that this can be explained from local positive interactions among plants. The model was then used to simulate the effects of increasing grazing pressure – a realistic experiment in view of such increases in many places in the world. It turned out that the deviations from power laws seen in the field data also emerged in the model simulations and, importantly, that they always and only occurred close to a transition into a desert. The researchers proposed that patch-size distributions may be a warning signal for the onset of desertification. Imagine that our complex social-economic-cultural systems also have such thresholds beyond which sudden catastrophic change might occur – quite a different metaphor from the one of smooth ongoing growth in material welfare usually presented…

A well-researched example of a regime shift is *Eutrophication of shallow lakes* (Scheffer et al. 2001), which is an archetype of ecosystems under stress of a disturbance e.g. a pollutant. An influx of nutrients from inflowing fertilizer and wastewater and industrial effluent cause a growth of phytoplankton, which in turn causes bottom plants to disappear as they get less or no light. The lake becomes turbid and also small animals living on the bottom vegetation die off, several fish species disappear and a monotonous community is what remains. Birds visiting the lake drop by an order of magnitude. *"Overall, the diversity of animal and plant communities of shallow lakes in the turbid state is strikingly lower than that of lakes in the clear state."* (Scheffer et al. 2002:198). These observed phenomena can be formalized in terms of a catastrophic change model with two branches of stable states (Appendix C.11).

The model indicates an important point for management: to restore the situation of the lower branch, one has to go back to much lower nutrient concentrations than when the switch to the upper branch occurred. A detailed analysis of the shallow lake area De Wieden in The Netherlands has shown that understanding of the ecosystem complexity can be useful indeed. Much effort and money has spent on reversing this trend by reducing the nutrient influx – in many cases without success. Instead of phosphorus (P) emission reduction, the goal of clear water can more effectively and at lower cost be realized by biomanipulation (removal of the benthivorous fish) (Hein 2005).

One of the challenges for (resource-)economic models is to incorporate the use of ecosystem services in a broader, complex dynamical context. An interesting example is about *rangeland management in northern Senegal*. There is a large amount of data available to test various models. Hein (2005) has constructed a simple model with logistic growth of the livestock, no feedback from grazing upon the pasture forage production (and hence livestock carrying capacity), given annual rainfall and fixed prices. In subsequent steps, this benchmark model is refined with stochastic variation in rainfall, a negative feedback of grazing upon rain-use efficiency, and price fluctuations in a situation of drought. It is found that the inclusion of these elements, reflecting the loss of resilience for drought due to high grazing pressure, indicates an optimal long-term stocking rate up to 20% below the benchmark model value. Besides, the current values are in the order of 50% *above* the indicated optima. How can these insights be implemented in simulation of long-term climate-induced changes in the (semi-)arid regions of the world? And, given the potential catastrophic changes in these regions as described above, how can our stories *and* our models prepare us better for such events and their consequences?

2.2.14 Non-renewable resources

Renewable resources have, as the word indicates, the potential to be used indefinitely – one may speak of sustainable resources. As we have seen, their exploitation only lasts if it meets certain conditions. There are also resources, that is: earthly substances, which have been formed in geological processes in the course of millions of years. They are non-renewable and their use is therefore finite. A characteristic feature is that their depletion tends to show up as rising discovery and exploitation costs (deeper, farther, lower quality…), although this has so far been offset by technological cost reductions.

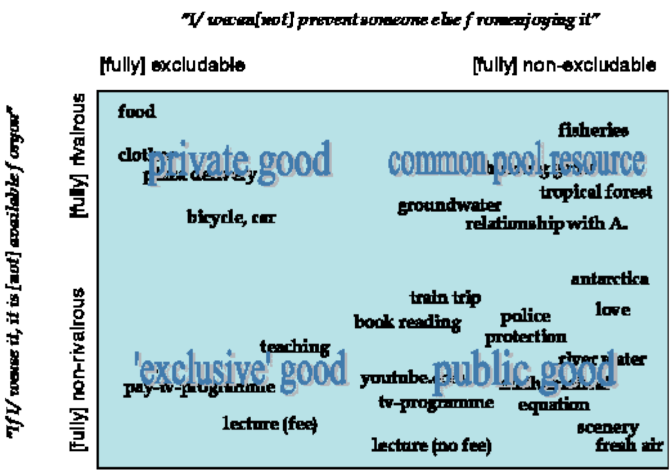
The well-known system dynamics model World3 (*Limits to Growth*: Meadows et al. 1971), was the first integrated model to explore the consequences of rising use of finite resources at increasing costs – and its spelled collapse in a world of exponentially growing population and industrial production. This would show up as stagnation or decline in economic activity because at some point production cost will rise so high that it absorbs the larger part of economic output. This idea was vigorously contested by economists with the argument that price increase will induce substitution, demand stabilization or reduction, and innovation. When prices of minerals and fossil fuels were stable or even declining in the 1990s, they were apparently right. But resource depletion came back as an issue in the first decade of the 21st century, when a combination of rapid industrial growth and geopolitical tensions caused great price volatility – notable for the world's largest drug: oil.

The issue is relevant because the depletion of strategic resources (oil, phosphorus a.o.) is usually conflict-ridden, as it is perceived as necessary for economic growth and power. In macro-economic models, the market 'solutions' of rising marginal and average production costs, inducing demand reduction as well as innovations and subsequent substitutes, generates smooth transitions without incurring any conflict or even price volatility. In the global markets and the approaching scramble for diminishing and deteriorating resource deposits of the 21st century, one should prepare for other modes of system behaviour (A1.A2: Chapter 1). Which ones?

Classical economics largely dealt with rent and royalty aspects and rising prices to reflect the opportunity cost of quality decline. Neoclassical resource models applied dynamic pathways with utility maximization (see e.g. Dasgupta and Heal 1979; Ströbele 1977 and paragraph 2.2.11). The resulting optimal depletion pathways are too abstract to be of much use. More recently, resource and environmental economics have worked out more specific applications (see e.g. Van den Bergh 2002) There are a number of system dynamic resource models (see e.g. Meadows et al. 1973, Fiddaman 2002, Ruth and Hannon 1997) and some essential features such as a long-term supply cost curve have been introduced in IAMs (Appendix D). These models are quite interesting inasfar as they simulate informational and strategic aspects of resource exploration and reserve position and cost and technology dynamics of resource exploitation and substitution. Agent-based models might contribute to further realism of the resource exploitation process but such models are hardly available in this field, possibly because the really interesting dynamics has to do with complex oligopoly and trade issues and political and institutional dynamics.

Not much news in terms of formal modeling has emerged to my knowledge, but we did not explore the issue in depth during the workshop. One of the interesting and controversial questions is whether resource abundance hampers or stimulates economic growth. In a well-known paper, Ross (2001) performed an analysis of 113 countries in the period 1971-1997 which suggested a link between large oil (and other mineral) wealth and authoritarian governance – the so-called *resource curse* hypothesis. There is a least tentative support for "*three causal mechanisms that link oil and authoritarianism: a rentier effect, through which governments use low tax rates and high spending to dampen pressures for democracy; a repression effect, by which governments build up their internal security forces to ward off democratic pressures; and a modernization effect, in which the failure of the population to move into industrial and service sector jobs renders them less likely to push for democracy*" (Ross 2001:356-57). More recent econometric analyses for a large sample of countries for the period 1970-1995 confirm that natural resource abundance (using mineral production share in GDP as a proxy) correlated negatively with economic growth – a resource curse. However, the effect reversed sign if other possible explanatory variables such as corruption, investment, openness, terms of trade and schooling are included (Papyrakis and Gerlagh 2004). In a long-term perspective, there is evidence that abundant natural resources tend to crowd-out other income-supporting activities, notably savings (Papyrakis and Gerlagh 2006). It would be interesting to incorporate this mechanism into economic growth models. The Oxford Centre for the Analysis of Resource Rich Economies (OxCarre: www.oxcarre.ox.ac.uk) examines in more depth and for individual countries the relationship between resources, economic welfare and governance. One can only hope that some of the more universal insights from this kind of research help to provide

Figure 2.8



The concepts of excludability and rivalry.

macro-economic regional and world macro-economic models with a more long-term and realistic perspective.

2.2.15 Managing the commons: the challenge of cooperation

The issues discussed in the previous two paragraphs beg the question: how to manage the earth resources which are a common heritage of mankind, although resource appropriation may well be one of the major drives in the rise and fall of civilizations. In principle, the resources are open to access and owned by everyone: they are Common Pool Resources (CPR). With ever more and more aspiring human beings around, sharing our finite planet becomes a must. Hence the urgent task to find appropriate institutions and arrangements to manage these CPRs. Much work has been done by Ostrom and colleagues (Ostrom 1990, Ostrom et al. 2002). One essential insight is that there is no single panacea – every situation has its characteristics features and thus problems and solutions (Ostrom 2007). This provides a warning against universalist claims (A1-B1 worlds; Scott 1998).

Another lesson, backed up by lots of experiments, is that managing commons – including public goods and bads – has to fulfill certain conditions (Dietz et al. 2003, Faysse 2005):

- the resource (use) can be monitored;
- the information on the resource (use) can be verified and understood at low cost;
- the resource (use) and its system environment changes at a modest rate;
- the resource user community has a dense social network, with face-to-face contact, which
- facilitates building of trust and maintaining of rule compliances;
- low-cost exclusion of outsiders from resource use;
- resource users support effective monitoring and rule enforcement;

Formal models (CA, ABM) can help to explore various management designs (Section 2.2.9).

Unfortunately, these conditions can rarely all be met simultaneously. Yet, they do give a clue about what should be included in economic models to make them more relevant and realistic in telling the stories we need for the 21st century.

Managing the commons is not only important in the quest for ecological sustainability, it is in the form of managing public goods an equally important task for the realization of economic and social sustainability. Economic science offers the concepts of excludability and rivalry to understand the social dilemma's involved in managing public goods (and bads) (Figure 4.10; Claassen 2008). If resource scarcity intensifies, whether on the source (depletion) or sink (pollution) side, the drive for exclusion and rivalry will increase. What kind of mechanisms and dynamics are operating? How can we better understand and manage the ensuing situations? And can such insights be incorporated in (economic) models? But – these questions were not addressed in our workshop.

Some agent-based models explicitly address the issue of competition versus cooperation in the exploitation of renewable resources. An early example was the investigation by Allen and McGlade (1987) (Section 2.2.12). More recently, dynamic interactions between different fisheries have been modeled and explored using the Stella ® software, in order to find out about harvest rules, stochastic natural perturbations, spatial heterogeneity and cheating (Low et al. 2001). Three management strategies (open access, constant quota and sole owner) were investigated for different assumptions on the spatial interactions between the fisheries. One result was that mismanagement can occur when the managers misperceive the appropriate scale at which populations operate: global optimal rules may cause local destruction. This suggests the benefits complement local management organizations instead of centralized management. There are far too many models of fisheries for an overview here. However, the complexity of the fish-cum-fishermen is clearly overlooked in 'textbook models' and more complex models suggest intricate relationships between the nature of the resource and the exploitation rules (see e.g. Janssen 2004, Brede and De Vries 2009). Another area of CPR-management was also investigated with a Stella ® model: irrigation infrastructures (Sengupta et al. 2001). As with fisheries and forests, the dynamics of these social-ecological system (SES) should be incorporated into the large-scale IAMs if we are to get a better idea of the prospects for quality of life in the future.

2.3 Summary

In the second half of the twentieth century it became clear that the 'real world' was more complex than the laboratory world of physics and chemistry. Real-world systems had threshold and catastrophic behaviours, had a variety of positive and negative feedback systems in operation, and could better be understood in terms of evolutionary games than simply rebounding billiard balls. The economic agent is more than *homo economicus*[1] - (s)he is social, and often irrational and cooperative. The notion of economic systems in equilibrium is false. In many cases there are informational and physical delays and unforeseen feedbacks and events which cause perennial non-equilibrium situations.

We have explored in this chapter several ways to remedy this situation. Clearly, a more in-depth understanding about market exchange processes is needed and the following should be explored:

- the role of (public) information
- drivers of (corporate) engines of growth
- how the consumer is involved
- the mechanism behind developments in science and technology, and
- how can resource management address the finite carrying capacity of the planet?

Many years ago a biological metaphor (predator-prey) was the dynamic in many economic processes and inspired modelling. More recently, another biological metaphor has provided an important avenue for economic research and modelling, namely evolution: change through reproduction, selection and mutation. It has led to a whole new set of models which can explain the penetration of new manufacturing techniques and consumer products. One mathematical equivalent of evolution, network theory, is providing us with new insights at meso and macro-levels from micro-inputs. Interaction is the keyword in all of these approaches.

The social sciences have always emphasised the inadequacy of the image of (wo)man in economic science and have proposed more refined models. Not surprisingly, agent-based modelling has proved to be popular among some groups of social scientists. It formulates human behaviour according to field observations and experiments, leading to disciplines such as behavioural and experimental economics. New agent-based modelling platforms are evolving and changing the very theory and practice of modelling. There is no clear borderline between the two. In addition complementary analytical work, which expands the concept of utility function with interaction networks and agent memory, is ongoing. Models of binary choice, opinion and attitude dynamics reflect the similarity between statistical mechanics models and impact function formalisms from social-psychology. It appears that mean field solutions are reasonable approximations for certain ranges of parameter values, but issues of aggregation and scale linkages remain important areas for further research.

The question of ecological sustainability is of particular importance in an economic growth/development context. Recent insights in ecosystems indicate that thresholds and feedback mechanisms can cause catastrophic regime shifts if inadequate models of the industrial 'no-limits' paradigm prevail. Resource management must allow for ecosystem resilience, analyze the occurrence of ecological thresholds at higher spatial and temporal scales – including climate change – and integrate thresholds and feedback mechanisms in macro-economic models. New, participative ways of dealing with uncertainty and strategic behaviour of stakeholders should be developed and used. An interesting approach is provided by the common pool resource (CPR) framework.

The kaleidoscope of models constructed in the last decades offer a fascinating and hopeful scenario. Is it possible to see a larger picture emerging? Fiddaman (2010) suggests that there are at least three mechanisms currently operating in economic processes: (1) rational intentional change, (2) gradient following, and (3) population learning. Traditional economic models ascribe all change to rational intentional change. When prices change, or are expected to change (or, in some models, are known to change in the future), agents immediately change their allocations to whatever is optimal, given the new conditions. The dominant processes in agent-based models are that changes in relative prices creating selection pressure. A middle ground is used in system dynamics models: agents have local information about profitable opportunities for change, but they proceed incrementally along the profit gradient, in the absence of global information about the system. This involves an element of deliberate change, depending on the level of understanding involved.

Each of these models has its problems in making the connection with real world observations. We have seen examples of models where simple interactions result in rich system dynamics. However, the relationship with social science field work is not always clear. For instance, the simplified interactions at the microlevel in econophysics network analyses are at the other extreme of the rationally and optimally behaving *homo economicus.* Similarly, the attractiveness of evolutionary mechanisms may lure us into a false kind of myopia: how does cooperation in all its forms show up? Can it be that the apparent intelligence and variety of the human individual as emanating from the behavioural sciences (psychology, anthropology, and sociology) evaporates in the crowd? Shouldn't we delve for 'deeper' mechanisms behind the observed aggregate system behaviour? Perhaps it is a good idea, as Bentley and Ormerod (2009) propose, to start with the 'zero-intelligence' model as the null hypothesis. We represent human individuals *as if* they are billiard balls, or ants, or social atoms. Then, as our understanding advances, we add 'depth' in the form of cognitive processing, memory and so on.

1 *Homo economicus*, or *Economic human*, is the concept in some economic theories of humans as rational and broadly self-interested actors who have the ability to make judgments towards their subjectively defined ends

3

Population-Energy-Economy-Climate (PEEC) models

3.1 Integrated Assessment Models (IAMs)

Many societal macro-problems are multi-faceted and have to be investigated in integrated interdisciplinary ways (see e.g. Rotmans and De Vries 1997). The World3-model in the report *Limits to Growth* to the Club of Rome, based on a system dynamics approach, was and still is a good example. Human-induced climate change is such a macro-problem and it is at the core of most of the so-called Integrated Assessment Models (IAMs). Climate change was not the only or earliest core of IAMs. For instance, transboundary air pollution was at the core of a number of Integrated Environmental Assessment Models (IEAMs).

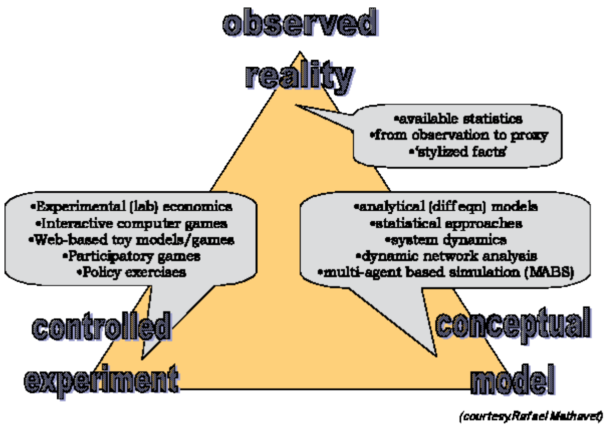
In first instance, integration meant the coupling of a (simple) macroeconomic model with a (simple) climate model, with carbon emission from the energy system as the linking variable. The DICE-model is the archetypical example, whereas the MERGE-model is an enlarged version with a more extensive energy system[xli]. Later examples are the EPPA-model, the IMACLIM-model and the WITCH-model. Most of these long-term economic models are neoclassical growth models with (nested) production function, considered 'top-down' because of the aggregate way in which price-driven equilibrating substitutions govern the dynamics and the (global) utility maximising algorithm drive the system from one equilibrium state to the next.

Another route has been to extend existing energy models, often denoted as 'bottom-up' because the approach is rooted in engineering models, with environmental submodels, examples being the RAINS/GAINS-model (Hettelingh et al. 2009), the MARKAL-model and its offshoots, the MESSAGE-MACRO-model, the GET-model, the EPPA-model and the IMAGE-TIMER-FAIR-model. These models are mostly using simulation in combination with least-cost optimisation algorithms. Systematic comparison of the various top-down and bottom-up models clarify the major differences in methods and results (Van Vuuren et al. 2009). An interesting development is the construction of hybrid-models like IMACLIM-R and WITCH, which attempt to integrate – to a larger extent than before – the bottom-up engineering approach with simulation of physical units with the top-down economic approach using price-equilibration and monetary units. The WITCH-model applies game theory to explore the dynamics of regional utility optimisation as against the outcome with a global 'central planner'. The IMACLIM-R model introduces technology by making in-between the equilibrium states changes in the input-output coefficients, in order to introduce explicitly processes of adjustment and inertia into the model.

Some main directions are visible in the last decades. First, already for decades the issue of carbon emissions was not associated with impending climate change ('sink side') but with finite high-quality energy sources ('source side': depletion). In energy-engineering models such as MARKAL and TIMER, oil and gas depletion is dealt with in the form of long-run supply cost curves. Macro-economic models introduced the same notion as a way to simulate long-term energy price increases towards some 'backstop' option level, for instance from solar devices or controlled fusion. In economic jargon: resource scarcity was identified as the cause of (marginal) productivity decline at fixed technology. Secondly, since technological developments and innovations are – in their dual role of cause and solution – a linchpin in future pathways, much emphasis is being given to modelling technology/innovation dynamics (Weyant et al. 2007). It connects to the New Growth Theory in economics: agent-based and evolutionary approaches could be, but are not yet, integrated.

Thirdly, because land cover change/use is increasingly recognised as an important source/sink of carbon, all models tend to incorporate parts of agriculture and forestry. This includes traditional fuels and allocation of land for renewable energy sources (de Vries et al. 2007a, van Ruijven 2008), but it easily flows over into issues of food production, water availability and sustainable livelihood. Fourthly, because the impacts of climate change on human health and economic activities are increasingly seen as inevitable, the models are focusing not only on emission reduction ('mitigation') but also on ways to adapt to climate change ('adaptation'). This broadens the scope of the models further as they now

Figure 3.1



Conceptual scheme of the relationship between conceptual models, observations and controlled experiments in dealing with complex macro-problems.

have to deal with developments in population (age, health), water sources and use, dynamic and interregional cost-benefit evaluations and so on[xlii]. Indeed, the functioning of ecosystems as provider of services in the broadest sense is to be considered. To summarise: energy system/ climate change oriented IAMs models gradually expand into sustainable development models (see for instance the Global Integrated Sustainability MOdel GISMO: http://www.pbl.nl/en/themasites/gismo/index.html).

Most climate change related IAMs are within the traditional economic and engineering paradigm[xliii]. There are no attempts to incorporate evolutionary or other forms of non-equilibrium dynamics, no agent-based modelling is introduced, and no insights from network theory about the role of interactions are inserted. This will be an important challenge for the years to come. However, extending IAMs with the formal models constructed in complex systems science is not the only way forward.

The triangle scheme in Figure 3.1 is shown to emphasise the continuous interaction there has to be between empirical data ('observed reality' – case studies), conceptual models and attempts to link the two via various methods ('controlled experiments'). Instead of extending the IAMs, with the risk to make them ever more intransparant to all but the modeler, one may simplify the model and focus on the interface between on the one hand the (knowledge about) the system being investigated, and on the other the person (user: policy analyst, student…) who tries to grasp the system dynamics in order to design desirable and effective interventions.
In this way the scientific observations incorporated in the model and the personal observations of the user are linked in flexible ways, which allow positive interactions and learning experiences. This approach has been consolidated into methods like simulation games and policy exercises. From a social science point-of-view, the approach may also serve as a laboratory in which human behaviour can be examined under more or less controlled circumstances – as done in experimental economics, for instance.

Of course, there is still room for large variety. One extremum is to open up the IAM for user-inspection, for instance via the web as is done with the GET-model (see www.chalmers.se/ee/getonline) which has been constructed as part of the GSD-project. Another extremum is the CLIMEX-project we present in the next chapter, developed also partly within the GSD-project, which focuses on the user in interaction with an extremely simple model. In the remainder of this report, we will first discuss two examples of simplified models and then discuss the CLIMEX-project.

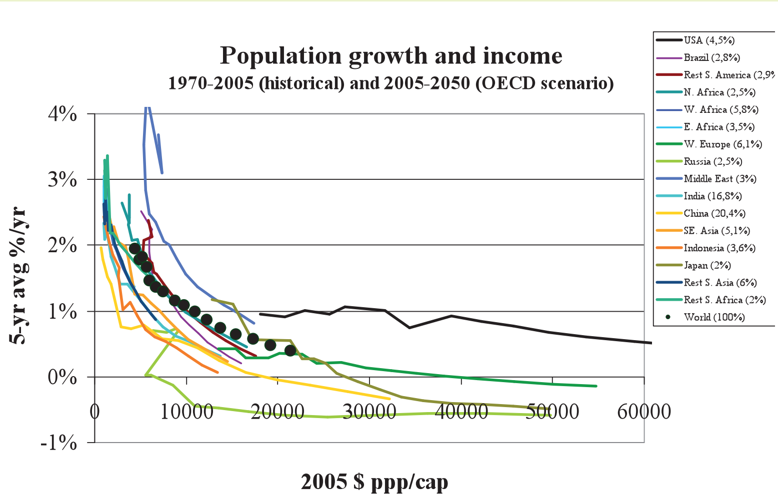
3.2 The simulation model SusClime

3.2.1 Introduction

An elementary population-economy-energy-climate (PEEC) simulation model has been made over a decade ago, to be used in a simulation gaming set-up (De Vries 1998). The essence of this model was exponential population growth at a rate which depends on income; a labour force whose productivity increases with rising capital-labour ratio; and two capital stocks to deliver energy, one carbon-containing fossil and the other non-carbon renewable. The model was explored for a two-country world in which the interactions consisted of a) fossil fuel trade, b) exchange of knowledge on renewable energy, and c) the atmosphere as a common sink for carbon dioxide emissions. It has been used in a simulation-gaming set-up, which taught us the difficulty of engaging people into a long-term risk issue[xliv]. Earlier work of e.g. Nordhaus with the RICE-model addressed similar questions as we do here; we feel that our explorations add some novel elements.

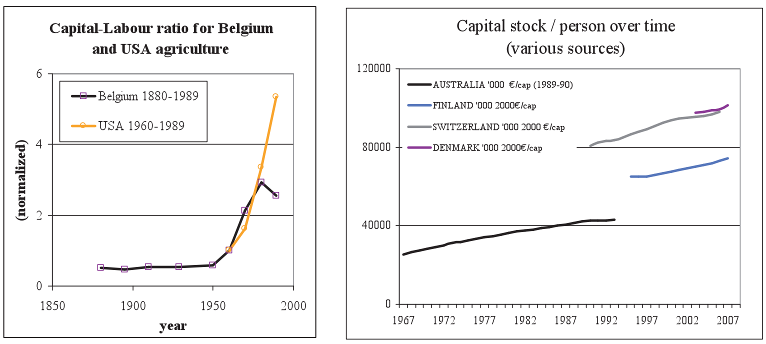
IIn this paragraph, I present a brief overview of the SusClime model in its later, updated form (Van Ruijven 2008, Roorda 2009). *Population growth* is connected to economic activity: its net growth is an exponentially declining function of income (consumption per capita). Using the world data of income as GDP/cap/yr (Y) and of population growth (PopGR) (Bakkes et al. 2008, OECD 2008), there is for most regions a good fit with

Figure 3.2



The 5-yr moving average population growth plotted versus income (GDP/cap/yr) for 16 world regions. The black dots are the world average values.

Figure 3.3



Left (a): the ong-term trends in the ratio of capital stocks and employment in agriculture in Belgium and the USA. Right (b): the growth of per person total capital stocks over time in four countries; residential buildings make up 35-45% of the total.

a power curve PopGR=aY^{-b} (Figure 3.2). Also an exponential decline curve gives a good fit. For low-income regions there is a wide spread, though, but the power curve remains a good fit (R^2>0,84)[xlv]. For the world: the black dots in the graph, a=74,6 and b=-0,973 (R^2=0,98).

As a model of the *econom*y, we postulate the existence of two capital stocks: goods producing capital, K_P, and consumption capital, K_C. Goods producing capital (K_P) represents raw material exploitation (excluding energy) and the processing and manufacturing of goods. Basically, it is the machinery and factories in the economy: tractors, food processing plants, chemical and car factories etc. Consumption capital (K_C) includes the aggregate of all capital that is used to provide welfare services, from direct consumption of food, paper etc. to mobility (cars, trains, airplanes, but also infrastructure) and shelter (dwellings, offices etc.). The capital stock K_C is associated with the delivery of income or consumption – in other words, consumption C is defined in units of annual income per unit of capital[xlvi]. Utility derived from income is considered a logarithmic function: U=ln(C).

For economic output we use the equivalent of a simple neoclassical production function of the Cobb-Douglas type. It is expressed as the labour-productivity λ as a function of the capital-labour ratio K/L with the labour force L a fixed fraction of the population. This represents the phenomenon that the amount of goods and services produced per labourer/employee tends to rise but at a declining rate with the amount of capital (and incorporated technology) at his or her disposal. It is a historical observation for sectors such as agriculture, where the capital stocks refer to tractors and other machinery, irrigation and other infrastructure etc. (Figure 3.3a). For the industrial sector such a relationship can also empirically be confirmed, although the variety in capital stocks necessitates a more disaggregated description for it to be meaningful. For the service sector, the link between capital stocks and labour productivity is a difficult one – how to measure output, what is the contribution of IC-technology, office space and other 'capital' components? However, at an aggregate level in the high-income regions it is clear that capital stocks per person have increased at a higher rate than population and contributed to the increase in labour productivity (Figure 3.3b). We assume there is no exogenous growth in TFP (Total Factor Productivity). Because of the decline in marginal labour productivity at increasing K/L ratio and the presumed decline in population growth with rising income, income levels saturate after a period of, initially fast, growth.

The model simplification is considered acceptable because the focus is on the *energy transition*: constraints to economic growth in the form of finite fossil fuel – for short: oil – resources and a finite sink for emissions from combustion – the atmosphere. Let us first look at *energy*. Energy is needed to operate the capital stocks K_P and K_C. In formula: $E_i = F\ \varepsilon_i\ K_i$ (i=C, P) with ε the energy-intensity, i.e. the amount of energy required per unit of capital stock. The energy-intensity is assumed to be an asymmetric bell-shaped function of per capita consumption to reflect phenomena of economic structural change and saturation (De Vries 2006; Van Vuuren et al. 2006).

Energy supply comes from fossil fuels and/or renewable sources. The fossil fuel resources face depletion: productivity in terms of energy units produced per unit of capital stock declines with cumulated use. Initially, each country has only a fossil fuel capital stock which is assumed to produce fossil fuel at rising marginal cost. Renewable sources (hydropower, solar and wind power, nuclear, bio-energy) are initially producing at high costs but due to learning-by-doing the capital stock gets a higher productivity with cumulated output.

In order to satisfy *energy demand*, investments into energy capital (I_E) are needed. They can be allocated among three options: energy efficiency (I_{Eff}), carbon (or fossil) energy production (I_{Fos}) and non-carbon (or renewable) energy production (I_{Ren}). Countries can also import or export fossil fuel: economic output can be spent on import of fossil energy (M_E).

Anticipated energy demand for fossil fuel and renewable energy respectively is determined on the basis of a multinomial logit formulation in relative costs c_F/c_{Ren} of the respective energy sources. The decision how much fossil fuel to trade with another country is made similarly, now in relative costs c_{FosImp}/c_{Fos}. The – simplified – procedure is to determine first the market shares of renewable and fossil energy, then calculate the market share of imported fossil energy in the resulting fossil energy. In formula:

$$MS_{Fos(t)} = \frac{1}{1+\left(\frac{c_{Ren(t)}}{c_{Fos(t)}}\right)^{-\lambda}} \quad \text{and} \quad MS_{Ren(t)} = 1 - MS_{Fos(t)}$$

in which MS is market share and λ_1 is the logit parameter which determines the sensitivity for cost cq. productivity differences. The market share is considered an indicated. ‘optimal’ market share, which tends to be satisfied via investment allocations.

If the costs of fossil fuel in the or another country is less than in the own country, $c_{FosImp} < c_{Fos}$, trade may be advantageous for both countries[xlvii]. The resulting average energy price for consumers and producers is calculated in order to determine the energy efficiency investments I_{Eff}. These have declining marginal productivity too: the effectiveness of a unit invested in energy efficiency decreases with the share of efficiency investments (I_{Eff}) in the total investments. In a next step, the required investments into carbon and non-carbon energy production capital are calculated and allocated within the constraint of available capital. This constraint is derived from a simple savings rate relationship.

If fossil energy is used, carbon dioxide (CO_2) is emitted into the atmosphere. If *emissions* into the atmosphere exceed the outflow from natural breakdown and absorbtion by the oceans and other sinks, there is a gradual build-up of this greenhouse gas in the atmosphere. This causes a rise in average global surface temperature and sea levels – in short: climate change. SusClime uses a greatly simplified climate model. The atmospheric CO_2-concentration is calculated from cumulated carbon emissions, using the formula of Maier-Raimer and Hasselmann (1987; Janssen and de Vries 1998). The potential (equilibrium) change of global mean surface temperature is described by:

$$\Delta Tp_{(t)} = \frac{\Delta T_{2XCO2}}{\ln(2)} \cdot \ln\left(\frac{p_{CO2(t)}}{p_{CO2(t=0)}}\right)$$

in which p_{co2} is the CO_2-concentration and the global mean surface temperature change associated with a doubled CO_2-concentration – the so-called climate-sensitivity which is currently estimated to be most likely above 1.5 and below 4.5 with a central estimate around 3.0 (IPCC, 2007). Inertia in the system (in particular due to the huge heat capacity of oceans that slows down the speed by which a new climate equilibrium is reached) implies that the actual temperature increase will lag behind the potential temperature increase, according to the formula:

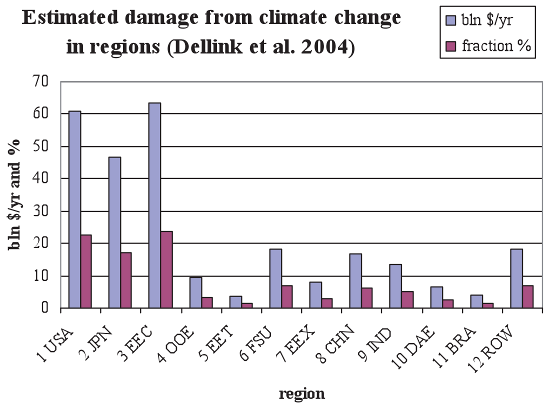
$$\frac{d\Delta T}{dt} = \beta \cdot (\Delta Tp - \Delta T)$$

where β is assumed 0.05, causing a delay in reaching the equilibrium temperature of about 20 years.

A highly uncertain aspect of climate change is the *feedback on the economic system*. A commonly applied approach is to use quadratic functions for market damages with increasing temperature, as in the DICE (Nordhaus, 1993) and MERGE (Manne et al., 1995) models. A more optimistic assumption is that there is an ‘optimal climate’ as far as the economy is concerned – an implicit assumption in the quadratic function approach – and that society is able to adapt to climate change (Hallegatte, 2005). The socio-economic system still faces impacts from climate change but only when it is *not* in equilibrium with the climate. Whenever temperature stabilises after a period of change, the economic system has the ability to adapt to the new climate regime and the impacts will diminish or even disappear.

Modelling such an endogenous adaptation of the economy is based on the notion of an ‘adaptive temperature’, i.e. the temperature to which the economic system is adapted (T_a). It equals the surface temperature (T_s) when economy and climate are in equilibrium, but diverges from it when the

Figure 3.4



Estimates of the monetary damage from climate change if a 2°C rise in average global surface temperature would occur (Dellink et al. 2004, based on Fankhauser 1995 and Tol 1997).

climate changes faster than the socio-economic system can adapt. The adaptation process is defined by:

$$\frac{dT_a}{dt} = \frac{1}{\mu} \cdot (T_s - T_a)$$

in which μ equals $5 \cdot LT_{(t)}$ (the lifetime of capital stocks), which implies that the economic system adapts to the changing climate in five capital turnover periods. If the adaptive temperature and the surface temperature differ, the unadapted economic system faces two impacts: 1) productivity losses (CC), for instance in agriculture and infrastructure, and 2) shorter capital life times (LT) caused by increased wear or destruction due to change in climate or early retirement for reasons of adaptation to climate change. Both impacts are assumed proportional to the maladjustment of T_a to T_s:

$$CC_{(t)} = 1 - \alpha_{CC} \cdot \left| T_{a(t)} - T_{s(t)} \right|$$

$$LT_{(t)} = LT_0 \cdot (1 - \alpha_{LT} \cdot \left| T_{a(t)} - T_{s(t)} \right|)$$

The parameters α_{CC} and α_{LT} respectively represent productivity loss and lifetime change for a maladaptation of 1 degree[xlviii]. In the real world, the severity of climate change impacts will differ from country to country. Although such impacts are largely unknown and cannot, or even should not, be quantified in monetary terms, we show one estimate (Figure 3.4). Note that such estimates do not include, at least not explicitly, the adaptation measures people will take in response to climate change. Nevertheless the estimates indicate probably correctly that regions will be affected quite differently – and respond and adapt differently as well (IPCC 2007).

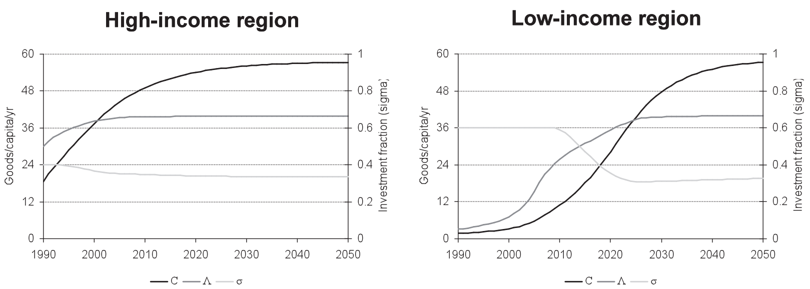
3.2.2 Some baseline results

Given capital allocation rules, the model can be used to construct a baseline or reference economic development path: fossil energy resources are abundantly available, and climate change has no impact on the economy. We have implemented the model for 2 regions only. The two regions are assumed to have the same population size (1000), but the high-income region is assumed to have a ten times higher goods producing capital stock (16000) and income (16) than the low-income region as of the initial year (1990). Investment allocation is based on simple, rigid rules (Van Ruijven 2008).

The outcome of this illustrative simulation is shown in Figure 3.5. The high-income region continues to increase its labour productivity by building up more goods producing capital. Once labour productivity reaches its maximum level (around 2010), the savings rate (σ) decreases, after which investments in consumption capital increase and income further rises towards almost 60 goods/capita/yr. The growth rate of income decreases from 9%/yr in 1990 towards zero at economic stabilisation. The low-income region, initialised at an income level of 1.6 goods/capita/yr, needs to build up goods producing capital to stimulate economic development. This is done during the first two decades. The savings rate (σ) goes to a maximum urealistic level of 60% and labour productivity jumps almost tenfold in a 30-year period as a result of the rising capital-labour ratio. Around 2030, labour productivity reaches its maximum level, investments shift towards consumption capital and income levels keep rising but more slowly. The initially low income grows at rates of 14%/yr before the decline towards stabilisation sets in. Clearly, these values are quite unrealistic and the model run is merely an illustration with a toy-model. Note also the absence of a positive TFP as the engine of economic growth.

In previous work we have experimented with investment decisions made by automated agents using a few simple rules (De Vries 1998). Recently, we have refined the agent decisionmaking process (Van Ruijven 2008, Roorda 2009). We used the model to identify strategies to cope with the potential impact of resource depletion and climate change on the development trajectories for both high-income and low-income regions. Each region is faced with an intertemporal dilemma between short term maximisation of consumption involving extensive use of (cheap) fossil energy, and the long-term impacts of depleting the finite fossil energy stocks and of climate change. The possibility of realising higher economic

Figure 3.5



Baseline economic development in SusClime, without fossil energy depletion and without climate change. Investment allocation is based on simple, fixed rules.

growth by importing fossil energy if endogenous resources become depleted adds another element.

Usually, agent-based models contain many (micro-)agents that are characterised by simple behavioural rules and through their interactions cause emergent behaviour at the macro-level (Chapter 2). In our model experiments, each region is represented by a single agent who makes investments and oil im/export decisions in order to maximise cumulated income within a time horizon (or look-ahead period) T. Using the same simple rules for investment allocations, the agents can influence the reference path by deciding for oil im/export (S_M) subsidising renewable energy (S_{Ren}) and/or a carbon tax on fossil fuel (oil) (C_{Tax}). The trade-off they face is between the highest possible income growth on the one hand and the damages from fossil energy depletion and climate change on the other.

The formal procedure is that each agent – a high-income and a low-income one in the two-region model – is characterised by a policy option vector (S_{Ren}, S_M and C_{Tax}) which is a function of its forward looking period (T, 20 or 40 years), and by an objective function (D) which reflects the agent's preferences. We analysed several objective functions: (combinations of) consumption (C), utility (U), goods production (Q) or import dependence (E_M), both cumulative or in the final year of the time horizon, eventually combined with discounting. Introducing a discount rate has the same effect as using a shorter time horizon. Due to the saturation of income at high levels in the absence of (exogenous) TFP-increase, the landscape of the objective function is rather flat at high income levels. Therefore, we decided to maximise the non-discounted income (C) at the end of the look-ahead period (T).

In the starting year (T_{ini}, 1990) the agent looks ahead for a period of T years and varies the policy vector (subsidies, taxes) in order to maximise the objective function D for its own region. When the agent has found an optimal value, the policy measures are set and the model is run again with the policy measures fixed for the starting year. Then, it goes on to the next 5-year period, while linearly interpolating the decisions for the years T_{ini}+1 to T_{ini}+4, and repeats the procedure.

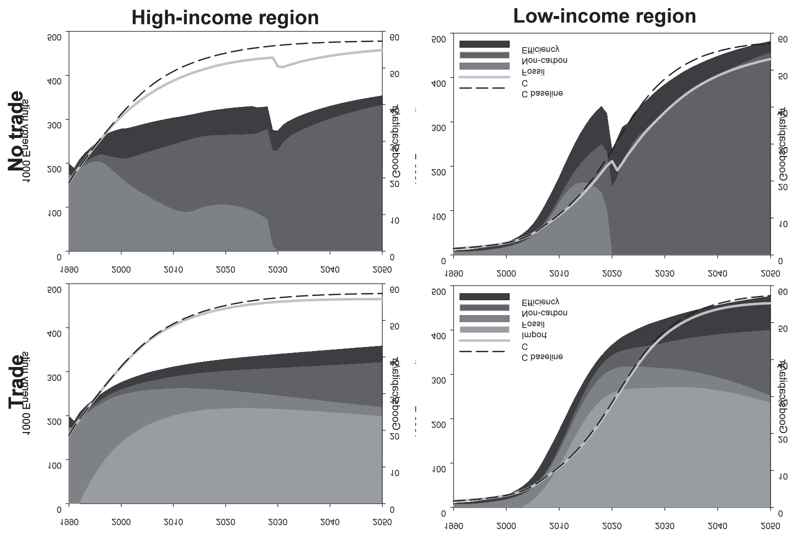
In order to explore how the high- and low income regions respond, we have first run experiments *without* climate change. The first experiment explored the situation with fossil energy constraints, not allowing for oil trade and without forward looking agents – the base case. Next, we allowed for oil trade. In the third experiment we examined the effect of forward looking agents as compared to the base case. Finally, in the last experiment the situation with fossil energy constraints and allowing for oil trade and with forward looking agents is investigated. For detailed results we refer to Van Ruijven (2008) and Roorda (2009). Here we confine ourselves to the illustrative results of two experiments.

Experiment 1. Let there be two forward looking agents with a forward looking period of 20 years, who in the absence of the option to import oil from elsewhere in the world can only subsidise renewable energy to accelerate the energy transition. For the high-income region, the agent is able to significantly reduce the impact of fossil energy depletion on income by investing early in renewable energy. It leads to a smooth energy transition although with decrease of about 10% in per capita consumption levels at its height (Figure 3.6, upper left graph). If the high-income region has the option to import oil, it starts subsidising imported energy and manages in this way to sustain the baseline income growth path (Figure 3.6, lower left graph).

For the low-income region, the depletion of fossil energy resources is a major obstacle to sustained income growth because renewable energy is so much ore expensive initially. Without trade, the agent performs better than without a forward looking agent (Figure 3.6, upper right graph), but the depletion of fossil energy clearly slows down economic development. If trade is possible, also the low-income agent subsidises imported energy and manages in this way to avoid most of the income loss (Figure 3.6, lower right graph). Imported energy becomes quickly the major energy source, with only after 2020 a gradual market penetration of renewable energy.

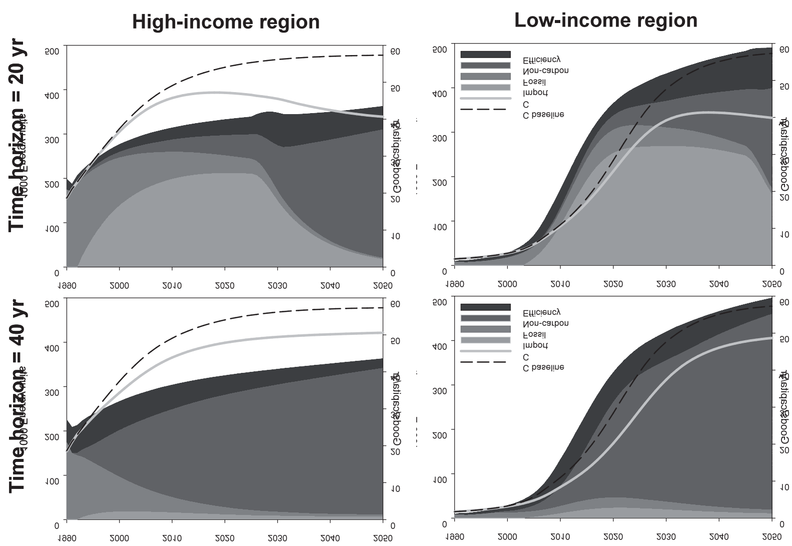
Experiment 2. How does our two-region world fare when the carbon emissions from burning oil and causing climate change are considered? Again, we show the outcome of only one simulation experiment, in which we examine the combined dynamics of fossil energy depletion, oil imports and climate change. The policy to combat climate change is

Figure 3.6



Energy supply and income (C) with depleting fossil energy resources with and without trade and with forward looking agents (only importing regions are shown).

Figure 3.7



Results of forward looking agents dealing with fossil energy depletion and climate change with different time horizons (only importing regions are shown).

applying a carbon tax. There are multiple dynamics in this experiment, which provide a useful framework to interpret today's arguments in a longer-term context. Depletion of fossil energy can force a transition to renewable energy, making climate policy less urgent. But it may also lead to increased fossil energy imports, with no or even higher carbon emissions (and impacts from climate change). Climate policy, on the other hand, will stimulate a transition to renewable energy, thus reducing long-term damages with the co-benefits of slowing down the use of indigenous and world fossil energy resources – but it has a short-term cost in terms of lower income growth.

As the results in Figure 3.7 show, both high-income and low-income 'short-term' agents start subsidising imported energy in order to postpone the economic impact of resource depletion. The high income agent changes its policy around 2030, gradually decreasing import subsidy while instantly applying a high carbon tax (Figure 3.7, upper left graph). However, this is not early and intensely enough to avoid significant income losses from climate change. The low-income agent follows a similar strategy but applies its carbon tax even later, in 2045, also too late to avoid a significant income loss (Figure 3.7, upper right graph).

What would happen if the agents look forward 40 years instead of 20 years in designing their policies? The high-income agent now immediately introduces a high carbon tax, phasing out fossil energy use and avoiding depletion of resources as well as the more severe climate change effects (Figure 3.7, lower left graph). The low-income agent applies the carbon tax also in an early stage, around 2000, initially using fossil energy to fuel economic growth but also largely avoiding the deleterious effects of depletion and climate change (Figure 3.7, lower right graph). In other words: a longer time horizon of policy-makers clearly diminishes the hardships of the transition.

This experiment shows, in a stylised way, some of the linkages between resource depletion and climate change. A long-term focus on avoiding climate change also slows down cost increases and depletion of fossil energy resources. The reverse is not necessarily true: a short-term focus on avoiding resource depletion may cause the agents to respond by stimulating energy imports – which will for the foreseeable decades be carbon-based. This will therefore aggravate the risks of climate change impacts. The potential co-benefit of an early transition towards renewable energy is therefore not observed in the short-term objective function. This corresponds to the observation in the world nowadays, that rising oil prices cause an increase in the deployment of coal (e.g. coal-to-liquid fuels for transport).

3.3 Climate change policy: the role of coordination[xlix]

Following up on the SusClime model, we developed a stylised economy-energy-climate model with which we explored the difference between optimising welfare for the world at large – a single planner – versus each region optimising welfare for its own. This is indicated as *collaborative* or *cooperative* vs. *competitive* management. In this setting the atmosphere, fossil fuels and a stock of accumulated knowledge about renewable energy technologies are common pool resources (CPRs) in collaboratively vs. competitively managed worlds.

The model is the same as in the SusClime model described in the previous paragraph, apart from minor changes in order to more easily parameterise the model. We consider three *common pool resources* which link the regions: the atmosphere, the finite oil resources and the knowledge stock about renewable energy technology. The first two are also operating in the SusClime model. The agent formulation is now more sophisticated. Each region is governed by a central agent who decides how to allocate investments over the goods producing economy and the carbon-based and non-carbon based (renewable) energy supply, the remainder being for consumption. Agents are faced with a dilemma situation. Economic growth requires energy and will therefore accelerate depletion and generate growth in carbon emissions, the latter leading to global warming and climate change induced damages. By developing non-carbon energy sources, which come at a higher cost than fossil fuels, growth of carbon emissions can be curtailed but at an (initially) lower rate of economic growth. Trying to optimise a consumption-related utility, agents base their decisions on the economically most rational investment portfolio for a finite time horizon. However, due to the CPRs they are constrained by the choices of other agents. It is this dilemma that we wish to investigate.

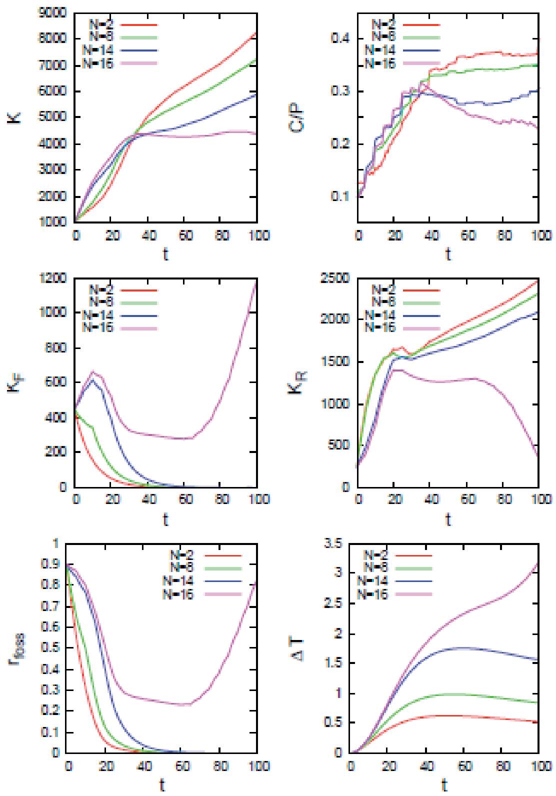
We consider two prototypical situations: (i) a collaborative environment where all agents strive to maximise a world utility – the global optimum – and (ii) a situation where agents optimise the utility of their own country – a solution that corresponds to a Nash equilibrium. The utility function is a time-averaged population weighted per capita function of the form:

$$U(C,P) = \frac{\int_0^T P(t)\log\left|C(t)/P(t)\right|dt}{\int_0^T P(t)dt}$$

In the competitive situation, agents decide to optimise their own utility function $U_i=U(C_i,P_i)$ in an iterative procedure, adjusting sequentially their decision on the basis of the decisions of the other agents until no further improvement is possible[l]. In the cooperative mode, agents decide in a similar procedure to optimise the world utility function $U=U(\Sigma C_i,\Sigma P_i)$. The difference between the competitive/regional and the cooperative/global outcome can be used to classify the severity of the *'tragedy of the commons'* (ToC) effect. We present results about the dependence of the severity of this effect on several key parameters: (i) the number of actors, (ii) the heterogeneity and severity of expected climate damages, (iii) assumptions about technology diffusion and (iv) fossil fuel depletion. Fossil fuel will from now on be indicated as oil.

The first and simplest experiment we do is to examine the change in utility as a function of the number of agents/regions, assuming all regions having the same population and capital stocks, abundant oil and no knowledge transfer. Only the atmosphere is a common pool resource. The model is parameterised in such a way that the cooperative strategy in this world leads to a rapid energy transition away from oil. In the competitive mode there is a utility loss relative to the cooperative mode, which rapidly grows when the number of agents increases and/or when the damage from climate change is larger. The mechanism is rather simple and the essence of ToC: each agent anticipates that other regions will emit carbon and therefore it is faced with some degree of climate change it cannot influence. The optimal response to this is to increase consumption earlier in the planning period, which requires fast initial growth. Rapid economic growth, however, can only be achieved when the use of 'cheap', i.e. fossil, energy is extended, which in turn contributes to climate change. When all actors reason in this way a vicious cycles is started which is only stopped when agents anticipate damage costs in their own regions equal to the benefits from spurring economic growth.

As an illustration of such a course of events in a competitively managed world, we show in Figure 3.8 the evolution of the capital stocks and some other variables for 2, 8, 14 and 16 agents/regions. For less than 16 agents the investments in oil rapidly decline and in renewable energy rapidly rise – but the energy transition is slowed down significantly when there are more agents. The income level at stabilisation is also lower with more agents, whereas temperature rise is higher.



Evolution of the production capital stock and per capita production, of the energy capital stocks, and of the fossil fuel/renewables supply mix ratio, and the effect on the climate (temperature change). The damage constant is a=0.1 (severe damages). Results are for worlds of 2, 8, 14 and 16 regions.

Above the threshold level of 16 regions, oil production even experiences a revival in a world getting ever hotter…

We have done a couple of other experiments with our toy-model. One first question to be explored is: what difference one finds between the cooperative and the competitive worlds when not only the atmosphere but also the oil resources and the renewable technology knowledge stock are *common pool resources*, and: accessible to all? This is the ideal world of the economist – because most efficient. We summarise our findings for a situation *without* climate change:

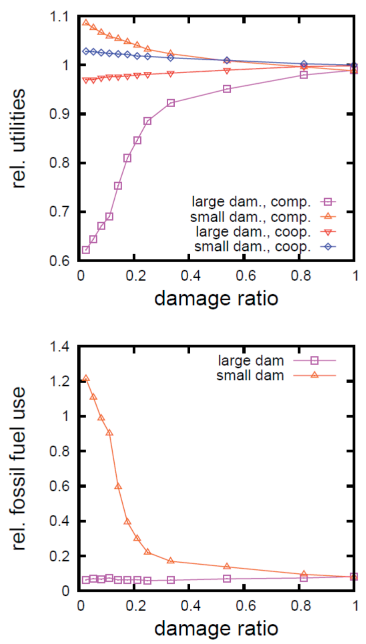
- treating the oil resource *or* the knowledge stock as a common pool has a similar effect: it intensifies the ToC by promoting early use of oil and making the transition to renewables more abrupt;
- treating both oil resource and knowledge stock as a common pool, a much steeper and non-linear decline in utility happens with an increasing number of competing agents. There are also situations now in which energy demand cannot be met and the economy suffers from energy shortages.

If climate change is included, that is: the atmosphere is treated as a common pool too, the situation worsens significantly. With more than 2 or 3 agents, the scramble for oil intensifies and over-all utility falls with 20-30% as compared to the cooperative world. Energy shortage become more severe as the transition to renewable energy becomes even more abrupt.

Another interesting question is how the outcome changes if the regions are dissimilar in population size, damage from climate change or income – a *heterogeneity* so obvious in the real world. We have looked at differences in a two-region world in population, in income and in damage from climate change. If there are two competing regions, one large and one small, the small country tends to benefit as it can free ride on the concerns and efforts of the large country. If the two regions have different income levels, the rich country with the larger economy and hence emissions cares most about climate change. Besides, the smaller economy is eager to have economic growth which requires cheap (fossil) energy. If knowledge is a common pool resource, the poor country will benefit from the rich country's energy transition. We also explored a more direct form of altruism, by introducing the utility of other regions in one's own utility function (Chapter 4). Such a formulation works out in the model as a more cooperative mode and hence an earlier transition away from oil.

If the two regions experience different levels of damage, the country with smaller damages increasingly lacks incentives to undergo an energy transition and tends to rely on oil. It contributes heavily towards global warming, thereby forcing the country suffering large damage into an early accelerated

Figure 3.9



The upper graph shows how regional utility (normalised by optimal utility if countries suffer equal damages) depends on the damage ratio for two management strategies and a region with large and one with small damage from climate change. The lower graph shows fossil fuel use (also normalised) for these same experiments.

energy transition for which it needs to invest a large (and over time increasing) share of its income. This is shown in Figure 3.9.

We do realise that these model experiments represent an extremely simplified world. Yet, at the same time one observes that many leading government officials and business people, and their (economic) advisers, are operating within a framework which actually isn't that far removed from our toy world. Competition in the search for high(er) income levels is the major driving force and the continuous comparison of costs and benefits of any (central) policy with other regions is precisely what we see in climate policy negotiations. A large discrepancy is that in the real world decisions are made on the basis of much shorter time-horizons – a mechanism that could be included into the model by introducing a (income-dependent) discount rate into the utility function. The inclusion of large discount rates into the model postpones the energy transition in all simulated futures. Another issue is that the number of agents is not simply equal to the number of countries, because countries with similar interests may forge coalitions. Indeed, as our model shows, such a reduction in the number of agents greatly enhances the prospect of a beneficial coordinated strategy. An interesting way to extend the model is to model the emergence of coalitions. Other directions for future work are incorporating explicitly the role of energy prices and energy efficiency and the role of technology in economic growth.

3.4 Summary

Most of the integrated assessment models (IAMs) of the population-economy system and its interaction with the climate system via the energy and food systems, are a combination of traditional neo-classical economic growth model and bottom-up simulation models of physical flows. Policy oriented model experiments usually takes the form of strategies to maximise utility over a relevant time horizon (100 years) and the relative costs and benefits of intervention strategies. Recently, the linkages are strengthened in the form of hybrid models such as IMACLIM-R and WITCH. It will be a challenge to introduce insights from complex systems approaches, as discussed in the previous chapter, into these large IAMs.

There are other ways in which the science-policy interface can be strengthened in order to improve decision making. In this chapter the focus is on model transparency and model use. A simple system dynamics model, SusClime, has been constructed in order to show some of the crucial trade-offs between resource depletion and climate change. The time horizon of the decision maker is a crucial parameter. A long-term climate change policy slows down cost increases and depletion of fossil energy resources. A short-term policy may actually aggravate climate change impacts by fuelling carbon addiction. This may place any long-term and co benefits of an early transition towards renewable energy out of sight.

In a follow-up toy-model we explore the costs and benefits of coordination, again in a highly simplified model world. What happens in a resource and climate-constrained world, in which a number of regions (not the single utility-maximising agent) steers the world into the twenty-second century? It is an exercise in managing the commons: the atmosphere as an inevitable global commons, the finite oil resources and the generated knowledge about renewable resources as human-designed global or regional commons. In fact the number of independent regions becomes an important variable in this model. If there are many small regions, noone will feel the incentive to act as each one is too small to significantly reduce the impact in their own region. The model experiments yield several other insights which can provide more insight into the current debate on climate policy. Divergent stories can be told, as suggested in Chapter 1, with an A1 world as a competitive one with full access to oil resources but not to knowledge, versus a B1 world with full access to both but working under a quota on the use of the atmosphere. Further research work on this area is required.

4

Communicating insights: interactive modelling and simulation games

'Scientific research and complexity science, in particular, should play an increasing role in the formulation, implementation and monitoring of policy. This will require better cooperation and exchange between the scientific and decision-making communities. '(CEC, 2006a:11). 'Thus there is a requirement for a new class of applications of simulation methods and computational technologies which can perform two interrelated tasks: Use modern mathematical and numerical simulation techniques in order to represent complex, dynamic systems in such a way that analyses can be carried out much more rapidly than with current models.
Develop and deploy new interactive ICT methods with effective visual interfaces, to effectively represent to stakeholders complex outcomes. ' (GSD, 2008:7).

4.1 The need for legitimacy

A changing climate is nothing new. To the contrary, it is an integral part of Earth history (De Vries and Goudsblom 2002). Natural events which were and are catastrophic for local or even regional life on Earth, such as earthquakes and volcano eruptions, have become part of risk management. An individual person can arrange an insurance against it, in which way the risk is collectively distributed. If the potential damage is too large for even re-insurance firms, the state takes over the responsibility – at least formally. This is the practice with other human-induced risks such as a nuclear power plant accident.

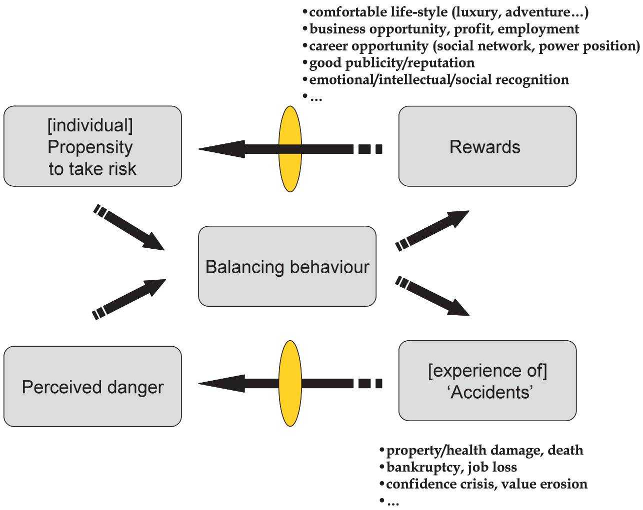
Society faces many other risks. Natural catastrophes are only one of Elias' trias of dangers: besides threats from outside there are the interhuman and intrahuman dangers. Can an individual insure himself against the risks of another World War or the collapse of the State? Evidently, these would be events for which humans would be co-responsible, yet it would often be hard to find culprits and hence make legal claims and compensatory demands afterwards.

Scientists are now almost certain that there will be climate change in the 21st century which a) will affect the lives of many human beings; b) in ways which are hard to predict (where, when, how?); c) and is at least partly caused by human beings; d) as a consequence of a large diversity of sometimes essential activities. The burning of fossil fuels is considered one of the main causal factors. Individual insurance and risk-reducing measures are possible. However, each person individually cannot do anything about the outcome and would therefore best go 'Business-as-Usual', also indicated as an *attentiste* ("wait-and-see", "after-you-Sir") attitude (Section 3.3).

The effects of climate change will be more visible and real to future generations and to people living in other regions than to those individuals responsible for the current CO_2 emissions. The collective (community, government) has to play a role in the anticipation, preparation and burden allocation of the (most) undesirable consequences. For this, it needs information to assess causes and risks, it needs a political decision-making process to translate this into efficient policy intentions, and it needs legitimacy in order to effectively enforce these policies. Such decision-making is being done at the interface between (energy and climate) experts with their scientific certainties and uncertainties embedded in their worldviews on the one hand, and the population at large with their value pluralism and diverse understandings on the other.

The perception of climate change: the cultural construction of risk. At this point it is worth reflecting a bit more on the notion of risk. All living organisms have to act under uncertainty and risk. Even when it builds up a lot of experience about the rewards and punishments of available options to act, the list of possibilities in an ever changing environment is never exhausted and uncertainty and ignorance will stay. Besides, there are – apparently random and unpredictable – fluctuations which make 'rational' deliberation even less satisfactory.

Figure 4.1



Scheme of the way in which individuals deal with risk: the Risk Compensation model (Adams 1995).

In biology, one can for simple organisms in relatively stable environments construct a rather narrow 'cost-benefit' evaluation of the action repertoire built up during the species/individual history. An empirical basis is provided by measurements of the organism's metabolism, whereas evolutionary game theory frames the possible actions in a larger strategy space (see e.g. Maynard Smith 1982).

The social sciences, including economic science, have to deal with the much broader action repertoire of human beings. Memory, imagination, values and mental maps, in short: worldviews, all play a role (De Vries and Petersen 2009). Metabolic rates and game-theoretic analyses will not suffice. It explains the empirical finding that human beings so often behave in contradiction with their best interests as defined in a narrow cost-benefit game-theoretic framework (Dietz et al. 2003). Concepts like bounded rationality and satisficing have emerged from this insight and broader formulations of rationality have entered the models of human behaviour.

4.2 Risk, uncertainty and climate change: conceptual models

4.2.1 The risk compensation model and Cultural Theory

Many theories have been proposed to deal with risk and uncertainty in complex macro-problems such as human-induced climate change (Apetrei 2010). The framework offered by Adams in his book *Risk* (1995) combines a constructivist notion of risk (perception) with the tenets of the Cultural Theory as proposed by Douglas, Thompson a.o. (Thompson *et al.* 1990, Verweij and Thompson 2006). This 'theory' can neither be proved nor disproved, but it provides an operational framework to deal in a systematic and intelligent way with the complexities of human behaviour under uncertainty and risk.

What is risk? One common definition is "*the perception of the probability and magnitude of some future adverse event*" (Adams 1995:180). In practice, it is often narrowed down to a particular period in time and particular causal and consequential events. Uncertainty is different, at least in scientific parlance: whereas risk deals with quantifiable probabilities, with uncertainty one even does not know the odds of certain outcomes. In this sense, Adams' theory of risk as a social construct and the associated conceptual model of risk compensation (Figure 4.1) is more about uncertainty than risk, because often the odds are indeed not known or even knowable.

The essence of the *Risk Compensation model* is that objective risks do not exist in the real world and that the risk-taking actions of individuals i.e. their behaviour, are a constant dynamic balacing between individual risk-propensity, perceived dangers, perceived rewards and experiences of bad outcomes or accidents. Although an enormous activity in modern society is related to risk management – think of insurance companies and road safety regulations – it appears difficult to interpret what is going on at the meso- and macro-level. Adams suggests that the Cultural Theory provides a useful framework here: the cultural construction of risk takes place within the four contending rationalities of the hierarchist, the individualist, the egalitarian and the fatalist. They function as filters (Figure 4.1), let us say X-filters (X=H, I, E, F).

What does this mean in the case of climate change? An individual may be more or less risk-prone, perceive certain dangers such as from floods or storms, remember stories from friends about drought or heat waves – and decide that the situation does or does not justify… selling her SUV, skip the annual trip to Madagascar, buy an A++ refrigerator or finally improve house insulation. The plurality in this process is easy enough to establish. How, however, do we come from such a bewildering micro-diversity to a more tractable meso- or macro-perspective on the role of science and government?

The quintessential element in the use of models to answer this question is the belief that one can deal with the – largely unquantifiable – risks of human-induced climate change in the form of a *cost-benefit analysis* (CBA). The CBA is the preferred tool of the *hierarchist* planner, whose rationality presumes an agreement about objectives (the 'objective function'), about values and about options for action. In the past decades, a rapidly expanding community of climate modelers, energy analysts/modelers and macro-economists have constructed a theoretical framework to be found in the prevailing tool to assess the costs and benefits of (no-)action: the Integrated (Environmental) Assessment Model (or IAM) (Section 3.1).

Most IAMs simulate a central global planner, as representative of the global governments or citizens, with perfect foresight in order to maximize per capita utility over the next one or more centuries (Appendix D). It represents a *hierarchist*, state perspective. Indeed, this may explain why the large number of IAM-based model simulations and scenarios have been considered of limited help in climate policy formulation. In the context of the risk compensation model (Figure 4.1), it will be clear that such model experiments completely neglect how individuals will respond to (the risks of) climate change (Chapter 3).

On the other hand, an *individualist* filter will tend to have a different, more optimistic view on the damages and adaptation possibilities resulting from climate change. She will emphasize the (attitude of) opportunities to be grasped – and be pessimistic on the costs of avoiding climate change if possible at all. This position perfectly fits with a high time preference: mitigation measures are a certain cost for me/us/here/now, climate change damage and adaptation uncertain costs for them/elsewhere/later. Hence, one cannot and should not expect more from the individualist than a rather myopic perspective, which only results in action if the evidence is strong enough to outweigh the risk of no-action and/or the urgency is high enough to create business opportunities. In the meantime, however, as they will be keen to point out, the entrepreneurial and innovative dynamics of market capitalism will deliver as yet unforeseen and unforeseeable solutions to the problem. No government interventions in response to alarmist environmentalists are needed. Neither are models.

As has convincingly been argued in Cultural Theory, there are more perspectives than these two. An important group in the present context are the *egalitarians* who take the risks of climate change very seriously and insist that all sections of society and all nations should contribute to avoid the worst. Contrary to the ones with an individualist filter, egalitarians will tend to overestimate the probability and extent of climate change while being optimistic on the costs and measures to reduce its causes. Like individualists, they have a healthy distrust and skepticism about CBA and IAM. CBA will be criticized because, among other reasons, many of the adverse changes to be expected cannot meaningfully be monetized (Adams 1995 Chapter 6). IAMs are discredited as reductionist tools which tend to disregard or underestimate the lives of the poor and of future generations.

Egalitarians play an important role in the over-all dynamic. First, they can provide or erode legitimacy of hierarchist interpretations and policies: *"Decisions about risk are esentially decisions about social priorities and the values by which our societies wish to be guided. To exclude the bulk of the population from these fundamental choices would be to ensure neither the equity nor the effectiveness of regulatory policies"* (Irwin, quoted in Adams 1995:197). Their view will not be shared by hierarchists and individualists, read: by Big Government and Big Business, but they will in most western democracies not too visibly or aggressively act against it as it may erode their political support basis. Secondly, egalitarians may stimulate innovative entrepreneurs by forging coalitions between government and business interests and designing and organizing support for regulations.

A last, fourth group are the *fatalists*. In certain ways, most people are fatalists with respect to possible climate change. One only has to be aware of – and believer in – what science tells us about the history of planet Earth and of the universe to get a feeling of utter insignificance and powerlessness. This may be countered by a belief in some supernatural Being or Force with special consideration for us human beings – which may inspire more egalitarian perceptions and behaviour but might as well take a fatalist turn. With regard to complex long-term macro-issues, the fatalists are hard to motivate to take any other position than opportunistic. In this way, the Cultural Theory provides a general framework for the analysis of risk perception in relation to climate change and permits the exploration of balanced, integrating worldview and ethic and of robust policy interventions.

4.2.2 Conceptual model for the CLIMEX experiment

As part of the GSD-project, it was decided to set up a simple experiment about people's perception of climate change risks and uncertainty and their behaviour (Apetrei 2010). It was inspired by experimental research by Milinksi et al. (2006, 2008). We developed a *conceptual model* for a similar experiment based on approaches in decisionmaking theory and contextualized for the specific situation of human-induced climate change. Although we aim at an interdisciplinary approach, by no means do we claim that this model is exhaustive in the factors it presents. Let us briefly introduce the main concepts of the model (Figure 4.2); details on the experimental setting are given in paragraph 4.4.

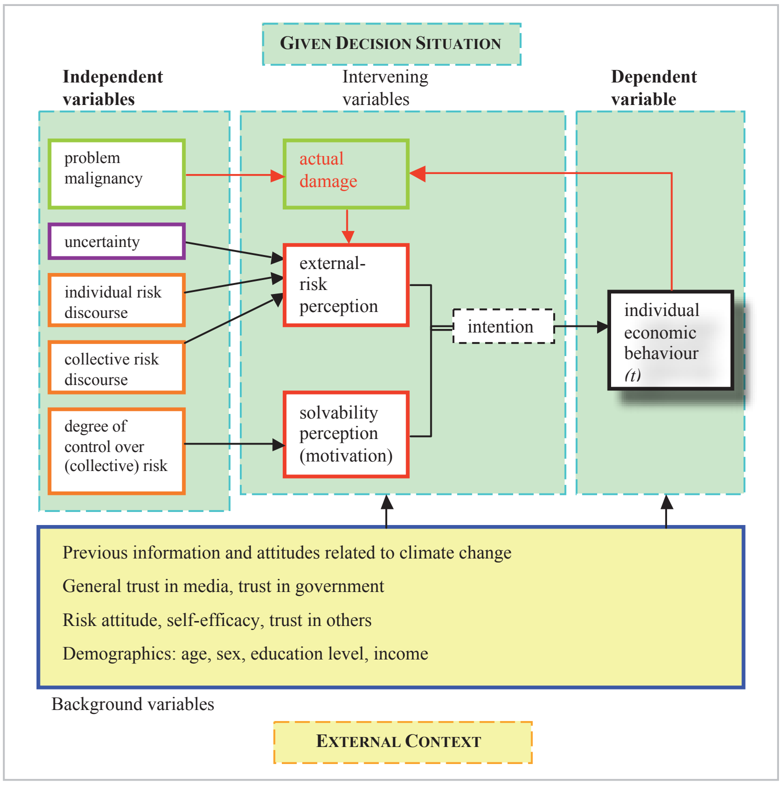
Climate change is expected to affect humans individually and collectively in the form of damage, which can partly and tentatively be expressed in monetary terms. We assume that there is an objective *actual damage* that one might incur due to climate change. This damage depends on natural conditions (*problem malignancy*), but also on whether people decide to address the problem of climate change by taking action or ignoring it. We focus here on *individual economic behaviour*: a person can decide to reduce the threat of climate change to a collectively agreed upon maximum at a cost (e.g. a tax), to ignore the problem and simply adapt to whichever costs or benefits for the individual may appear, or to adopt a strategy that is somewhere in between these two extremes. The last strategy may be the most common one: reduce the risk to a level acceptable to me as individual, by a combination of collective and individual measures.

Table 4.1

Attitudes and actions with regard to Climate Change (CC) in the four IPCC 1999 scenarios (De Vries 2001)

	A1	B1	A2	B2
Probability of CC	medium to large A2>A1>B2	smallest	highest	small to medium A1>B2>B1
Attitude towards CC	economic growth has priority	other environm. concerns have priority; no-regrets and side-benefits	muddling through - not an issue / fatalist	local environm. concerns; incapable to solve global environm. issues
Actions if CC is large	barricades; adapt on your own; mitigate tensions by compensating poor	formulate and implement global CC policy [too late but feasible], including adaptation	not feasible: world community incapacitated; cope on your own	some regions suffer; cope on your own, but [ineffective] attempts to share the burdens
Actions if CC is small	proud: "you see, ours is the best of all possible worlds"	proud: "you see: the high-tech and SD-orientation did it"	"well, this time we were lucky...so far"	"well, we were lucky... but our local concerns may have helped"
Attitude towards CC policy	reluctant, although rich enough to make compensatory gestures	reluctant if it slows down the narrowing of the N-S income gap	no expectations: impossible anyway	low expectations: full of good intentions, but they fail

Figure 4.2



Conceptual model of decisionmaking in the face of climate change related risk and uncertainty (Apetrei 2010).

According to the *protection motivation theory* (Steg and Vlek 2009), a behavioural strategy is chosen following an internal evaluation of the risks involved and the perceived control. In our model, we call these two elements *external risk perception* and *solvability perception* respectively and consider them intervening variables between the outcome variable (behaviour) and the explanatory variables. At any point *t* in time, the *external risk perception* is a subjective interpretation of the current *actual damage*, and it is shaped, among other things, by *uncertainty* and the *individual and collective risk discourses* that dominate the decision situation. The *collective risk discourse* refers to the main societal message regarding how individual contribution can reduce the collective risk of climate change, while the *individual risk discourse* encompasses the mainstream view about whether climate change will affect all people equally or not. The *solvability perception* variable depends, in its turn, on the *degree of control over risk*. The latter is interpreted here as being a (fixed) characteristic of the decision situation. On the other hand, *solvability perception*, like *risk perception*, is strictly subjective.

From the point of view of the decision-maker, the 'independent variables' are parameters that characterize the decision situation and are relatively fixed, while the 'intervening variables' consist of those factors that are constantly updated based on new information/feedback from the environment. In this way, the (economic) behaviour of the individual person is understood as the continuous interplay between external environment and internal evaluation. Of course, when pondering their actions, people cannot completely isolate themselves from their identity and their broader system of beliefs. When making evaluations about the decision situation they are in, they also involve their values, or make use of the experiences and lessons from other aspects of their lives. It is this set of factors that we group in the *background variables* as external context.

Consistently with the finding of Viscusi and Zeckhauser (2006) that when it comes to climate change people's appraisal is a combination of rational and behavioural elements, our conceptual model tries to integrate both elements from decision theory and behavioural science. The 'given decision situation' (upper) part of the model lists the variables that are directly linked to the climate change problem and decision-making, while the 'external context' (lower) part comprises the collection of prior/external characteristics or beliefs that the individuals bring as additional input to their decisions.

In view of the experimental set-up to be presented later on (Section 4.5), the variables in Figure 4.2 deserve further explanation. First the dependent variable *Individual economic behaviour*. This reflects one, and only one, aspect of human behaviour in the face of anticipated climate change: which monetary sacrifice is an individual person willing to make to change the outcome for the better? An obvious measure are the expenses – in our experiment this is the contribution to a Climate Fund. If we assume that there is an *'optimal' behaviour* along the lines of cost-benefit analyses, an individual may accept just enough short-term costs necessary to sustain the current level of needs satisfaction in the future, but not more. In other words: I will invest, but only as much as I know I need to, in order to minimize my expected future costs. Such behaviour, economists would say, is rational. A more sophisticated measure of economic behaviour would be the deviation from such 'rational' behaviour. Qualitatively, we are also interested to observe the *behavioural strategies* that people develop when coping with different characteristics of the decision situation.

Then there is the group of independent variables:
- *Problem malignancy* represents the 'difficulty' of the problem: how hard is it to control or remedy;
- *Uncertainty* is a measure of the (un)certainty about the problem and about its causes, consequences and remedies. It is explicated along three dimensions/ sub-variables:
  - *Knowledge of the causes/mechanisms of damage*: whether the decision maker has 'expert awareness' in the terms of Raaijmakers et al. (2008) about which steps lead to which outcomes. This is factual information and is different from the more 'subjective' interpretations and beliefs that the decision maker might already have about climate change;
  - *Information availability*: whether the decision maker obtains information about the feedback of his actions on the climate system in time to influence his next decision or not;
  - *Information reliability*: whether the feedback that the decision maker receives about the consequences of his actions is accurate or distorted by other factors in the social environment.
- *Collective vs. individual risk* (Milinski et al. 2008) distinguishes between whether the problem represents a broad, societal risk or a risk close to daily life. In the latter case, people might exhibit quite different behaviour than in the former [li]. In the collective risk discourse, one can make a distinction between two forms of risk reduction: mitigation (cause) and adaptation (impact). Regarding the individual risk discourse, it matters whether climate change is seen as a global problem: 'One for all and all for one' where the *actual damage* affects us all with equal probability, or as a probability that the individual may or may not be affected: 'to each his own'.
- *Degree of control over collective risk* represents whether or not individual actions have a direct effect on the actual damage or not.

The second group are the intervening and background variables. The intervening variables represent some (cognitive) factors that presumably mediate between stimuli and behaviour. Background variables constitute a collection of prior characteristics and beliefs of the subjects that might influence the entire spectrum of variables within the 'given decision situation'. We consider:
- *External-risk perception* is defined here closely to the concept of 'worry' (Raaijmakers et al. 2008) and is the result of the 'threat appraisal' (Steg and Vlek 2009). It is an attitudinal component that forms during the deliberation process;
- *Solvability perception* refers to whether or not the subject feels in control of the collective risk while playing the game and can be interpreted as the result of the 'coping appraisal' (Steg and Vlek 2009);
- *Intention* is a variable mediating between perceptions and behaviour, in order to distinguish between 'effect' and 'disposition to act' (Weirich 2004). We do not measure it.
- The *actual damage* is an intervening variable that is dynamically updated at different time intervals. Depending on the individual economic behaviour vis-à-vis climate change, the actual damage could increase or decrease in time. This variable thus captures the evolution of climate change. To the extent to which this evolution has a feedback effect on the social system, it also influences the external risk perception from one moment in time to another.

The background variables are self-explanatory and serve as controls for the independent variables. Together with the intervening variables, they play an active role in shaping the behavioural strategy.

4.3 Interactive models and simulation games in resource management and climate change

The conceptual models presented above reflect social science insights – but they usually lack systematic empirical backing. As we have seen in previous chapters, this is one of the problems of complex systems theories and models in general: how to validate them on the basis of controlled experiments and/or fieldwork? The econometric approach is to collect data on observed behaviour and perform statistical analysis. Another, more recent and successful approach is to create a simulated world which lends itself to controlled experiments: interactive models and simulation games.

Simulation games have become important educational and management tools in combination with (interactive) computer models. Besides teaching insights and skills, they have also become tools to study complex social-cultural situations. We will not dwell on the hundreds of books on this topic and instead focus on some models and games of relevance in the present context.

Among the first simulation games about resource dynamics were the Stratagem and Fish Banks Ltd. Games designed by Dennis Meadows, one of the authors of the *Limits to Growth* report to the Club of Rome in 1971. The objective was to teach some of the key insights from the World3 model of the *Limits to Growth* report: how to bring a country from a low-income high-population growth trajectory towards a sustainable state (*Stratagem*) and how to avoid overexploiting a renewable resource in a situation of open-access (*Fish Banks Ltd.*).

Many games have been developed since then, partly under the aegis of the International Simulation and Games Association (ISAGA). One of them sprang from involvement in simulation of energy systems and policy: the *PowerPlan* interactive model (Benders 1996, De Vries and Benders 1989). It was primarily a decision-support system (DSS) or tool. Numerous DSS have been developed in the engineering and environmental sciences, but the focus is usually on the management of a well-structured, clearly bounded system.

Building upon previous experiences, De Vries and Meadows constructed a simple game on energy-climate in order to clarify the greenhousegas effect and its causes called *SusClime*. The model has been introduced in the previous chapter (Section 3.2). In essence, the game offered players the opportunity to invest in energy efficiency and – more expensive – renewable energy in order to reduce CO_2-emissions and avoid the productivity-decreasing impacts of climate change later on. The model was later extended to more regions, which were in interaction not only via the atmosphere as a sink (for energy-related CO_2-emissions) but also via trading a finite amount of fossil fuel (oil) and via exchanging of knowledge about renewable energy (De Vries 1998). This multiregion simulation model/game has been played with up to 4 teams/countries a dozen times. Several lessons have been learnt from it, in particular:

- The impacts of climate change are so far into the future that it is hard if possible at all to make it part of an exciting game dynamic;
- The communication and excitement about trading oil and negotiating oil prices drew disproportionately much energy from the players, at the expense of discussions about a long-term strategy.

The last point is confirmed in the numerous times the Fish Banks Ltd. Game has been played: the interaction among the fishing teams represents a strong communication and socialization aspect.

Recently, a number of interactive models about the economy-climate system (Appendix F) and about Common Pool Resource (CPR) management (Appendix G-H) have been released for use on the internet. Here, we only briefly discuss a simple interactive simulation tool called *InterSus*, which Markus Brede and De Vries set up in 2007-2008 (Appendix K). The objective was to experiment with how participants perceive the climate change risks and associated costs and benefits on the basis of an extremely simple model-cum-decision interface. It had two versions: one with a single player (InterSus1.0) and one with several players (InterSus2.0). The essence of the InterSus1.0 version is the following:

- The player is asked to invest part of GDP in order to generate income (GDP/cap) growth;
- The player is informed of the fraction of GDP to be invested in the supply of energy and is given a warning that the carbon emissions will have in the long term negative impacts on income;
- Then, the player has to make a second decision: decide on a target for the fraction of energy supplied by non-carbon options 20 years from the decision year.
- The player is shown a screen with 6 graphs, which would show over time the population, their average income, the fraction of non-carbon energy supply and the CO_2-emissions and average surface temperature change.

The model is initialized with 5,9 bln people in 1995 and a World Gross Domestic Product (GWP) of 20 10^{12} US 1995$.

The main objective or goal of each player is to maximize the income (GDP minus investments divided by population) averaged for the period 2080-2100 in 4-year decision periods (or rounds). Before the game is played, the player receives a questionnaire with three questions which is meant for basic identification in terms of worldview, risk attitude and willingness to pay now for benefits later. Besides, the player is told that (s)he can earn some money if (s)he performs well. Appendix G shows the player's questionnaire, instruction texts and computer decision screen. From playing the InterSus 1.0 and 2.0 versions, we have gained some important insights which have helped to design a follow-up strategy. First: we should simplify the InterSus interactive game design in order to address much more focussed issues, which would be more amenable to scientific experiments and analysis. Secondly, the simulation model SusClime has to be extended with agent-based decisions in order to explore the long-term dynamics of the energy transition in combination with climate change impacts (Chapter 3).

4.4 CLIMEX – An Interactive Decision-Making platform

'*For a wide range of debates about risks, of which the greenhouse effect is but one of the largest, there is little or no prospect of science settling the issue. We are all…confronted by the need to make judgments about potentiual risks on the basis of inadequate evidence… People are arguing from different premises, but if science is incapable of forging an agreement about premises, what more can one say?'* (Adams 1995:176).

4.4.1 Introduction

As a follow-up to the InterSus experiment and as part of the GSD-project, an interactive decision-making platform – CLIMEX – was developed by Apetrei, Michel, Brede and De Vries. The conceptual model behind the experiment has been presented in paragraph 4.2. Cristina Apetrei, Markus Brede and I (BdV) developed an interactive decision-making platform – CLIMEX. The programming part was realized by Christian Michel, who developed CLIMEX as a PHP-based environment that runs in any browser. This platform has been designed to be very flexible, allowing the experimenter to manipulate the independent variables in multiple ways, and thus accommodating many variations of the experimental conditions. Moreover, it is accessible online, thus permitting the scaling of this kind of economic experiments to very large samples. More details about the functionalities of CLIMEX, as well as screenshots, are given in Appendix L. In this paragraph we briefly describe the set-up of the platform and the experiments and results in the context of the GSD-project (Apetrei 2010).

The existing CLIMEX game version can be played by a single person or by more than one player. In the multi-person version, one can also play against automated agents. Both versions have a simple set-up. Both versions have a simple set-up. A participant plays T rounds of an investment game. The player gets an annual income *I*, which is to be interpreted as discretionary income. (S)he is told that the accumulated savings will be lost with a certain, high probability. The player is also told that a part of this income can be put into a Climate Fund which will reduce the risk that the accumulated savings are lost at the end of the game. The software interface was designed to be flexible, so that it would permit the administrator to construct his or her own series of experimental configurations. Basically, the following choices are to be made (Appendix L):

- Players: add the name of a player with a password to be entered upon playing via the website;
- Game Setup: define the characteristics of the damage function i.e. of how much the risk of loss is reduced by the content of the Climate Fund;
- Layout Setup: define and input names and units of the variables in the game, welcome text etc;
- Treatment Setup: choose a particular Game Setup and Layout and choose whether a delay and/or additive and/ multiplicative noise are inserted, and if so how much;
- Experiment Setup: make a set of games to be played by inserting elements in the list of Treatments, with or without pause.

If in this way an experimental setup has been defined, one can start up a New Experiment by choosing the experiment from the constructed list and add the name of the player. The player is then informed that he can play the game on the website by introducing login name and password.

A participant plays *T* rounds of a single (or multiple) player investment game. The number of rounds is known in advance. Every round $t=1..T$ he receives an income *I* (*I*=constant) which he has to allocate to two funds: (i) an amount $s(t)$ into a savings fund in which the participant can store his income (and which is the basis of his later payout) and (ii) an amount $I-s(t)$ into a climate change insurance fund that mitigates possible future *individual* risks to his savings fund (corresponding to the *actual damage* in our conceptual model).

Participants are told that not investing into the climate change fund will forfeit a large part of the savings fund and investing more into it will reduce the risk of losses of the savings fund. In the case of our particular experiment, the instructions that the participants receive contain explicit references to climate change as a decision context. However, this is a choice that we make in the context of this study, as CLIMEX can also be used with decision situations that are not contextualized, but involve other public good investments.

In every round, before deciding on the investment allocations, participants are informed about expected losses to their savings fund (actual or perceived damage, see Uncertainty variable in Section 4.2.2.). This information is not always completely describing the objective reality, but is sometimes incomplete, to reflect *uncertainty*. The 'objective' reality is described by the *actual damage* variable, and is calculated in our game as a function $f(t)$ of the accumulated points at time t in the climate change insurance fund. The more points one decides to invest in the fund, the less the damage he might incur to his savings.

It is straightforward to show that (i) from a mathematically rational point of view there is an optimal savings level which is completely determined by the function f and (ii) that given the savings level the time distributions of the savings investments does not matter because only the fund content in the last round is used to calculate the actual incurred damage (i.e. saving much in the beginning and putting all investments into the climate fund at the end is equivalent to fully investing into the climate fund in the beginning and saving all income in the end).

4.4.2 Experimental design

The experimental approach is pragmatic and consistent with the novel idea of manipulating some variables that are usually only elicited by means of social science methods. The attempt is to have *a factorial design* where every independent variable can take different values and a *treatment* represents a combination of these values. The choice of dependent and independent variables is in line with the conceptual model presented earlier and is briefly discussed in this paragraph. The experimental design and data analysis refer only to the single-player experiments and with limited settings of the parameters/ independent variables.

Dependent variable: Individual investment behaviour (Section 4.2.2). The formalization of this variable depends on whether the risk is interpreted in a collective or an individual context. In the simplest form of the game, individual investment behaviour can be formalized as the *game score obtained* by the subjects under different conditions. Under the assumption of rationality in the form of utility maximization, looking at the game score would allow for comparisons of performance between different treatments.

However, the risk may be interpreted as a personal risk: the outcome of any round is entirely chance dependent and participants may gain either all their savings or nothing. For such situations the *level of investment in the climate fund* may be a more appropriate variable to be explained.

In addition, for all treatments in our game it is possible to calculate the 'optimal' investment strategy corresponding to a maximum score (or maximum expected value) that could be obtained by a player. While in some conditions participants lack the necessary information to derive this 'optimal' strategy, we want to see how far away from it their guesses are. Hence, we will also calculate the *deviation* of the individual results from this best possible score. The smaller the deviation, the more 'rational' (in Bayesian terms) the investment behaviour is.

Independent variables. We only present the variables chosen in our analysis:

- *The shape and parameters of the damage function f.* We choose to experiment with two types of *damage functions* (linear/non-linear), which show different responses of the 'climate' to human activity over time. Due to our parameterization, the linear function provides participants with a more difficult problem, as it requires greater efforts (investments) in order to reduce the damage level. The more difficult problem implies a greater *problem malignancy*.
- The three dimensions of *uncertainty* are operationalized by including three aspects:
  - *Knowledge of the causes/mechanisms of damage* (function known/not known): whether the damage function is known or not to the players;
  - *Information availability* (delay/no delay): whether there is a time delay or not in the feedback given to participants during the game, from one round to another; and
  - *Information reliability* (noise/no noise): this refers to a randomness factor that is included in the feedback information given to the participants.

As to the *collective and individual risk discourses*, we have chosen for the individual 'to each his own' interpretation: a dice is thrown once for all players and whatever a player might have gained is either kept or lost. Regarding the *degree of controlover collective risk* (full/shared): we have only experimented with the single-user frame, because the multi-player version of the interactive platform was not yet ready at the time of the experiments. For the actual parameter settings of the functions, we refer to Apetrei (2010).

Experiment design. We conducted the experiment in *four* sessions of *1.5 hours* each. In every session there were *20 participants*, which were randomly selected from a mixed database that is regularly used by other researchers in the field of experimental economics. Each player was asked to play 6 games (we call it 'round' in our experiment), each game being different from the other ones in terms of dependent variables (called Treatment).

We decided to focus on the *malignancy* and *uncertainty* variables. Furthermore, we gave up some of the combinations with the 'known function' condition, since – from a 'rational' point of view – noise and delay do not matter when the *actualdamage* is known. The final design was as follows:

- every participant plays 6 games in total that differ significantly from one another; we hypothesize that this will prevent any major learning effects. This was confirmed by the outcomes;
- we distinguish between noise and delay, but also study the joint effects of these two factors;
- we maintain some of the treatments with 'known function' and 'noise' or 'delay', but mostly for control/exploratory reasons, as no significant effects are expected;
- replication: every treatment is replicated twice;
- ordering effects are controlled for by subdividing each group into two more groups that play the functions in different sequences.

For more details we refer to Apetrei (2010). The players could gain a maximum of about 20€ during the experiment of ≈ 45 minutes.

While the final individual payment was being counted, a questionnaire was distributed that collected information about the general background of the participants and their experiences with the game. The questionnaire asked two questions about risk attitude and the resulting scores were compared for consistency. A series of other questions gave further information on how the participants view the climate change problem (likeliness, impacts, willingness-to-pay, level of knowledge about and confidence in information sources).

4.4.3 Experimental results

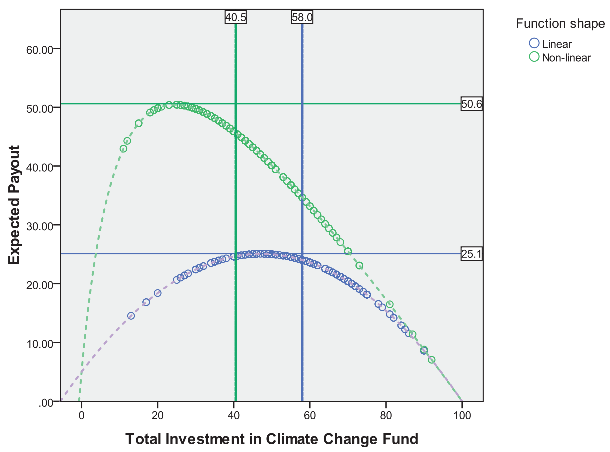
The participants (N=80) had a rather homogenous background: 58% female, 30% economics students, 90% an income level below 1500 €/month. From the questionnaire answers, it can be concluded that the participants have an above average risk-averseness, consider a 2°C temperature rise and significant monetary consequences 'likely', and are willing to do something about. This is not a group which can be considered representative of the Dutch population.

We analyzed the behaviour of the participants in terms of total investment put into the Climate Fund (Figure 4.3). One of our hypotheses was that people would be more 'rational' when the malignancy of climate change is higher, in other words: the more difficult (linear) function shape requires more financial effort in order to reduce the risk significantly and consequently participants will be more concerned with the return on their investment in the climate fund. This hypothesis was confirmed, as the data in Figure 4.3 show[lii]. Contrary to expectations, we did not find any relationship between the rationality of behaviour and the level of uncertainty. Also unexpectedly, we found that the order of the experiments does have an effect on individual economic behaviour: those who started with the harder, linear function behaved more rationally than those who had started with the less difficult, non-linear function. This result can probably be explained in terms of solvability perception. Finally, there was a positive relationship between investments in the Climate Fund and the risk score and a negative one between investments in the Climate Fund and the level of trust in the government.

4.5 Summary and conclusions

In this chapter the focus is on the third phase of the GSD-WP3 project: controlled experiments with a web-based interactive platform in order to investigate behavioural rules and the role of uncertainties in the face of long-term risks. We first

Figure 4.3



The horizontal lines mark the maximum possible expected payouts for each function. The vertical lines indicate the median value of the total investments in the climate fund. Each median line has the colour of its corresponding distribution.

The scores of the particpants (N=80): total investment in the Climate Fund vs. the expected payout at the end of the experiment.

briefly reflect on the role of legitimacy and then present two conceptual models of how people may deal with uncertainty and risk in the face of large-scale macro-problems. Next, we introduce a couple of interactive models and simulation games about resource use. The objective was to explore how a Global Dynamics & Climate Change 'Managing the Commons' Interface should look like. The associated appendices give more details on the – growing – list of resource-related models and games.

The last part of this Chapter is devoted to an experimental set-up, called CLIMEX, which was inspired by the research of Milinski et al. (2006, 2008). It contains a very simple game, to be played via the internet, in which people are asked to contribute to a climate fund in order to reduce the future risk of damage from climate change. In a carefully controlled experiment with eighty students, we found evidence for a quite limited role of economic rationality and a possibly significant effect of other influences such as the order in which experiments were done, the risk attitude and the level of trust in the government. A follow-up multi-player version is being tested in order to examine social dilemma elements.

5

Summary and conclusions

This report is one of the deliverables in the EU Coordinated Action project Global System Dynamics and Policies, funded by the Future & Emerging Technologies division of the European Commission (Work Package 3 – see Appendix A). It gives an introduction on the topic of economic growth models in the context of macro-problems such as resource depletion and ecosystem degradation. Background material can be found on the GSD-website www.globalsystemdynamics.eu. The objective of the reported activity is to collect different pieces for an improved and/or new economic theory, which can deal more adequately with the challenges of the 21st century. Together these pieces, or fragments, make up 'elementary models for a sustainable economy', as the corresponding workshop has been named. What I present here is an incomplete attempt at synthesis and is meant as an invitation to contribute. Although contributions have come from many sides, the final responsibility of the report is mine. The views and insights presented are not those of any of the supporting institutes. They are mine, but because they reflect the insights and views of many colleagues I occasionally use *we* instead of *I*.

Current mainstream economic concepts and theories are representative of the industrial era, in which material growth and progress as an outcome of applied science and capitalist arrangements brought great benefits to many. This era is over. The side effects and hidden costs of this form of growth and progress have essentially changed it.

New concepts and theories are needed. Since the 1960s, economic science has seen the birth of subdisciplines such as resource and environmental economics, ecological economics, institutional economics and others. Their practitioners acknowledged resource depletion, environmental pollution (air, water, soil), ecosystem degradation, community destruction and human destitution as phenomena which were aspects inherent to the industrial era growth model. They advocated, often successfully, adjustments.

Yet, many of these aspects are still poorly understood and, not well represented in mainstream economic thinking and modelling. Modern' economic growth theory does not explain key positive feedback mechanisms such as innovation dynamics. It also fails to provide satisfactory mechanisms which explain the lack of income convergence, trade disadvantages, resource mismanagement, the role of institutions (governments, finance) – all increasingly important features of a world which is now heading for a population of 9 billion people and increasing resource scarcity.

A natural consequence has been that mainstream economic theory, although taught in schools in its original form, is not relevant to the real world or, worse, is outright misleading. In other words, many relevant stories about the world are not told and cannot be told. One approach in the search for updated concepts and theories is to tell divergent relevant stories (scenarios) and consider the implication for (economic) models. We have done in Chapter 2 a preliminary exercise for the four SRES IPCC scenarios. In the last decades, the ingredients for twenty-first century concepts and theories have been emerging – often denoted by the term 'complexity science'. Can they be of any help, and if so, how? Chapter 2 addresses this question.

The social sciences have always emphasised the inadequacy of the image of (wo)man in economic science and have proposed more refined models. Not surprisingly, agent-based modelling has proved to be popular among some groups of social scientists complementing system dynamics research efforts. It formulates human behaviour according to field observations and experiments, leading to disciplines such as behavioural and experimental economics. New agent-based modelling platforms are evolving and changing the very theory and practice of modelling. There is no clear borderline between the two. In addition complementary analytical work, which expands the concept of utility function with interaction networks and agent memory, is ongoing. Models of binary choice, opinion and attitude dynamics reflect the similarity between statistical mechanics models and impact function formalisms from social-psychology. It appears that mean field solutions are reasonable approximations for certain ranges of parameter values, but issues of aggregation and scale linkages remain important areas for further research.

The question of ecological sustainability is of particular importance in an economic growth/development context. Recent insights in ecosystems indicate that thresholds and feedback mechanisms can cause catastrophic regime shifts if inadequate models of the industrial 'no-limits' paradigm prevail. Resource management must allow for ecosystem resilience, analyze the occurrence of ecological thresholds at higher spatial and temporal scales – including climate change – and integrate thresholds and feedback mechanisms in macro-economic models. New, participative ways of dealing with uncertainty and strategic behaviour of stakeholders must be developed and used. An interesting approach is provided by the common pool resource (CPR) framework.

The kaleidoscope of models constructed in the last decades offer us a fascinating and hopeful scenario. Is it possible to see a larger picture emerging? Fiddaman (2010) suggests that there are at least three mechanisms currently operating in economic processes: (1) rational intentional change, (2) gradient following, and (3) population learning. Traditional economic models ascribe all change to rational intentional change. When prices change, or are expected to change (or, in some models, are known to change in the future), agents immediately change their allocations to whatever is optimal, given the new conditions. The dominant processes in agent-based models are changes in relative prices creating selection pressure. A middle ground is used in system dynamics models: agents have local information about profitable opportunities for change, but they proceed incrementally along the profit gradient, in the absence of global information about the system. This involves an element of deliberate change, depending on the level of understanding involved,.

Each of these models has its problems in making the connection with real world observations. We have seen examples of models where simple interactions result in rich system dynamics. However, the relationship with social science field work is not always clear. For instance, the simplified interactions at the microlevel in econophysics network analyses are at the other extreme of the rationally and optimally behaving homo economicus. Similarly, the attractiveness of evolutionary mechanisms may lure us into a false kind of myopia: how does cooperation in higher-level institutions emerge? Can it be that the apparent intelligence and variety of the human individual as emanating from the behavioural sciences (psychology, anthropology and sociology) evaporates in the crowd? Shouldn't we delve for 'deeper' mechanisms behind the observed aggregate system behaviour? Perhaps it is a good idea, as Bentley and Ormerod (2009) propose, to start with the 'zero-intelligence' model as the null hypothesis. We represent human individuals *as if* they are billiard balls, or ants, or social atoms. Then, as our understanding advances, we add 'depth' in the form of cognitive processing, memory and so on.

In Chapter 3, the focus is on the third phase of the GSD-WP3 project: controlled experiments with a web-based interactive platform in order to investigate behavioural rules and the role of uncertainties in the face of long-term risks. We first briefly reflect on the role of legitimacy and then present the risk two conceptual models of how people may deal with uncertainty and risk in the face of large-scale macro-problems. Next, we introduced a couple of interactive models and simulation games, about resource use. The objective is to explore how a Global Dynamics & Climate Change 'Managing the Commons' Interface could and should look like. The appendices provide more details on the growing list of resource-related models and games.

The last part of this Report is devoted to an experimental set-up, called CLIMEX, which was inspired by the research of Milinski et al. (2005, 2007). It contains a very simple game, to be played via the internet, in which people are asked to contribute to a climate fund in order to reduce the future risk of damage from climate change. In a carefully controlled experiment with eighty students, we found evidence for a quite limited role of economic rationality and a possibly significant effect of other influences such as the order in which experiments were done, the risk attitude and the level of trust in the government. A follow-up multi-player version is being tested in order to examine social dilemma elements.

The overview in this Report should be considered as an attempt at synthesis: it provides model-based investigations from different disciplines and is an invitation to think and explore together, in search for new building blocks for a sustainable world. Such a cooperative effort is necessary because the field is still very fragmented. Whether a synthesis is possible and whether it can or even should, lead to a new and comprehensive economic theory – as suggested by Beinhocker in his call for a Complexity Economics – is still shrouded in uncertainty. What is certain, however, is that, in order to sustain a decent quality of life for human life on earth, we need to share insights and models with each other and we must be guided by valid visions of the possible and desirable.

Endnotes

i. From the cosmological perspective Jantsch (1976) expounds in his book, human societies are dissipative structures which are only interested in their own integrity and rebirth in a continuous process of reconstruction, exchange and elimination – like all organisms. Their internal non-equilibrium can only be maintained with a permanent supply of high-quality energy and removal of low-quality energy. Compare this to somebody.

ii. In the present context, it is interesting to note that none of the words bifurcation, complexity, evolution, feedback, Kondratiev, system appear in the index.

iii. In economic theory the relation with empirical observations is a difficult one. *"The Hotelling rule is an economic theory [about resource depletion]…a theory is not necessarily correct… [a theory] may fail to 'fit the facts' because it refers to an idealized model of reality that does not take into account some elements of real-world complexity. However, failing to fit the facts does not make the theory false; the theory only applies to the idealized world for which it was constructed… The history of attempts to test the Hotelling principle is an excellent example of the problems faced by economists… many of the variables used in our theories are unobservable or latent variables. Shadow prices are one class of such latent variables. The best we can do is to find proxy variables for them. But if the theory does not work, is that because the theory was poor or because or proxy was not good?"* (Perman *et al.* 2003:527-529).

iv. The logistic substitution model as developed and applied by Marchetti and others (see e.g. Grübler 1998) suggests indeed that economic processes in terms of macro-variables are hardly influenced by large-scale social-political turmoil as experienced e.g. in the two world wars. It implies that large catastrophes may well coincide with large monetary transactions e.g. in warfare or reconstruction, and with ongoing waves of innovation.

v. One hypothesis is that this led to lower transaction costs, which stimulated economic growth – Luiten van Zanden (2009). The inquisitive mind doing experiments and inventions, the combination of (military) competition and interaction among European states, and church-related changes in family and entrepreneurial law are also mentioned as precursors to the Industrial Revolution. Economists know this branch of science as New Institutional Economics.

vi. An example of the inclusion of infrastructure as an external input into private production functions is Glomm and Ravikumar (1994). They examine the role of congestion – an aspect of infrastructure which is nowadays analyzed in detail in sectoral models (transport, energy) but, to my knowledge, without connections to macro-economic growth models. An example of more recent empirical work is Canning and Pedroni (2004; http://www.williams.edu/Economics/wp/pedroniinfrastructure.pdf) who use physical indicators (paved roads, telephones, electric power). Using the Barro-model with infrastructure investments a (variable) part of savings, they find for a set of countries over the period 1950-1992 *"clear evidence that in the vast majority of cases infrastructure does induce long run growth effects"*, but with a great deal of variation in the results across individual countries. The relationship may be bidirectional.

vii. This is not to deny, of course, that an enormous amount of data, analyses and models have been gathered and constructed to shed light on issues such as inequity, infrastructure and the like. The series of World Development Reports by the World Bank are a rich source in this respect. See http://publications.worldbank.org/ecommerce/catalog/product?item_id=7014177 .

viii. There is a mounting literature on the role and nature of the service sectors in the economy. Their role is crucial in making any sense of long-term forward projections of GDP and the implications for physical resource flows (see e.g. Schettkat and Yocarini 2006, De Vries 2006).

ix. For a discussion of these axes, their names and interpretations, and their shortcomings, we refer to Nakicenovic *et al.* (2000), De Vries (2006) and De Vries and Petersen (2009).

x. In his book *The Origin of Wealth – Evolution, Complexity, and the Radical Remaking of Economics* (2005), Beinhocker describes the new Complexity Economics. Co-evolution is the keyword. The world is populated by humans who are constantly adapting in the search for survival in the infinitely large space of all the possible Physical Technologies, Social Technologies, and Business Plans. Philosophically speaking it can be considered a form of neo-darwinism.

xi. See Sterman's book *Business Dynamics – Systems Thinking and Modeling for a Complex World* (2000) for an in-depth discussion of the many mechanisms which make the world deviate from the perfect world of neoclassical economic theory.

xii. Hirsch, in his book *Social Limits to Growth* (1977), was among the first to notice the feedback between the market system and the dominance of individualist values: *"A market economy probably encourages the strengthening of self-regarding individual objectives and makes socially oriented objectives more difficult to apply. The reason is that interests of self-concern and self-regard can be enlisted much more effectively in support of commercial sales efforts."* (Hirsch 1976:82).

xiii. This work has been seminal in understanding the successes and failures in managing Common pool Resources (CPRs), by investigating real-world historical cases, by in-depth agent-based modeling (see e.g. Janssen 2004) and by empirical behavioural economic research.

xiv. The sociology of the network society has comprehensively been explored by Castells in his magnum opus *The Rise of the Network Society* (1996). The advent of the network society happened in a wave of novel ICT developments and of the spread of global capitalism after the fall of the iron curtain.

xv. See for instance http://www.utrecht2040.nl/ for the views of Rifkin on 'distributed capitalism' as hallmark of the Third industrial Revolution.

xvi. It still resounds in the name of the economic planning bureau in the Netherlands, founded by Tinbergen: Centraal Plan Bureau (CPB).

xvii. One type of conflict has been denoted as 'resource curse'. It is the situation that local elites can stick to authoritarian rule, because they use the income from (oil) resources to suppress their populations or to uy their consent. The hypothesis is based on the empirical correlation between a state's reliance on either oil or mineral exports and its level of democracy (Ross 2002).

xviii. This chapter is to a large extent based on the preparations for and discussions during the workshop Elementary Models for a Sustainable Economy, organized in Utrecht 21-24 january 2010 by Bert de Vries. For the list of participants and the pdf's of the presentations, see www.globalsystemdynamics.eu. See Appendix B for details.

xix. Occasionally they replaced more valid but less formalized 'vernacular' knowledge, with sometimes tragical consequences (see e.g. Worster 1999).

xx. An archetype is *'the original pattern or model of which all things of the same type are representations or copies.'*(www.m-w.com). A more adequate definition might be the connotation which Jung gave to it: an inherited idea or mode of thought, but then not as deeply rooted in the human race as he meant.

xxi. See e.g. Scrieciu (2007) on the danger of and the debate about using CGE-models as the 'back-bone' tool to carry out reliable integrated assessments of sustainable development strategies.

xxii. Sterman goes as far as to say *"Validation and Verification Are Impossible"* in his treatment on Business Dynamics (2000:846). *"All models are wrong, but some models are more useful than others"*.

xxiii. Many of the methods are rooted in branches of physics, where mathematics always had its first and foremost applications and where the link with experimental falsification was strongest. Those who prefer to stick close to the underlying physics in their applications to more complex eco-socio-economic systems use the word *econophysics* to denote their research (see e.g. the journal Physica A). See for a good introduction into the foundations of these methods the book *Complexity* by Mitchell (2009).

xxiv. One way to get an idea of the explosion of research in this direction is accessing (for free) the site of the Journal of Artificial Societies and Social Simulation (JASSS - http://jasss.soc.surrey.ac.uk/JASSS.html).

xxv. An estimated one third of the GDP-growth in the Netherlands between 1990 and 2000 is related to an increasing fraction of women entering the formal labour market.

xxvi. Such as the desire for private jets and spaceflights, personal robots and life extension at all costs.

xxvii. Almost every official GDP-growth projection in OECD-countries assumes – desires, plans for – between 2 and 3 %/yr GDP-growth, as if in a competitive bidding process. This is possible because high income in GDP/capita is judged as an achievement and as a measure of well-being. In low-income regions such as China and India, official projections extrapolate the trends in the last decade and assume GDP-growth rates between 7 and 11 %/yr.

xxviii. This representation is common in economics literature, with all kinds of proposed relationships. See e.g. the book *Causes of Growth and Stagnation in the World Economy* and earlier work of Kaldor.

xxix. There is a large literature on Kondratiev long waves, see e.g. J.S. Goldstein, *Long Cycles: Prosperity and War in the Modern Age*, Yale Univ. Press, New Haven, 1988.

xxx. But - all traders wish to influence price. Once sellers or buyers are large enough they may be able to influence prices and behave strategically. Gone is the spontaneous order and coordination and strategy enter.

xxxi. Hasselmann (2009) gives another example of a simple production-consumption-wage interaction model which generates business cycles.

xxxii. See Sterman (2000:20.1) for a number of examples of and data about commodity cycles: hogs, cattle, copper, aircraft and tankers, and a generic commodity market model. See Mass (1977) on a generic model of economic cycles. See Hasselmann (2009) for a formulation on the basis of the Lorenz equations in meteorology.

xxxiii. Sterman (2000:645) gives a nice example of the difficulty to forecast macro-economic variables: the case of inflation. A rather simple trend extrapolation model with anchoring was able to reproduce the forecasts of one of the most authoritative economic forecasting panels. One explanation is *"a herd mentality in the forecasting community"*.

xxxiv. The fifth and last of these waves, called 'computerisation of the economy' by Freeman and Louca (2002), also deals directly with energy but at a more subtle, informational level. See also Tylecote (1992).

xxxv. The two alternative generating mechanisms are referred to as the Real Business Cycle (RBC) and the New-Keynesian (NK) paradigm (Dosi *et al.* 2008). Critical observers like Ormerod (1998), Sterman (2000), Beinhocker (2005), Dosi *et al.* (2008) and others judge these theories inadequate and improbable, for a variety of reasons.

xxxvi. The notion of novelty as an element of consumerism has a direct link with the established role of habit formation ('preference drift'), besides the importance of relative not absolute income ('reference drift'). See also footnote xxix.

xxxvii. See e.g. Hirsch: *Social Limits to Growth* (1977), Wachtel: *The poverty of Affluence* (1983) and Layard: *Happiness – Lessons from a New* Science (2005) and Van Praag et al. in Kahneman and Tverski (2005).

xxxviii. If the log $[f_i/(1-f_i)]$ with f_i the market share of product or process i is plotted over time, one finds a series of upward (rise) and downward (fall) sloping straight lines. See e.g. Grubler (2000) for a discussion with many historical examples.

xxxix. Such models belong to the general class of probit models, among these the multinomial logit model (Appendix C).

xl. Scott (1998) provides an interesting account of this phenomenon with examples about scientific forestry in 19th century Germany ('Normalbaum'), land measurement techniques in 19th century France, and 'high-modernist' cities and 'social engineering' in Russian and Chinese agriculture in the 20th century. The immanent logic of this simplification-for-control can be recognized as the tension between the A1/B1 world on the one and the B2/A2 world on the other (Chapter 1).

xli. See Appendix D for more information on the various models mentioned in this chapter.

xlii. The Global Integrated Sustainability Model (http://www.pbl.nl/en/themasites/gismo/index.html - GISMO) is an example of an attempt to make such an integration step, as a follow-up to the TARGETS-model (Rotmans and De Vries 1997).

xliii. See for instance Scrieciu (2007) and Crassous (2008) for a critique of the existing IAMs in the context of climate change.

xliv. Indeed, one of the lessons was that the immediate excitement and rewards of oil trading absorbed most of the attention, at the cost of almost complete neglect of (the threat of) climate change.

xlv. For instance, Indonesia is on the low side with PopGR = 113,25 $Y^{-1,1503}$ (R^2 = 0,841) and the Middle East on the high side with PopGR= 1631,5 $Y^{-1,2493}$ (R^2 = 0,8988). The high-income regions follow a logarithmic decline of the form PopGR=a-b LN(Y). With a=0,045 and b=-0,0042 for Western Europe and a=0,0135 and b=-0,0133 for Japan, both with R^2-values around 0,95. All the former USSR republics, including Russia, as well as Central Europe are close together and following a path of logarithmic decline but with a worse fit ($R^2 \approx 0,5$) – and with negative population growth rates for the last decade. The USA follows also a logarithmic decline at significantly higher growth rates than Europe and Japan and a reasonable fit ($R^2 \approx 0,8$). One may see here, among other effects, the flow of interregional migration.

xlvi. It can be shown that modelling economic development via the maximization of a consumption capital stock is a special case of the conventional formulation of maximizing utilities. In particular, maximizing consumption capital corresponds to the choice of a utility function and a discount rate that equals the rate of depreciation of the consumption capital stock.

xlvii. An issue then is which country gets which part of the cost differential. Our simplistic solution is to define a world market fossil energy price p_W as the inverse of the arithmetic average of the productivity in the two regions.

xlviii. We use the same values for $\alpha=\alpha_{CC}=\alpha_{LT}$ but distinguish two assumptions on the severity of climate impacts: mild with α=0.05 and severe with α=0.1.

xlix. This paragraph is based on a papersubmitted for publication: M. Brede and B. de Vries, *The effects of competition on climate change and resource use*, and presented as: Brede and B. de Vries, The atmosphere as a commons: The benefits of global coordination. Proceedings of the 15th AISDRC: Taking up the Global Challenge (2009).

l. The procedure is implemented as a stochastic hillclimber.

li. This temporal and spatial dilemma is clearly existing in the case of climate change. A collective risk could be, for example, the probability that the global mean temperature will increase by 4°C. On the other hand, whether climate change will affect or not one individual's property is a matter of chance and thus, individual risk.

lii. This conclusion is not a solid one, because of limited comparability between the two experiments (Apetrei 2010). The functions were not normalized on the same value, so we could only say something about the level of investment in the fund…and that it appears roughly from the graph in Figure 4.3 that indeed there is a higher agglomeration of points around the Expected Payout in the case of the linear function. This suggests that people might have indeed been a bit more cautious and hence rational.

Appendix A EU CA Project Proposal Summary and GSD Work Package 3 Description

Global System Dynamics and Policies: simulation and visualisation technologies

Summary
Society currently faces a set of new challenges that are both global in scale and highly dynamic. Examples are: climate change, energy security, globalization of the economy and communication, living standard inequalities with associated potential for conflicts, and the spread of new diseases such as HIV. The problems are highly dynamic, the relevant global systems changing rapidly relative to a reference undisturbed state. And they are novel: the prediction and confirmation of anthropogenic climate change, or the appearance and then widespread diffusion of HIV are issues that have arisen only in very recent history.

The necessary networks combining scientific expertise and dialogues with stakeholders attempting to explore new ways of working do not exist. It is necessary to undertake a pilot coordination action to recombine existing scientific and policy expertise. It is also necessary to broaden the scientific network and initiate dialogues with policy makers before FET developments can be specified in detail and new processes of dialogue with policy makers can be organised. Therefore, the purpose of this coordination action is to create a new set of links between scientists and stakeholders which can then initiate further projects to develop new simulation and visualisation methods to analyse these issues and to seek new ways in which science can support policy and decision making. The proposed coordination actions are:

i. *initiating a scientific network*
The project will organise a series of workshops and conferences to bring together the scientists specialising in the analysis of these global challenges and scientists specialising in ICT FETs for the analysis of complex, dynamic systems. Demonstrations of the numerical methods, through working groups of researchers from the two sets of disciplines, will provide a common basis for discussion. Web-based networking will be a further set of coordination actions. A website for the project and dissemination will be provided and maintained, but a more advanced application will also be developed. A prototype of web based model exchange and development using the GET energy system model as an example will be produced. The project will also organise a set of 'Question time' forums, in which younger scientists will be able to communicate their ideas and discuss the challenges with senior scientists. The outcome will be the formation of new interdisciplinary networks of scientists, which can then proceed to develop new methods and technologies. It will enable joint definition of multidisciplinary problems in computational methods for systems simulation, applied to coupled complex social and natural systems.

ii. *initiating a dialogue between policy makers, industrial decision makers and the new scientific network*
The participants in this action will use their extensive existing networks with European policy makers and industry to engage in a process of communication of the potential of the ICT FETs. The objective is to initiate a dialogue to develop new processes of interaction between scientists and stakeholders which can be facilitated through the application of ICT FET simulation tools for rapid analysis of these complex dynamic systems, together with the analysis of very large, dispersed data sets. An internet based visualisation of policy outcomes in energy system transitions will be developed, to provide the basis for a continuing dialogue on how ICT FETs can be used to communicate the relative merits and demerits of different policies along different dimensions of these global challenges. GSD will provide a pilot web-based networking resource to enable communication of the new methods and demonstrate possibilities for new structures for interaction between policymakers and the scientific community.

GSD Work Package 3 Description

Work package No:	3		**Start Date / Event:**		1			
Work package title:	**Web-based experiments to improve social dynamics modelling and assist climate change policy process**							
Activity type:								
	WP Leader	**Other participants with major involvement**						
Participant No:	2	3	5					
Person-months per participant:	3		0,5					

Objectives:

Coordinating activities regarding the design of a population-economy-energy-climate simulation model (with WP1) and (with WP5) of a web-based interface for interactive simulation and visualization; set-up for a test of the role of perceptions and information on the response of selected group participants in climate change experiment.

Description of work:

3.1 Coordinating activities for the design of an elementary population-economy-energy-climate (PEEC) simulation model

3.1.1 During a workshop with invited experts from various disciplines, an inventory of existing 'elementary models' of the dynamics of population-economy-energy-climate (PEEC) will be made with partners in this and other projects. A stylized representation of the system and algorithms to implement this elementary model for any number of countries, including an empirically based initialization, will be explored. Special attention will be given to adequate representation of key linkages between countries: (energy) trade, technology transfer and climate change cause (emission trading) and impact (damage fund) aspects.

3.1.2 Another focus during the same workshop will be on the exploration of two aspects:

*can the model communicate the essential dynamics of the system in a transparent and convincing way for a group of 'experts'?

*can we identify and incorporate the points where meaningful intervention can take place by a group of users, individually and/or collectively?

To this purpose, a second workshop will be organized. The results will be written down in a report, which serves as the platform for an improved model version to be used in the simulation-game context.

3.2 The Global Dynamics & Climate Change "*Managing the Commons*" Interface (MCI)

3.2.1 Together with the other partners, an inventory will be made of the available tools to set up interactive simulation sessions via the web (such as virtual gaming tools) and assessed for their usefulness and adequateness for the MCI. The criteria are in first instance: user-friendliness of instalment and use, ease of connection to the PEEC simulation model; and costs of instalment and maintenance.

3.2.2 From this inventory – which will be available at the end of stage 3.1.2 – a choice for one or more ICT-tools will be made, which allows the installment and testing of a web-based interactive experiment with the PEEC-model. This will be, with the results of 3.1.2, a basis for the design and construction of an advanced simulation-game environment.

3.3 Learning about perception-response aspects in the climate change debate and policy

The third phase of the project will start after phase 3.1.3 and 3.2.2 have been completed. It will organize a second workshop to go through all the steps needed to make controlled experiments with a large group of web-connected participants, using research done on multi-agent modelling and experimental economics. Aspects to be studied are:

* participants' response in relation to their background (discipline, value perspective);

* formulation of behavioural rules for social-economic parts of the PEEC system;

* identification of crucial uncertainties in relation to complex dynamics of social-ecological system. Preliminary experiments with will in this way be strengthened and provide a platform for further work.

The results will be presented in the form of a report.

Appendix B Workshop *Elementary models for a sustainable economy*, Utrecht 21-24 january 2010

Workshop organized **21-24 January 2010 in Utrecht**, as part of the EU Global System Dynamics (GSD) Coordinated Action program (www.globalsystemdynamics.eu). Organizer: Prof. Bert J M de Vries, Utrecht Centrum voor Aarde en Duurzaamheid (UCAD; www.ucad.nl)

1. Participants list

Claes Anderson (Chalmers University Goteborg) claeand@chalmers.se	complex systems and physics
Cristina Apetrei (Utrecht University) c.apetrei@gmail.com	M Sc student Utrecht University *[Saturday]*
Peter Baudains (UCL) p.baudains@ucl.ac.uk	GSD-project participant *[Saturday]*
Jeroen van den Bergh (ICREA-UAB Barcelona/VU Amsterdam) jbergh@feweb.vu.nl	environmental and resource economy, evolutionary economics *[Thursday]*
Pieter Bots (TU Delft) p.w.g.bots@tudelft.nl	Computer/information science *[Saturday]* http ://dana.actoranalysis.com
Markus Brede (CSIRO Canberra) markus.brede@csiro.au	complex systems and physics
Klaas van Egmond (Utrecht University) egmondn@geo.uu.nl	Scientific Director UCAD *[Thursday and Friday morning]*
Nils Ferrand (CEMAGREF Montpellier), nils.ferrand@cemagref.fr	MABS and environmental games and policy exercises *[unable to come; written contribution]*
Tom Fiddaman (Ventana Systems) tom@metasd.com	system dynamics and physics *[unable to come, written contribution]*
Tatiana Filatova (TU Twente) t.filatova@utwente.nl	evolutionary economics *[Saturday and sunday]*
Klaus Hasselmann (ECF-PIK Berlin) klaus.hasselmann@zmaw.de	physics and meteorology
Lars Hein (LUWageningen) lars.hein@wur.nl	physics, environmental science *[Friday]*
Peter Janssen (PBL) peter.janssen@pbl.nl	mathematics *[Thursday]*
Kristian Lindgren (Chalmers University Goteborg), kristian.lindgren@chalmers.se	complex systems and physics
Erik Lysen (Utrecht University)	Managing Director UCAD *[Thursday and Friday morning]*
Piotr Magnuszewski (IIASA/Wroclaw University) magnus@iiasa.ac.at	physics (social physics/games)
Christian Michel (Utrecht University) mail.christian@gmail.com	M Sc student Utrecht University *[Saturday]*
Sido Mylius (PBL) sido.mylius@pbl.nl	evolutionary ecology
Karolina Safarzynska (IVM-VU) Safarzynska@ivm.vu.nl	evolutionary economics *[Friday]*
Clara Schmitt (Université Paris I) clara_schmitt@yahoo.fr	urban geography
Alexei Voinov aavoinov@gmail.com	ecology
Vilhelm Verendel (Chalmers University Goteborg) vive@chalmers.se	physics
Bert de Vries (Utrecht University/PBL), bert.devries@pbl.nl	physics/chemistry
Gérard Weisbuch (ENS Paris) weisbuch@lps.ens.fr	mathematics and complex systems
Gönenç Yücel (TU Delft) G.Yucel@tudelft.nl	PhD Researcher, Policy Analysis and Management
Aart de Zeeuw (Universiteit van Tilburg), a.j.deZeeuw@uvt.nl	mathematics, economics/game theory

2. Programme

Thursday 21 january 2010 Elementary Models (EM): modelling economic agents

Thu 21/1	Morning	9.30 h Introduction to the workshop – Bert de Vries 9.45 h Introductory round of participants 10.00-10.15 h Introduction to the day – Bert de Vries 10.15 h – 13.15 h Examples of elementary 'models of agents' (each 20 min + 10 min Q&D) • Kristian Lindgren: **Evolutionary games: competition, cooperation, and on a fundamental problem of the Nash equilibrium concept** • Gérard Weisbuch: **Economic choices among heterogeneous interacting consumers** • Markus Brede: **Synchronization in the micro- and macroeconomy: ideas and concepts** • Jeroen van den Bergh: **Evolutionary Modeling and Environmental Economics**
Thu 21/1	Afternoon	14.30 – 18.00 h Discussion: what are essential elements of agent in economic decisionmaking models? What insights does this give in the mechanisms/theory of economic development/growth?

Friday 22 january 2010 Elementary Models (EM): the economy-ecology interface

Fri 22/1	Morning	9.00 h – 9.15 h Introduction to the day – Bert de Vries 9.15 h – 12.30 h Examples of elementary economy-ecology models (each 20 min + 5 min Q&D) • Sido Mylius: **Elements from evolutionary dynamics** • Lars Hein: **Implications of ecosystem services and regime shifts for economic models** • Aart de Zeeuw: **Managing ecosystems for resilience** • Klaus Hasselmann: **Stabilities and Instabilities of Economic Growth – System-Dynamic, Agent-Based Simulations using MADIAM** • Piotr Magnuszewski: **Consumer choice and interaction models** • Bert de Vries: **Finite resource and climate dynamics in a competitive/cooperative setting**
Fri 22/1	Afternoon	14.30 – 17.00 h Discussion: what are essential elements ecosystem dynamics/constraints to be included in models of economic development/growth? 17.00 – 17.50 h Karolina Safarzynska: **Producer-consumer co-evolution and innovation dynamics**
Fri 22/1	Evening	Rounding up the two days: *The ideal EM-catalog*

Saturday 23 january 2010 From model to message: interaction and games

Sat 23/1	Morning	9.00 h – 9.15 h Introduction to the day – Bert de Vries 9.15 h – 12.30 h Experiences with existing interactive models and games (each 20 min + 5 min Q&D): ▪ Claes Anderson: **Cellular Automata and Network approaches in Urban Modeling** ▪ Kristian Lindgren: **Interactive modeling via the web: GETonline** ▪ Piotr Magnuszewski: **Simulation games about water management and climate change: some field experiences** ▪ Pieter Bots: **Interactive models and games: experiences with communicating system's insights and engaging stakeholders** ▪ Bert de Vries: **The use of interactive models and games in resource management issues: some examples**
Sat 23/1	Afternoon	Discussion: ▪ Which targets groups (policy makers, students…?) ▪ Which elementary models can be used for interaction/games? ▪ What can be learnt from the experiences with existing interactive models/games? ▪ How to improve existing and construct new interaction/game models?

Sunday 24 january 2010 Wrapping up, reporting, follow-up and departure

Sun 24/1	Morning	9.00 h – 12.00 h Final session 1. Rounding up on elementary models about 2. Lessons about modeling for the science-policy interface 3. Follow-up activities

3. Introductory document

Bert de Vries, Utrecht 18 december 2009, with contributions by Markus Brede, Nils Ferrand, Tom Fiddaman, Piotr Magnuszewski and Gérard Weisbuch. Please add comments via Track Changes or send comments to bert.devries@pbl.nl.

The workshop will be a 4-day intensive, with 5-8 core participants (CP), 5-8 topical experts (TE) invited for one or two days, and some interested or associated partners. The CPs will be responsible for the drafting of workshop proceedings and, preferably, a published report or paper.

Background
As part of WP3 in the GSD project, the aim was to construct an elementary population-economy-energy-climate model, which would then be used in an interactive modeling platform to explore how the climate problem and its causes and consequences are perceived in a dynamic context (see Annex). A simple model SusClime has been constructed and tested in a preliminary interface, in cooperation with Chalmers and as part of a Ph. D. thesis (van Ruiven 2008). A simple interface CLIMEX has been constructed, in which in first instance very simple Climate Fund experiments are done, in connection with a M. Sc. Thesis (Apetrei 2009). Thirdly, a model has been built in which the benefits of regional coordination vs. competition in a world with finite energy resources and climate change have been explored, as a prelude to an interactive web-based simulation game (Brede and De Vries 2009). The regional model is, as in the SusClime model, based on a neo-classical economic growth model with finite energy resources and greenhouse gas emissions causing climate change: a prototypical Economy-Energy-Climate (EEC) model.

From this work I have drawn some conclusions which have led me to adjust the original content of the WP3 workshop. These are:

- The prototypical EEC-model can give interesting insights when applied in a game-set-up, but it lacks a number of key issues in economic growth modelling, notably innovation dynamics, structural change, resource trade and impact dynamics;
- Experimental and behavioural economics requires very rigorous and confined experiments, which makes it hard to bridge the gap between such experiments and the incorporation of their outcomes for EEC-models and their interactive design.

As a consequence, I feel the need to identify those elements in complex system research which can improve the prototypical EEC-model, both for simulation model construction and experiments and for their interactive use for communication and learning purposes.

Objective of the workshop:
In a broad sense, the objective of the workshop is to explore the following questions:

- Which are the most important dynamic relationships in today's world economy which permit a (more) adequate understanding of and interference with complex phenomena such as resource (over)exploitation, loss of ecosystem services and climate change? More in concreto: which are the key issues a Model of a Sustainable Economy (MSE) should be able to explain and/or predict, and which are the mechanisms behind these issues?
- Can (and should) those relationships, issues and mechanisms be formulated as a series of simple elementary models [1], departing from the hypothesis that many fragmented pieces of a new economic theory are already around for quite some time?
- If such elementary models are identified, how can they be formulated and applied for communication between scientists on the one hand and policymakers and interested lay people on the other?
- A final question is whether such a series of elementary models can (and should) be coupled as 'building blocks' into an Integrated Assessment Model (IAM) which is a more adequate tool to explore world problems than the existing economy-energy-climate IAMs? And if so, how?

The first two questions are about identification of existing models and providing a tentative taxonomy; the third and fourth question are at the heart of the GSD-project on the science-policy interface with respect to complex systems science (CSS). We should build upon lots of research done in the last decades and surveyed in books like The *Origin of Wealth* (Beinhocker 2006) and *Nexus* (Buchanan 2002). Similarly, we will use the experience in interactive modeling and simulation gaming and the insights from experimental and

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[1] We use the word *elementary model* to denote formal statements (model) which represent presumedly essential ingredients of real-world processes in a transparent, possibly graphical and interactive, way. Other words for such models are *toy models*, *archetypical models* and *building-block models*. If derived from more elaborate models, one often speaks about *metamodels*. If basically a correlation, it is what economists refer to as *stylized fact*.

behavioural economics, to explore interactive, web-based ways to communicate the novel scientific insights. The last question points at one of the follow-ups to this workshop if it is successful.

A first tentative list of elementary model descriptions is given in separate documents (*EMLit* and *EMCatalog*) which will be available at the workshop. A list of important papers and books have been identified, which are the bibliographic asset for the workshop. The ambition is to start writing short versions of relevant models (equations, assumptions, representative outcomes) and converge to a set of topical models to be worked out for communication purposes.

Methodological issues:

Where to start? Evidently, the classical equilibrium and behavioural assumptions and the neoclassical growth model with its (nested) production function is inadequate for the 21st century challenges ahead [2]. Important concepts of (neo)classical micro- and macro-economic theory should be incorporated, but new approaches have emerged which bring economic science more in line with the advances in the natural and social sciences. This has led to new offshoots such as evolutionary, institutional, behavioural and experimental economics [3]. Analogs from the physical sciences (physics, chemistry, biology) can guide the understanding of more complex systems – such analogs have played an important role in the evolution of complex system dynamics from non-linear system dynamics and statistical mechanics (Weisbuch 1991). To explore these in the form of elementary formal models is one major task in this workshop.

Divergent methods are available for these explorations: integral-differential calculus, statistical approaches, network dynamics, system dynamics and Multi-Agent Based Simulation (MABS) models will be explored for their adequacy in introducing heterogeneity and explaining behaviour (Weisbuch *et al.* 2004, Janssen 2005, Brede and De Vries 2009, De Vries 2009). It seems wise to use all these methods and use both analytical and simulation methods, and examine how they can, each in their own way, contribute to understanding by a lay audience. Obviously, what has become known as *complex systems science* or *complexity science* has an important role to play [4].

A relevant and as yet unsolved question is whether, and if so how, a macro-economic model can be built from units and interactions at the micro-level, for instance to make the link to IAMs. The micro-to macro-step could be explored in several directions. How do multi-agent formulations connect micro to macro? Can a condensed set minimal required set of micro-rules be formulated to generate economic growth at the macro scale – probably yes? Is the micro-approach at all necessary to explain macro aspects of the economy?

Framing the workshop:

Given the ambitious task of the workshop, it is important to find a common and shared frame of reference for the process of collection and selection of models. I suggest the following qualitative embedding of the economic system we are studying:

- There has been a structural evolution of economic systems from the biomass-based subsistence to the industrial economy and on to the service (or information or experience) economy. The three do exist simultaneously and will do so for the decades to come. The corresponding diversity of Social-Ecological Systems (SES) should be explicitly acknowledged (see e.g. De Vries and Goudsblom 2002, Day 2004, Costanza *et al.* 2007).
- There is a co-existence of the formal monetary economic system and, linked, the natural ('ecosystem service') economy and the informal ('amateur', 'shadow') economy. Their dynamic mechanisms may differ substantially (in resources, behaviour, beliefs etc.) and it is therefore important to agree on clear system boundaries and definitions.
- Partly in association with the two previous phenomena, there seems to be a trend towards more heterogeneity of economic agents along dimensions of behaviour and worldviews (including social-economic variables, physical space etc.). This is a complex phenomenon with various layers, making up a dynamic balance between uniforming tendencies of globalization and diversifying tendencies of individualization and regionalization.
- Economic systems are expanding beyond ecological constraints – growth is the balancing act between human aspirations and social stability on the one hand and the ecological constraints on the other. This

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2 See e.g. the book *The Mystery of Economic Growth* (2004), by the economist Helpman. See for textbooks on economic systems and growth for instance: Weil (2004) and Jones (2002); on evolutionary economics Döpfer *et al.* (2005); on resource and environmental economics Van den Bergh (2002) and Perman *et al.* (2003); on ecological economics Common and Stagl (2005); and on critical economics Ekins and Max-Neef (1992), Ormerod (1998) and Kay (2004).

3 Some researchers have coined the word *econophysics*; in a similar vein the word *social physics* is used. Both reflect attempts to find universal empirical laws for economic and social system evolution. Most social scientists still abhor such names.

4 Some general yet good introductions into complex systems science are: Solé and Goodwin (2000), Buchanan (2002) and Perez and Batten (2003); and with an emphasis on economics: Ormerod (1998). See Holland (1995) on complex adaptive systems and Batty (2005) on spatial dynamic models. A good introduction in the system dynamics approach is Sterman's *Business Dynamics* (2000). Beinhocker (2005) focuses specifically on economic science in his book *The Origin of Wealth* about Complexity Economics.

context should guide us to evaluate the relevance of models, i.e. to assist in promoting desired development over undesirable growth. It is the main focus of our effort in this workshop.

The **objectives** of the workshop are:

- Make (a start with) a catalog (taxonomy) of elementary models for a sustainable economy. Focus areas: *agent internal and interaction representation* and *ecological vs. social-economic model elements*
- As part of this: identify *applications* on the basis of the elementary models which are relevant in the context of the search for a sustainable economy
- As part of this: identify the aspects in the two focal areas which are *not* addressed in the models, despite their relevance (in qualitative research)
- Identify *which lessons* from the elementary models and their relevant applications in the two focal areas should be communicated to a wider audience (policy makers, students, public) and *which methods* are to be used (interactive models, simulation games)
- Make (a start with) a catalog of such interactive/web-based simulation models/games for testing.

Proposed focus in the search for elementary models:
Given the diverse nature of economic activities and the variety in interfaces with natural and human systems (i.e. SES), we propose to structure the workshop around three focal points:

1. what are the key elements of an adequate representation of the decisionmaking processes of economic agents?
2. what are the key ingredients of our understanding of the economy-ecology interface?
3. how can the previous insights, in the form of interactive models/games, be effectively communicated to policy makers and interested and people?

This focus is an important downsizing of the earlier proposal. The aim of the workshop is to identify key mechanisms and their formal model equivalents and to explore their transformation into interactive (web-based) games. The intent is to be 'pragmatic'. However, this does not exclude philosophical discussions about whether formal representations of agents as in econo/sociophysics are principally meaningless.

Ad 1. Modelling economic agents (Day 1 – do 21 jan 2010)
Mainstream micro-economic theory postulates the representative agent with a concave utility function, who consumes in isolation and with a given set of preferences and perfect foresight (*homo economicus*). These micro-economic foundations, rooted in 19th century physics, were transferred to a macro-economic theory according to which these agents behave in competitive ways such that the system is permanently in equilibrium or on its (fast) way towards it. This is an unacceptable simplification – a view which has been documented in an increasing number of publications and from various angles (see e.g. Ormerod 1998, Kay 2004, Beinhocker 2005, Jackson 2008). For instance, empirical research shows that (absolute) income ('GDP/cap') is not the driving force behind growth – it is as much (relative) income position that feeds desire for material growth [5]. Also the phenomena of habit formation, repetition and imitation have been suggested as driving forces (Jager *et al.* 2000). The recent subdisciplines of behavioural and experimental economics focus on the presumed irrationality of economic agents or, in other words, on the many deviations from the representative *homo economicus.*

It is hardly possible at this stage to give an adequate and complete overvirew of what is going on the field of 'complexity economics', to use Beinhockers's phrase. A number of partly connected directions become visible [6]:

- *System dynamics*: the role of delays and information flows was already a key element in Forrester's Urban and World Dynamics Models, following up on Simon's ideas about satisficing and bounded rationality. This has been expanded in theory and in practice in Sterman's (2000) book *Business Dynamics*. Several chapters are devoted to issues like the diffusion of innovations, the engine of economic growth, the labour market dynamics and the modeling of human behaviour (consumer choice, price formation a.o.).
- *Evolutionary game theory*: an equally fascinating strand of research has revealed the evolutionary character of economic systems. Among the first mergers was the combination of game theory and evolutionary strategies in biology in the work of Smith (1982) and Axelrod (1984, 1997). This has evolved into elaborate mathematical theory (cf. Nowak 2006) as well as a large variety of simulation models of evolutionary dynamics (reproduction, mutation/crossover, selection) in a variety of fields. This in turn has been influential in the emergence of behavioural economics (Gintis 2000, 2005).
- *Evolutionary economics*: working along similar lines, Nelson and Winter (1982) started to work out the idea that many economic processes are evolutionary in nature – formalizing Schumpeter's ideas about creative destruction. From micro-data they built up an evolutionary growth model for an economy with

[5] See e.g. Hirsch: Social Limits to Growth (1977), Wachtel: The Poverty of Affluence (1988), Layard: Happiness – Lessons from a New science (2005) and Van Praag *et al.* in Kahneman and Tverski (2005).
[6] See for readable 'popular' accounts: Buchanan (2002) and Beinhocker (2005).

macro-pattersn similar to those found in real-world economies. This has spawned a large literature of research and models on the evolution (replication/selection/mutation) of firms and consumers. Most models though focus on either the supply (firms) or the demand (consumers) side; modeling the co-evolution of heterogeneous groups of interacting producers and consumers are still rare (Safarzynska 2010).

- *Dynamic networks*: building upon mathematical graph theory and using the power of computers, dynamic relationships between objects have been researched in ever larger detail. Combined with system analysis (differential equations), this has led to novel insights about the structure of complex systems and their evolution over time. Indeed, as a method of analysis it easily merges with ABM and evolutionary models in order to simulate social networks in which the simulated agents are embedded.
- *Agent-Based Models* (ABM [7]): in hard to separate ways the developments evolutionary and network modeling was accompanied by ever more explicit and sophisticated representations of the human agent (see e.g. Allen and McGlade 1987). The quadrant scheme proposed by Ferber (2007), and shown below, illustrates well the directions for modeling human agency. It seems that the earliest work on simulating agents was the Sugarscape world by Epstein and Axtell (1996), but the later real-world oriented work is largely about stock market behaviour – presumably because such good data are available and the behaviour of agents can be delimited quite well. It is, of course, fascinating to read how simulated agents imbued with rather simple rules can reproduce quite some features of the real-world economy, for example income distributions, non-equilibrium price formation and hierarchical relationship. Agent-based modeling is giving novel tools to emerging disciplines like behavioural and experimental economics and opens the way for a much richer and more empirical investigation of human behaviour under uncertainty and risk.

Internal-Individual (I-I) I → Subjectivity < mental states, emotions, beliefs desires, intentions, cognition…> "Interiority"	External-Individual (E-I) It, This → Objectivity <agent behavior, object, process, physical entities > "Observables, exteriority"
Internal-Collective (I-C) We→ Inter-Subjectivity < shared / collective knowledge invisible social codes and implicit ontologies, informal norms and conventions> "Noosphere"	External-Collective (E-C) Them, All This → Inter-Objectivity <reified social facts and structures, Organizations, institutions> "SocioSphere"

(Ferber (2007) in: Dessalles et al. 2007)

One of the ways to approach this array of methods and applications is to focus on how the human agent in economic processes – as consumer, producer, citizen, competitor – is represented and how this is related to empirical data. In the present context it seems most promising to focus on two related areas: the dynamics of growth and the dynamics of innovation.

a) The dynamics of economic growth

Among the interesting topics are: co-evolutionary producer-consumer growth models (Safarzynska), energy in the production function (Ayres), government role in-between innovation drive and unemployment (Jackson).

b) The dynamics of innovation

This is clearly related to the previous topic: most economic growth is explained by 'innovation' in a broad sense. Interesting models are, besides extensions of neo-classical model (Lucas, Aghion…), the models with evolution-driven innovations (Nelson and Winter; Safarzynska and Van den Bergh)..

The focus will be on simple, archetypical models of consumers and/or producers as interacting agents with explicit preferences and beliefs. With such elementary formulations as the foundation, it becomes possible to explore macro-consequences of micro-heterogeneity: in income, in age, in values and beliefs / worldviews/perceptions. There is evidence that the degree of inequity, for instance, and transboundary migration/globalization are related to people's satisfaction/happiness and may therefore directly or indirectly affect social (in)stability. Such phenomena put constraints on the degree of market efficiency which people accept. Issues like these can, again, be analyzed with AB/MA models as well as other approaches. It would be progress already if we can identify some key dynamic mechanisms which can usefully be hypothesized and made transparent and [empirically] plausible.

Ad 2. The economy-ecology interface (Day 2 – fri 22 jan 2010)

Since the 1960s economic theory has started to (re)consider *ecophysical resources and constraints*. It started with resource and environmental economics, expanding later into ecological economics. Mainstream thinking

[7] Some people prefer to speak about multi-agent simulation (MAS) models.

is centered around ideas such as price mediated equilibria in natural resource (and pollutant) markets, factor substitution (notably manufactured and natural capital), long-term supply cost curves, optimum utility trajectories etc. 'Getting the prices right' may be part of the solution for some resource problems, but it is widely felt that the shortcomings of mainstream models are far more serious. For instance, the strategic behaviour of resource exploiting agents (REF) and the possibility of catastrophic regime shifts in ecosystems are necessary ingredients in adequate appraisal of resource-economy interactions (see e.g. Allen and McGlade 1987, Scheffer *et al.* 2009). What is the relation between the economic system and the environment as a supplier of ecosystem services (in the broadest sense)? In the search for elementary models, we focus on three subdomains. The focus is on a set of realistic elementary models which can serve to highlight crucial aspects of resources as part of the economy as an open system.

a) Exploitation of renewable resources (fisheries, forests, soils, groundwater…).

Most existing models start with the logistic growth equation for the resource dynamics; numerous refinements have been published in the last decades. Exploitation in the form of a harvest function is introduced and, in the first work on biomathematics, sustainable and optimal harvest patterns were proposed. Both on the producer and the consumer side, these models are recognized nowadays as inadequate – serious management failures are proof.

Among the first to argue for an integrated approach which includes the human agent behaviour and strategies were Allen and McGlade (1987), who illustrated the problems by distinguishing between Cartesian (hierarchical/optimizing) and Stochast (exploratory/random) exploitation strategies. The educational game Fish Banks Ltd. (Meadows 1991) successfully framed the 'tragedy of the commons' and has been explored in analytical fashion in later work (see e.g. Weisbuch and Duchateau-Nguyen 1998, Brede and De Vries 2009 a.o.). The agents in these models have cognitive capabilities and direct and indirect social interactions. Also a variety of system dynamics models have been constructed about the exploitation dynamics of renewable resources (see e.g. Ruth and Hannon 1997, Costanza *et al.* 2003, Mashanova and Law (2005).

A more institution oriented direction in the field focuses on renewable resources as a Common Pool Resource (CPR) and the various governance regimes (Ostrom 1990, 2002). Given the empirical evidence that neither full market-based nor full government-based governance leads to sustainable management, recent research on how to govern (global) commons yields novel solutions balancing competition and cooperation, and between bottom-up and top-down.

Renewable resources such as fish and timber are often essential for low-income regions, either as part of subsistence life or as a source of export-based revenues or both. They may not count in monetary terms as compared to OECD-income levels – but their deterioration jeopardizes the livelihoods of millions of people with subsequent undesirable and possibly disastrous consequences in terms of urban slums, environmental refugees etc. Most macro-economic models do not deal at all with these developments, other than 'solving' it by a modernization mix of rising labour productivity and expanding trade. What else should and can we offer?

b) The depletion of finite resources

In the well-known system dynamics model World3 (*Limits to Growth*: Meadows *et al.* 1971), it is suggested that depletion of finite resources (fossil fuels, meineral ores) will cause stagnation or decline in economic activity because at some point production cost will rise so high that it absorbs the larger part of economic output. This has been contested by economists with the argument that price increase will induce substitution, demand stabilization or reduction, and innovation. The empirical data are as yet inconclusive. However, finite scarcity of resources and in particular of fossil fuels is an important factor in economic growth (see e.g. Ayres and Warr 2005) – and a worldwide quality decline cq. cost increase will affect the growth aspirations of economic late-comers.

Classical economics largely dealt with rent and royalty aspects and rising prices to reflect the opportunity cost of quality decline (Hotelling and Hartwick rules). Neoclassical resource models applying dynamic pathways with utility maximization (see e.g. Dasgupta and Heal 1979; Ströbele 1977) are too abstract to be of much use. There are a number of system dynamic resource models, sometimes as part of IA-models (see e.g. Fiddaman 2002, Ruth and Hannon 1997). It appears that AB/MA models are hardly available in this field, possibly because the really interesting dynamics has to do with complex oligopoly and trade issues. There are a number of new initiatives among economists regarding the role of finite resources – for instance, research on the 'resource curse' and the links between resources, trade and conflict at the Oxford Centre for the Analysis of Resource Rich Economies (OxCarre – www.oxcarre.ox.ac.uk).

The issue is relevant because the depletion of strategic resources (oil, phosphorus a.o.) is usually conflict-ridden, as it is perceived as necessary for economic growth and power. In macro-economic models, the market 'solutions' of rising marginal and average production costs, inducing demand reduction asn well as innovations and subsequent substitutes, generates smooth transitions without incurring any conflict or even price volatility. In the global markets and the approaching scramble for diminishing and deteriorating resource deposits of the 21st century, one should prepare for other modes of system behaviour. Which ones?

c) The environment as a sink and the degradation of ecosystem services

The use of environmental compartments as a free sink in the economic system has been a serious consideration by economists since the 1970s. Initially, it was either in aggregate terms as part of an expanded production function or in a more policy-oriented firm/household micro-level (see e.g. Van den Bergh 2002). In most models it enters the economic system in a cost-benefit framework i.e. additional expenditures (counting in GDP-growth) are made to keep environmental impacts within acceptable limits within an optimizing framework or as a tax- or subsidy-driven containment strategy (see e.g. Hettelingh *et al.* 2009). Monetization and commodification may actually tend to conceal the real long-term risks.

The greatest shortcoming is that ecosystem services and their – possibly catastrophic non-linear – change cq. degradation are not considered. The discount rate is often accounting for risk attitudes. Another problem is that ecosystem interferences and risks e.g. regarding biodiversity loss, should be considered in geographical space in view of the local specificities. For linear system responses, the conventional approach may be adequate – there are numerous examples where pollutant fluxes have been reduced within (renegotiable) limits. However, global economic activity has increased and become interconnected to the extent that the real threat comes from erosion of ecosystem vitality and biospheric processes. Large-scale long-term risks are distributed across highly uneven populations in terms of causes, impacts and adaptive capacity. On top of this, according to recent insights ecosystem behaviour may respond highly non-linearly to continued disturbances (see e.g. Scheffer *et al.* 2009).

As with the management of renewable resources, the issue of the commons and its various management strategies is at the core. The focus in the workshop will be on the introduction, in the form of elementary models, of the interaction between economic activity and ecosystem degradation. The role of (risk) perceptions of (economic) agents is important and behavioural economics/game theory may provide insights about its role (see e.g. Sterman and Sweeney 2002).

Again, as in the previous sections, macro-economic models do not have much to offer. The usual approach is, following the textbooks on environmental economics, to incorporate expenses for pollution abatement – which then seems to fix the problem at the 'pressure' side while contributing to economic and income growth. There are good reasons to distrust this solution, because it neglects the accumulation effect of substances on ecosystem services and it neglects the risks of non-linear sudden changes. Can this be improved, and how?

Ad 3. Communication: interactive models and games (Day 3 – sa 23 jan 2010)

The working hypothesis of this workshop is that novel approaches to understanding and modeling social-ecological systems (SES) can be condensed into a limited set of insights which in turn should be communicated to a larger audience of policy makers, students and lay people. The third part of the workshop will focus upon the interesting but difficult question: what are the essential insights from – as yet fragmented – elementary building blocks of SES and how can those effectively be communicated and applied?

In practical terms, a couple of interactive models and simulation games will be presented and discussed. The aim of this day is:

- to assess which elementary insights can be identified from the previous two days and are worth to be communicated and applied with interactive models and/or games;
- to learn from existing interactive models and games, which aspects are essential from a communication/learning perspective;
- to get a feel for the opportunities offered by novel, e.g. Web2.0, technologies; and
- construct a preliminary list of elementary models which could serve as a first tentative library of interactive models and games for the exploration of sustainability of SES.

Of course, this endeavour is embedded in broader questions about social control, autonomy vs. heteronomy and the impact of information on changing behaviours. Some researchers question the usefulness of computermodels in decision support – as Nils Ferrand, who has long experience in participatory games, states: "I need and develop games for the streets domain."

During the day a number of existing simulation models/games will be presented by practitioners. As of today, the following items are on the list:

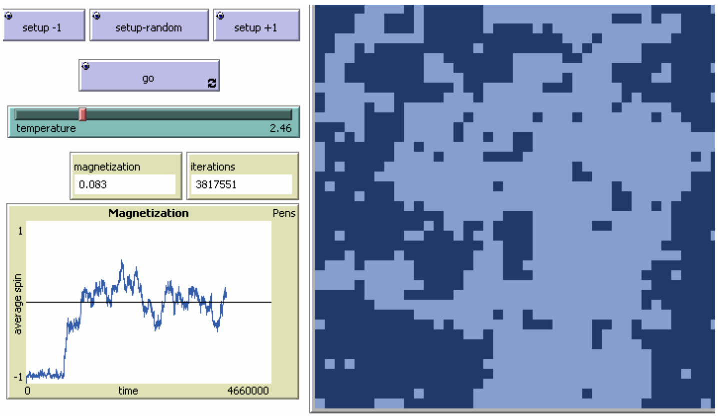
- Stratagem and Fish Banks Ltd. (Meadows). Some of us (BdV) have quite some experience with these two games. Besides, STRATAGEM has been made internet-based at Mendelejev university in Moscow and a couple of hundreds play-histories are available for analysis. An interactive web-based model similar to Fish Banks is under construction at Chalmers (Anderson).
- The GET model to explore world energy futures, developed at Chalmers (Azar. Lindgren *et al.*), has been made interactive as part of the GSD-project. The latest version will be presented (http://css.chs.chalmers.se/getonline-a-new-webtool-for-energy-scenarios/comment-page-1?instance=tml-1&action=lostpassword).
- SusClime (De Vries; Van Ruijven, Brede). This is a simple interactive climate game, which has been used as a game to explore the dynamics of oil depletion and climate change. A few publications focus on model features and a game-theoretic analyses.

- A web-based game made by Magnuszewski et al., which has been played before the workshop by four participants. More info will be available at the workshop.
- the CLIMEX interactive website, which is a website on which players can decide how much to contribute to a Climate Fund in order to reduce the risk of future loss (http://www.tcgon.net/clsim/panel/; Apetrei, Brede, De Vries, Michel). It has a single- and multi-user (social dilemma) version. The single-user version has been tested with 80 students and €-rewards and the results are being analyzed (Apetrei).
- There is also wider experience available (Nils Ferrand), for instance on social experiments (dealing with ways of using models in social experiments for various purposes, from model verification to behavioral change. How to build on field experiment); on participatory modelling for planning (including multi-level stakeholders in real planning processes - stages - constraints - robust "hand based" simulations of causal systems and coherency of action plans); and on an old weird model of social vulnerability (*The Garçon de Café model*... for after-brandy time, linked to the viability theory of Aubin - would have been good to have someone form Aubin's thinking tradition).
- The Sustainable Floodplain Management game developed by Magnuszewski and Szendimir (IIASA), with the focus to assist people to manage (land) resources effectively in a dynamic world of growing complexity and accelerating changes. Participants play the roles of farmers or managers (administrators in government) in river basins. In this play environment they can explore many possible futures, looking at the consequences of their decisions on the sustainable development of floodplains. There will be many opportunities for interactions, negotiations, coalition formation between participants. The skills learned during the workshop are not restricted to floodplain management problems. Insights gained can be applied to many management situations where resources are shared in complex social and environmental landscapes. The game-plus-workshop has the explicit goal to present the system tools for diagnosing and solving complex management problems.
- A rather straightforward interactive model to assist in understanding the climate problem and in exporing alternative emission pathways are the FAIR-model developed at RIVM (now PBL) and used as a decision support tool during several COP-conferences to explore allocation regimes (Den Elzen et al.; http://www.pbl.nl/en/themasites/fair/index.html).

Appendix C Tentative list of elementary CSS models [8]

C.1 *The Ising model*

Strong points: simplicity, analytically solvable, analog/metaphor value
Weak points: (too) simplistic and aggregate to be of (policy) use
Literature: Weisbuch (1989); Solé and Goodwin (2000). See also NetLogo (Ising Model)

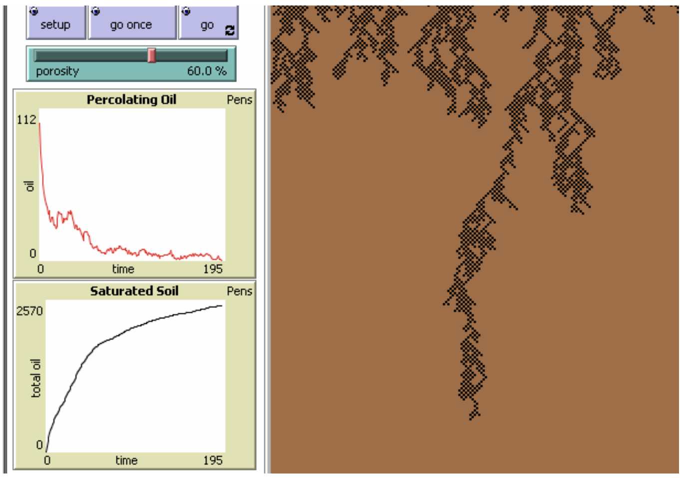


This is a model of a magnet at the microscopic level. The magnetic moments (spins) of the atoms in the magnet can either be up or down. Spins can change as a result of being influenced by neighboring spins and by the ambient temperature. The overall behavior of the system will vary depending on the temperature. [NetLogo]

Mathematically, the Ising model can be explored by assuming that the nodes in a lattice have value 1 ('occupied') with probability p – and thus be empty with probability (1-p). Suppose an occupied cell is a tree that can burn – and will only start burning if a neighbouring tree burns. Then, upon setting a row of trees in fire (e.g. bottom line), the fire will spread. For intermediate p-values not much happens; but for an intermediate p-value (0.59) complex patterns emerge. This is what the percolator model (C.2) also shows.

C.2 *The percolator model*

Strong points: simplicity, analytically solvable, analog/metaphor value
Weak points: (too) simplistic and aggregate to be of (policy) use
Literature: S. Solomon, G. Weisbuch, L. de Arcangelisc, N. Jan, D. Stauer (2000). Social percolation models. Physica A 277 (2000) 239-247. See also NetLogo (Percolation)



This model shows how an oil spill can percolate down through permeable soil. It was inspired by a similar model meant to be done by hand on graph paper (see *Forest Fires, Oil Spills, and Fractal Geometry*, Mathematics Teacher, Nov. 1998, p. 684-5). [NetLogo]

The percolator model is akin to the Ising model. Relevance: introducing percolation in a network of agents (clients, consumers, producers…), it is seen that the bounded-rationality outcome differs from the full-rationality outcome in traditional economic theory. Solé and Goodwin (2000; Ch 7) apply it to habitat destruction.

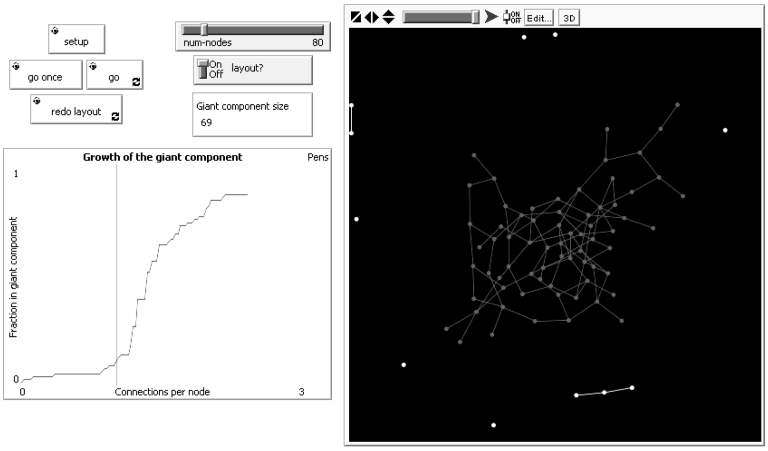
C.3 *Elementary network models*

Strong points: focus on structure of interactions
Weak points: hard (as yet) to find generalizable outcomes
Literature: Newman, M. (2003); Brede, M. and J. Finnigan (2006); Watts, D. J. (1999)

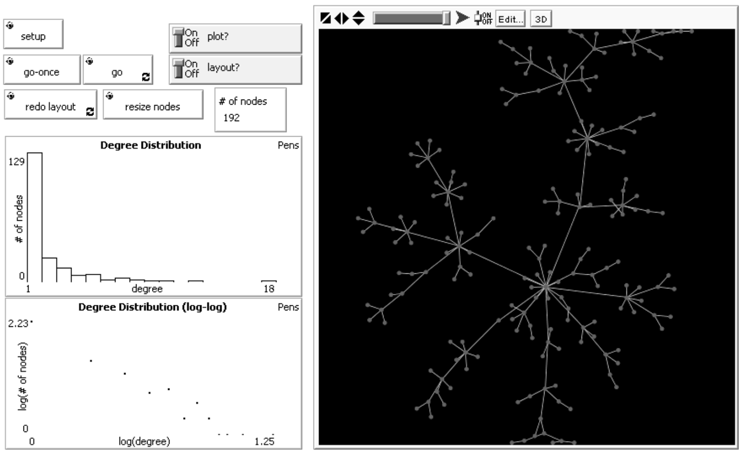
Network analysis has been revived with the advent of increasing computing capabilities and is nowadays applied in almost all scientific disciplines (Strogatz 2001). In physics and engineering, most analyses are on the interactions between similar objects/processes, e.g. coupled oscillators in order to focus on the complexity caused by the nonlinear dynamics of the sites. In the life and social sciences, the emphasis has been more on the architecture of the networks and the genesis and functionality of the structure.

[8] The Journal Physica A, Theoretical and Statistical Physics, has a section Econophysics, where models from physics are applied to ecological, economic and social systems. There is also a Sociophysics but apparently no Ecolophysics; use of physical analogs in ecology has a (too) long history.

One can try to understand the structure of the network under consideration by simulating its growth. Such a process of network building – dynamic network analysis – is done by setting up a number of vertices and connecting them according to certain rules. The first attempt to construct a large network was the 'random net' or 'random graph' by Rapoport and collaborators in 1957. *Random networks* have one interesting property: if one adds randomly edges to a set of vertices, initially at low p≈0 the vertices are weakly connected. When the number of edges approaches n, there is a sudden change in the connectivity: the network becomes a high-density, high-p state in which a large fraction of the vertices are joined together in a single giant component. Such a *phase transition* suggests that the process of adding connections in networks may cause rather sudden changes in its functioning. The figure is based on a simulation with NetLogo.



Instead of linking vertices randomly by adding edges, one may also perform the growth process such that the most connected existing nodes are preferred. Such a *preferential attachment* procedure produces many weakly linked nodes but some highly connected 'hubs'. Such networks are called *scale-free networks* because they remain unchanged under rescaling of the independent variable k with a multiplication factor. These networks show self-similarity and are also called *power-law networks* because their degree distribution follows a power-law, i.e. $p_k \sim k^{-\alpha}$ with α constant. A third interesting type of network is the *small-world network*. These are efficient combinations of the regular and the random. Many social networks have a small-world nature in which a few nodes with diverse contacts cause the phenomenon that each node can be reached within only a few (<10) steps. In comparison with a scale-free network, a small-world network can be considered 'egalitarian'. The figure is based on a simulation with NetLogo.



Most investigations of networks are based on observations of the properties of real-world networks. According to Newman (2003) there are four loose categories:

1. *biological networks*: the classic example is the network of metabolic pathways but others are protein interaction networks, genetic regulatory networks, food webs, neural networks and blood vessels;
2. *technological networks*: these are man-made networks designed typically for distribution of some commodity or resource. Examples are the river and canal networks, road and railway networks and airline routes, the electric power grid and communication networks such as telephone and Internet [9]. Much of these networks are related to space- and geography-governed infrastructure;
3. *information* (or knowledge) *networks*: a classic example is the network of citations whereas more recent ones are the World Wide Web and networks of people's preferences for objects used in targeted advertising; and

social networks: a set of people or groups of people with some pattern of contacts or interactions between them. Well-researched networks are dealing with intermarriages, sexual contacts, mail contacts, friendship relations, business and collaboration relationships, and influence networks of executives and politicians.

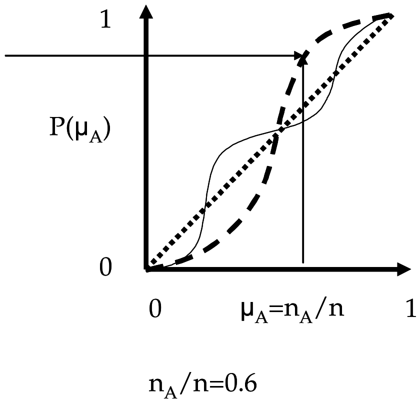
[9] The Internet networks constitutes of the physical connections between computers making up the Internet; not to be confused with the World Wide Web.

C.4 *The Nonlinear Polya Process (NPP) model in economics*

Strong points: brings in stochasticity
Weak points: application in real-world and large models?
Key literature: Arthur, B., *et al.* (1983), Kirman, A. (1993).

A simple formulation to simulate a choice process is the multinomial logit (MNL) equation, which sets a market share for a given ratio of the cost of different products. It is reversible. The MNL-formulation often fails, e.g. the QWERTY typewriter/keyboard vs. Dvorak; the VHS video systems vs. Betamax; alternating current (electricity) vs. direct current; DOS/Windows personal computer operating system vs. Apple and/or Linux a.o.. One reason is that it neglects the possibility of positive feedback. The nonlinear Polya process (NPP) is a simple model with path dependence.

There may be 'one winner who takes it all' because of what economists call positive or increasing returns to scale (absent in macro-economic production functions). Once an option (good, service) has reached a certain market share, all kinds of factors – economies of scale and scope, access and inertia of infrastructure etc. – operate to give it an even larger market share.

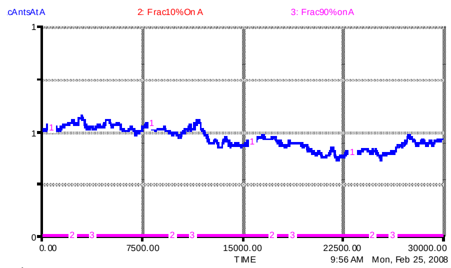


In the Polya generator or Non-linear Polya Process (NPP) model the choice process is considered a series of random choice events. It is also called the *generalized urn model.* Consumers or producers are making sequentially a choice between two competing options A and B. Let the probability that a certain choice is made, P(A), depend on the history of the choice process via the number of times process A has been chosen, n_A. Let P(A) be a function of n_A. Number the events e=1..n and indicate the market share of option A as $\mu_A = n_A/n$. The probability that the next event is a choice of A, P(A), is a function of the number of times option A has been chosen, $P(A)=\Phi(\mu_A)$.

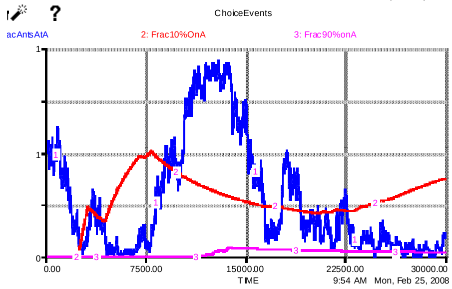
Consider two options for a Polya random process with an input between 0 and 1 representing a new entrant on a choice market. Then, the new entrant chooses on the basis of the previous choices made:

- $P(A) = 1-\mu(A)^{\beta}$ with $\beta>0$ i.e. decreasing returns: whenever n(A) is below (above) a certain value, P(A) is either more (less) than proportional; and
- P(A) a higher-order function of $\mu(A)$ i.e. increasing returns with multiple equilibria: when $\mu(A)$ is in a certain range it may tend up (positive) or down (negative);

with $\mu(A)$ = fraction of option A in total and P(A) = probability that next entrance chooses option A, P(A) = $F(\mu(A))$. The first case is the equivalent of a MNL-choice process: the more A penetrates, the more the counterforces will drive it back to a single equilibrium reflecting the relative preferences of choosers.. The second option is one with two or more equilibria which is much harder to predict and reflects increasing returns to scale in certain domains. The NPP-model is, like the MNL-model, not dynamic: it only counts discrete events without any statement on the rate at which they occur.



If only the probability of individual ants play a role, there will be an average around 50-50%



...but if encounters with other ants (interaction) plays a role, the behaviour may become very different (contagion)

What the NPP-model indicates and what is absent in neo-classical models: *history matters!* If a choice process is also determined by past outcomes, which is the essence of memorizing and learning, processes become path-dependent. It explains lock-in situations. Processes with positive returns to scale happen in the real world:

- industrial location: the probability that a new firm is established in region A increases with the number of firms already there;
- information contagion, with reputation as a particular example: the more option A earns a better reputation (quality, reliability etc.) in the course of events, the more often it is chosen;
- standards, networks and infrastructure: if the task to be performed requires connections with other users, each next user has an advantage in choosing the one with most users connected.

A widely known and inspiring example of the generalized urn model is given by Kirman (1993) in his paper *Ants, Rationality, and Recruitment*. Introducing stochasticity with subsequent reinforcing loop effects in such a simple model causes path dependence: 'history matters'. In economics the generalized urn model (Arthur et al. 1983) pointed at the same message and became important in understanding increasing economies of scale and subsequent lock-in in economic systems (cf. Appendix C.6). The graphs show an implementation in Stella of the simplest version.

C.5 *Threshold models*

Strong points: include direct social interaction
Weak points: mean-field type of approach only
Key literature: Granovetter M. (1979); Levy M. 2005) 71–87; Schelling (1978). See also NetLogo (Segregation)

Another kind of models involving explicitly social interactions are threshold models, which general idea states that an individual will adopt some opinion on the condition that a certain minimum, threshold, number or fraction of others has already adopted it:

$$P(+1)=\begin{cases}0 \text{ for } m<m^{Th} \\ 1 \text{ for } m\geq m^{Th}\end{cases},$$

where threshold value m^{Th} may be constant or may be a random variable of some distribution. This may be viewed as a kind of Non-linear Polya Process (NPP) model. Thus, stationary value of 'mean choice' may be obtained from self-consistent equation of the form:

$$m^* = f(m^*),$$

where $f(m^*)$ may have nonlinear form and thus there may exists a variety of number and character of existing equilibriums.

C.6 *Threshold models with memory*

Strong points: include direct social interaction and dependence on former state
Weak points: binary choice only, difficult to parameterize
Key literature: Nowak A., *et al.* (1990) 362–376; Lewenstein M., *et al.* (1992); ; Hołyst, J., *et al.* (2000) 199

Threshold models (and also the Brock-Durlauf model – C.5) include social interactions not mediated by the market. The next step to adequately modeling complex systems is adding the former state of an individual himself/herself to the list of factors, on which the choice of an individual is dependent. This modification is reflecting the psychological tendency toward consistent or habitual behavior, which is how an agent's former choice influences the current one. Examples of such models are Nowak-Latane model and Holyst-Kacperski model. They are formulated within impact function approach:

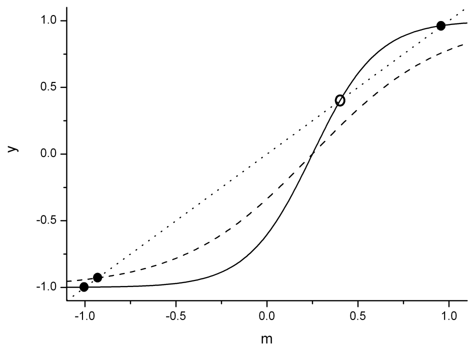
$$\sigma_i^t=\begin{cases}\sigma_i^{t-1} \text{ with probability } 1-F_i(I_i) \\ -\sigma_i^{t-1} \text{ with probability } F_i(I_i)\end{cases}$$

where $\sigma_i^{t,t-1}$ denotes current and former choice, respectively, F_i is some cumulative distribution function that has to be defined in a specific model, and I_i is a so-called impact function. An impact function depends on the former choice made by the individual himself/herself, as well as on the choices of other individuals.

The Nowak-Latane model is defined with a step form of F_i: $F_i(I_i)$ = ½ (sgnI_i + I) (deterministic rule: an agent maintains a former choice when the impact function takes a negative value, and changes the decision when the impact function takes a positive value), and with impact function [NL0]:

$$I_i = f_p\left(\sum_{j\neq i} P_{ij}\left(1-\sigma_i\sigma_j\right)\right) - f_s\left(\right.$$

,



Where f_p and f_s are the so-called persuading and supporting functions, respectively.
The Holyst-Kacperski model is defined with a logistic form of F_i and impact function:

$$I_i = -b_i - \sigma_i h_i - \sum_{j\neq i} J_{ij}\sigma_i\sigma_j$$

where b_i denotes the strength of "inertia" of an individual (so-called self-support).

Stationary states in both models are found from some condition: m* = f(m*), which in the case of Holyst-Kacperski model has one or three solutions and in Nowak-Latane model may have multiple solutions (thus within NL model there may exist multiple of equilibriums).

A graphical analysis of the Holyst – Kacperski model is shown in the figure. Equilibrium points are found as the intersection of curves y=m (dotted line) and y=f(m) for values of parameters: β=1.5 (parameter of logistic distribution), J=2, h=-0.5 and b=1 (solid line); b=0 (dashed line). Full circles correspond to equilibriums and open circles to unstable stationary states.

C.7 *Brock-Durlauf (BD) social interaction model*

Strong points: include direct social interaction
Weak points: difficult to parameterize
Key literature: Brock W., and S. Durlauf (2001); Durlauf S. (1999); Brock W., and S. Durlauf (2001).

Direct social interactions not mediated by market can be responsible for the novel, emergent phenomena whose prospect may provide explanations of collective social phenomena. Recently, models with social interactions are gaining increasing attention. One of the efforts to include social interactions is the Brock-Durlauf (BD) binary-choice ($\sigma_i = \pm 1$) model, belonging to the class of Random Utility Models with interactions between agents incorporated by adding a social term to individual utility functions. The particular form of utility function in BD-model reads:

$$U_i \equiv U_i^{\det}(\sigma_i) + \sum_{j\neq i} J\sigma_i\sigma_j + \varepsilon_i(\sigma_i) \text{ and } U_i^{\det} = h\sigma_i$$

with the second term involving social interactions and with random term (which corresponds to the unknown irregular factors of the decision making process) described by logistic cumulative distribution function with width parameter Β.

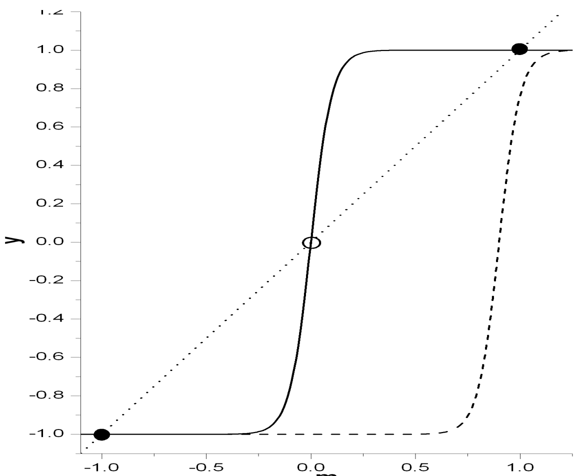
The probability of choosing the state (+1) may be obtained basing on the comparison of utility function values:

$$P(+1) = P(U(+1) > U(-1)) = \frac{1}{1+\exp\left[2J\sum_j \sigma_j + U^{\det}(+1) - U^{\det}(-1)\right]},$$

In the BD-model one can get for a fully connected network within the mean-field approach equilibria [10] from the self-consistent equation for stationary values of a "mean choice":

$$m^* = \tanh\left(\beta\left(Jm^* + \frac{1}{2}\left(U^{\det}(+1) - U^{\det}(-1)\right)\right)\right) = \tanh\left(\beta\left(Jm^* + h\right)\right),$$

which may have one or three solutions – in the case of three solutions, two of them are stable and correspond to system equilibriums. The BD-model (defined by logistic distribution of random variable) is an extension of the logit model to include social interactions. If one puts $J \equiv 0$ (removing interactions) and notices that the utility may be treated as a negative cost, the second form of binary-choice formula for market share of certain option is regained.



Although the BD-model was formulated as static model, its dynamic counterpart may be easily found. The transition probabilities:

$$P(\pm 1 \to +1) = \frac{1}{1+\exp\left[2Jm + U^{\det}(+1) - U^{\det}(-1)\right]}$$

$$P(\pm 1 \to -1) = 1 - P(\pm 1 \to +1) = \frac{1}{1+\exp\left[-\left(2Jm + U^{\det}\right.\right.}$$

---

[10] Within the mean-field approach (MFA) one assumes that all individuals interact with each other (fully connected network) with the same strength. We will also assume that the number of individuals, N, is large enough to make $\sum_{j\neq i}\sigma_j \Big/ N-1 \approx \sum_j \sigma_j \Big/ N$. Moreover, one also assumes that parameters are either the same or drawn from the same distribution for all of the agents. Here we define *equilibrium* as a stable stationary state, within which the 'mean choice' $m \equiv \sum_j \sigma_j \Big/ N$ does not change in time. Note, that it is not necessarily equilibrium in a strict physical meaning.

lead to strictly the same stationary states as in the static version of the BD-model. Moreover, binary-choice BD-model has already been generalized to the discrete choice (multiple choice) model. The figure shows a graphical analysis of the BD model: a crossing of curves y=m and y-tanh(β(Jm+h)) and for values of parameters β=10, J=2 and h=0 (solid line) and h=-1.8 (dashed line). Full circles correspond to stable stationary states and open circles to unstable stationary states.

C.8 Generalized binary choice model

Strong points: possibility of realistic modeling wide variety of the systems

Weak points: binary choice only, difficult to parameterize

Key literature: Ostasiewicz, K., et al. (2008); KOstasiewicz, K., *et al.* (2009)

Based on a utility function approach there was proposed [SA1,SA2] a general framework to construct binary-choice models, including both social interactions and "inertia" of individuals, covering, as special cases, all kinds of models mentioned above (dynamic version of logit model, BD model, Scheffer shift model, NPP model, threshold models, NL model, HK model). This model belongs to the class of Random Utility Models.

Having dependence on the former state of the agent it is convenient to introduce two utility functions: $U^{\pm}$, corresponding to the former state $\sigma_i = \pm 1$:

$$U_i \equiv \frac{1}{2}\left[(1+\sigma_i)U_i^+(\sigma_i')+(1-\sigma_i)U_i^-(\sigma_i')\right]$$

where σ_i' denotes the present choice of an individual, σ_i - his/her previous choice, and:

$$U_i^{\pm} = \sigma_i' h_i \pm \sigma_i' b_i \pm \sigma_i f^{\pm}\left(\left\{\sigma_{j\neq i}\right\}\right)+\varepsilon(\sigma_i')$$

where h_i denotes the strength of individual preferences, b_i the strength of an individual's inertia and $\varepsilon_i(\sigma_i)$ a random term with some cumulative distribution $\varepsilon(-1)-\varepsilon(+1) \propto F(z)$.

All the above models may be obtained by proper choice of values of parameters and/or forms of the functions. In logit models utility function does not depend in explicit way on the choices of others (costs may be treated as a negative utility):

$$U_i \equiv U_i^{\det}(\sigma_i)+\varepsilon_i(\sigma_i).$$

In the case of two options, and having the fully connected network the stationary values of 'mean choice' (or fraction of a certain choices) may be obtained within mean-field approach as some function of difference:

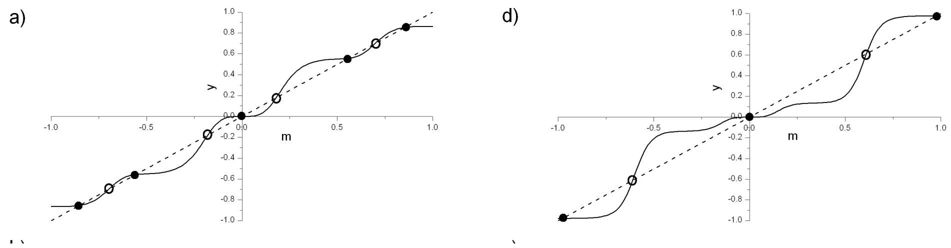
$$\Delta U^{\det} \equiv U^{\det}(+1)-U^{\det}(-1):$$

$$m^* = f\left(\Delta U^{\det}\right).$$

A dynamical version of the BD-model may be obtained from the general form by substituting: b_i=0, $f^+ = -f^- = \sum_{j\neq i} J_{ij}\sigma_j$ and $F(z)$ described by logistic cumulative distribution function. Threshold models also can be reproduced by proper choice of distributions.

As it has been shown [SA1], impact function models are strictly equivalent to the utility function models: consequently, NL model and HK model may also be reformulated within utility function approach: For the Nowak-Latane model: $f^{\pm} = -f_p\left(\sum_{j\neq i} P_{ij}(1\mp\sigma_j)\right)+f_s\left(\sum_{j\neq i} S_{ij}(1\pm\sigma_j)\right)$, with f_p and f_s as persuading and supporting functions, and $\varepsilon_i \equiv 0$; for the Holyst-Kacperski model: $f^+ = -f^- = \sum_{j\neq i} J_{ij}\sigma_j$, and F(z) described by logistic cumulative distribution function.

The stationary values of 'mean choice' for this generalized binary-choice model is determined by a self-consistent equation of the form: m*c = f(m*) which, in general, may be strongly nonlinear and thus produce a rich variety of existing equilibriums. The model formulated for binary-choice situations may be probably extended for multiple-choice formulation, although resulting formulae may not be so compact.



The figure sketches a graphical analysis of generalized binary-choice model with Weibull function:

$$f_s = C_s\left[1-\exp\left(-\left(\frac{x}{d_s}\right)^{a_s}\right)\right],\ f_p = C_p\left[1-\exp\left(-\left(\frac{x}{d_p}\right)^{a_p}\right)\right].$$

Equilibrium points are found as the intersection of curves y = m (dashed lines) and y = f(m) (solid lines) for values of parameters: figure a) h=0, b=2, P=S=1, C_s = C_p = 1, d_s = 0.8, d_p = 0.3,,a_s = 10, a_p = 4, β = 1.41, and figure d) h=0, b=0.1, P=S=1, C_s = 0.7, C_p = 1, , ,d_s = 0.8, d_p = 0.4, a_s = 10, a_p = 4, β = 5.56. Full circles correspond to equilibriums and open circles to unstable stationary states.

C.9 *A public opinion shift model*

Strong points: very good example of importance of social interactions
Weak points: difficult to parameterize
Key literature: Scheffer M.,*et al.* (2003)

The model is a variation of the basic BD model. It can be used to predict how the mean public attitude changes in response to a new and slowly increasing environmental problem. It is based on utility function approach, and deals with a set of individuals for each of whom there are simply two modes of "'opinion or 'attitude' with respect to a problem: active (+1) or passive (-1). It takes effort to be active, but activation also generates pressure on authorities in the direction of one's own interest. Utility function for individuals has the form:

$$\tilde{U}(\sigma) = U(\sigma) + \varepsilon(\sigma),$$

where U(σ) include both individual utility and cost of deviating from the overall group tendency:

$$U(\sigma) = U_i(\sigma) - c(\sigma - m)^2 .$$

The model shows the hysteresis the same like in the BD model.

C.10 *The replicator model*

Strong points: simplicity, fundamental bio/ecological insights
Weak points: too easily transferred to social-economic systems?
Key literature: Hofbauer, J. and Sigmund, K. (1998); Nowak, M. (2006).

Evolution is a process of reproducing populations, with selection through competition and novelty and diversity through mutation. A formal description of reproduction dynamics is (Nowak 2006:15):

$$\dot{x} = ax$$
$$\dot{y} = by$$

The relative rate of change of x and y equals: $\dot{\rho} = \frac{\dot{x}y - x\dot{y}}{y^2} = (a-b)\rho$ with ρ=x/y. For a>b, population x outcompetes population y. Assume that the two species compete in a niche of fixed size i.e. total population x+y is constant; population size can now be interpreted as relative abundance or frequency. Let us associate the growth parameters a and b with fitness and define the average fitness as φ=ax+by. A population only changes if its frequency deviates from the average fitness if:

$$\dot{x} = x(a - \varphi)$$
$$\dot{y} = y(b - \varphi)$$

Using y=x-1 this can be rewritten as a logistic growth equation: $\dot{x} = (a-b)x(1-x)$. Equilibria only occur for x=0 or x=1 and either species outcompetes the other into extinction. Departing from these simple growth equations and generalizing, the basic equation for selection dynamics is (Nowak 2006:17):

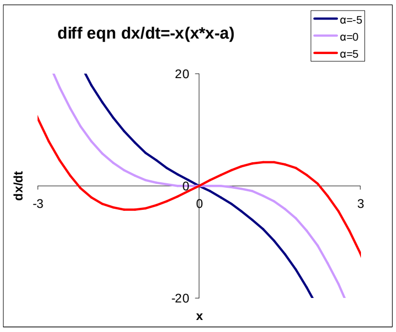
$\dot{x}_i = x_i(f_i - \varphi)$ for i=1..n and under the conditions $\sum_{i=1}^{n} x_i = 1$ and $\sum_{i=1}^{n} \dot{x}_i = 0$. This linear equation has a single globally stable equilibrium: survival of the population with the largest fitness. For a growth equation of the form $\dot{x} = ax^c - \varphi x$ a third attractor emerges (cf. neoclassical growth model: $\dot{k} = ak^\alpha - k/LT$ where always α<1). For c<1 there is subexponential growth and room for both species; for c>1 there is superexponential growth and the interior attractor is unstable: survival of the first.

C.11 Catastrophe cusps

Strong points: interaction fast and slow dynamics

Weak points: too easily transferred to social-economic systems?

Key literature: Scheffer, M. *et al.* (2009).



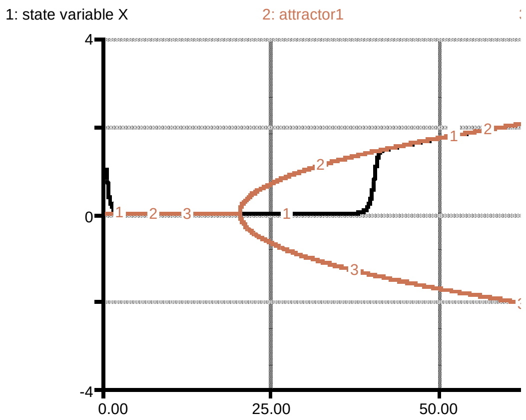
The existence of more than one basin of attraction may cause a sudden shift in system structure and behaviour – a so-called *regime shift*. The class of nonlinear equations which have been proposed to analyze this phenomenon is a third order equation:

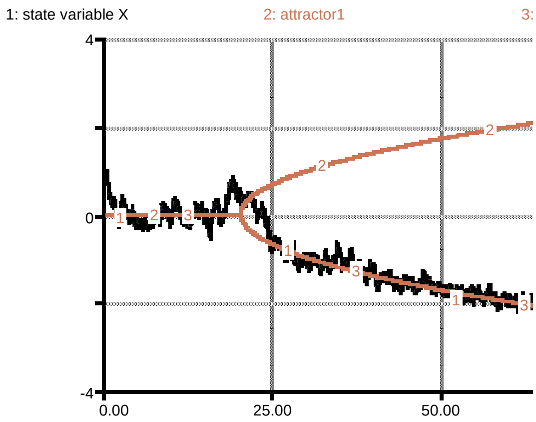
$$dX/dt = -X(X^2 - \alpha)$$

This equation was at the basis of catastrophe theory as developed in the 1960s and 1970s by Thom and Zeeman. A change in the parameter α leads to a structural change in behaviour. Recall that an attractor occurs for the X-value at which dX/dt=0. In case of eqn. 12.4, one root is X=0 and the other is:

$$\frac{dX}{dt} = 0 \Leftrightarrow X = \pm\sqrt{\alpha}$$

For α≤0, X=0 is the only globally stable attractor. For α>0 it has two locally stable (X=±√α) and one globally unstable attractor (X=0). This is seen from the phase diagram for three different values of α. If we consider the state variable X, for instance: the size of a population, as the fast variable and the structural parameter α, for instance: its sensitivity to climate change, as the slow variable, the time-path of the state variable X will for (slowly) rising α gradually move from one with a globally stable attractor to one which has two locally stable attractors and therefore can undergo a rather sudden switch from one equilibrium state to another.





Such a bifurcation can be simulated with a simple Stella ® model, in which the value of α ranges from -2 to +4. Until α=0, there is only one globally stable attractor. Thereafter, for α>0, there are two locally stable attractors. What does this mean? If we simulate the 'fast' state variable X while also changing the 'slow' variable α (which is in most models a fixed 'structural' parameter), we see that the system remains until α=0 in the stable equilibrium (X=0). Thereafter it stays in the now unstable equilibrium (X=0) until a sudden switch around year 40 to one of the two (here: upper, X=+√α) stable attractors. A qualitative analog interpretation is that the system experiences 'catastrophic change' like what happens with sudden crystallization in an oversaturated solution.

Most real-world systems random fluctuations occur. With a random disturbance on the state variable X, the system starts (α≥0) to follow one of the stable attractors – though it is not possible to say which of the two. If the random disturbances become bigger, a new phenomenon may occur: for a large enough fluctuation there may be a sudden shift from one attractor to the other. Upon doubling the extent of the random fluctuations in our simulation experiment, the state variable switches path at around year 35 when a particularly extreme disturbance triggers a sudden, catastrophic change. However, the higher α is, the higher the disturbance has to be in order to cause such a switch, because the two attractor pathways diverge. Thus, the resilience of the system declines for $\alpha \to 0$. For instance, if we fix α=1 at step 30 (arrow position) and draw the trajectory of X, it is seen that the system fluctuates between the two attractors.

C.12 Fletcher-Hilbert (FH) land exploitation model

Strong points: goes beyond the concept of 'sustainability' to establish a paradigm of 'resilient exploitation' that calculates the capacity of landscape exploitation systems to survive in uncertain and variable human and natural environments

Weak points: highly aggregated

Key literature: Fletcher and Hilbert (2007)

The formal part of Fletcher-Hilbert model of land-exploitation systems is similar to the canonical predator–prey system, in which human-made capital, H, consumes natural capital, N. These variables are aggregate measures of sub-systems which may be quite complex in detail. Land area is assumed fixed and sufficiently homogeneous that spatial variability can be ignored. Dynamical equations for N and H are the following:

$$\dot{N} = rN\left(1-\frac{N}{K}\right) - f\left[N,H\right]C_{\max}H$$

$$\dot{H} = \sigma\left[N,H\right]P - bH = \sigma\left[N,H\right]aC_{\max} f\left[N,H\right]H - bH \text{ ,}$$

with

$$f\left[N,H\right] = \frac{N}{\gamma C_{\max}H + N}$$

$$P = af\left[N,H\right]C_{\max}H$$

and σ=N/A the savings rate, i.e. the fraction of production that is reinvested to purchase new human-made capital; r the maximum growth rate of natural capital; K the carrying capacity of N , i.e. amount of N in a stable unexploited system; C_{max} the maximum consumption rate of natural capital per unit of human-made capital; γ the half-saturation of decreasing marginal returns, i.e. time required to consume half remaining natural capital at maximum consumption rate; a the production coefficient, i.e. how consumed N is transformed into production, measured relative to the value of a unit of H; and b the rate at which human-made capital depreciates. Depending on the parameters, the model displays a single non-trivial equilibrium, two equilibriums, or stable limit cycles. Of course, as with the catastrophe models under C.11, many other models have been proposed to simulate resource exploitation dynamics and the challenge is to incorporate the dynamics and/or the insights into the larger IAMs.

Appendix D Brief description of some economy-energy-climate IAMs

For other overviews see e.g. Nakicenovic and Swart (2000) and Van Vuuren *et al.* (2009)

1. DICE and derivatives

The DICE model is kind of an avatar in the economy / climate modelling arena. It was constructed and published by Nordhaus in 1992 and can be investigated on the model inventory of Fiddaman: (http://www.metasd.com/models/Library/ClimatePolicy/NordhausDICE/). This website gives, besides a critical analysis and literature references, also a series of other related system dynamics models. One of these is the FREE model, which Fiddaman developed for his Ph.D. thesis in 1997 which also contains a detailed assessment of the DICE and derived models (Fiddaman 2002).

2. MERGE http://www.stanford.edu/group/MERGE/

Many papers and reports have been written about the MERGE model and its applications, e.g. Manne et al. (1995) and Mann and Richels, *MERGE: An Integrated Assessment Model for Global Climate Change* (2004). The model has started as a DICE-like multi-regional optimal control model, in which a global planner optimizes utility (defined as the logarithm of consumption) over a long (2100) time horizon. In this 'benefit-cost' mode abatement and damage cost functions are used, leading to an optimal economic growth path. The model can also be run in a 'cost-effective' mode, which calculates the optimal emission path given a climate target (concentration or temperature).

The central accounting equation is that the single-good output Y in any region r and year t is allocated over consumption C, investments I, energy costs EC, market damages from climate change MD, and net exports X. Within a period prices and quantities equilibrate, then the next year's output is calculated from a CES production function in capital (K), labour (L) and energy. Capital stocks are depreciated at 40%/decade. Capital and labour but also capital-labour and energy are substitutes; within the energy sector substitution between electric (E) and non-electric (N) takes place. Besides, autonomous improvements in labour and energy productivity are simulated. In formula form:

$$Y = C + I + EC + X - MD = \left[a(K^{\alpha}L^{1-\alpha})^{\gamma} + b(E^{\beta}N^{1-\beta})^{\gamma}\right]^{1/\gamma}$$

with $\gamma=(1-\sigma)/\sigma$. By increasing b autonomous energy-efficiency improvements are introduced.
Trade between regions is simulated on the basis of a single internationally traded good (Heckscher-Ohlin formalism), which is considered an acceptable simplification for long-term modeling. Emissions from energy come from burning of fossil fuel, which constitute a finite resource with depletion effects. Climate change is modelled as a delayed temperature rise from rising concentration and radiative forcing levels.

Economists increasingly agree that non-market losses, related to e.g. health and ecosystem service losses, may be equally or more important in the assessment of climate change damage than market losses such as crop losses and shoreline damages. Indeed, the whole idea of strict distinctions and confinement to only market losses is fortunately losing ground. MERGE assumes that 'market' losses are a fixed percentage of GDP for a 2,5°C global average temperature increase (MD= 0,25% for HI and 0,5% for LI).

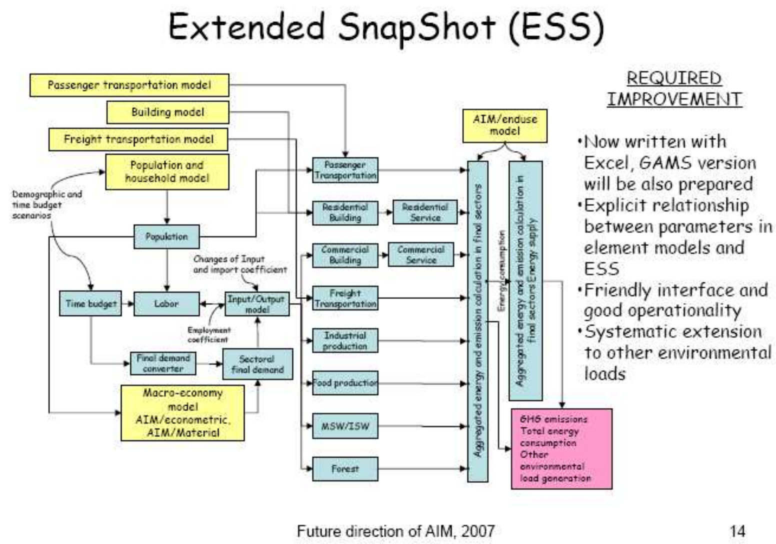
'Non-market' losses are approximated with a quadratic function in the global average temperature rise via an economic loss factor ELF:

$$ELF(x) = \left[1 - \left(\frac{x}{catt}\right)^2\right]^{hsx}$$

where x is a variable that measures the temperature rise above its level in 2000, hsx depends on the region (1 for HI and less for LI) and catt is a catastrophic temperature parameter chosen so that the entire regional product is wiped out at this level (17.7° C. for a normalization of ELF(2.5°) =0.98 in HI). This formulation is admittedly speculative but "the general principle seems plausible. All nations might be willing to pay something to avoid climate change, but poor nations cannot afford to pay a great deal in the near future.".

3. AIM http://www.stanford.edu/group/EMF/projects/group21/PresentDec03/Fujino.ppt#8 and several other sites which are hard to access

The Asian Integrated Model (AIM) has been developed at the Japanese NIES Kainuma et al. 2003). This model has a strong energy end-use orientation, with detailed representations of industrial process plant and consumer appliance stocks and the associated changes in technology and user characteristics (cf. Markal). The driving forces, such as GDP/cap and IVA/cap, are exogenous determinants of energy services demand. The elaborate energy model is embedded in a series of submodels: a CGE-model of the economy, a climate model, a population/health model, and food, water, hydro and land/vegetation models. Yet, it is largely a bottom-up model (cf. IMAGE-TIMER) where energy use/supply and climate change impacts are mostly simulated in physical/engineering terms. This may change as the plans for the period until 2013 foresee a more integrated global macro-economic CGE-model, an extended energy end-use model, and an interactive tool to explore scenario consistency (ESS; see figure below). Regarding this last development, there is as yet no new information.



4. EPPA
http://globalchange.mit.edu/igsm/eppa.html and relatedly the Integrated Global System model http://web.mit.edu/globalchange/www/climate.html

The MIT Emissions Predictions and Policy Analysis (EPPA) model provides projections of world economic development and emissions along with analysis of proposed emissions control measures. It is used to analyze the processes that produce greenhouse-relevant emissions and to assess the consequences of policy proposals, providing estimates of the magnitude and distribution among nations of their costs and clarifying the ways that changes are mediated through international trade.

EPPA is a multi-sector, multi-region computable general equilibrium (CGE) model of the world economy. It utilizes the GTAP dataset (maintained at Purdue University), augmented by data on the emissions of greenhouse gases, aerosols and other relevant species, taxes, and details of selected economic sectors. Provision is made for analysis of uncertainty in key human influences, such as the growth of population and economic activity and the pace and direction of technical advance.

The model is formulated in two versions with contrasting representations of agent expectations. The recursive-dynamic (myopic) version is the more computationally efficient, allowing for an explicit treatment of capital stock turnover and greater regional and technology detail. The dynamic (forward looking) formulation provides the capability to examine questions where forward-looking behavior is particularly important.

The model projects economic variables (GDP, energy use, sectoral output, consumption, etc.) and emissions of greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs and SF_6) and other air pollutants (CO, VOC, NO_x, SO_2, NH_3, black carbon, and organic carbon) from combustion of carbon-based fuels, industrial processes, waste handling, and agricultural activities. Different versions of the model have also been formulated for targeted studies to provide consistent treatment of feedbacks of climate change on the economy, such as effects on agriculture, forestry, bio-fuels and ecosystems and interactions with urban air pollution and its health effects.

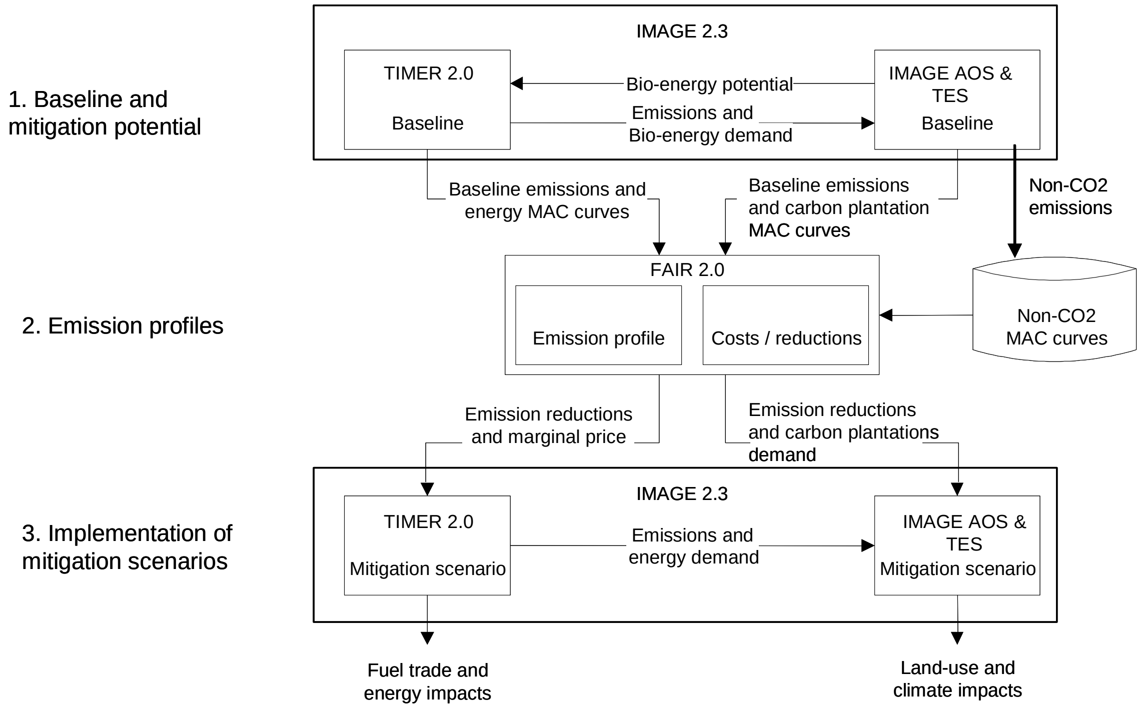
5. IMAGE-TIMER-FAIR http://www.mnp.nl/en/themasites/fair/index.html

The Integrated Model to Assess the Global Environment (IMAGE; formerly: Greenhousegas Emissions) (www.mnp.nl/image) has been developed since the early 1990s as a model of intermediate complexity to evaluate the consequences of greenhousegas emissions from fossil fuel burning and land use land cover change (LUCC) and explore possible strategies to mitigate them. The present IMAGE2.4 version (Bouwman et al. 2006) is an integrated model which simulates the population and economic dynamics as drivers of demand for energy and land use services, at the 27 region level, which in turn interferes with the element cycles (C, N). These are simulated in a rather simple climate dynamics model (MAGICC-based), which yields the (change in) global average surface temperature. This is unfolded over the 65000+ 0,5°x0,5° gridcells, in order to explore the consequences for agriculture and livestock and biodiversity.

Population is simulated with the Phoenix model which has rather detailed birth rate and death/morbidity rate modules – see www.mnp.nl/phoenix. It has 100 age cohorts and is being extended with modules on health care and education services. For the economic system, several macro-economic models are used: the WorldScan model of the dutch CPB, the International Futures (IFs) model (www.ifs.org) and the DART model of Kiel University. Most of the dynamics follows neo-classical growth theory, with a number of explicit linkages to the population (health, education) and energy and agriculture modules. Climate change impacts are simulated in the form of changing land use/land cover with associated changes in agricultural productivity – but the damages and costs to ecosystem services, health and economic assets are not considered, neither directly nor indirectly (via feedbacks).

The FAIR model is an interactive, decision-support tool to analyse environmental and costs implications of climate mitigation regimes for future commitments for reducing emissions of greenhouse gases. The model links long-term climate targets and global reduction objectives with regional emissions allowances and abatement costs, accounting for the used Kyoto Mechanisms. The results can be analyzed at various geographical scales, i.e. for the 26 world regions (FAIR region model), 27 EU Member States (FAIR EU model) and 224 UN countries (FAIR world model).

The scheme below gives an overview of the complete modelling platform as it is being used for a variety of climate change / policy related applications.



Linkage and information flows of the applied modelling framework integrating TIMER, IMAGE and FAIR (note CP = carbon plantations; MAC = Marginal abatement curve.) (Source: van Vuuren et al. 2006).

6. IMACLIM-R http://www.imaclim.centre-cired.fr/

The IMACLIM-R model, developed at CIRED, is an attempt to combine the advantages of empirical I-O data and applications with long-term economic growth modeling, in order to get a better assessment of the transition costs involved in drastic changes in consumption styles, technologies and geographic patterns. It is based on the belief that "it is almost impossible to find tractable functions with mathematical properties suited to cover large departures from reference equilibrium over one century and flexible enough to encompass different scenarios of structural change…"(pp. 7). Thus, it is an attempt to be explicit about the pseudo-dynamics in economic modeling: one jumps from an equilibrium in at time t via reduced but technology-rich dynamic models to the next equilibrium at time t+1 (cf. change processes in classical thermodynamics).

7. The WITCH model (Bosetti *et al.* 2007) http://www.feem-web.it/witch/docs2.html

At the Fondazione Eni Enrico Matei (FEEM) in Italy an attempt has been made to bring model integration one step further, by letting a bottom-up energy model provide the specifications for energy as a production factor and consumer good in a top-down neo-classical optimal growth model.

- The WITCH (World Induced Technical Change Hybrid) model has been developed at the Fondazione Eni Enrico Mattei (FEEM). It attempts to combine several innovations as compared to the prevailing models around 2005:
- Link a CGE macro-economic top-down optimal growth model in monetary units (cf. MERGE) explicitly to a bottom-up energy model in physical units (cf. POLES, TIMER);

- o Let each region have its own central planner chossing the optimal time-path for the regional control variables; this permits a game-theoretic analysis of strategic behaviour (Nash game) with as compared to a global central planner (cf. RICE)
- o Endogenize wherever possible technological change e.g. via explicit R&D investments, and include the feedbacks from climate e.g. via an simple but explicit damage function.

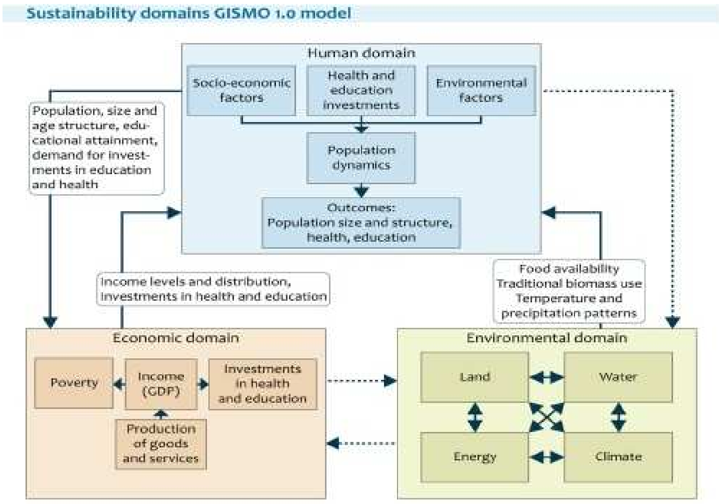
8. CIMS: CIMS is an engineering-economic model of the U.S. economy based on a similar model developed for the Canadian economy by the Energy and Materials Research Group at SFU (Jaccard *et al.* 2003) http://www.iaee.org/documents/denver/roop.pdf

CIMS is a state-of-the-art, integrated set of economic and energy models capable of the widest range of combined energy and economic analysis available in Canada. Energy flows are at the centre of CIMS; like its predecessor, the ISTUM family of models, it tracks the flow of energy, beginning with production processes, through to eventual end-use by individual technologies. Unlike the partial equilibrium ISTUM models, which compete technologies against each other to serve prespecified demands for end-uses, CIMS is a full equilibrium system that incorporates macroeconomic demand feedbacks, second order macroeconomic effects, demand dependent energy supply costs and energy trade.

CIMS' focus on detailed energy flows through technologies makes it ideal for modelling air quality and greenhouse gas emissions. Emission levels of all pollutants are technology specific; unless a model operates on an individual technology basis, as CIMS does, the emission estimates can only be approximated by economic activity. http://www.emrg.sfu.ca/Our-Research/Policy-Modelling.

9. GISMO: Global Integrated Sustainability Model. Netherlands Environmental Assessment Agency (PBL) http://www.pbl.nl/en/themasites/gismo/index.html

The GISMO-model is an offspin of the earlier IAM Targets (Rotmans and De Vries 1997), in which the emphasis is on detailed regional simulation of demographic and economic growth processes. It is being structured as an interactive modeling framework which allows the user to inspect divergent scenarios for key demographic and economic variables, with afocus on the quantified representation of the Millennium Development Goals (MDGs). Particular emphasis is put at the dynamics of health and education (life expectancy, expenditures etc.) as an important link between population growth and economic activity. The scheme shows the set-up of the model.



Some other IAMs:

- o GAINS model (formerly RAINS): http://gains.iiasa.ac.at/gains/EUR/index.login?logout=1 for online access with username and password;
- o For an overview of climate-economy models in use for the US government see http://www.epa.gov/climatechange/economics/modeling.html. The following is from this site.
- o The GCAM model, formerly MiniCAM model, is developed at Pactific Northwest Labs in the USA. Info is given on the site http://www.globalchange.umd.edu/models/.
- o MADIAM is an IAM under construction and is described in a paper by Weber *et al.* (2005) and in Hasselmann (2009).

Appendix E The theory and practice of agent-based modeling

As a sequel to the MAPS 1 Conference in 2009, a collective of the UMR organized a follow-up MAPS 2 meeting to evaluate a couple of Ph.D. student projects started during the MAPS 1 meeting and to assess the state of the art about Agent-Based modeling (ABM) tools and standards. The meeting **Teaching of/with Agent-Based Models in the Social Sciences** was held 8 and 9 april 2010 at the the Ecole Normale Supérieure d'ULM (ENS-ULM). The MAPS 1 meeting was an initiative of some young scientists in France, who wanted to promote ABMs and chose NetLogo as platform. This appendix is based on some impressions (BdV) from this MAPS2 meeting.

Uri Wilensky, Professor at the Northwestern Institute of Complex Systems (NICO) in Chicago (ccl.northwestern.edu) and creator of the presently most widely used ABM platform: NetLogo, gave the afternoon lecture ***NetLogo: A Multi-Agent platform for research and education.*** In the course of 2010 a textbook will appear about how to work with NetLogo and with demo-models. Wilensky advocates the view, not surprisingly, that existing ways of modeling have to be disrupted and replaced by agent-based modeling – at a young age of the students. It will be a slow and painful process – he makes the comparison with the replacement of the Roman numerals by the Arabic-Hindu numerals which took several centuries.

It is a novel way of making sense of dynamic processes and of structuration. It is a break with the existing, Leibniz-based calculus. Yet, it is also a continuation: inferring rules for agents is like differentiation, inferring consequences of rules is the equivalent of integration. But essential differences are ABM-aspects such as:

- order is seen to come from below, not as a result of a deterministic process as the Deterministic/Centralized (D/C) mindsets thinks; cf. a flock of geese
- it democratizes ideas of random events and of rules guiding behaviour;
- it is a way of restructuring traditional content in existing models.

Wilensky gave a brief genealogy, in which NetLogo, as a derivative of Logo and StarLogo, comes from Von Neumann/Ulam replicating machines, via Logo by Papert, Game of Life by Conway, CA by Wolfram, Holland a.o. and SIMD by Hillis to ABM as practiced by people like Resnick, Wilensky and Langton.

NetLogo is designed for both teaching and research and can avoid the miscommunication often occurring between programmer and scientist. It aims at 'model literacy', advocates that the modeler 'should think like an agent' and is already widely used on US (high) schools. There are over 100 demo models on ccl.northwestern.edu/netlogo/models. He illustrates the different approaches with the two key equations describing a fire in a forest – and the ABM way of describing such an event/process. Discrete object-oriented modeling is better than continuous modeling in many cases as it is more intuitive. There is now a list of models from a variety of disciplines available. Wilensky considers the next step to be participatory simulations via the internet: HubNet, with a mix of human and simulated agents. The NetLogo has many new features. It is being used in many disciplines – only economists have serious problems / resistance using it. Validation of model is a tricky issue.

During the discussion a number of suggestions and doubts are expressed. One danger is that people may not criticize the models they make but instead overestimate them. especially with children who increasingly live in virtual worlds and may think they really made a model which reflects the world – but it does not, it reflects what they personally see and experience which is not neceassily the same as 'objective' and widely shared science. The link with [social] science should be carefully examined and using ABM brings in an additional responsibility for the teacher. Wilensky agrees but emphasizes that students, whatever the model, do learn modeling…

The morning lecture the next day was by Volcker Grimm (Helmholtz Institute, Germany) who gave a presentation ***Protocols and methods to communicate with and about models.*** He gave an overview of theory and practice of a ODD protocol for the construction of ABMs, which will soon be published as a book (www.openabm.org and www.railsback-grimm-abm-book.com) . The idea is to develop a standard for the design principles of ABMs to structure the existing ad-hoc situation – "ODD is meant to be a soft weak magnetic field which orients (ABM-)modeling". Grimm proposes and hopes that the combination of NetLogo + ODD becomes the Lingua Franca of ABM. He also showed a list of models which are or can be framed in an aent-based platform, most of these fom ecology. His lingua franca idea would imply:

- A coherent and efficient scientific method
- Unifying perceptions
- Facilitating communication.

In the discussion is was suggested (Dawn Parker) to introduce something in-between ODD as a set of design principles and the actual (NetLogo) coding, e.g. basic neighbourhood methods, learning mechanisms. I fully agree that such a 'library of elementary mechanisms' would be useful. There was also some doubt whether ODD would work to design models – but it may work in communicating your model. The relation between ODD and IML was another issue – as most of the practitioners of the French CORMAS group work with UML.

Christophe LePage of the French ABM CORMAS group (INRA – Montpellier, Avignon) gave a presentation ***Teaching agent-based simulation for renewable resource management*** on the CORMAS platform (www.cormals.fr and www.cormas.cirad.fr/indexing.htm). The literature survey LePage did also shows that an increasing number of publications (35%) mentions the platform on which the research nis based. It is now having only a small 'market share' if based on citations in the literature, behind the US platforms NetLogo, RePast and SWARM. The strength of CORMAS is its use with stakeholders in what is being called *companion modeling* (see further on). Its weakness is that its use of the language Smalltalk and Visualworks means that a user has to learn object-oriented programming (Smalltalk) – which in turn has the advantage that the actual code is very readable for non-programmers.

LePage distinguishes three ways in which CORMAS (and other platforms) are / can be used:

- Abstract models (see e.g. Pepper and Smuts in Kohler and Gumermann 2000);
- Applied models (see e.g. Etienne et al. and further on)
- Action research (see e.g. d'Aquino 2003, Gurung 2006).

The CORMAS-team is especially interesÔÅÄ in participant-participant interaction and uses three approaches:

- Role playing games;
- Companion modeling: ComMod
- ABM model construction with CORMAS (workshops in montpellier in may and june 2010).

An important scheme for their work is the one connecting model development, stakeholder inputs (giving the model 'trust' and 'ownership' feeling) and the (generic) model.

The afternoon lecture was given by Michel Etienne, another key person in the CORMAS-team: ***Companion modeling (ComMod): a participatory modeling approach.*** Etienne's talk was about the pioneering work the CORMAS group did over the past 10-15 years in developing and applying ABMs in combination with participatory methods, leading to their own brand of Companion Modeling **ComMod**. The basic principles are:

- Collaboratively tackling a question
- Co-construct a shared representation
- Implement it in a computer model
- Visualize dynamics and collaborative design scenarios

Website: www.cormas.fr. A booklet in French has been published with practical recommendations for companion modeling: Daré, Ducrot, Botta and Etienne (2009). *Repères méthdologiques pour la mise en oeuvre d'une demarche de modélisation d'accompagnement* (2009). A book on companion modeling in english is soon to be published.

What do people learn during this process? Experiential learning – does it work? Five key learning:

1. Better understand system at stake: the dynamics and complexity of the socio-ecosystem
2. Learning knowledge and techniques: technical options to reach desired state
3. Learning about others: understand that people don't see the same things
4. Communicational learning: social learning in order to share knowledge etc. and for group decisionmaking, learn to defend interests
5. Organizational learning.

Examples:

a) integrated or shared water management (aGUaLOCA: Brazil). People start thinking in qualitative terms, call in experts etc.
b) water availability, migration and (shortage of) farm labour (Lam Dome Yaï, Laos). People effectively changed their behaviour regarding water use, crops etc.
c) participation in how to manage and develop multiple use regions e.g. wetlands (Vendres, France). Goal is to elicit stakeholder strategies, ask relevant questions and confront different point of view (Mathevet et al. 2008)
d) learning about negotiation mechanisms (TerAguas, Brazil) (Ducrot and Barban 2008). How to interact with stakeholders, better organize and articulate expectations, change way of interacting with people (more listening)
e) discussion of 4 groups of stakeholders about land management (Causse Méjan, France) (Etienne 2009). It was about better understanding SES, construct scenarios, setting a concerted management plan in groupsd of farmers, forest owners, National Park agents and conservationists.

Learning dynamics along the process: time is important in learning so many projects are followed through time e.g. Mae Salaep (Thailand). Getting aware of collective issues (learning by doing) step 1; identifying collaborative solutions (learning by negotating) step 2; exploring scenarios (learning by visioning) step 3.

C-learning between scientists and stakeholders (Njoobaari, Senegal). You make model and use it in a process of sharing with stakeholders, in a social situation where the complexity of the reality can be discussed -> co-learning. How the scientists are in the process (arrogant, provocative etc.) is also important.

Confronting types of knowledge (Pays de Caux, France). Investigation of social network (scientific, technical and lay knowledge input) weaved during the ComMod process, in this region of intensive agriculture (Souchère et al. 2009).

Co-constructing a collaborative representation of a highly complex situation (Camargue, France) (Mathevet et al. submitted). Issue: from individual to collective mental models? One of the items is the knowledge gap between members and non-members of Water Board Commission.

Learning for action and social change: involve local academics, co-facilitate process, involve progressively the technical services of policy makers into the process. All worked out in projects, in Doi Tiew (Laos), Mae Salaep (Thailand) and Gard (France).

Do people change behaviour once back in reality? See William Dare (2001). Learning in reality mainly occurs in unpredictable situations that have to be discussed in the debriefing. Literature: Daré et al. 2008 (Laudun, French). Are people replacing one heuristic for a (more correct) other one?

Active learning: learning with students, not stakeholders. New service to train people at Agricultural Schools. Items:

- formalize a joint representation of a complex system
- immerse students in situated actions so that they can experience this complexity
- use the modeling of this complexity to imagine alternative management (scenarios).

There is extensive evaluation of what students have learned (Gril et Goutay 2010; Etienne et al. 2008). Are there already generic lessons/theories which can be put into [agro-economic] textbooks? Le Page's answer: hardly general theories but useful experiments in which one can evaluate the role of the context in the observed beliefs, behaviours etc.

There were also some morning presentations with specific applications of ABM. F Rebaudo presented *Teaching pest management through agent-based models in tropical socio-ecological systems: insights from the potato tuber moth in Ecuador.* The essence: teach the farmers the mechanisms and consequences of human-related long-distance dispersal (of disease) events. Why using ABM? One practical reason: it was found that young farmers become interested if you use computers and models (and cooperate sometimes because the computer is given: 'development brokers'). Another reason: introduce the heterogeneity among farmers.

Nicolas Brax presented *When predictive modeling meet participatory simulation: a feedback on potential and issues of a combined approach.* This research was done with Electricité de France and concerned the study of water management in the Midi-Pyrenées in France. It was meant to help resolve various interests among EdF (hydropower) and farmers (irrigation). They used the consumat approach (Jager *et al.* 2000) and tried to combine modeling on the one hand (anticipatory, decision support) and participatory simulation on the other (perception, stakes, negotiation).

Mathias Rouan and colleagues did a project: *Role-playing game and learning for young people about sustainable development stakes: an experiment in transferring and adapting interdisciplinary scientific knowledge*. This research project was meant to use role-playing games and CORMAS-based companion modeling to improve the understanding and management of the resources of an island before the coast of Bretagne (Groumelon *et al.* 2010). They made models, 3D-representations and other ways to engage stakeholders, and designed and applied a role-playing game together with local teachers and managers. The game takes one day, including a guided tour, and supposedly fitted into school curricula. It uses a CORMAS interface and wireless connectkions, with a newly designed gameboard. Requirements for the game: robust, intuitive, simple. There have been 13 sessions with 230 students in march-april 2010. See www.menir.univ-brest.fr/projects.MEDIA for more info and download. It has not been investigated if the players actually show different behaviour afterwards.

Thomas Louail presented the AccesSim model: *Simulation of accessibility in urban setting and an experiment in teaching applications: the AccesSim model*. This is a teaching tool to communicate geographical core notions, such as accessibility, network relations, centrality and territorial inequalities. Louail give an interesting list of pros and cons of ABM:

PROs	*CONs*
Focus on entities and behaviour	More realistic → harder to control
Expressive, heuristic, anthropomorphic	GUIs simplicity hides internal complexity
More structure, less abstraction	Computation may dominate reasoning

AccesSim uses NetLogo to simulate pedestrians who wish services on a city transport network with shopkeepers and people as agents. People (=children) have one action: buy pain au chocolat (!). They can post their experience at a bakery on a blackboard, which serves as the neighbourhood memory spot. The taste of the pain au chocolat is not included.

In second instance the model has been developed into a game, with two roles: Mayor (positions bakeries and has access to indicators) and Baker (aspire to be most popular, compare with other bakers). A nice GUI has been made in NetLogo, with nice use of icons. Player strategies are either Blind red fish or Math's professor's son. Transmitted notions:

- spatial inequalities based on accessibility
- individual vs. collective interests
- choices, compromises, multi-criteria DSS
- role models: good identification of child-players with the two roles.

It is a simple model from a behavioural point of view but teaches some interesting notions. To be inspected at www.spatial-modelling.info/-education-module- .

Christope Sibertin-blanc gave the view of a professor in sociology (IIRIT, Toulouse): *The validity of simulation results in social sciences*. In the context of the sociology of organized action, Sibertin-blanc discussed the ways in which the object of interest is processed into model outcomes and implementations and discussed how validation might look like. He suggested that the theory of systems is the referential domain, with the object domain (re)constructed in an analytical way with 1. active entities 2. passive entities 3. transitions (from one to other state probability) 4. relationships (between active, passive events and relationships). He emphasized that a model is a simplification intended to produce some knowledge – it is not reality; and that in social sciences the interpretation of the results in terms of the social reality is essential.

Alex Smajgl (CSIRO, Australia) presented set-up and experiences of an interesting project in Indonesia: *Agent-based learning process for decision makers in Indonesia*. This presentation was about an interesting project asked for by the Indonesian government about the *problem*: the government spends 25% on fuel subsidies, so these have to be reduced. The *question* was: how are the impacts of such a subsidy reduction on poverty [thresholds]? The team made two ABMs, one for East Kalimantan and one for Java, trying to assess changes in livelihood. The constructed the model across three tiers of governance, in search of optimal combinations of policies. It was found that the beliefs about the relation fuel subsidy – poverty differed across the governance levels and was inconsistent:

Central gov't	*Local gov't*
Fuel subsidies benefit mainly the middle class, not the poor (source of belief: consultants)	Fuel subsidies help the poor (source of belief: local situation, less analytic and context specific)
Fuel price increases increase poverty	Idem
Fuel price reductions benefit the poor	Idem

One explanations is the urban context vs. the rural reality. The model outcomes gave sometimes contradictory results which could only be understood by deeper analysis e.g. fuel price ↓ use of local fish/forest ↑ poverty ↑. See cms.csiro.au/resources/Indonesian-Pathways-Resources.html .

An interesting aspect of this project is the explicit investigation of beliefs at different government levels and among agents. They show up somewhere along the line Vision – [sectoral] Goals – Actions/Strategies, with the last two connected by causal relations. The causality however is a perceived causality, in other words: a belief, or better: different and multiple beliefs. Question is: how to reveal beliefs? 3500 household interviews were organized, which led to 19 household typologies. Five 2-3 day workshops were organized to elicit beliefs, about how the system does/would respond to interventions. Most beliefs were very general. It is interesting to examine the relations with values/worldviews.

The models were made in RePast, with the local people using the principles 1. first train then conduct and 2. teach the teachers. The central government was interested in process and tool; the district heads wanted the tools but missed the skills. ABM was chosen – partly because in another (Danish-funded) project a system dynamics approach was used.

Finally, some key notions from the panel discussion:

- interaction between: teaching of students ↔ participation of stakeholders, with learning=engaging
- role of ABM in science: theory – experiments interactions
- further developments: online teaching and materials; creation of archive / library of models; grid-computing…
- how to keep models up-to-date?

Appendix F Literature and websites about climate change policy and climate change models/games

The interactive models and games indicated here are an inventory of available tools to set up interactive simulation sessions via the web (such as virtual gaming tools). It is an incomplete selection of what is interesting in the context of the GSD WP3 project. The various models and games are in first instance evaluated for their usefulness and adequateness in the GSD-framework. The criteria are in first instance: relationship with complex macro-problems, in particular sustainability and climate change; user-friendliness of installment and use; and costs of installment and maintenance.

Climate change dynamics and negotiations

Quite some interactive, simple emission-climate models have been developed and made available via the web (see e.g. http://www.ccb.wur.nl/index_files/main_files/models.htm). The *C-ROADS model*, http://climateinteractive.files.wordpress.com/2008/09/c-roads-overview-slides-dec-08.ppt#2, is an example of how to teach a non-expert audience the essential elements of the climate system in the system dynamics framework of stocks, flows, feedbacks and delays (Sterman 2008). It provides policy makers and policy analysts in government, NGOs and the private sector, as well as the general public, a better understanding and intuitive feel for the broad brush, long term consequences of climate change given various GHG reduction strategies. This very rapid simulation model reproduces the response properties of state-of- the-art three dimensional climate models. All equations and the model in Vensim can be downloaded from the web. It is fast (500 yr in 0,1 sec), transparant and easy-to-use. See also www.climateinteractive.org.

The C-ROADS model offers a series of emission pathways connected to a simplified climate dynamics model. It distinguishes 3/7/14 regions for the emission part and lets the user make changes in emission growth parameters. The model has carefully been calibrated on the basis of historical time series and forward calculations with other economy-climate models such as MiniCAM. It has a per capita and a per unit of GDP convergence scheme according to which emission reductions can be allocated. A useful exercise is to explore the impacts of stated emission targets for countries.

Another simple interactive model is the Java Climate Model (JCM), which permits a detailed interactive analysis of emissions and associated energy and climate related indicators (http://www.astr.ucl.ac.be/users/matthews/jcm/index.html).It offers extensive graphics on emission and climate parameters.

Yet another simple emission-climate model can be found at www.chalmers.se/ee/ccc2 of Chalmers University, Goteborg Sweden. It takes a Business-as-Usual scenario as reference, for which the user can introduce emission reduction percentages (Annex I, Non-Annex-I and Deforestation) and explore the CO2-concentrations for various climate sensitivity values.

A couple of simple, interactive models on climate dynamics and emission-climate relationships are available at http://geoflop.uchicago.edu/forecast/docs/models.html

Harvard Project on international Climate Agreements http://belfercenter.ksg.harvard.edu/files/Harstad.pdf
with paper How to Negotiate and Update Climate Agreements (November 2008):
http://belfercenter.ksg.harvard.edu/files/HarstadWeb2.pdf

A broad qualitative description of climate policy architecture (in German):
http://www.ufz.de/data/10_2008_Hansjuergens9517.pdf

See also Architectures for agreement: addressing global climate change in the post-Kyoto world. Edited by Joseph E. Aldy and Robert N. Stavins. Cambridge New York: Cambridge University Press, 2007, to be found at: http://assets.cambridge.org/97805218/71631/frontmatter/9780521871631_frontmatter.pdf

Paper by John Sterman on Climate Simulation experiments: http://climateinteractive.wordpress.com/tag/mit/
with a follow-up in the C-ROADS project, a simple emission-climate model available at
http://climateinteractive.org/simulations/C-ROADS .

See the websites on Coalition Theory Network: http://www.personeel.unimaas.nl/r.ilkilic/CTN2009.htm.

Climate Change related Indicators

See http://www.germanwatch.org/klima/ccpi-meth.pdf for a *Climate Change Performance Index* (CCPI), measuring the weighted greenhousegas emission of countries They also make every year an updated Climate Risk Index (CRI), see http://www.germanwatch.org/klima/cri2009.pdf , yielding a ranking of countries on the basis of extreme weather events during a certain period.

The best known attempt to make an index covering the change in climate in relation to impacts is the *Climate Change Index* (CCI) developed by Bättig *et al.* (2007). It is composed of annual and seasonal temperature and precipitation indicators, which are aggregated to a single index that is a measure for the strength of future climate change relative to today's natural variability.

Indices from quite different angles have also been proposed. The HSBC bank has launched a Climate Change Index, highlighting which companies could be good investment targets because they are likely to benefit most from efforts to curb global warming. The Oxford Center for Water Research has proposed a *Climate Vulnerability Index* (CVI), meant as an extension of the Water Poverty Index (WPI) (see http://ocwr.ouce.ox.ac.uk/research/wmpg/cvi/).

Under the London Accord three tools are offered to calculate potential future CO_2-prices under different policy scenarios and estimate the possible impacts on your business: http://www.london-accord.co.uk/index.php?option=com_tcmodel&Itemid=131 . It makes explicit use of scenarios in a simple interactive tool.

Simulation-games on climate change

Overview of several general games: http://www.univie.ac.at/virtuallabs/

A first brief inventory shows a number of board games as well as computer-supported games in the area of climate change (e.g. KeepCool, Wind of Change developed by PIK, Climate Challenge, LogiCity, Ecoville, Wedgegame) which can serve as communication tools in individual and team learning processes, and in stakeholder dialogue processes (see also Pfeiffer and Nowak 2006, Milinski *et al.* 2006).

The BBC developed an interesting newspaper-like game on climate change: http://environmental-economics.blogspot.com/2007/02/game-theory-climate-change-game.html . It has a political setting wherein, as president of the EU, "You must tackle climate change and stay popular enough with the voters to remain in office."

Related to the London Accord is *WarmGame* – A game for all Seasons, developed by Z/Yen Group Ltd. (http://www.zyen.com/). It is is a role playing game where six major carbon producing countries try to reach multi-lateral agreement to tackle climate change.

See also *Games for Change*: http://www.gamesforchange.org/main and some other games who all were found to operate without problems as of march 2010:

- GlobalWarming Interactive: http://www.globalwarminginteractive.com/ is a game called CO2FX, which is a USA web based multi-user educational game which explores the relationship of global warming to economic, political and science policy decisions. It is rather sophisticated, with the player as decisionmaker for a country starting in 1960. Simple animation of e.g. CO_2-molecules, factories etc.
- KeepCool: http://www.spiel-keep-cool.de/ is a game developed in Germany by Eisenack and Petschel-Held (in German and English). It is sold as a board game and the site is explanatory. See also: http://rs.resalliance.org/2005/10/08/climate-change-games/.
- *V Gas* is a 3D *serious game* in which players explore and live in a house that is built to mirror their own. Players begin the game by building a profile including variables such as water use and transportation behaviors, heating and cooling practices, food purchases, and electrical appliance usage. Once the profile has been built, the player can begin the simulation which introduces different scenarios ranging from heat waves to mad cow disease. The player adjusts their lifestyle according to how they would react to these events in real life. All the while, the players' decisions are being measured and recorded, and their overall contribution to N_2O, CO_2, and CH_4 to the atmosphere is measured. For info, see: http://en.wikipedia.org/wiki/V_GAS. It is unclear how to access the game.
- The *Stabilization Wedge Game*, or what is commonly referred to as simply the 'Wedge Game', is a serious game produced by Princeton University's Carbon Mitigation Initiative. The goal is to demonstrate through this game that global warming is a problem which can be solved by implementing today's technologies to reduce CO_2 emissions. The object of the game is to keep the next fifty years of CO_2 emissions flat, using seven wedges from a variety of different strategies which fit into the stabilization triangle. For info, see: http://en.wikipedia.org/wiki/Stabilization_Wedge_Game.
- *Wind of Change* is a climate change game developed in 2004 at PIK-Germany. Info is given on: http://www.pik-potsdam.de/news/press-releases/archive/2005/the-winds-of-change-are blowing. See for a related, MADIAM-model based climate game description: http://www.cosis.net/abstracts/EAE03/05766/EAE03-J-05766.pdf .
- The *ECF Climate Computer Game*, developed by the European Climate Forum (ECF) for an exhibition in 2003 in the Deutsches Museum in München. Information is given on:

http://www.eniscuola.net/convegni/convegni26.pdf . A free version (in German), it is said, can be downloaded from: http://www.european-climate-forum.net but it is no longer available.

- Website www.climatequest.org is an interactive portal meant for education about climate change e.g. you choose a car or bike to cross over Antarctic ice sheet, you have 40 seconds and the ice breaks down because you emit ghgs. If you are in time at another control point, you earn time. Crazy and misleading zero-level game.
- The research and educational FIDS (Facility for Intelligent Decision Support) project offers models on the economy-climate the site http://www.eng.uwo.ca/research/iclr/fids/nserc-sysdynamics.html.An Integrated System Dynamics Model for Analyzing Behaviour of the Social-Economic-Climatic System in Canada.
- ClimWay: http://climcity.cap-sciences.net/# is largely informational about energy use in a village and what can be done about it, with simple animations (in French).

Sustainability-related games:

In the context of a more web-based interactive gaming set-up the sustainability oriented *SUSTANIA* game developed by the ETH Zurich is an interesting example of how to run a World3 like world (see http://www.seneth.ethz.ch/game/index_DE. Simulationsspiel SUSTANIA, by the same person who classified simulation games, Markus Ulrich.

Ecoville: http://ecovillelejeu.com/index.html is an online simulation game about the sustainable development of a village (in french). See also: http://www.ademe.fr/particuliers/jeux_2006/ECOVILLE/index.htm

See also http://ucs.ch/service/download/ and especially:
http://ucs.ch/service/download/docs/articlesimgamesenvissues.pdf
http://ucs.ch/service/download/docs/aufhohersee.pdf
and http://ucs.ch/service/download/docs/sustaniaatlanta.pdf

Other resource-related educational games:

For various games on environmental issues, see http://www.visumsurf.ch/spiele/ and:

- *Stratagem* and *Fish Banks Ltd.* are two games developed by Dennis Meadows in the 1980s and 1990s. Stratagem is about managing the transition from a poor population with a low income towards a sustainable state. Fish Banks Ltd. Is a common pool resource management game, where up to 6 teams go out fishing for a couple of years in order to experience the Tragedy of – and occasionally the sound management of – the Commons. See: http://ivem.eldoc.ub.rug.nl/ivempubs/Software/Stratagemmanual/ and http://www2.ed.gov/pubs/EPTW/eptw7/eptw7d.html
- Tom Fiddaman has constructed a website: http://www.metasd.com/models/index.html , with a model library which contains system dynamics models of several levels of complexity on climate policy, economy, energy, environment and business.
- A well-known site about natural resources and agent-based simulations is the *Cormas* CIRAD site http://cormas.cirad.fr/indexeng.htm . This group is well-known for its companion-modelling approach, which combines simulations games with agent-based models (see also Appendix C).
- *WaterAlert*: http://www.unicef.org/voy/explore/wes/explore_1818.html. This is a UNICEF-based interactive tool, in which the user is getting information on the situation in a village and is asked to listen to the villagers and make some important, practical decisions concerning the water supply and quality.
- *FoodForce*: www.foodforce.com contains a collection of popular simple games, some of which have to do with resource management.
- Interactive games on solving dilemmas between different stakeholders can be found at http://rs.resalliance.org/2006/03/12/interactive-agroecological-story/ cf. especially the link towards http://www.alwayssunny.com/lab/lindissima/
- A set of simple resource models for interactive exploration is made by Fabio Boschetti (CSIRO) on http://www.per.marine.csiro.au/staff/Fabio.Boschetti/netlogo/Toy_Models_html.html . It is constructed on a NetLogo platform
- At CIRAD, Montpellier, a number of models have been developed and applied by Nils Ferrand and colleagues:
  - SIMSKI: simulating the reaction of people to reflexive information, crowd control (extension of the famous Orlean model of market) – is lying the best management strategy? And DEBALLAGE, in draft version: stimulating and simulating abstract debates for participatory planning;
  - JEANS, with D. Mangalagiu, F. Amblard and L. Antunes: simulating an extended production chain system to assess social and environmental impacts from a complex system point of view;
  - PHARMINVEST, with D. Mangalagiu and colleagues from PCW: impact of investment strategies in the pharma sector on innovation dynamics.

- o 2LE/2LG: two level processes, experiments, games: when policy makers and 'tapholders' interact around models to design new, efficient and feasible policies, also addressing coherency, information, etc.
- o WAT-A-GAME: a versatile platform for games and participatory simulations ("with hands and marbles") and playing water use and water sharing in your own basin. It has been used extensively now (> 20 sessions; movies are available) and includes economy, regulation, pollution, etc.

Management and economics models and games:

- At http://eeps.caltech.edu/ Charles Plott runs the Laboratory for Experimental Economics and Political Science; he is also editor of the Handbook of Experimental Economics Results Vol. 1 (2004) North-Holland
- At http://people.virginia.edu/~cah2k/ Charles Holt of the University of Virginia presents experimental economics games. A good example of a web-based interactive game is the Traveller's Dilemma on the site of Charles Holt (University of Virginia): http://veconlab.econ.virginia.edu/tddemo.htm.
- An interesting site offers, upon subscription, *Building Blocks for Economics* with a variety of interactive basic models: http://www.econmodel.com/classic/cobweb.htm.
- www.marketplace-simulation.com by Ernie Calotte in Knoxville

Toolkits and demos about agent-based modeling, network models etc.

- An excellent tool to explore agent-based models is the software package NetLogo made by Wilensky of Northwestern university http://ccl.northwestern.edu/netlogo/. It has a free download version and a whole list of instructive elementary models.
- A website with examples for learning how to use agent-based modeling platforms is the *StupidModel* and Extensions site by Railsback and colleagues. The model codes are available in several impe,entations (NetLogo, Java Swarm a.o.): http://condor.depaul.edu/~slytinen/abm/StupidModel/.
- An extensive website on General Software and Toolkits: Agent-Based Computational Economics (ACE) and Complex Adaptive Systems (CAS) is maintained by Tesfatsion of Iowa State Univsersity. See http://www.econ.iastate.edu/tesfatsi/acecode.htm .
- www.bsg-online.com and also Open University (Johnson)
- *AnyLogic* simulation and software services has made an interactive modeling environment, with interesting and advances features and with demos on its website: http://www.xjtek.com/anylogic/why_anylogic/. Demoversions of the software can be downloaded. The demo models are about various kinds of networks, urban and population growth, opinion and threshold phenomena and the like.
- As part of Introductory System Dynamics courses of Delft University of Technology, Erik Pruyt has developed an interactive platform *Forio Simulate* on which one can insert one's own model. Over two dozen models about all kinds of topics are downloadable for inspection: Dutch Hospitals, lungpest in China, Food for Energy, the Kaibab model, Fish Banks and many others. See http://forio.com/simulate/e.pruyt/
- The Behaviour Composer is a software package developed at Oxford University in order to make it easier to build your own MAS-model, see http://modelling4all.nsms.ox.ac.uk/. It defines a *prototype* as the generic name for the thing(s) that constitutes your model e.g. ants, foxes, people, cars; and a *micro-behaviour* for a block of computer code that you can add to a prototype. In this way, an object can be given characteristics like MOVE FORWARD, WANDER-RANDOMLY, REPRODUCE etc. This permits a rather straightforward introduction of agents.

Appendix G An educational game: harvesting trees [11]

A harvesting game developed by Janssen and Bousquet (2008) has been played with two groups of 36 students each, as part of the M Sc Course Sustainability Science in the M Sc Sustainable Development at Utrecht University. The essence of the forest harvesting game is that a number of players (6) is asked to harvest from an initial stock of 100 trees in 10 subsequent periods. Every 20 trees harvested earn them 1€, which was paid out at the end of the game. Initially, there is no communication. The protocol can be found at: http://www.public.asu.edu/~majansse/ dor/Cardenas%20Janssen%20Bousquet%20PROTOCOL.pdf. In the coming years the authors intend to put the field experiments also on line as a web-based game, and then it will be easier to process with larger groups. The forest harvesting game is being tested in three field experiment cases and in a laboratory context. Simultaneously, experiments are done with two other common pool resource (CPR) games, one on irrigation and one on fisheries.

HARVEST GAME - INSTRUCTIONS FOR THE FACILITATOR

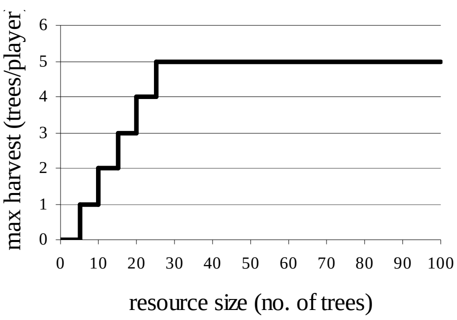
Each team, 1…6, consists of 5 members: A, B, C, D and E. You are the facilitator of

team no. ☐

FIRST GAME

Your role of facilitator is:

- Put the 100 trees on the table
- Hand out the decision sheets to the 5 team members
- Tell them to write down their team letter and team number on the sheet
- Explain to them that they are asked to harvest trees from a community forest
- Show them the graph below: the maximum harvest per person per period is 5, and it will decline stepwise if the forest has less than 25 trees
- Ask them to make a decision: how many trees will you harvest this period?
- THERE SHOULD BE NO COMMUNICATION
- Ask them to write this number down on the decision sheet (period 1) and then hand over the decision sheet to you
- Put for each tree harvested a sticker on the decision sheet (or let team member do it)
- Ask them to take the number of trees they harvest (period 1) out of the forest
- Put 10% of the remaining number of trees back in the forest (regrowth)
- Start the next round (period 2)… etc.



Maximum harvest table

Current resource level (no. of trees in forest)	Individual maximum harvest level (trees/person/period)
25-100	5
20-24	4
15-19	3
10-14	2
5-9	1
0-4	0

[11] With kind permission of and thanks to Francois Bousquet and Marco Janssen.

SECOND GAME

In essence we play the same game again, with three important differences:

1. the team members can communicate about their decisions
2. the team members choose a management regime aimed at sustainable resource use
3. individual team members may disobey the commonly agreed rule (cheating), with a finite chance to be caught and having to pay a penalty.

You as a facilitator should do the same steps as in the first game, with some differences put in capital letters:

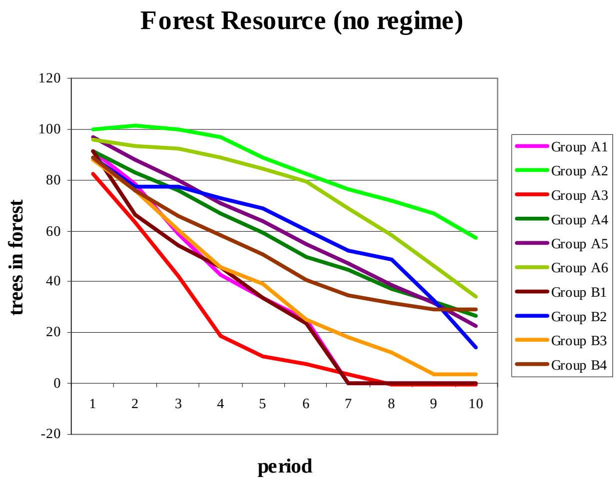
- Put the 100 trees on the table
- Hand out the decision sheets to the 5 team members
- Tell them to write down their team letter and team number on the sheet
- Explain to them that they are asked to harvest trees from a community forest
- Tell them they have agreed to introduce a sustainable management regime and that they have to choose one of two possible rules:

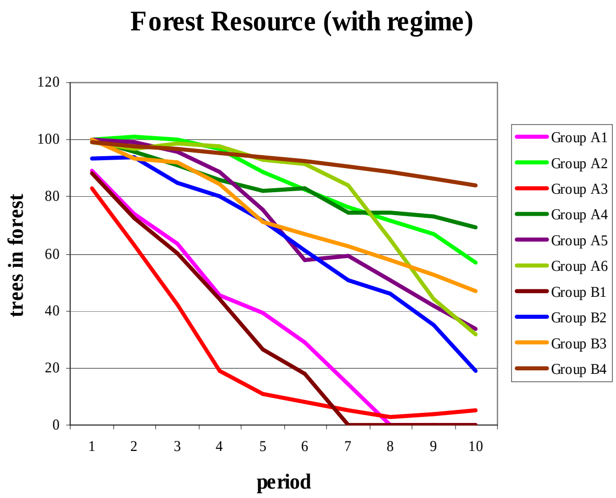
  Rule #1. ONLY TWO PARTICIPANTS CAN HARVEST in a round. The instructor draws randomly 2 persons out of 5 persons who get harvest rights.

  Rule #2. EACH OF YOU CAN HARVEST LEGALLY 0, 1 OR 2 UNITS PER ROUND.
- Once they have made a decision, let them write RULE #1 or RULE #2 on their sheet
- In case of RULE #1, you draw randomly one out of five letters – those are the team members who have harvesting rights for this round
- Ask the two with harvesting rights (RULE #1) or all team members (RULE #2) to make a decision: how many trees will you harvest this period?
- Ask them to write this number down on the decision sheet (period 1) and then hand over the decision sheet to you
- Put for each tree harvested a sticker on the decision sheet (or let team member do it)
- In case someone has harvested without having rights (RULE #1) or having harvested more that 2 trees (RULE #2), you roll a dice. If it shows 6, all cheating is punished by taking in the harvest plus an additional 3 trees
- Ask them (excluding cheaters caught) to take the number of trees they harvest (period 1) out of the forest
- Put 10% of the remaining number of trees back in the forest (regrowth)
- Start the next round (period 2)… etc.

From the system ('bathtub') dynamics it is evident that the players should collectively harvest not more than 10 trees/round if they wish to preserve the forest size at its initial value (100). If each harvests the permissible maximum of 5 trees, after some rounds the forest will have less than 25 trees and the permissible harvest declines. In essence, this is what happened in almost all rounds (see graph). In the second session the players were offered ways to overcome the social dilemma by making explicit agreements among each other (regime). The outcome i.e. the depletion trajectories were for most teams lower than without this inducement to cooperate – but nevertheless most teams faced depletion (see graph). A few findings of these sessions were:

- it is a nice game to illustrate the role of information and (lack of) cooperation in managing a commons;
- we used coloured stickers which had to be glued on the game form as indications of their decision;
- the participants could come and claim with us 20 c/tree harvested (that is, per sticker glued on their piece if paper) afterwards;
- we told the participants that they would not only get money but collectively also the same amount per tree of the remaining trees still in the forest after 10 periods;
- we installed one of the students as an external facilitator, who would get (in game #2) half of the rewards from the remaining trees in the forest. This was an important and useful step given our shortage of facilitators (3 for 6 groups);
- in the first round we did not show anything, but they saw how many trees were taken and then replaced. Keeping the sticker numbers glued secret was a bit of a problem;
- in the second round, when they chose a strategy (we only had strategy 1 and 3), we discovered that some participants immediately calculated that an always-defection (fraud) strategy was the best one - so we in some cases started increasing the probability of being caught.


Forest Resource (no regime)
120
100
80
60
40
20
0
-20
trees in forest
1
2
3
4
5
6
7
8
9
10
period
Group A1
Group A2
Group A3
Group A4
Group A5
Group A6
Group B1
Group B2
Group B3
Group B4


Forest Resource (with regime)
120
100
80
60
40
20
0
trees in forest
1
2
3
4
5
6
7
8
9
10
period
Group A1
Group A2
Group A3
Group A4
Group A5
Group A6
Group B1
Group B2
Group B3
Group B4

Appendix H An educational game: Climate Fund

An interesting, simple game with regard to energy-climate issues has been designed and reported on by Milinksi *et al*. (2006, 2008). It has been played with ten groups of 6 students each, as part of the M Sc Course Sustainability Science in the M Sc Sustainable Development at Utrecht University. The essence is that the participants can reduce the risk of climate change by contributing to a Climate Fund – however, the risk reduction will only occur if their collective contribution exceeds a certain threshold level. The usual public goods games confirm that the collective benefit will not be produced: a *Tragedy of the Commons* unfolds. The game was also played with additional features such as: inducing cooperation by punishment of non-cooperators and by reward for actors with a good reputation, and changing the amount of information (well-informed vs. ill-informed) available to the actors.

Milinski *et al.* set up the game with 10 groups of 6 students. There are 6 players, playing 10 rounds and each player receiving initially 40€. In every round a player chooses to invest A, B or C € into a Climate Fund account (0,2,4). If the Climate Fund account contains <120€, the climate is lost with a 90% chance and all players loose all their money. If it contains >120€ each player receives what is left in his account. In our version we experimented with some constraints on communication and the use of stickers to show their contribution. It turned out to be difficult, in the actual experiments, to avoid exchange of information in the stage where teams started to come close to the required threshold.

CLIMATE FUND GAME

Number: FIRST ROUND

Write your contribution of 0€, 1€ or 2€ to the CLIMATE FUND in period 1, then go to the game facilitator and show it. Maximum contribution during 10 periods = 12€.

The facilitator will indicate when to go to period 2 and decide again.

1 2 3 4 5 6 7 8 9 10

You are member of team .

Team Letter: SECOND ROUND

Team Number:

Write your contribution of 0€, 1€ or 2€ to the CLIMATE FUND in period 1, then go to the game facilitator and show it. Then, put that number of stickers on the paper with your Team Letter in the column with your name and colour.

Maximum contribution during 10 periods = 12€.

The facilitator will indicate when to go to period 2 and decide again.

1 2 3 4 5 6 7 8 9 10

Appendix K InterSus Instruction Form and set-up

Dear Madam, Sir,

Thank you for participating in this experiment about perception and decisionmaking in relation to the economy-climate policy debate.

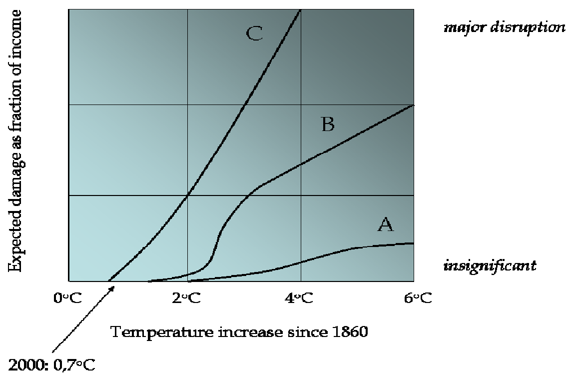
Our questions are simple:

1. please fill in the questionnaire below. It asks you some personal data. These data will be kept secure, but feel free not to fill in your name. The data will be used in the analysis of the game runs.
2. you are asked to make 6 simulation experiments. The first one is a trial run for 4 periods of 4 years each. The next five runs are for 26 periods, that is, from 1995 to 2100.
3. your goal is to maximize the average income of the inhabitants – among them possibly your grandchildren – during the period 2080-2100. You can earn a small price: a maximum of 3 €.

Personal data:
Name:

Gender: M / F Country:
Age: <25 25-50 >50

Question 1. Please indicate in the diagram below which of the curves indicating the damage (as fraction of present/future income) from rising temperature you judge most probable.



Question 2. Given your answer to question 1, which fraction of total investments do you think should be invested on average between now and 2050 in renewable (non-carbon) energy supply options?

- o <10%
- o 10-50%
- o >50%

Question 3. Given your answer to the previous questions, how much income growth for the average world citizen do you think is feasible between now and 2100?

- o >4 times the 1995-level (that is: >12000 $/year/person)
- o 2-4 times the 1995-level (that is: 6000 – 12000 $/year/person)
- o <2 times the 1995-level (that is: <6000 $/year/person).

The simulation-game experiment
In the folder InterSus1.0 you have a file *InterSus.bat*. Double click on it. You will be asked to fill in a codename. This should be the letter-number combination on the upper righthand corner of this instruction.
After you have filled in the codename and have clicked on OK, you will see the screen below.

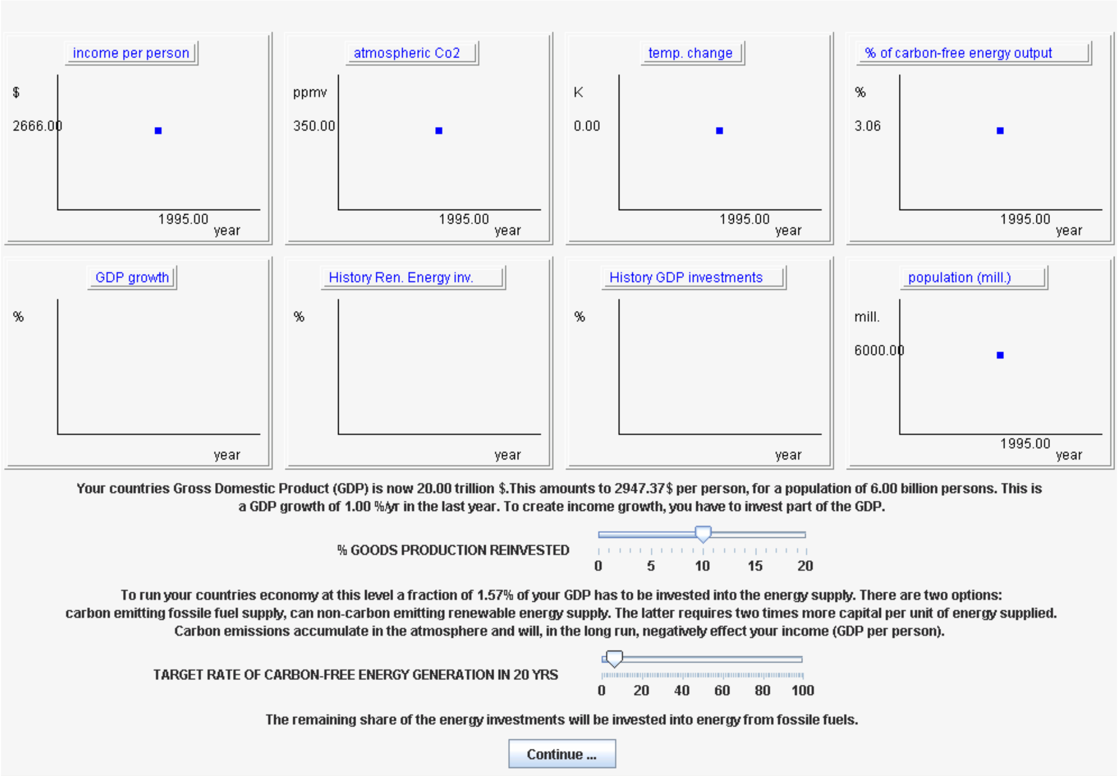
You are asked to make **two decisions** for the world:

1. how much of the total goods (and services) produced in this year (that is: of Gross Domestic Product or GDP) you wish to invest, with a maximum of 20%; and
2. which fraction of this amount you wish to invest in renewable (that is: any non-carbon) energy supply, with a maximum of 100%.

Question 1 is the upper slider; question 2 is the lower slider. Please always click on the numbers below the slider after you set the slider.

The first decision influences income growth. The lower it is, the more goods (and services) are available for consumption (income=production minus investments) in this year. Existing capital goods (factories, houses, hospitals, schools, roads etc.) have an average lifetime of 10 year, so you have to invest to maintain it. And more if you want growth.

The second decision influences the carbon emissions and therefore future climate change, with a possible feedback on the economy. To avoid it, you can invest in renewable (non-carbon) energy supply, but at twice the investments per unit of energy supplied. Hence, it will effect income growth.



Description	Average income 2080-2100 (see announcement on screen)
Run 1 with medium climate sensitivity	
Run 2 with medium climate sensitivity	
Run 3 with unknown climate sensitivity	
Run 4 with unknown climate sensitivity	
Run 5 with unknown climate sensitivity	
Your average score is (final announcement on screen):	Score=
You get from the operator:	(Score – 2) €

You are asked to play the game six times. The first one is a trial run for only 20 years. Please fill in for the next five runs the average income in the period 2080-2100, which is announced on the screen, in the column above after each of the runs 1 to 5. **Your goal is to maximize the income during the 2080-2100 period over the five successive runs.** The indicators on the screen allow you to closely monitor the results of your once-in-an-election period decisions.

The Table below shows the set-up for the Single-world InterSus1.0. Using the name-setting conventions in the Table, the first round of experiments is on a cd-rom with a folder InterSus1.0 with the following sequence:

1. SB0 the player exercises with the screen and decisions, 4 rounds (2008-2024)
2. SB1 the player plays first time, until 2100 (23 rounds); results will be linked to questionnaire outcomes (perspective)
3. SB2 the player plays second time, which gives a chance to adjust behaviour on the basis of outcome of previous result
4. SR third time, but now the player is faced with large uncertainty about climate impacts as it can be either mild, average or severe
5. SRGx fourth time, but now the player is faced with the existence of emissions from elsewhere, with a Ghost strategy x; this option has not been tested.

In each game the decisions and outcomes are stored in a logfile, with the time in the name for later identification. The InterSus1.0 version has been played with about 30 persons in a test version.

Set-up of experiments:

<table>
<tr><td colspan="4">S SingleWorld version</td><td colspan="4">M MultiRegion version</td></tr>
<tr><td colspan="4">Climate sensitivity</td><td colspan="4">Climate sensitivity</td></tr>
<tr><td>A mild</td><td>B average</td><td>C severe</td><td>R random</td><td>A mild</td><td>B average</td><td>C severe</td><td>R random</td></tr>
<tr><td colspan="4">G Ghost player</td><td colspan="4">G Ghost player</td></tr>
<tr><td colspan="3">a unconcerned about climate change</td><td colspan="2">b average concern</td><td colspan="3">c severe concern about climate change</td></tr>
<tr><td colspan="4">0 game mechanics: play 4 periods (2008-2024)</td><td colspan="4">0 game mechanics: play 4 periods (2008-2024)</td></tr>
<tr><td colspan="4">1 full-period play first time</td><td colspan="4"></td></tr>
<tr><td colspan="4">2 full-period play second time same clim sens</td><td colspan="4"></td></tr>
</table>

To analyze the results, one option is to find an indicator for the decisions e.g. weighted (linearly/exponentially) path of investment [fractions] over time. These are then plotted as a function of the objective i.e. average income in 2080-2100. Separate plots of income and climate (ppm, ΔT) can be added.

Regarding the over-all context as inspired by the 'battle of perspectives' (Janssen and De Vries 1998): span the whole emission and impact spectrum from low emissions and high climate sensitivity from an egalitarian perspective vs. high emissions and low climate sensitivity from an individualist perspective. To make this work, in the sense that the player's outcomes cane be related to his/her worldview, a more elaborate questionnaire will be needed.

For a next multi-user version, it is anticipated that each player can look up a table with some key indicators on other regions. There will also have to be some additional features: make a table with key indicators of all regions as look-up table, make in first instance (M1) all regions/countries identical for experimental control, and take out/adjust random noise in multiplayer version. Besides, there is the logistics of synchronous play which has to be resolved.

The following comments have been received from the players:

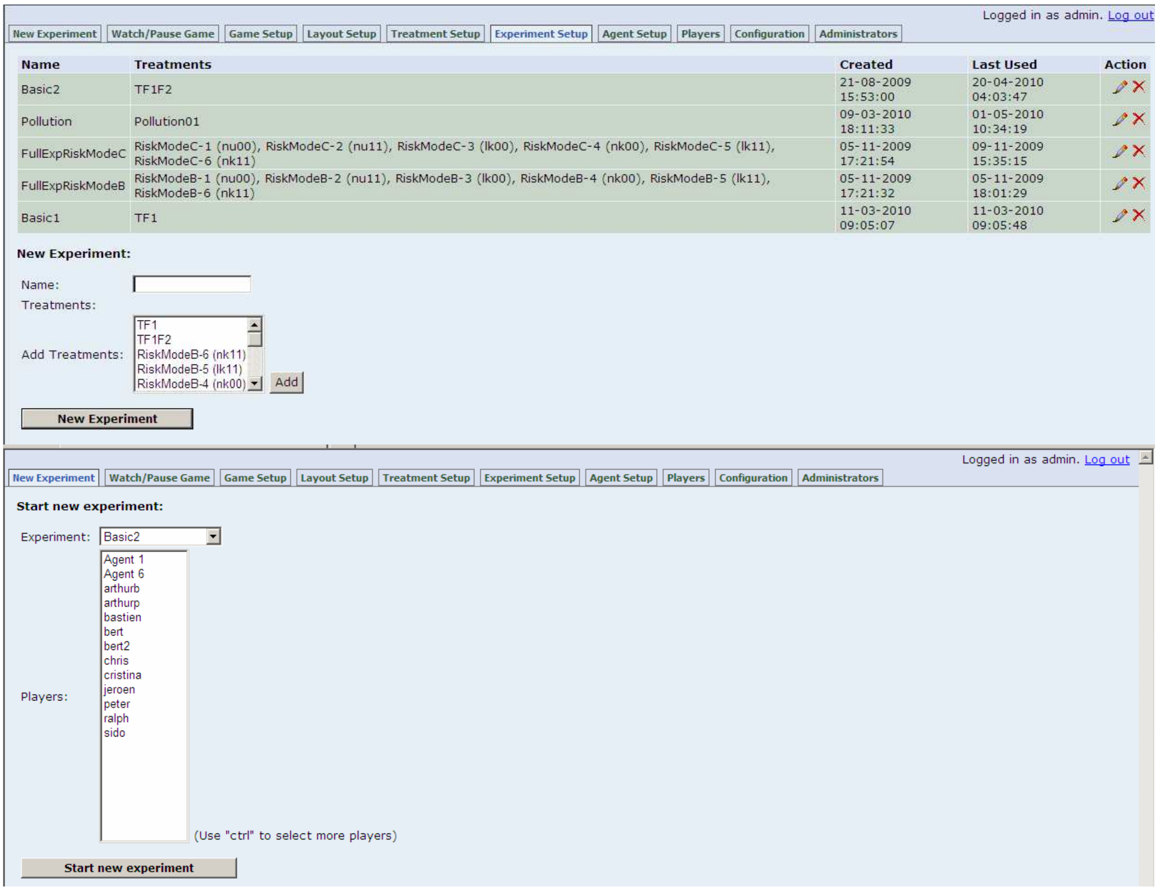
- do not tell when it ends (randomize between 2080-2100?) and say that people should play until message GAME OVER
- see if history 1995-2007 can be implemented, with decisionmaking from 2008 onwards
- adjusting graphics scales?
- download decision & result logfile with time in the name; later to be renamed by operator (to know who played, how often he played…)
- option of playing against a ghost region?
- name experiments according to S1, S2 etc. for Single, M1, M2 for Multi
- there are three scenarios with respect to climate sensitivity – how to choose? Proposal: put in name sign A, B and C for mild, default and severe impacts
- indicate near the decisionbar the 'natural decay rate' of capital (1/LT)
- replace Goods Prodn graph by a graph of income = Goods Prod minus investments
- graph of population may be taken out, or replaced by a number
- should it be possible to stop before 2100?
- put bigger letters near decision screen/bars and use icons
- reinvestment -> Investment in the economy… History of Inv Dec…

Appendix L The CLIMEX interface

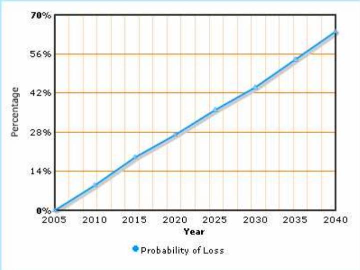
Initially, the platform was for a single player. Later it has been extended to a multiplayer version. The website to play is: http://mclsim.tcgon.net/ where one is asked to give a user name and a password. These have been given by the game administrator: http://mclsim.tcgon.net/panel/new_game.php for which a user name and password are needed too (Apetrei 2010).

The version can be operated under http://www.tcgon.net/clsim/panel/. The administrator has large flexibility:

- first, a Game Setup is chosen. This specifies the relationship between the amount of money in the Climate Fund (CF) and the damage (either as a fraction lost or as a probability to loose all). The general shape of the function has been so far D=1/(1+a*CF+CFref) or D=a+b*CF.
- Defining the Game Setup as F (F_i, i=1..f), a Treatment Setup can be made by adding a delay, a multiplicative and/or an additive multiplier. All three work on the information shown to the player.
- Given a choice of Treatment Setup T (T_i, i=1..t), an Experiment Setup can be constructed b y forming combinations of different T's. In between one can opt to have a pause.
- In the Layout Setup the administrator can define the layout of the player screen, choosing for instance what is shown and what is not and with which texts.
- The other options are: to edit the texts at begin and end of game; the list of players; the list of administrators; the Watch/Pause Game mode in which an overview is given of all experiments done or going on and their status; and finally New Experiment for the start-up of a new experiment.
- It is also possible to introduce automated players in the multiplayer version. These can be given strategies such as random, tit-for-tat etc.



Screens for the facilitator: setting up and starting experiments.



Year	2010	2015	2020	2025	2030	2035	2040
Income	10	10	10	10	10	10	10
Investment	0	0	5	5	0	0	0
Savings	10	10	5	5	10	10	10
Savings (Accumulated)	10	20	25	30	40	50	60
Individual Climate Fund	0	0	5	10	10	10	10
Total Climate Fund	3	3	8	13	18	18	18
Probability of Loss	9%	19%	27%	36%	44%	54%	64%

Individual Fund Contribution of All Players:

Year	2010	2015	2020	2025	2030	2035	2040
Agent 1	0	0	0	0	0	0	0
Agent 6	3	0	0	0	5	0	0
bert	0	0	5	5	0	0	0

You have reduced the probability of being hit by climate change and thus lose all your savings to **64%**.

Player screen after a game has been played.

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In the last decades the science-policy interface has become more important and more complex too. In this report we search for novel ways to extend or reframe the economic and environmental theories and models upon which policy recommendations are, or should be, based. The methods and applications of Complex System Science, in particular, have been explored and are found to be still fragmented. But they certainly can and should form the basis for introducing behavioural and innovation dynamics which make these theories and models more like what happens in the real world. In combination with interactive simulation and games, of which some examples are discussed in this report, science can in a post-modern context contribute more effectively to the strategic decisionmaking in government and other institutions. This will direly be needed in view of the new and global challenges facing us.

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