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SPECIAL ISSUE

THE HUMAN ACTOR IN ECOLOGICAL-ECONOMIC MODELS

# Behaviour in commons dilemmas: *Homo economicus* and *Homo psychologicus* in an ecological-economic model

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**Abstract**

In mainstream economy, behaviour is often formalised following the rational actor-approach. However, in real life the behaviour of people is typified by multidimensional optimisation. To realise this, people engage in cognitive processes such as social comparison, imitation and repetitive behaviour (habits) so as to efficiently use their limited cognitive resources. A multi-agent simulation program is being developed to study how such micro-level processes affect macro-level outcomes. Sixteen agents are placed in a micro-world, consisting of a lake and a gold mine. Each agent's task is to satisfy its personal needs by fishing and/or mining, whereby they find themselves in a commons dilemma facing the risk of resource depletion. *Homo economicus* and *Homo psychologicus* are formalised to study the effects of different cognitive processes on the agents' behaviour. Results show that for the *H. psychologicus* the transition from a fishing to a mining society is more complete than for the *H. economicus*. Moreover, introducing diversity in agents' abilities causes the *H. economicus* on the average to decrease its time spent working, whereas for the *H. psychologicus* we observe an increase in the time spent working. These results confirm that macro-level indicators of sustainability, such as pollution and fish-harvest, are strongly and predictably affected by behavioural processes at the micro-level. It is concluded that the incorporation of a micro-level perspective on human behaviour within integrated models of the environment yields a better understanding and eventual management of the processes involved in environmental degradation. © 2000 Elsevier Science B.V. All rights reserved.

*Keywords:* Commons dilemma; Resource; Consumat; Simulation; Multi-agent; Dynamics; Psychology

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## 1. Introduction

To improve our understanding of the world, scientists usually try to capture important aspects of a real-world system in a model. Scientific models allow for experimentation with different assumptions regarding how the real-world system works, thereby improving our understanding of the processes that govern the behaviour of a real-world system. Scientific models can, in a broad sense, be considered as more or less formalised mental maps (Rosen 1987, 1991). They play a crucial role in research and their development often proceeds through isomorphisms, that is, by hypothesising that two different real-world systems share the same formal description. This modelling-by-analogy has played an important role in economic science in an attempt to describe complex economic (sub)system(s). For instance, there are clear isomorphisms between neo-classical equilibrium theory and the laws of chemical equilibrium as formulated by, e.g., Guldberg and Waage (1867), and between theory on the production of goods and classical thermodynamics. In the physical sciences, the rather black-box macro-level description of physical systems has been complemented with micro-level descriptions in which system elements are identified as separate entities having certain characteristics such as mass and velocity. In ecological and economic systems the elements have many more degrees of freedom and a much larger variety in their interactions — which makes them complex systems — and hence a modelling tool must be applied that is capable of dealing with this complexity whilst yielding comprehensible outcomes. Multi-agent simulation provides a tool that is suitable for studying how micro-level characteristics affect macro-level system behaviour.

The growth in computer processing speed was one of the important conditions for the rapid growth of multi-agent simulations to study behavioural dynamics in social settings. Overviews of this developing area can be found in Vallacher and Nowak (1994), Doran and Gilbert (1994), Gilbert and Conte (1995), Conte et al. (1997), Liebrand et al. (1998) and Gilbert and Troitzsch (1999). Especially within the paradigm of game theory many simulations have been developed that involved the management of a common resource. However, in these simulations the agent rules are usually aimed at maximising outcomes instead of representing real human behaviour.

In the multi-agent approach applied in the work presented here, agents are equipped with explicit behavioural strategies that depend on information and expectations about the environment — including other agents. In this way more behavioural richness can be incorporated in the simulations than has been done so far. This allows including a larger part of valid insights from social science research about human behaviour. Thus the multi-agent model gives a more intricate understanding of the system and of the ways in which it could be influenced. The disadvantages mirror these advantages: multi-agent models are hard to validate empirically, and they often have to rely on anecdotal evidence for their credibility. The reason is that it is difficult to find unequivocal empirical evidence for the very micro-level laws that give the models their richness. It may well be that this ’weakness’ of our empirical knowledge is an inherent feature of complex systems (Janssen and De Vries, 1999). An interesting point is to see whether these simulations give rise to certain macro-properties (’emergent properties’) which link them to the classical macro-approaches in social and economic science.

In this paper we demonstrate a multi-agent modelling approach aimed at introducing psychological rules that guide the behaviour of artificial agents. These artificial agents, which we have named ‘consumats’, are being tested in the ecological-economic model called ‘Lakeland’. Lakeland includes a renewable fish stock and a gold mine as need-satisfying behavioural opportunities. Before we demonstrate the consumats’ behaviour in Lakeland, we will first discuss a social-scientific perspective on resource management and the common dilemma paradigm. Following that, we will dedicate a separate section to the consumat model.

## 2. Human behaviour and renewable resources

Man's relation with ecosystems is a double-faced one. On the one hand, we depend on ecosystems as resources for food, building materials and a healthy environment to live in. On the other hand, we often plunder and pollute ecosystems as if we were independent from them. This often results in the depletion of natural resources. The central question here is why people bite the hand that feeds them.

Economists were one of the firsts to put resource depletion on the research agenda. In the late 18th and early 19th century, Malthus, Ricardo and Mill all concluded that scarcity of natural resources could lead to diminishing returns, and thus to a reduction in economic output (Norton, 1984). According to Malthus (1789), land resources were a limiting factor in feeding an increasing population. Ricardo (1817) distinguished different types of land, and argued that first, land of the best quality is used before land of a lower quality is used, a process leading to increasing marginal costs of additional land use. According to Mill (1848), resource productivity could be maintained or even improved if one promotes technological development. The arguments from the early days of economics still hold in the current discussions on the limits to growth. Since our focus is on renewable resources, we will discuss this type of resource economics in more detail.

A renewable resource, such as a fish stock, timber and clean air, has a maximum carrying capacity depending on the environmental conditions (Clark, 1976). Changes in these environmental conditions can affect the carrying capacity of the resource. The maximum sustainable yield from a renewable resource is the maximum quantity that can be withdrawn from the resource without reducing its size after renewal of the resource (e.g., restoration of the fish stock). From a classical economic perspective, however, one is not interested in this sustainable yield, but in the level of extraction (e.g., harvest, catch) that maximises the returns on investments. The optimal level of extraction is the level where the marginal costs equal the marginal returns from extraction. If one considers extraction during a number of periods, economists are interested in maximising the present value of extraction, that is, the discounted stream of costs and benefits from the efforts to extract. Since discounting is dependent on returns from other investments, depletion of the renewable resource is likely when reinvesting the revenue from resource extraction is more profitable, e.g., fishermen investing their revenues in better ships.

When more agents have free access to the resource, the situation becomes that of a common property. Hardin's frequently cited article on the *'tragedy of the commons'* explains why people often tend to overexploit collective resources (Hardin, 1968). Here the individual agents are not primarily concerned with their marginal effect on the resource, but with the actual returns from extraction they derive for themselves. This leads to a higher extraction rate, which increases the chance of resource depletion, but certainly results in economic overexploitation (Norton, 1984, p. 119). However, collective resources are not always plundered, but are often exploited in a sustainable way, frequently guided by group norms regarding the harvesting behaviour (e.g., Ostrom et al., 1999). Such situations, in which the behaviour that is in the individual's interest is not optimal from the group's aggregate perspective, and vice versa, are called *commons dilemmas* (Hardin, 1968).

The commons dilemma, involving a conflict between individual and collective interests, has intrigued scientists since Machiavelli (1525), who addressed this problem in the context of the political consequences of social (in)equality. Today, the commons dilemma is being used to understand the (over)use of exhaustible natural resources without property rights. Exhaustible resources may be renewable, such as fish stocks and timber, and non-renewable, such as oil wells and ore. Mainstream economists argue that there exist several rationalities that may guide man's use of renewable resources. For example, types of rationality lead to individual rationality, the Nash equilibrium, Pareto efficiency and strong equilibrium (Dasgupta and Heal, 1979). Economic research clarifies that certain rationalities, when applied to a renewable resource, may yield outcomes that are less optimal and sometimes even disastrous. For example, individual rational behaviour may result in uneconomic harvesting behaviour, even if such behaviour does not jeopardise the resource itself (Norton, 1984).

Much economic research is aimed at the conditions under which certain types of rationality are dominating, and what types of measures are feasible to affect this domination. In this research, economists employ the 'rational actor' approach. This implies that individual choice behaviour is being modelled following the assumption that people have perfect knowledge and try to optimise their outcomes. Research using this rational-actor approach is usually focused on finding the conditions for an optimal resource extraction rate, provided that the actors employ an individual optimising strategy. Moreover, it can be calculated what governmental measures are necessary to attain an optimal extraction rate given that all agents are following such an optimising strategy. This approach provides an essential back-curtain against which the fallacies of actual economic behaviour may be perceived.

Where economics is generally a normative science studying the optimal way of allocating scarce resources, (social) psychology is a more descriptive science studying the actual decision making of human actors. Luce and Raiffa's *Games and Decisions* (Luce and Raiffa, 1957) awakened a fascination for the conflict between individual and collective interests in many social scientists also outside the economic tradition. Especially social psychology questions what factors affect the actual harvesting behaviour of people confronted with renewable and non-renewable common resources. Combining a social-psychological view on behaviour with the economical principles that apply to renewable resource management may add to the understanding of the discrepancies between optimal and actual resource-use behaviour.

A major assumption in social psychology is that people do not always optimise their outcomes, but often engage in satisficing behaviour (Simon, 1976). Because people have limited cognitive resources, much of their daily routines are automated. Here, optimising is not focused exclusively on behavioural outcomes, but also on managing cognitive resources. Automating behaviour, for example, prevents people from spending hours in supermarkets deliberating over the various brands of products they can buy. Instead, people often habitually repeat their originally deliberate choices for as long as the outcomes are satisfying. However, a current habit may yield far from optimal outcomes because new, better behavioural opportunities may have been introduced. Especially in the context of depleting renewable resources, it may be so that people who consume in a habitual manner may be unaware of the developments in the resource size, which may cause under- or over-harvesting.

A second major assumption of social psychology is that people often learn about new attractive behaviours by using information about other people's behaviour. This so-called social processing can also be understood as a strategy to economise their cognitive efforts, and thus it fits in a broader perspective on optimising. A major finding is that people tend to engage in social processing when they are uncertain (Festinger, 1954). This is relevant for understanding how people use renewable resources such as ecosystems, because these are often quite complex systems, and their dynamics may yield more or less surprising outcomes. For example, a fish stock may manifest large oscillations related to variations in factors such as water temperature, fish-harvest, the availability of food (e.g., algae) and pollution (e.g., Walker and Livingstone, 1992). As a consequence, people may experience different levels of uncertainty regarding the state of the resource, which may affect their harvesting behaviour.

Many social–psychological laboratory experiments have been aimed at unravelling the factors that affect people's harvesting behaviour. Here, subjects are confronted with a common resource and they have to decide how much to take from that resource. Because this *experimental game* may last for an extended number of rounds in a prolonged period of time, people have to take the long(er)-term effects of their behaviour on the resource into account. This can be easily related to the concept of *sustainability* that is discussed a lot within the environmental sciences. Typical founders in this experimental tradition were Jerdee and Rosen (1974), Rubenstein et al. (1975) and Brechner (1977). Group factors, personal factors and resource characteristics have been experimentally found to affect subjects' harvesting behaviour in a resource dilemma.

Group factors that have been found to increase harvesting are, e.g., a larger group size (e.g. Fox and Guyer, 1977), a low identifiability of the individual behaviour (e.g., Jorgenson and Papciak, 1981) and a weak group identity (e.g., Brewer, 1979; Edney, 1980). Personal factors that have been found to increase harvesting are, e.g., a weak belief that personal restraint is essential to maintain the resource (e.g., Jorgenson and Papciak, 1981; Samuelson et al., 1984), high uncertainty regarding the behaviour of others, (Messick et al., 1988), and an individual or competitive social value-orientation (Messick and McClintock, 1968; McClintock, 1978). Several resource characteristics also affect the harvesting behaviour of people. Obviously, the relevant resource dynamics are important. People will harvest more when the resource size is larger and the larger is its regenerative capacity. Several researchers found that increased environmental uncertainty (see above) also caused people to harvest more (Messick et al., 1988; Suleiman and Rapoport, 1989; Budescu et al., 1990; Rapoport et al., 1992; Hine and Gifford, 1996; Wit and Wilke, 1998). Effects of uncertainty have even been demonstrated to affect the harvesting behaviour of experienced fishermen managing a simulated fish stock (Moxnes, 1998).

Whereas experimental laboratory research has taught us a lot on the factors that affect behaviour in commons dilemmas, these results cannot be translated directly towards real-life situations. Most psychological experiments are conducted within the hour, whereas real-life dilemmas may exist for decades or even longer. Moreover, the choices that people make while playing an experimental game usually have no far-reaching consequences for their lives. In real-life dilemmas, however, the choices one makes may determine one's quality of life to a far extent.

Field experiments and observations may provide the data that allow for inferring behaviour-determining factors in real-life situations. Field experiments, however, provide data of limited validity because they are based on limited (quasi-)experimental variations applicable during relatively short time periods. Observational data usually do not allow for drawing causal inferences because the complex relations between the variables and environmental conditions are not well known.

Computer simulation of artificial agents in a commons-dilemma situation offers a tool to experiment with more real-world conditions and with long time-series. Despite the fact that computer simulations are usually quite simple in comparison to the real world, the dynamics being explored may help interpreting real-life dilemmas. As such, simulation is an approach which, in combination with other methodologies, contributes to the understanding of why people in commons dilemmas behave like they do and what strategies may be viable in altering less sustainable behaviours.

Within game theory, many simulations of commons dilemmas have been developed. The computer tournament for the most viable strategy, being organised by Axelrod (1980a,b, 1984), was an important stimulus for this kind of research. Many researchers developed strategies for automata, such as win-stay, lose change, or win-stay, lose-defect. These strategies were being applied in automata playing iterative games so as to explore the dynamics of resource use (e.g., Liebrand and Messick, 1996). A very good strategy appeared to be cooperating unless the other automata defected in the previous round. This strategy is known as Tit-for-Tat. Later, more sophisticated rules were developed, e.g. by equipping the automata with a memory for the behaviour of other automata (Lindgren and Nordahl, 1995; Molander, 1985; Nowak and Sigmund, 1992), or by equipping the automata with evolutionary strategies (genetic algorithms), which allowed them to adapt their choice behaviour to the behaviour of the other agents (e.g., Axelrod, 1987; Macy, 1996). However, most game theoretical simulations were primarily focussed on developing optimal strategies instead of trying to develop strategies that reflect human decision-making. To increase the behavioural richness in this simulation paradigm it is necessary to represent the cognitive processes that guide the harvesting behaviour of real people in agent rules.

In real-life dilemmas, cognitive processes that appear to be relevant for understanding how renewable resources are being managed, refer to deliberate choice behaviour, social comparison, imitation and habit formation, respectively. Many behavioural theories are available to guide the development of agent rules involving such cognitive processes, e.g., theories on deliberate behaviour, normative conduct, social comparisons and learning processes. Because the type of cognitive processing a person engages in depends on the situation it encounters, it is necessary to specify under what conditions, which theory-based rule will guide an agent's behaviour. To take account of a variety of essential behaviour determinants and mechanisms, a conceptual model for consumer behaviour has been developed that integrates relevant behaviour theories (Jager et al., 1997; Jager, 2000). This conceptual model has been used to develop a comprehensive set of theory-based agent rules (Jager et al., 1999; Jager 2000), which we have named the *consumat approach*.

## 3. The Consumat approach

Many behaviour theories each explain *parts* of the various processes that determine consumer behaviour. Due to this, social psychology is sometimes said to be in a pre-paradigm state; according to some scholars there is a need for a meta-theory of human behaviour (Vallacher and Nowak, 1994). Such a meta-theory should provide a framework to integrate simplified versions of relevant expert-theories of behaviour. The

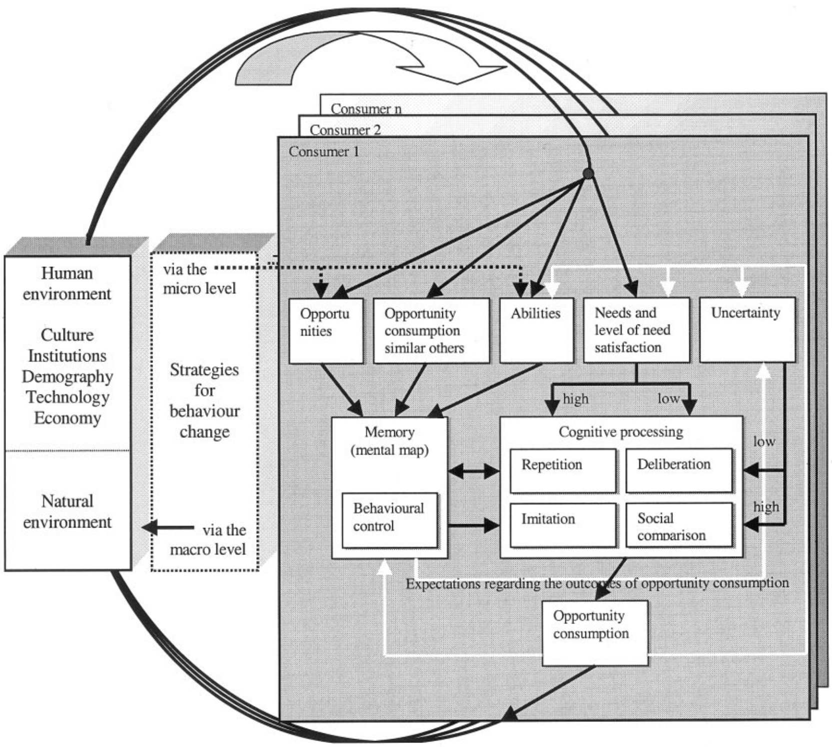


Fig. 1. The conceptual model of consumer behaviour (source: Jager, 2000).

consumat approach as introduced by Jager et al. (1999) is based on a comprehensive conceptual model of consumer behaviour, which could be the basis for such a meta-theory. This conceptual model is schematised in Fig. 1.

The driving forces at the collective (macro-) and the individual (micro-)level make up the environmental setting for consumer behaviour. The collective level refers to technical, economical, demographic, institutional and cultural developments. At the individual level there are the needs of consumers, the opportunities to be consumed, and individual abilities for consuming the opportunities. Furthermore, consumers have a certain degree of uncertainty regarding the outcomes of behaviour.

Dependent on the level of need satisfaction, which is based on the satisfaction of different needs, and the degree of uncertainty, certain cognitive processes determine the choices for consumption along the dimensions *social processing* and *reasoned behaviour*. Consumats having a low level of need satisfaction and a low degree of uncertainty are assumed to *deliberate*, that is, assessing the consequences of all possible decisions given a fixed time-horizon in order to maximise level of need satisfaction. Consumats having a low level of need satisfaction and a high degree of uncertainty will engage in *social comparison*. This implies the comparison of its own previous behaviour with the previous behaviour of consumats having somewhat similar abilities, and selecting that behaviour which yields a maximal level of need satisfaction. When consumats have a high level of need satisfaction, but also a high level of uncertainty, they will engage in the *imitation* of the consumptive behaviour of other, somewhat similar consumats. Finally, consumats having a high level of need satisfaction and a low level of uncertainty habitually *repeat* their previous behaviour. When consumats engage in reasoned behaviour (deliberation and social comparison), they will update the information in their mental map, which serves as a memory to store information on abilities, opportunities, and characteristics of other agents. From the consumption of opportunities, a new level of need satisfaction will follow. Uncertainty in the consumats is defined as the difference between the actual and the expected level of need satisfaction. When this difference exceeds the uncertainty tolerance level, the consumat will engage in social processing; below this uncertainty tolerance level the consumat will engage in individual processing. Consumption leads to changes in abilities, opportunities and the social and physical environment, which will affect consumption in subsequent time steps.

Based on the conceptual model, a multi-agent computer simulation model has been developed. The consumats are equipped with various needs, and they may consume opportunities to satisfy these needs. The specific level of consumption from a specific set of opportunities $j = 1..J$ is being notified as $x_j$, which stands for, e.g. a certain number of hours spent fishing. For opportunity $j$ and a need $i$ from a specific set of needs $i = 1..I$, the level of needs satisfaction $N$ at time $t$ is formulated as a diminishing marginal utility function, which implies that the more of an opportunity is being consumed, the less utility one gets from consuming yet another unit of that opportunity:

$$N_{i,t} = 1 - \exp(-\alpha * x_j) \tag{1}$$

with parameter $\alpha$ indicating the sensitivity of $N_i$ for the consumption of opportunity $j$ at time $t$. The total level of need satisfaction of a consumat is a weighted multiplication of the satisfaction of the set of needs $i = 1..I$.

$$N_t = N_{1,t}^{\gamma 2} * N_{2,t}^{\gamma 2} * \ldots * N_{\mathrm{n},t}^{\gamma \mathrm{n}} \tag{2}$$

It is postulated that there is a critical value for $N$, $N_{\mathrm{MIN}}$, below which a consumat is dissatisfied and may change its behavioural mode. Because of the multiplicative need-satisfaction function, a very low level of need satisfaction for any single need may result in a low overall $N$ and hence cause dissatisfaction.

The consumat is equipped with abilities that refer to, e.g., financial means, time perspective (time-horizon used in calculations) and harvesting capacity. The consumat is also equipped with a mental map to memorise previous behaviours of itself and others, and to memorise the need satisfying potential of various opportunities. The consumat $k$ experiences uncertainty $U$ at time $t$ proportional to the absolute difference between the expected consumption of opportunity j, $E(x_j)$, at $t-1$, e.g. during harvest, and its actual consumption at $t-1$:

$$U_{k,t} = \mathrm{ABS}(E[x_{j,t-1}] - x_{j,t-1}) \tag{3}$$

A maximum level of uncertainty tolerance, $U_T$, is postulated: if the uncertainty exceeds this value, the consumat will become uncertain. Depending on the consumat's level of need satisfaction and uncertainty level, it may engage in four different cognitive processes: deliberation, social comparison, repetition and imitation; see below. It is important to note that a distinction is made between social processing (social comparison and imitation) and social information (e.g., relative financial budget, the behaviour of other consumats). For example, consumats may individually deliberate on how to maximise their outcomes, thereby making assumptions on the behaviour of the other consumats.

### *3.1. Repetition (consumat is satisfied and certain)*

Repetition stands for automatic individual processing, and relates to classical and operant conditioning theory (Pavlov, 1927; Skinner, 1953). A major assumption in these theories is that behaviour is reinforced when the outcomes are positive. A consumat engages in repetition when it is satisfied ($N_{i,t} \geq N_{\min}$) and certain ($U_{k,t} \leq U_T$). Repeating implies that the consumat does not update its mental map. It will just repeat the previous behaviour (opportunity consumption) in order to remain satisfied.

$$x_{j,t} = x_{j,t-1} \tag{4}$$

Thus, the consumat is motivated to consume the previously consumed opportunity. Only when it appears that the behavioural control over this opportunity has dropped to zero, indicating that the consumat lacks sufficient resources (e.g., money) to consume the opportunity in question, the consumat will switch towards deliberating to find an opportunity that is both satisfying and feasible.

### *3.2. Deliberation (consumat is dissatisfied and certain)*

Deliberation stands for reasoned individual processing, as conceived by decision and choice theory (Janis and Mann, 1977; Hogarth, 1987) and theory of reasoned action (Fishbein and Ajzen, 1975; Ajzen, 1991; Ajzen and Madden, 1985). A central assumption of these theories is that people assess the possible outcomes of their specific behavioural opportunities $o$, and choose the behaviour that maximises these expected outcomes. Consumats engage in deliberation if the level of need satisfaction is below the minimum threshold level ($N_{i,t} < N_{\min}$), and when they are certain ($U_{k,t} \leq U_T$) about behavioural outcomes. Deliberating starts with updating the mental map. This updating implies that information is gathered regarding the need-satisfying capacities of opportunity consumption, the resource demands of opportunities (e.g., financial costs), the consumat's own abilities and the previous behaviour of other consumats. This information is being used to calculate the expected outcomes in terms of level of need satisfaction and the behavioural control over all these opportunities. This calculation yields a maximum expected level of $N$ for a particular set of feasible opportunities.

$$x_{j,t} = \max N_i(x), x \in X \tag{5}$$

In the calculations the consumat uses a fixed time horizon. Outcomes that fall beyond the time horizon are not taken into consideration, and thus do not affect current behaviour. The consumat will be motivated to consume the specific opportunities that jointly yield the highest perceived need-satisfaction that is feasible in terms of behavioural control.

### *3.3. Imitation (consumat is satisfied and uncertain)*

Imitation stands for automatic social processing, and relates to social learning theory (Bandura, 1977, 1986) and the theory of normative conduct (Cialdini et al., 1991). Both theories suggest that imitating others' behaviour may be beneficial. Social learning theory states that watching another person being rewarded for understandable and reproducible behaviour may result in the imitation of that behaviour. The theory of normative conduct states that people often do what others would approve of them to do. A consumat engages in imitation if it is satisfied ($N_{j,t} \geq N_{\min}$) and uncertain ($U_{k,t} > U_{\mathrm{T}}$). When the consumat engages in imitation, it will read the mental map and recall the consumat that functioned most recently as a comparison-consumat. It will do what this consumat $s$ did in the previous time-step. The consumat is thus motivated to consume whatever the other similar consumat has been consuming in order to keep satisfied.

$$x_{k,i,t} = x_{s,i,t-1} \quad (6)$$

in which $x_{s,i,t-1}$, is the previous behaviour of a similar consumat and $X_{k,i,t-1}$ is the previous own behaviour. Also the behavioural control over this behaviour is being calculated. Only when it appears that the behavioural control over this opportunity is below zero, the consumat is not capable of consuming this opportunity, and consequently will switch towards social comparison (see below).

### 3.4. Social comparison (consumat is dissatisfied and uncertain)

Social comparison stands for reasoned social processing, and relates to social comparison theory (Festinger, 1954; Masters and Smith, 1987) and theory of reasoned action including social norms (Fishbein and Ajzen, 1975). Social comparison theory states that people have a drive to evaluate the behaviour of similar others when they feel uncertain about which behaviour to perform. Moreover, the theory of reasoned action states that the behaviour of other people is often considered as a norm. A consumat engages in social comparison if it is dissatisfied ($N_{i,t} < N_{\min}$) and uncertain ($U_{k,t} > U_{\mathrm{T}}$). While engaging in social comparison, the consumat first will update its mental map. Then it will observe the previous consumptive behaviour of the other consumats having somewhat similar abilities. When other consumats' abilities differ no more than a certain percentage from its own abilities, those consumats are assumed to be similar, and thus comparable. The consumat will calculate the expected outcomes for reproducing the opportunity consumption of the other consumat. The consumat will be motivated to copy either the other consumat's behaviour, or its own previous behaviour, depending on which of the two yields the highest need-satisfaction.

$$x_{k,i,t} = \max N_i(x_{k,i,t-1}, x_{s,i,t-1}), x_{s,i,t-1} \in X_{s,i,t-1} \quad (7)$$

in $x_{s,i,t-1}$ is the previous behaviour of a similar consumat, $X_{k,i,t-1}$ is the previous own behaviour and $X_s$ the set of behaviours of similar consumats at $t-1$. Also the behavioural control over this behaviour is being calculated.

### 3.5. Validation of the consumat approach

As was noted in the introduction, it is difficult to validate a multi-agent simulation because of the complexity of the systems that are being simulated. We tried to validate the consumat approach on two levels: the micro-level rules and the resulting behavioural dynamics.

Regarding the micro-level rules, the validation rests in the fact that the consumat rules are being developed on the basis of validated psychological theories. Of course, a severe reduction took place in order to develop the cognitive processing rules. Moreover, the rules that determine when which cognitive processing rule is being followed are quite rudimentary because no validated integrated behavioural model exists to validate these rules. However, the formalisation of relevant behavioural processes in the consumat is expected to increase the behavioural richness in simulation models in comparison to formalising agents that exclusively engage in outcome-maximising processes.

The validation of the resulting behavioural dynamics resides in the capacity of the consumat approach to replicate empirical findings. Here, we are confronted with a validation problem because resource management experiments using real people have not collected data on the cognitive processes people engaged in. The validation option that remains open is to check if the simulation results are at least in accordance with the effects that have been found in empirical studies. Therefore, we decided to confront our consumats with a simple renewable resource (Jager et al., 1999). We concentrated on the effect of uncertainty because this had been investigated by several researchers using human subjects, yielded clear results, and appeared to be relatively simple to formalise in the consumat approach. Just as in empirical studies, we found that an increase in uncertainty caused consumats to harvest more from a common resource. These results at least increase the face-validity of the consumat approach.

The consumat simulation of a common resource revealed three dynamical processes that explained why increased environmental uncertainty provokes over-harvesting. These are, respectively, the optimism effect, the imitation effect and the adaptation effect. The *optimism effect* holds that deliberating consumats, when confronted with a positive fluctuation in resource growth, are more likely to develop an over-harvesting habit because over-harvesting increases the chances of the consumat being satisfied in the short run. The *imitation effect* implies that consumats, when uncertain and satisfied, are likely to imitate the behaviour of the other consumat, even when this behaviour is less optimal than one's own previous behaviour. The *adaptation effect* holds that no new behavioural opportunities are being adopted during social processing, and as a consequence the consumats are not capable of adapting their behaviour to changing circumstances, such as a serious depletion of the resource. An essential aspect of these *process effects* is that they are originating from the different behavioural processes that the consumats engage in. Consequently, the consumat-approach, introducing a broader perspective on rational behaviour, allows for the expression of relevant consumer dynamics, such as habit formation and social learning, in ecological economic models. Empirical study of these process effects is important both for a better understanding of the behavioural dynamics of resource management as well as for validation of the consumat approach. In the following section we will present various simulation experiments using consumats in an ecological economic model.

## 4. Fish, gold, and the happiness of consumats

To experiment with simulated behaviour in an ecological–economic model, we place the consumats in a 'micro-world' called 'Lakeland' (De Greef and De Vries, 1991). Lakeland consists of two natural resources: a fish stock in a lake and a nearby gold mine. The lake is being modelled as a simple ecological system of fish and shrimps. The introduction of consumats in an ecological–economic model implies that different behavioural processes, such as social comparison and imitative behaviour, underlie consumats' harvesting behaviour. We place sixteen consumats in Lakeland, and these consumats catch fish from the lake to satisfy their need for food. Moreover, they may also export fish, and the returns can be spent on assets such as luxury goods. Import of fish is also allowed. If the gold mine is opened, consumats may also dig for gold. The money that is earned by mining can be spent on fish imports and/or on luxurious assets. The pollution that is caused by mining is reducing the carrying capacity of the lake for the fish and shrimp populations. The consumats determine how they allocate their time on leisure, fishing and mining. They are equipped with certain abilities for fishing and mining, and want to satisfy their four needs: leisure, identity, subsistence and freedom. These needs, which are supposed to play an important role in this case, are selected out of a larger set of needs as described by Max-Neef (1992). We assume that the satisfaction of the leisure need relates to the share of the time spent on leisure. The identity need is satisfied by the relative amount of money the consumat owns in comparison to consumats with similar abilities. The subsistence-need relates to the consumption of food. The freedom need is assumed to be related to the absolute amount of money the consumat owns, which can be spent on whatever assets the consumat prefers.

In Fig. 2 we depict the variables used in the simulation model in regard to the conceptual behavioural model as depicted in Fig. 1.

To study how the different possible behavioural processes may affect the interactions with the simulated environment, we decided to focus on experimental manipulations of consumats' sup-

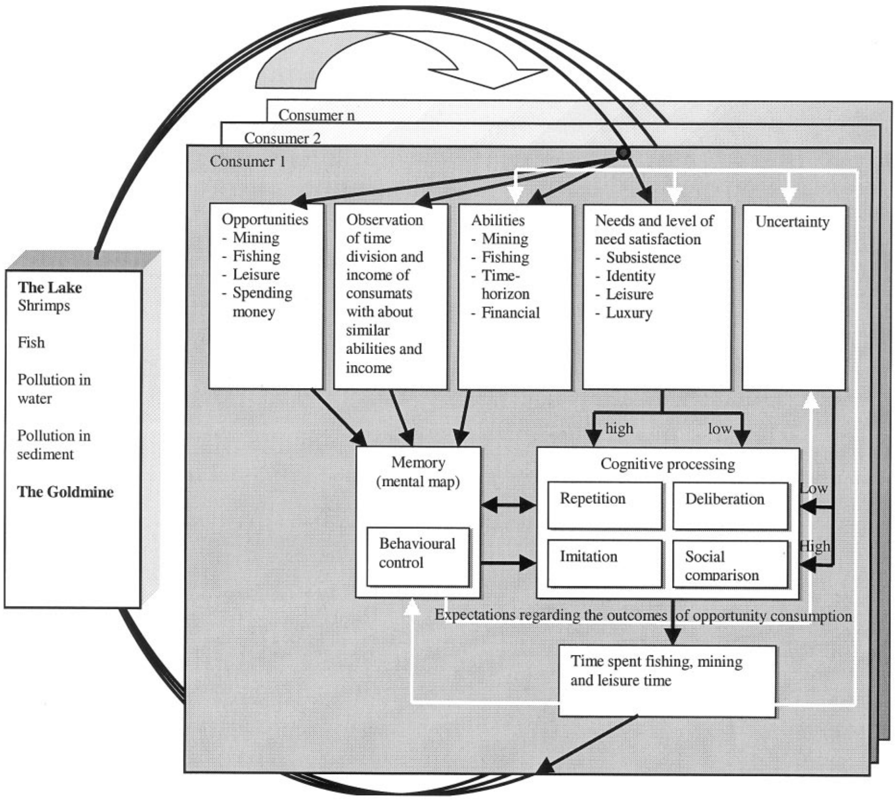


Fig. 2. The variables used in the simulation model.

posed tendency to engage in particular behavioural processes. These experiments were performed in two set-ups of Lakeland, one in which only fishing is allowed, and a second in which mining is allowed besides fishing. First we will describe the results we obtained with Lakeland where only fishing is allowed, and in a next section we will present results of introducing mining in Lakeland.

### 4.1. Fishing in Lakeland

In the first simulation experiments the set-up of Lakeland does not allow consumats to dig gold, and thus they fully depend on their fishing capacities to satisfy their needs. Varying the minimal level of need satisfaction and the level of uncertainty tolerance allows for the specification of consumats that engage in one or more of the four behavioural processes distinguished in Fig. 2. Two types of consumats have been formalised to show how different types of behaviour affect the management of the fish stock. The first type is relatively quickly satisfied, but also quickly uncertain ($N_{min} = 0.05$, $U_T = 0.05$). This leads this type of consumat to engage in all four behavioural strategies. This consumat, having a large degree of freedom regarding the behavioural strategies, will correspondingly be denoted as the *Homo psychologicus*.

The second consumat type is virtually never satisfied or uncertain ($N_{min} = 0.95$, $U_T = 0.95$). This causes this type of consumat to engage exclusively in outcome-optimising deliberation. This consumat can be considered as a simple version of the optimising agent in economic models, and it will consequently be denoted as the *Homo economicus*. The *H. economicus* is self-supportive, i.e. not learning from the behaviour of other consumats nor making explicit assumptions about the decisions of others. The consumats employ a time horizon (cognitive ability) of 10 time-steps when engaging in reasoned processing (deliberation and social comparison). Moreover, the consumats have a fishing ability of 6600, indicating that they are capable of catching 6600 units of fish per time-step when the fish stock is on its carrying capacity level (the maximum number of fish-units is about 23 000). Factors that affect the actual catch are the fish density, the fish growth function (in our model about 2.3, indicating that at each time-step the number of fish is multiplied by 2.3 for as long as the maximum is not reached) and the length of the fishing season (in our model 80% of the time). Consequently, we have a very viable fish stock, which renews itself very quickly, and hence is quite difficult to deplete. To introduce environmental uncertainty in the model, a stochastic function in the fish catch has been formalised.

For both experimental conditions (*H. economicus* and *H. psychologicus*) 100 model runs have been performed, for which the average outcomes will be presented. Each experiment involved sixteen consumats with identical fishing abilities inhabiting Lakeland. Thus, all consumats were either *H. economicus* or *H. psychologicus*, depending on the experimental condition. The consumats start with an equal financial budget. Because they are depending on each other regarding the management of the resource, the consumats are actually caught in a commons dilemma.

In reporting the results we will focus on a few essential variables. First, the behaviour and behavioural processing of the consumats will be observed. Second, the developments in the fish stock will be considered. Third, the developments in the need satisfaction of consumats will be observed. Finally, attention will be given to the developments in the financial budget of the consumats, which provides a material index of welfare in the model.

Each simulation experiment involves 50 time-steps, each time-step representing a year in which consumats must decide how much time to spend on fishing and leisure in order to satisfy their needs.

### *4.1.1. Results*

Looking at the behavioural processes the consumats engage in, it appears that the *H. psychologicus* engages in all four behavioural strategies, as was intended. Fig. 3 shows for time-step 1 to 50 the proportion of time each behavioural process is engaged. These results are an

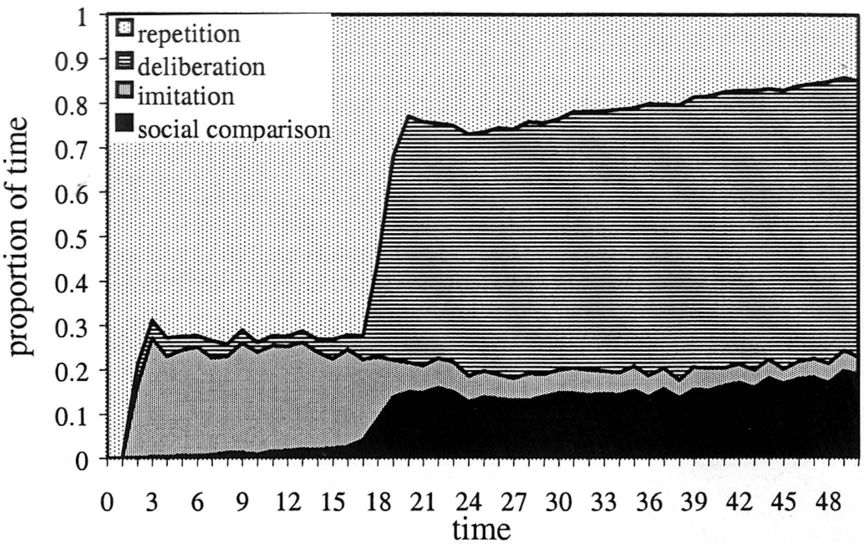


Fig. 3. Proportional distribution of the four behavioural processes for the *homo psychologicus*.

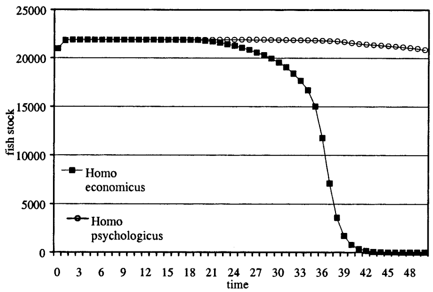


Fig. 4. The development of the fish stock in time for the two consumat-type conditions.

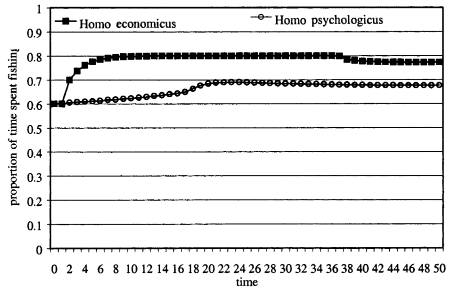


Fig. 5. The proportion of time spent fishing for the two consumat-type conditions.

average outcome of 100 simulation runs under the condition of all consumats being *H. psychologicus*.

The sudden shift from much repetition to much deliberation at $t \approx 18$ is caused by the fact that the initial financial budget that the consumats use to buy luxury goods or to import/buy fish has depleted around that time. This worse financial situation causes the consumats to be dissatisfied more often, causing them to engage in deliberation more often. Because the consumats are occasionally uncertain and hence engage in social processing (imitation and social comparison), this decrease in need-satisfaction also causes the relative high proportion of imitation before $t \approx 18$ to change towards social comparison (see Fig. 3). The *H. economicus* engaged purely in deliberation, as it was defined to do.

Fig. 4 shows the development in time of the fish stock for these two conditions (100 simulation runs per consumat-type condition). It can be observed that the fish stock depletes for the *H. economicus*, and remains at a high level for the *H. psychologicus*.

These effects can be attributed to the proportion of time spent fishing, which is graphically depicted in Fig. 5. *H. psychologicus* slowly increases its fishing to 0.7 of the time, whereas *H. economicus* more rapidly increases its fishing to 0.8 of the time. The explanation of these effects will be done below in two separate sections for the *H. psychologicus* and *H. economicus*.

Differences in time spent fishing have consequences for the financial budget of the consumats. Fig. 6 shows that the higher proportion of time spent fishing by *H. economicus* yields a higher financial budget during the first 35 time-steps. However, starting from the moment that the fish stock becomes depleted, the financial budget of *H. economicus* quickly drops to zero. For the *H. psychologicus* a decline of the initial financial budget can be observed until a relatively stable budget is reached that is purely earned by fishing.

### 4.1.2. Homo psychologicus

As was shown in Fig. 3, during the 100 experimental runs the *H. psychologicus* engages in all four behavioural strategies. Consumats start fishing for 60% of the time (initial setting). An occasional bad catch may yield a lower financial budget in comparison to other consumats. As a consequence, this consumat's level of need satisfaction for 'identity' drops below the critical level, causing it to engage in reasoned processing (deliberation or social comparison). When deliberating, this consumat will increase its time spent fishing

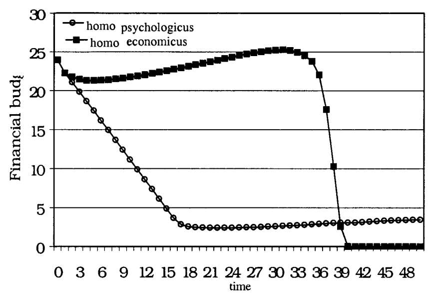


Fig. 6. The financial budget for the two consumat-type conditions.

to about 80% (while the satisfied consumats remain at 60%) to increase its financial budget. This is mostly a satisfactory action, and as a consequence this consumat will continue to process automatically. This implies repetition of its own previous behaviour, or imitation of the behaviour of similar consumats. The latter may cause the consumat to decrease its time spent working again. Other satisfied consumats may simply imitate the increase in time spent working without ever engaging in reasoned processing. However, most of them remain fishing for 60% of the time. In some runs, however, the number of consumats that imitate the increase in time spent fishing is so large that the resource becomes seriously depleted. This causes the slightly downward development of the fish stock beyond step 36 that can be seen in Fig. 4. On the average, the proportion of time the consumats spend fishing increases to about 67%.

The consumats that increase their time spent fishing will be more likely to catch a surplus of fish that they can sell on the market. This allows them to earn some money for luxury products, which satisfies their need for freedom. Moreover, their level of need-satisfaction for identity is relatively high because they have more money than the consumats that did not increase their time spent fishing. However, the increase in time spent fishing is not that large that their level of need-satisfaction for leisure drops significantly. Finally, they catch enough fish to satisfy their need for subsistence. Because the needs of the consumats that increased their time spent fishing are staying at a sufficient level, they experience a high general level of need satisfaction, causing them to remain processing in an automatic manner. This implies repeating their own previous behaviour, or imitating the behaviour of similar consumats.

The consumats that did not increase their time spent fishing in the beginning (say, the first 15 time-steps) will catch somewhat less fish, using it exclusively for their own consumption. Not selling fish on the market implies that their financial budget declines, which causes the over all decline of financial budget for the *H. psychologicus* condition (Fig. 6). As a consequence, these consumats cannot afford to buy luxury goods at a given moment in time. Because of that, their need for freedom decreases below the critical level around $t = 20$, causing them to deliberate and socially compare regarding better opportunities. However, often they calculate that increased working may increase their level of need satisfaction for freedom, but at the cost of their level of need satisfaction for leisure and identity. Despite the fact that they remain dissatisfied as regards freedom, they do not change their behaviour because there is no other behavioural opportunity yielding a higher overall level of need satisfaction.

In most cases the consumats have a reasonable level of need satisfaction for subsistence, identity and leisure, and a low level of need satisfaction for freedom. In about half of the simulation runs a subgroup of consumats increases their time spent fishing in an early stage, resulting in a higher level of need satisfaction for freedom in the long run.

To obtain an indication of distribution of income, Lorenz (1905) and Gini (1912) developed income-disparity indexes. The Gini index (Gini, 1912) is a measure for distributional equality, and provides a macro-level indicator of economic equality in a society. In the simulation experiments, the Gini index is being used to indicate financial equality. A Gini index of 1 denotes complete financial equality, a Gini index of 0 complete financial inequality. In the experiments with Lakeland the consumats all start with an equal financial budget, which implies a Gini index of 1.0. In the first 20 time-steps a drop to about 0.20 was observed. After this sharp decline in the Gini index, in about half of the simulation runs an increase towards 1.0 can be seen, whereas the other half shows an irregular pattern, oscillating between 0.20 and 0.30. This oscillating pattern occurs in the simulation runs where a group of consumats increased their harvesting behaviour in the early time-steps because they experienced ‘bad luck’ regarding their harvest. Moreover, some consumats not experiencing this ‘bad luck’ may still increase their time spent fishing because they imitate the consumats that had ‘bad luck’. Especially this last group of consumats will earn a lot of money. Because the consumats that increased their time spent fishing earn more money than the other consumats, the Gini index remains low, indicating distributional inequality.

#### 4.1.3. Homo economicus

*H. economicus*, which is never satisfied and never uncertain, exclusively engages in deliberation. The consumats in this condition immediately increase their time spent fishing to maximise their outcomes. Despite the fact that the consumats, having a time horizon of 10, anticipate the collapse of the fish resource, they continue fishing intensively. Around time-step 40, the fish stock is depleted and the level of need-satisfaction of the consumats drops to 0.0. This situation typically resembles the tragedy of the commons, showing that behaviour following individual rationality may lead towards a collective disaster. The consumats implicitly 'expect' that all other consumats will continue their over-harvesting. Consequently, each consumat 'realises' that their individual behaviour hardly affects the depletion of the resource. Following the principles of individual rationality, all consumats consider a high harvesting level as optimal, and consequently they do not succeed in reducing their harvest to a more sustainable level. This situation resembles a sort of self-fulfilling prophecy, as the fish stock depletes because the consumats expect it to deplete. This outcome is a typical example of what happens if no property rights exist on an exhaustible resource and the fishermen behave in an own-outcome maximising manner.

Using the same decision rules for a single 'meta-actor' with needs and abilities that are sixteen times as large as those of each of our sixteen consumats would result in the meta-actor decreasing its harvesting now so as to maximise its outcomes over the forthcoming ten time-steps. This is due to the fact that it has full control over the fish stock because it is not being confronted with fifteen other consumats.

In the condition of the *H. economicus* the consumats earn an almost equal amount of money for as long as the fish stock is not depleted, resulting in a Gini index of about 0.97. When the fish stock is depleted at around $t = 40$, and consumats' income has dropped to 0, some con-

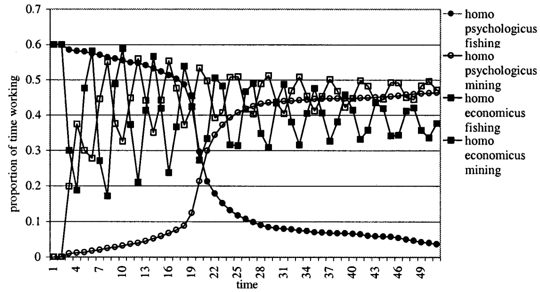


Fig. 7. Time spent fishing and mining for the two consumat-type conditions for $t = 1$ to $t = 50$.

sumats will run out of money earlier than other consumats do, causing the Gini index to drop to a level of 0.6. Very quickly all consumats have finished up their finances, and this equal financial situation for all consumats obviously yields a Gini index of 1.0.

#### 4.1.4. No variation in fish catch

Some variations of the default case have been performed to assess the sensitivity of several crucial assumptions. In the previous experiments, the harvest of a single consumat at a given time-step was partly dependent on chance, just like any real-world fisherman may have lucky days and bad days. In the present condition, all random variation in the fish catch of the consumats has been eliminated. For the rest, the previous experimental consumat-type conditions (*H. economicus* and *H. psychologicus*) are being replicated. Removing random variation now causes the *H. psychologicus* to be certain all of the time, which would cause it to engage exclusively in individual processing (deliberation and/or repetition).

Because the *H. psychologicus* does not experience occasional 'bad luck' regarding the harvest, its level of need satisfaction remains at a satisfactory level. Consequently, the *H. psychologicus* engages only in repetition, fishing for 60% of the time instead of increasing the time spent fishing to about 67% as found in the previous experiment that included a stochastic function in the fish catch. These results, showing an increase in harvesting when uncertainty increases, are in accordance with the results obtained with a simple resource (Jager et al., 1999). The *H. economi-*

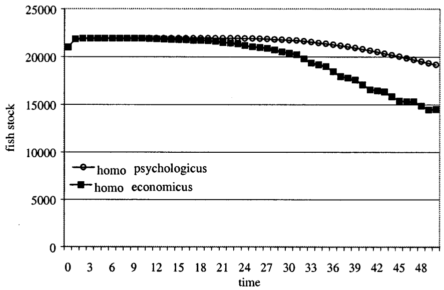


Fig. 8. The fish stock for the two consumat-type conditions for $t = 1$ to $t = 50$.

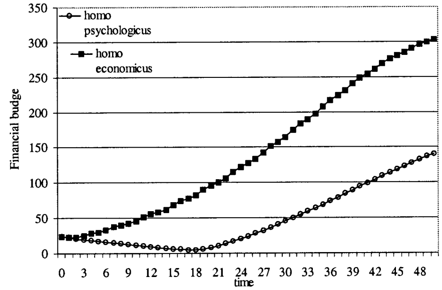


Fig. 10. The financial budget for the two consumat-type conditions.

*cus*, however, did not alter its harvesting behaviour in response to removing all random variation in the fish catch. This is due to the fact that the *H. economicus* has a high tolerance for uncertainty ($U_T = 0.95$), and thus is less sensitive to variations in the harvest.

### *4.2. Introducing mining in Lakeland*

In the next series of experiments the set-up of Lakeland allows the consumat to engage in mining starting from the first time-step. Consumats thus can alternately fish and mine to satisfy their needs. Besides a fishing ability of 6600 (see previous section), the consumats have a mining ability of 100, indicating they are capable of harvesting a maximum of 100 units of gold per time-step. It depends on the market dynamics (e.g. world fish price versus local fish price) how much fish they can buy for a unit of gold. As a starting condition, the consumats are fishing for 60% of the time, and they do not yet engage in mining. For the rest the design of two consumat-type conditions as used in the first series of experiments is being replicated. Because the mining of gold induces pollution of the lake, which in its turn affects the fish stock, data on the development of pollution concentration in the lake will also be presented.

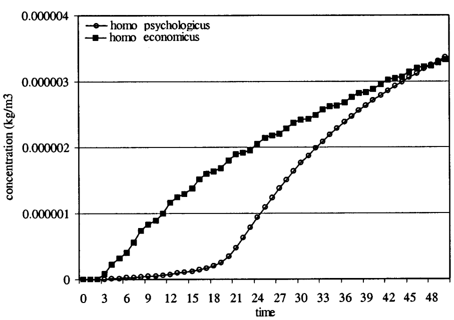


Fig. 9. The pollution concentration for the two conditions for $t = 1$ to $t = 50$.

#### *4.2.1. Results*

Fig. 7 shows the time spent fishing and mining for *H. economicus* and *H. psychologicus*, respectively. Again, the results involve 100 simulation runs per consumat-type condition. It can be seen that *H. economicus* very quickly switches to mining, but instead of a smooth transition an oscillating pattern between time spent fishing and mining can be seen. *H. psychologicus* shows a slow increase in mining until at about $t = 20$ the transition is completed.

Looking at the consequences for the fish stock (Fig. 8), first it can be observed that for *h. economicus* the fish stock does not fully deplete within fifty time-steps, as it did in the previous condition (Fig. 4).

The introduction of mining implies that the consumats spent less time fishing. Because *H. psychologicus* spends less time fishing than *H. economicus*, the latter depletes the fish stock to a larger extent. However, *H. psychologicus* depletes the fish stock at a higher rate than in the previous condition, despite the fact that it spends less time fishing. A major reason for this is that the slow but persistent move towards mining increases the pollution that causes the fish stock to decrease (Fig. 9). This further accelerates the transition to mining, as the fish catches per hour keep decreasing.

Due to the mining, the consumats are capable of earning more money than in the previous condition without mining. As Fig. 10 shows, this yields a higher financial budget for both types of consumats than in the previous experiment (Fig. 6). Continually deliberating, *H. economicus* succeeds in attaining a higher financial budget than *H. psychologicus*.

### 4.2.2. Homo psychologicus

*H. psychologicus* shows a transition from a fishing society to a mining society. In the first time-steps some consumats may have bad luck and harvest such a small number of fish that they become dissatisfied. Because this will cause them to engage in deliberation, they perceive mining as a satisfactory alternative opportunity. At about $t = 18$ more consumats become dissatisfied and start mining. The more consumats engage in mining, the larger the chances for uncertain consumats who are fishing and will also start mining on the basis of imitation or social comparison. At that moment the transition from a fishing society to a mining society becomes manifest. Occasionally a mining consumat may engage in fishing for a few time steps on the basis of imitation. However, this will usually lead to dissatisfaction within a few time-steps, and the consumat will go mining again. Nevertheless, due to imitation, in some simulation runs a few consumats always remain fishing. At the micro-level a lot of behavioural change occurs in the working behaviour of *H. psychologicus*. At the macro-level a decrease can be observed in the Gini index from 1 at the start to about 0.25 at $t = 20$. After the transition to a mining-society, the Gini index rises again to a level of about 0.8, indicating that income differences between consumats have decreased as a consequence of them all engaging in mining.

### 4.2.3. Homo economicus

The oscillating pattern demonstrated by *H. economicus* (cf. Fig. 7) is caused by the fact that all sixteen consumats change their behaviour at the same time. This repetitive switching between more mining/less fishing and more fishing/less mining may be explained by the fact that each consumat, being in the deliberation mode, has been formalised so as to expect that all others will behave as in the previous time-step. The consumat thus deliberates that when all others increase their time spent mining, increasing the time spent fishing may yield the highest outcomes, and vice-versa. However, all the consumats reason in this direction at the same moment, and as a consequence, they all end up doing about the same in the same time-step. Over time the extremes in these oscillations converge, indicating that in the long run a more stable working time distribution is likely to emerge. Because all the consumats behave more or less the same, the Gini index remains at a level of about 0.99, indicating that the incomes of the consumats are almost equal.

## 4.3. Introducing diversity in consumats' abilities

In the previous experimental conditions all consumats in both consumat-type conditions had equal abilities regarding fishing (6600 fish units

Table 1
The design of 16 consumats with different fishing and mining abilities

| | | Mining ability | | | |
|---|---|---|---|---|---|
| | | 67 | 89 | 11 | 133 |
| Fishing ability | 4400 | Consumat 1 | Consumat 2 | Consumat 3 | Consumat 4 |
| | 5867 | Consumat 5 | Consumat 6 | Consumat 7 | Consumat 8 |
| | 7333 | Consumat 9 | Consumat 10 | Consumat 11 | Consumat 12 |
| | 8800 | Consumat 13 | Consumat 14 | Consumat 15 | Consumat 16 |

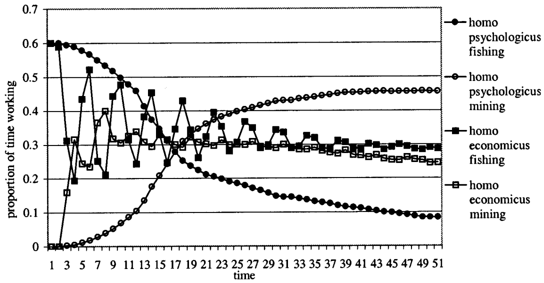


Fig. 11. Time spent fishing and mining for the two-consumat type conditions with consumats having unequal abilities.

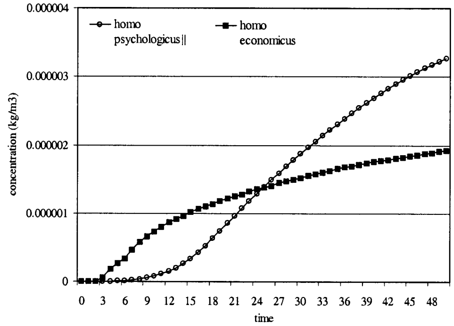


Fig. 13. The pollution concentration for the two consumat-type conditions for $t = 1$ to $t = 50$.

per time-step) and mining (100 units of gold per time-step). However, in real life a differentiation in abilities can easily be observed. The multi-agent approach makes it very easy to formalise consumats having different abilities. The central question is how such a differentiation affects the behaviour of the consumats and the ecological–economic system as a whole. To formalise this, the consumats are equipped with differing fishing and mining abilities. Four different levels of fishing ability and four different levels of mining ability make $4*4 = 16$ different ability settings, thus equipping each consumat with a unique set of abilities. As settings, the average is rather arbitrarily chosen to be equal to the previous experimental conditions, the consumats with the highest ability having twice as much ability as the consumat with the lowest ability. Table 1 shows the design with respect to the allocation of the two abilities to the sixteen consumats.

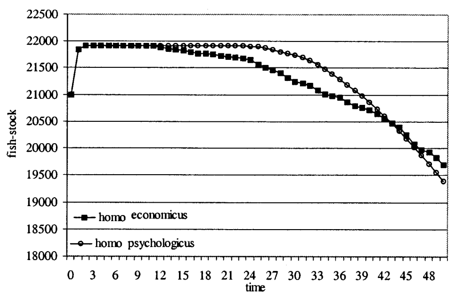


Fig. 12. The fish stock for the two consumat-type conditions for $t = 1$ to $t = 50$.

As in the previous experiments, the average mining ability is 100 gold units/time-step and the average fishing ability is 6600 fish-units/time-step. The consumats will socially compare to or imitate only the behaviour of approximately similar other consumats. If consumats are engaging in social processing, they compare themselves with consumats having about the same quantity of food and money. Regarding food, the consumat considers other consumats having 30% more or less food as similar to themselves. Regarding money, this percentage is set at 20%. Formalising similarity on the basis of changing variables implies that the group of consumats with whom a consumat compares may change continually, depending on its own state and the state of other 'similar' consumats. Again, two consumat-type conditions are created to contrast *H. economicus* and *H. psychologicus*.

### 4.3.1. Results

The results of this experiment are depicted in Fig. 11. These results look very similar to those of the previous experiment (Fig. 7). However, closer observation shows that in the case of *H. psychologicus* the transition from a fishing to a mining society takes more time, starting earlier and ending with the consumats spending more time fishing than in the previous experiment with equal abilities. This quicker start of the transition is caused by the consumats with a low fishing ability and a high mining ability, which will be quickly dissatisfied because of their low fish catch, and then perceive mining as a more attractive opportunity. In contrast, the consumats with a high fishing ability and a low mining ability are more likely to continue fishing, causing that at $t=50$ the time spent fishing is about twice as large as in the previous experiment. As a consequence, the average fish harvest of a population of consumats having unequal abilities is larger than the harvest of a population of equal consumats. In other words, harvesting behaviour is differentiated depending on variation among abilities.

Looking at the consequences for the fish stock (Fig. 12), it can be observed that in the beginning the fish stock depletes more rapidly in the condition of *H. economicus* (see further below).

However, despite the fact that *H. psychologicus* spends less time fishing, after time-step 43 the fish stock depletes more than in the case of *H. economicus*. This is caused by the fact that the intensive mining by *H. psychologicus* pollutes the lake, which causes the fish stock to further decrease.

Due to the pollution of the lake (Fig. 13), the fish population decreases, and also the average catch decreases. This will make mining a relatively more attractive opportunity, and it may thus stimulate consumats to go mining. Even when the pollution causes the fish stock to collapse, consumats can satisfy their needs by importing fish. It can easily be imagined that in such a case the eventual depletion of the gold mine will leave the consumats with no opportunity at all to satisfy their needs.

Looking at *H. economicus*, two major differences with the equal abilities experiment (Fig. 7) can be seen. First, the oscillating pattern dissipates more quickly in the unequal abilities experiment (Fig. 11). This is due to the fact that the

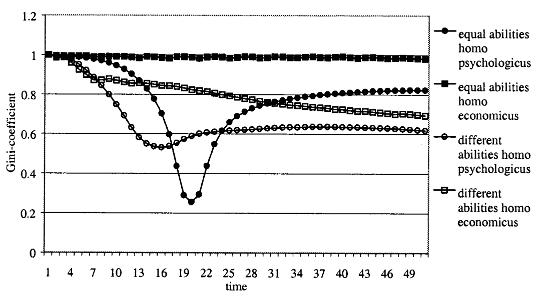


Fig. 14. The Gini coefficient for equal and unequal abilities.

consumats do not behave equally because they all have different abilities. The resulting behavioural diversity means that each consumat has less extreme expectations regarding the average time spent working of the other consumats. This in its turn causes the consumats to behave less extremely for themselves. As a consequence, the oscillations in time spent working converge, thereby further stabilising the expectations, and hence the time spent working. The second difference with the equal abilities experiment is that the times spent fishing and mining are lower. Due to this effect the fish stock is depleted less severely at time-step 50 than in the condition with equal abilities. The explanation for this is that consumats with a high ability do not want to harvest as much as they are capable of, and the consumats with a low ability are not capable of harvesting as much as they want.

In contrast with *H. psychologicus*, for *H. economicus* the average harvest of a population of consumats having equal abilities is larger than the harvest of a population of unequal consumats. These results demonstrate that an increase in the diversity of consumat abilities may have different effects on the sustainability of a system, depending on the behavioural processing the consumats engage in. Apparently the effects of increasing diversity are not unidirectional, which emphasises the need for more research to investigate the role of diversity in resource management situations.

The introduction of diversity has an impact on the equality of the income of consumats. In Fig. 14 the Gini index is presented for *H. economicus* and the *H. psychologicus*, both for equal abilities and for unequal abilities. It comes as no surprise that adding variance in the consumat abilities causes the Gini index in general to be lower than in the no-variance condition. Logically, more variance in ability results in more variance in income. Moreover, it can be observed that *H. psychologicus* generally displays a lower Gini index than *H. economicus*, indicating that non-outcome-optimising behavioural processing strategies contribute to diversity in behaviour and in resulting income.

For *H. psychologicus* with equal abilities the relatively quick transition from fishing to mining

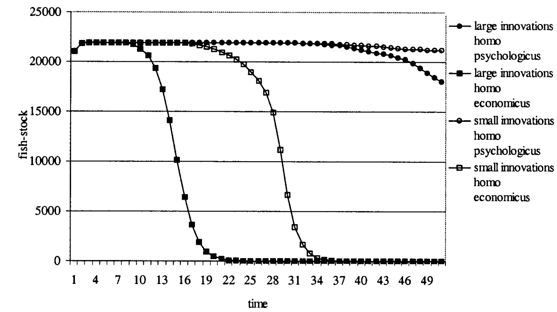


Fig. 15. The fish stock under conditions of small and large technological innovations.

causes a relatively short period where the one consumat is fishing, whereas the other consumat switches to mining. This yields large income differences concentrated in a short period of time, which is being reflected in the sharp drop in the Gini index around time-step 20. In the condition of *h. psychologicus* with unequal abilities, the diversity in income is larger on the average, as can be seen from Fig. 14. However, because the transition is not as complete as in the equal-abilities condition, and less compressed in time, there will be no short period of time where the diversity of income is being concentrated. Apparently, a faster transition leads to larger income differences among consumats.

### 4.4. Introducing learning and technological innovation

The following experiment introduces technological innovation and learning by consumats to increase their harvest of fish. Here, mining is not allowed, making the consumats again fully dependent on the fish stock for the satisfaction of their subsistence, identity and freedom needs. It is assumed that technological innovations only emerge when a consumat is deliberating. During deliberation there is a random chance that the consumat detects a new fishing opportunity that yields more fish per hour fishing. This is being formalised as an increase in fishing ability. This increase in fishing ability resembles a technical innovation, e.g., engines with more power or better fishing nets. Once a consumat adopts a new technology, the other consumats can also adopt the new technology. The technology level increases slowly towards the highest available technology level among the consumats. In this condition all consumats start with equal abilities. Regarding fishing, they start with an ability to catch 6600 fish-units per capita. Two types of innovations have been experimentally tested, namely, small technological innovations, implying an increase of 100 fish-units in fish catch per capita, and large technological innovations, implying an increase of 200 fish-units in fish catch per capita. Again two consumat-type conditions are created to contrast *H. economicus* and *H. psychologicus*.

#### 4.4.1. Results

Fig. 15 shows the development of the fish stock for *H. psychologicus* and *H. economicus* given the two types of innovation.

In case of the *H. psychologicus*, it can be observed that the fish stock starts decreasing relatively late. This is due to the fact that the consumats (easily satisfied) do not engage in deliberation that often, and consequently have a smaller chance of detecting an innovation. As a consequence, they remain unaware of the innovation, causing that the dissipation of the innovation through the population of consumats proceeds at a slower rate. In the case of *H. economicus* and large technological innovations, in the fish stock collapses very fast because of the fast dissipation of new technology. If a single consumat discovers a new innovation, the next time-step all other consumats will also be aware of this innovation. In the case of small technological innovations, the collapse occurs somewhat later.

These experiments indicate that technical innovation that increases the productivity by which resources are exploited may significantly affect the depletion rate of a resource. It also suggests that the rate at which this happens is strongly tied to the social conditions under which innovations may be diffused.

## 5. Conclusions

In mainstream economies, the behaviour of man in relation to renewable resources is traditionally formalised following the 'rational actor' approach. In this approach, usually large aggregates of people are represented by a single, rational actor with perfect foresight and a single, individual set of preferences. In this paper we introduce the consumat approach as an alternative approach, which differs on two aspects from the rational actor approach. First, instead of using a single type of decision making, deliberation, as in the rational actor approach, the consumat approach comprises four cognitive processes, namely *deliberation*, *social comparison*, *repetition* and *imitation*. Second, because the formalisation of social processes necessitates the modelling of several interacting agents, a *multi agent* simulation approach is being used instead of using a single 'meta-actor'.

Using the consumat approach, we are capable of studying the interactions between a multitude of agents and their environment. For example, in this paper we demonstrated that the formalisation of the four cognitive processes in the *homo psychologicus* yields a very different transition from a fishing society to a mining society than in case of the *homo economicus*, which could engage in deliberation only. Moreover, these different transitions have consequences for the population of fish in the lake due to overharvesting and/or pollution. The multi-agent structure of the consumat approach also allows for studying the effects of diversity amongst agents (e.g., abilities) on their interactions with the environment.

Also, the multi-agent structure allows for the calculation of quasi macro-variables such as income distribution. This provides an interesting heuristic to explore hypotheses between (in)equality and (economic) growth. In successive experiments it would be of interest to follow the recommendation by Kumar et al. (1996) of studying the volume of poor people, the severity of the poverty and the distribution of poverty in combination. This would draw a more profound perspective on distributional equity and the behavioural dynamics affecting it. Moreover, it would be interesting to equip the consumats with cultural perspectives (e.g., Thompson et al. 1990; Janssen and De Vries, 1998) or basic orientors (Bossel, 1996; Krebs and Bossel, 1997) and explore how these co-determine the dynamics of ecological–economic systems.

For further application in ecological economic models, we suggest that the consumat approach can be used as a tool box, providing the modeller with heuristics for introducing relatively simple behavioural dynamics into integrated models. In this way, the consumat approach can be used to simulate social processes and habitual behaviour, next to deliberate behaviour, in order to unravel the behavioural dynamics underlying consumption of common properties and to design suitable management strategies for our common good.

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