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Consumats in a commons dilemma

Testing the behavioural rules of simulated consumers

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Contents

Abstract

In this paper we report on a series of computer simulation experiments on the management of a common resource. We were particularly interested in the effects of uncertainty and satisfaction on the harvesting behaviour of simulated agents. Because the experimental study of the long-term dynamics of resources that are being depleted to a serious extend can hardly be done using real human subjects, we experimented with simulated consumers. These simulated consumers, or ‘consumats’, have been developed using a multi-theoretical framework integrating various theories that appear to be relevant in understanding consumer behaviour. The consumat is equipped with needs and abilities, and may engage in different cognitive processes, such as deliberating, social comparison, imitation, and repeating previous behaviour. In a first series of experiments we tested these cognitive processes on their functioning. In a later series we experimented with the consumat attributes and the resource characteristics. It was found that an increased uncertainty resulted in an increased ‘optimism’ of consumats regarding future outcomes, an increased likelihood of imitative behaviour, and a lesser adaptation during resource depletion. These ‘process-effects’ caused higher uncertainty resulting in higher levels of harvesting, an effect that has been demonstrated previously in experiments with real human subjects. The paper concludes with a discussion on the ecological validity of the simulation results.

1: Introduction

Many environmental issues bear a commons dilemma character: the behaviour that is in the individuals' interest is not favourable from the group perspective, and vice versa. For example, it is in the interest of the individual fisherman to harvest a lot of fish. However, all the fishermen together should moderate their harvesting in order to preserve the fish-stock and guarantee future harvesting. This conflict between individual and collective interests has intrigued scientists since Machiavelli (1525), who addressed this issue in the context of the political consequences of social (in)equality. More recently, Luce and Raiffa's *Games and Decisions* (1957) awakened a fascination for this conflict in many social scientists. Hardin's (1968) article on the commons dilemma describes how this conflict affects the management of collective resources, explaining why people often tend to overexploit them. The commons dilemma paradigm proved fruitful to describe a variety of situations where individual and collective interests collide, such as ocean fishing, tax paying, waste dumping end forest management.

In the field of psychology, a vast amount of experiments have been performed on choice behaviour in commons dilemmas. Many factors have been found to determine the harvesting behaviour (or consumption) of actors in a resource dilemma. Experiments are of limited use however, because they don't allow the study of significant changes in people's lives, under the long time periods (often decades) that are often involved in environmental problems. Therefore, computer simulations are being used to study the long-term dynamics of resource dilemmas.

In most computer simulations of commons dilemmas, consumers are usually operationalised following a rational actor principle. The rational actor is here assumed to be an individual with fixed preferences over the consumption and production of goods and services. This actor deliberates on the potential contribution of consumption to personal well being, where well being depends on the degree to which actor's preferences are satisfied. As the rational actor has no endogenous preferences, it does not consider the behaviour and opinions of other actors. However, people do not always behave according to the rational actor principles. Often people perform habitual behaviour, or they imitate the behaviour of other people. In this paper we present a conceptual, multi-theoretical model of behaviour that guided the development of a set of behaviour rules for a simulated consumer. The rules of these simulated consumers are tested in a series of simulation experiments with a collective resource. In the following section, we will first discuss the commons dilemma. Following this, section 3 is devoted to existing simulation models within the commons dilemma paradigm. In section 4 we will outline the conceptual multi-theoretical model of behaviour. Section 5 will present the operationalisation of the model as well as a series of simulation experiments performed with this model. General conclusions and suggestions for further research are discussed in section 6.

2: The commons dilemma

Applied to environmental problems, the commons dilemma addresses the behavioural mechanisms of environmental overexploitation. In a commons dilemma a collective opportunity, or resource, exists from which all individuals may consume. If this collective opportunity has a certain growth capacity, we may conceive it as a renewable resource. If such a resource, e.g., clean fresh water, fish, pasture land or natural forest, is being consumed at a rate that overshoots its natural growing rate, the availability of the resource will decrease. If consumption remains at a high level, the resource may even vanish. A certain limitation to the consumption of the resource is required to preserve it for a longer time, allowing its consumption to be sustainable. Hardin (1968) made the commons dilemma a well-known concept in his classical text in *Science*. In this article Hardin presented the story of the decline of common pastures for herding cattle.

Many experiments have been performed in the laboratory to determine which factors affect the harvesting behaviour of individuals. In the resource dilemma paradigm, inspired by the *Science* article of Hardin (1968), 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 tradition were Jerdee & Rosen (1974), Rubinstein, Watzke, Doktor & Dana (1975) and Brechner (1977). Group factors, personal factors and resource characteristics have been experimentally found to affect harvesting behaviour in a resource dilemma. Group factors influencing behaviour in a dilemma are e.g. group size (e.g, Fox & Guyer, 1977), the pay-off structure of the dilemma (e.g., Kelley & Grzelak, 1972), communication (e.g., Dawes, McTavish & Shaklee, 1977), identifiability of the behaviour (e.g., Jorgerson & Papciak, 1981), group identity (e.g., Brewer, 1979; Edney, 1980). Personal factors that have been found to affect harvesting behaviour are the belief that personal restraint is essential to maintain the resource (e.g., Jorgerson & Papciack, 1981; Samuelson, Messick, Rutte & Wilke, 1984), uncertainty regarding the behaviour of others, also denoted as social uncertainty (Messick, Allison & Samuelson, 1988), the expectations regarding the behaviour of other persons (e.g., Dawes *et al.*, 1977), their trust in other people (Yamagishi, 1988), the social value orientation of a person (Messick & McClintock, 1968; McClintock, 1978), personality factors such as extraversion and agreeableness (Koole, Jager Van den Berg, Vlek & Hofstee, 1998), personal responsibility (e.g., Latané and Darley, 1968), and the perception of a dilemma as a moral issue (Van Lange, Liebrand & Kuhlman, 1990). Besides the growing capacity of the resource, which of course is an essential characteristic, also the uncertainty regarding resource size and growth, also denoted as environmental uncertainty, plays a role (Wit & Wilke, 1998; Hine & Gifford, 1996; Suleiman & Rapoport, 1989; Messick, Allison & Samuelson, 1988).

Factors that have been found to contribute to defective behaviour are a large group size, a high pay-off for defective behaviour, social uncertainty, environmental uncertainty, an individualistic or competitive social value orientation, extraversion and a low personal responsibility. Cooperative behaviour is being stimulated by communication, the identifiability of personal behaviour, a strong group identity, belief that personal restraint is essential, trust in other people, a cooperative social value orientation, agreeableness, high personal responsibility and the perception of a dilemma as a moral issue.

The above-mentioned experiments represent only a small part of the large number of studies that have been conducted about commons dilemma problems. This experimental paradigm has taught us a lot about the factors that influence human behaviour in such situations. However, the laboratory setting of this research differs significantly from real world situations. A first difference deals with the time scale of the dilemma. Whereas experimental games in a laboratory setting seldom exceed a time limit of one hour, in the real world negative collective outcomes (e.g. extinction of a resource) may occur only after several years, decades, or even generations. A second difference is that in comparison to experimental games, real-life dilemmas confront people with choices that involve important outcomes. For example, a fisherman's catch determines his income. Moreover, these outcomes are multidimensional in the sense that the satisfaction of several needs may be involved. For the fisherman his catch determines if he can support his family, his status in relation to other fishermen and the leisure time he has available.

Whereas the choices that people make while playing an experimental game usually have no far-reaching consequences for their lives, in real-life dilemmas the choices one makes may determine one's quality of life to a great 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 experimental variations during relatively short time periods. Observational data usually do not allow for drawing causal inferences because the complex relations between them are not well known.

Computer simulation offers the possibility to experiment with more extreme conditions and with long time-series, provided that the simulations are based on a valid conceptual model of the relevant phenomena. 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 another technique 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. In the following section a short overview is presented regarding the use of computer simulations in research about commons dilemmas.

3: Experimenting with simulated commons dilemmas

Several simulations have been developed that capture the dynamics of some existing common resource. Because a fish-stock is easy to understand as a renewable resource, several researchers have made use of "fishing games" to study the harvesting behaviour of real people (e.g, Spada, Opwis, Donnen, Schwiersch & Ernst, 1987; Meadows, 1989; Gifford & Wells, 1991; Mosler, 1993; Summers, 1996; Hine & Gifford, 1996. Experiments in this tradition have contributed significantly to the understanding of how people manage a renewable resource and what individual and group factors affect their decisions about harvesting behaviour, for example the effects of uncertainty regarding the resource size. However, studying how actor decision strategies perform against each other under various experimental conditions is not possible because real people usually show (unexplained) variance in their strategies. The definition of strict strategies formed the first step in defining artificial agents playing games. This definition of rules for artificial agents got an impulse by the computer tournament arranged by Axelrod (1980a; 1980b; 1984). In this tournament, various rules/strategies were tested in an iterated game that reflected the classical Prisoner's dilemma. 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 (TfT). Two TfT automata will quickly arrive at stable cooperating behaviour. However, if one of the automata makes a mistake (operationalised as 'noise'), this stable cooperation disappears.

Since then, many developments have taken place with respect to multi-agent simulation of commons dilemmas. Some of these developments were aimed at finding better decision strategies. Within this context evolutionary strategies have been developed which involve adaptation to the behaviour of other agents in the game (e.g., Axelrod, 1987; Macy, 1996). Other developments were aimed at developing decision strategies that reflected actual human decision-making. Many of these approaches are based on a rational-actor approach, that is, the agents are trying to optimise their personal outcomes (e.g., Bousquet, Cambier, Mullon, Morand and Quensiere, 1994; Grant & Thompson, 1997). However, people do not always optimise their behaviour. Ernst (1998) therefore developed an artificial agent that is based upon psychological theory. Briefly, following Ernst, these artificial agents have ecological knowledge (on the resource), social knowledge (on others' ecological knowledge, intentions and motives) and action knowledge (schemata that allow to react in a flexible manner to the behaviour of others whilst preserving the strategically defined goal). The essential difference with a rational-actor approach is that Ernst's agents were equipped with three prototypical motives: (1) an orientation towards maximising individual gain, (2) maximising the resource level, and (3) minimising the outcome-differences between participants.

Such artificial agents have been tested in the Fishing Conflict Game (Spada, Opwis, Donnen, Schwiersch & Ernst, 1987). This game comprises a simple aquatic ecosystem, in which participants have to decide on how much fish to harvest. The results show that the behaviour of the artificial agents was comparable to the behaviour of human subjects playing the Fishing Conflict Game. Moreover, people could play the game with the artificial agents without being able to identify them as computer-simulated agents. These agents thus performed behaviour that went beyond the rational/optimal resource management strategies that have been used in many other simulation studies. Because Ernst concentrates on attitude theory, cognitive processes that refer to social comparison and processes of habit formation are not included in his simulations. The simulated agents predict the behaviour of the other agents without directly interacting with them. However, social comparison processes and habitual behaviours seem to be very relevant in understanding how renewable resources are being managed.

Many theories are available to guide the development of agent rules, e.g., theories on human needs, motivational processes, social comparison theory and conditioning theory. Regarding human behaviour, not all theories are relevant at the same moment in time. To use these theories for the development of agent rules this implies that it should be defined under what conditions, which theory-based rule will guide the agent's behaviour. To take account of essential behaviour determinants and mechanisms, a conceptual model for consumer behaviour has been developed that integrates relevant theories on behaviour. This conceptual model is being used to develop a comprehensive set of theory-based agent rules. In the next section we will sketch the conceptual model and clarify the rules that make up the operational computer model of consumer behaviour, to be discussed later on.

4: A conceptual model of individual consumer behaviour

To a greater or lesser extent many behaviour theories are relevant for understanding human consumption. Examples are, e.g., theories about human needs (e.g., Maslow, 1954; Max-Neef, 1992), motivational processes (Ölander & Thøgerson, 1994), social comparison theory (Festinger, 1954; Masters & Smith, 1987), classical and operant conditioning theory (Pavlov, 1927; Skinner, 1953), social learning theory (Bandura, 1977; 1986), decision and choice theory (Janis & Mann, 1977; Hogarth, 1987), theory of reasoned action (Fishbein & Ajzen, 1975; Ajzen, 1985; 1988; 1991; Ajzen & Madden, 1985), theories on relative deprivation (Masters & Smith, 1987) and the theory of normative conduct (Cialdini *et al.*, 1991). These various behavioural theories all explain parts of the processes that determine consumer behaviour. For example, theories on human needs may explain the preferences a consumer has, whilst theories on social comparison and learning explain how consumptive behaviours can proliferate through a population.

A conceptual model of consumer behaviour has been developed as an organising framework that allows for a process description of consumer behaviour (Jager *et al.*, 1997). This conceptual model, as presented in Figure 1, combines the above-mentioned theories in a system-dynamical framework (e.g., Forrester, 1968).

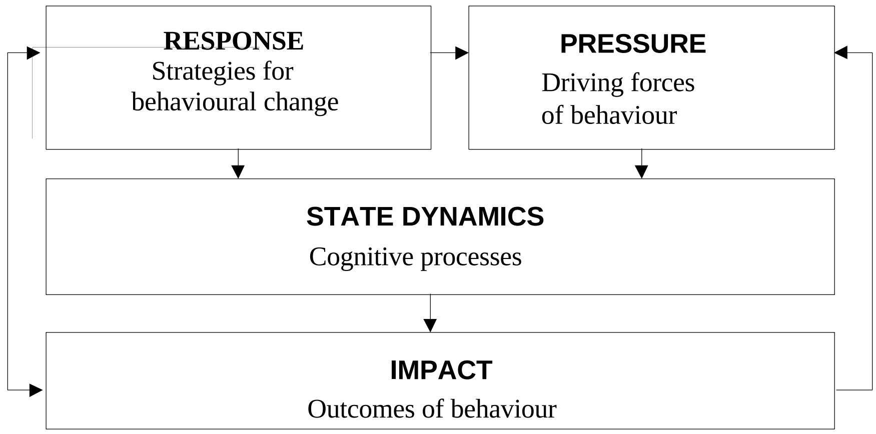

Figure 1: The structure of the conceptual model of consumer behaviour

Four systems can be distinguished in the conceptual model of Figure 1. First, a Pressure system is describing the driving forces of behaviour. Second, a State system is describing the underlying cognitive processes. Third, an Impact system describes the various outcomes of behaviour, and fourth, a Response system is aimed at the description of strategies for behavioural change. In the following the four systems will be outlined shortly. A more elaborate description of the subsystems may be found in Jager *et al.* (1997).

The Pressure system

The Pressure system describes the driving forces behind consumer behaviour. A distinction can be made between variables at the collective level (macro) and at the level of the individual consumer (micro). The collective level refers to technical, economical, demographic, institutional and cultural developments (Opschoor, 1989; Stern, 1992; Vlek, 1995). These collective-level-pressures affect the individual-level-pressures, e.g., economic developments affect the price of an opportunity. The individual level addresses the needs of the consumer, the opportunities that may be consumed, the abilities the consumer has to engage in consuming and the uncertainty of the consumer regarding the outcomes of behaviour. Regarding the needs of the consumer, along with Max-Neef (1992) we distinguish among nine fundamental needs: subsistence, protection, affection, understanding, participation, leisure, creation, identity and freedom. The individual-level-pressures result in consumers being more or less motivated to elaborate on their opportunity consumption and to be more or less certain about the opportunity characteristics, e.g. the availability of an opportunity. Moreover, the pressure variables determine the consumers' preference for and feasibility of the available opportunities.

The State system

The State system comprises the cognitive processes the consumer may engage in. Two theoretical dimensions regarding cognitive processing are acknowledged. The first dimension is about the degree of cognitive effort associated with the process. Reasoned behaviour is associated with a high motivation to elaborate upon consumption, whereas automatic processing goes along with a low motivation to elaborate. When a consumer is dissatisfied, he/she will be motivated to elaborate on alternative opportunities for consumption. A satisfied consumer will not be motivated to elaborate about alternative opportunities for consumption, because the current opportunities appear to be satisfying.

The second dimension concerns the social versus the individual orientation of the cognitive process. Individual processing is dominating when one feels certain about the consequences of consumption, when the behaviour is private and the needs involved are more individually relevant. Social processing is more likely when one is uncertain about the consequences of behaviour, when the behaviour is public visible and the needs in question are more socially relevant. Social processing usually involves comparison processes with other people who are about similar with respect to abilities and opinions.

The two distinct dimensions of cognitive processes yield a fourfold perspective on prevalent behavioural theories. First, reasoned individual processing, which we will call *deliberating*, is addressed by decision and choice theory (Janis & Mann, 1977; Hogarth, 1987) and the theory of reasoned action (Fishbein & Ajzen, 1975; Ajzen, 1985; 1988; 1991; Ajzen & Madden, 1985). Reasoned social processing, which we will call *social comparison*, is the topic of social comparison theory (Festinger, 1954; Masters & Smith, 1987), relative deprivation theory (Masters & Smith, 1987) and theory of reasoned action (social norms). Automatic individual processing, which we will call *repeating*, is the subject of classical and operant conditioning theory (Pavlov, 1927; Skinner, 1953). Automatic social processing, which we call *imitation*, is addressed by social learning theory (Bandura, 1977; 1986) and the theory of normative conduct (Cialdini *et al.*, 1991). In the following Figure 2 the four cognitive strategies are positioned on the two axes.

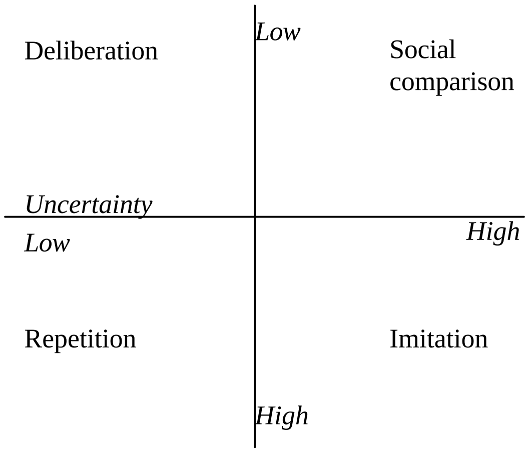

Figure 2: The four cognitive strategies positioned on the two axes

A person engaging in cognitive processing must have an awareness of the own abilities, the opportunities to choose from and the behaviour similar others have performed in the past. This information is being memorised in what we call a 'mental-map'. Besides retrieving information from this mental-map, people also update this mental-map on the basis of their experiences. Especially when people are engaging in reasoned processing (deliberation or social comparison), they are likely to memorise the information they reasoned on in their mental map.

The Impact system

The Impact system describes the outcomes resulting from performing a given consumption behaviour at the individual and the collective level of consumption. At the individual level, the outcomes refer to the consumats level of need satisfaction, changes in abilities and perception of opportunities. At the collective level, changes affect all consumats, as in the case of scarcity of opportunities.

The Response system

The Response system comprises the policy strategies aimed at behavioural changes. Two main interest parties that spend a lot of effort in changing (or consolidating) consumptive behaviours are the government and the suppliers/producers of opportunities. However, also various consumer organisations, special interest groups, churches and the like may spend efforts in trying to change consumer behaviour. If an interest party is not satisfied with certain impacts of consumer behaviour, they may react by altering pressure variables. For example, if a producer wants the consumers to consume more of a certain opportunity, he may make this opportunity cheaper or increase its need satisfying capacity. In view of Sheth & Frazier (1982), Cook & Berrenberg (1981), De Young (1993) and Vlek & Michon (1992) we distinguish five types of general strategies for behavioural change: (1) providing physical alternatives and arrangements, (2) lawful regulation and enforcement, (3) financial-economic stimulation, (4) social and cognitive stimulation, and (5) changing values and morality. Changes in pressures may affect the behavioural process consumers engage in, and thus may affect the behaviour of consumers and the resulting impacts.

A conceptual model of consumer behaviour

The relations between the concepts and variables that have been discussed in the Pressure system, the State system, the Impact system and the Response system respectively are graphically depicted in the following Figure 3.

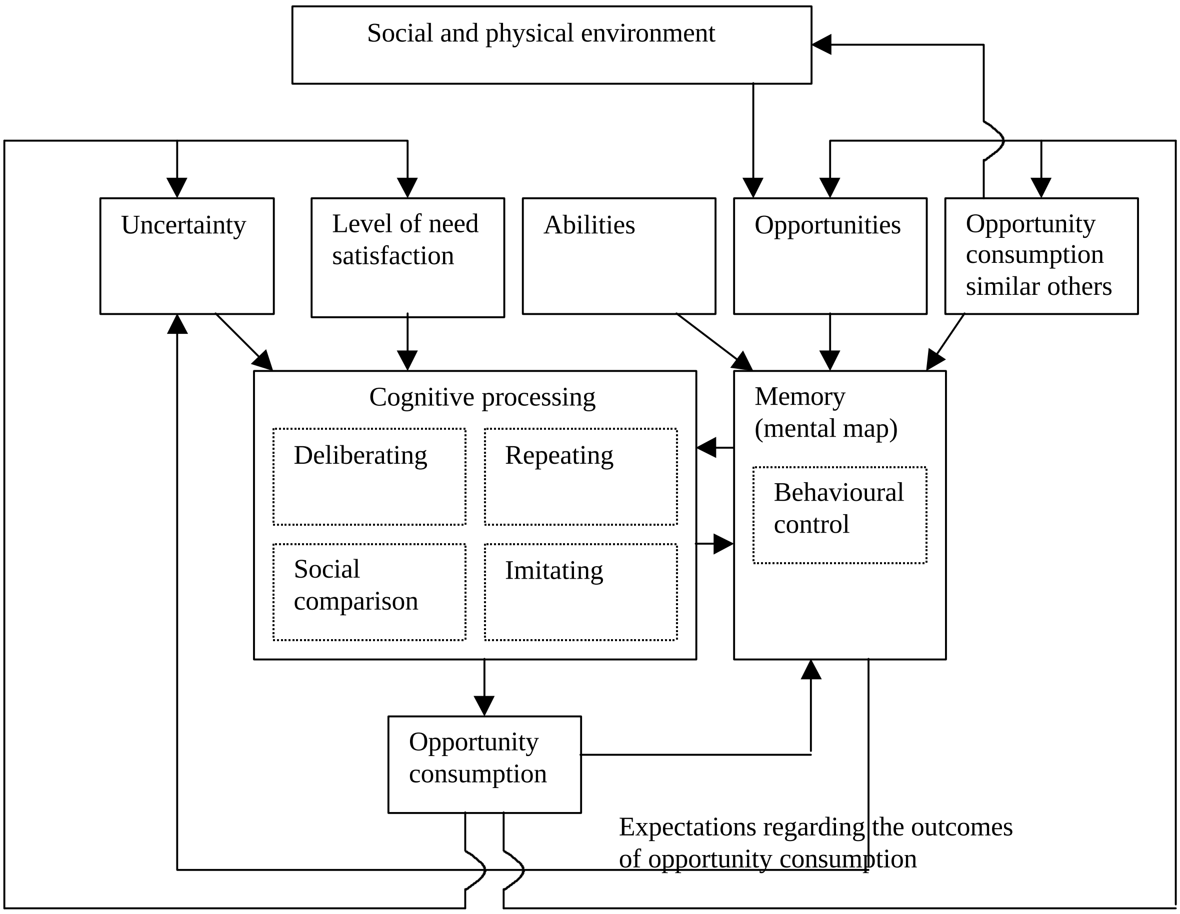

Figure 3: The conceptual model of consumer behaviour

Whereas a conceptual model is a very useful tool for diagnosing consumer behaviour in the real world, it is not an operational model that allows for experimentation with behavioural dynamics. The translation of the conceptual model into an operational model requires an appropriate modelling methodology. Because we are interested in the dynamical processes that follow from the interaction between consumers, we propose to model more than one consumer, thereby using a ‘multi-agent’ modelling approach. Placing the simulated consumers in a simple environment where they are depending on a common resource, offers us a framework to experiment with the social dynamics governing the social dilemma.

5: The multi agent modelling approach

Multi-agent modelling makes use of various methodological tools, such as neural networks, cellular automata, fuzzy logic, genetic algorithms, cybernetics, artificial intelligence, sets of non-linear differential equations (chaos and catastrophe theories). For those interested to learn more about multi-agent modelling techniques we refer to Langton (1989; 1995), Holland (1975; 1992a; 1992b; 1995), Goldberg (1989), Rietman (1994), Sigmund (1993) and Janssen (1998). Our approach seems to fit within the study of Artificial Intelligence (AI), wherein the autonomous-agents research or behaviour-based AI currently is popular. In this field the behaviour of adaptive autonomous agents is studied in the physical world (robots) or in cyberspace (software agents). This field in AI is highly inspired by biology. The phenomena of interest are those traditionally covered by ethnology and ecology (in the case of animals) or psychology and sociology (in the case of humans). The agents often comprise sensors to derive information from the environment and intelligent functions such as perception, planning, learning, et cetera. The behaviour of a system is defined as a set of regularities observed in the interaction dynamics between characteristics and processes of the system itself and the characteristics and processes of the environment it operates in.

Distributed AI is a relatively recent development of artificial intelligence studies (Bond and Gasser, 1988). It concerns the properties of sets of intercommunicating agents coexisting in a common environment. The researchers aim may be to study the properties of such systems in an abstract way, or to design systems of immediate practical use, or to use such a programmed multi-agents system as a model of a human or other real-world system.

In our simulation model we operationalise one or more interacting agents, which we call 'consumats', analogous to the term 'animats' that Wilson (1985) coined to notify simulated animals. These consumats can consume 'virtual opportunities'. Because the consumats interact directly (e.g., by imitation) and indirectly (e.g., under scarcity of opportunities), macro-phenomena may emerge from individual behaviours.

In defining the rules for an agent, a balance should be found between simplicity and realism. Simplicity is required to keep the behaviour of a group of consumats accessible for scientific research, whereas realism adds to the validity and relevance of simulation results. We chose to develop a set of simple rules that in combination represents a multitude of relevant behavioural processes. This allows the construction of a series of experiments, starting with a consumat with one behavioural rule as a baseline experiment. In succeeding experiments new behavioural rules will be introduced and tested against the baseline experiments. In the final experiments we will experiment with consumats equipped with the full set of behavioural rules. Following this structure, we believe to have found a balance between experimental accessibility, expressiveness and the representation of real life dynamics. In the following, we will operationalise the Pressure system, the State system, the Impact system and the Response system of our conceptual behavioural model, respectively. This operationalisation refers to the rules of a single consumat. In the simulation experiments more consumats applying the same rules will be operationalised.

6: Operationalising the consumat

In the previous sections we discussed the conceptual model of behaviour and the multi-agent modelling approach. In this section we will operationalise the rules of a single consumat. In later experiments, more consumats will be operationalised simultaneously in multi-agent simulation experiments. Following the conceptual model of consumer behaviour, we will operationalise the Pressure system, State system, Impact system and Response system respectively.

6.1: The Pressure system

The Pressure system comprises needs, opportunities and abilities. The associated levels of need satisfaction and uncertainty are affecting the cognitive processing in the state system.

The needs of the consumat

A consumat is equipped with several needs that may be more or less satisfied. Technically, the level of need satisfaction for need *i* (LNS_i) is represented by an index varying between 0 (fully dissatisfied) and 1 (fully satisfied). The level of LNS_i depends on the stock-level of need satisfyers. For example: a consumat may have a lack of food (low stock) and as a result experience hunger (low LNS for 'subsistence'). The relation between stock-level and LNS follows a *diminishing marginal utility* function. This function implies that the increase in LNS_i, given the input of an opportunity *x* with a certain need "*i*" satisfying capacity (NSC_i), depends on the actual stock-level of the need satisfier in question. The higher the stock, the lower the increase in LNS_i after consuming opportunity *x*. The overall level of need satisfaction ($LNS_{1..n}$) is represented by the importance-weighted average of the needs involved.

In the experiments presented in the current paper we equipped consumat *i* with two needs: (1) a need for subsistence (LNSs) and (2) a need for leisure (LNSl). Consuming from a resource R (which will be described next under opportunities) results in a certain quantity of individual consumption. The higher the individual consumption (CI_{it}) of consumat *i* at the current time-step *t*, the higher the need satisfaction for subsistence of consumat *i* at *t* ($LNSs_{it}$). The LNSs follows a diminishing marginal utility function, which implies that, the higher the LNSs, the less an additional unit of consumption contributes to the LNSs. Figure 4 shows the shape of such functions which determine the sensitivity of the consumats LNSs for consumption. This shape is determined by the factor α. A high α results in a quicker increase of LNSs as a function of individual consumption than a low α (e.g., 1-exp(-1) = 0.63 versus 1-exp (-2) = 0.86). Two consumats that consume equally may experience differences regarding their LNS because of different α's. The value of α thus resembles individual preferences as depicted in the shape of their diminishing marginal utility functions.

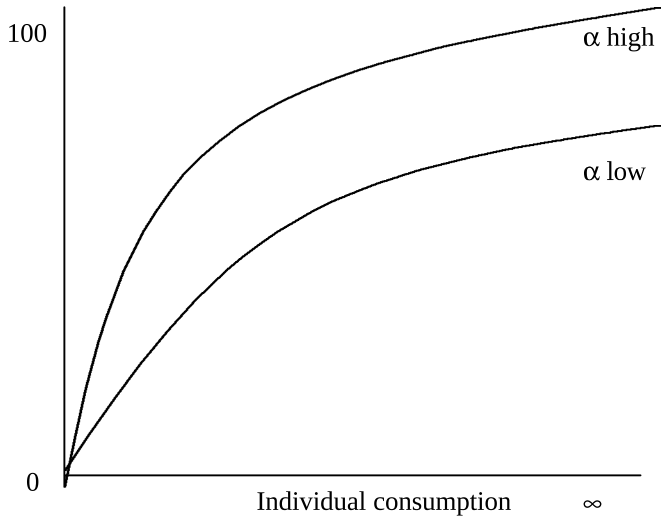

Figure 4: Sensitivity functions of LNS for different a's

The following formula 1 captures the level of need satisfaction for subsistence following from individual consumption and α.

(1) $LNSs_{it} = 1-\exp(-\alpha_{is} * CI_{it})$

The need for leisure is the second consumat need we operationalised in our experiments. The satisfaction of the need for leisure LNSl for consumat *i* at time-step *t* increases at a decreasing rate with the amount of time left over for leisure. The amount of time spent on working is denoted with x, ranging from 0 (0 hours of working) to 1 (24 hours of working). The time for leisure can be denoted as 1 – x. The value of α here indicates how sensitive the consumat's LNSl is for leisure-time. We use equal α's (α_s and α_l) for both needs involved, however, in future experiments we may introduce more complex weighting functions, allowing α's to differ between needs and consumats. Formula 2 captures the level of need satisfaction for leisure following from leisure time and α.

(2) $LNSl_{it} = 1- \exp(-\alpha_{il} * (1-x_{it}))$

The overall level of need satisfaction of consumat *i* at time-step *t* is a weighted multiplication of the satisfaction of the two needs. The value γ functions as weighting factor for consumat *i* regarding the relative importance of the different needs in the overall level of need satisfaction. Setting γ at a value of .5 results in equal weighting of both needs in the overall level of need satisfaction. Formula 3 captures the overall level of need satisfaction as a weighted multiplication of the level of need satisfaction for respectively subsistence and leisure.

(3) $LNS_{it} = LNSs_i^{\gamma i} * LNSl_i^{1-\gamma i}$

A critical value LNSmin is being used to determine whether a consumat is satisfied or not. LNSmin ranges from 0 (always satisfied) to 1 (never satisfied). The consumat is satisfied when its needs are satisfied above the minimum level as defined by LNSmin (i.e., when LNS_{it} > LNSmin). LNSmin can be defined for each consumat separately, allowing to operationalise consumats that differ regarding their critical satisfaction level. The satisfaction of the consumat plays an important role in determining the type of cognitive processing it engages in. If the consumat is satisfied, it will engage in automatic processing, whereas a dissatisfied consumat engages in reasoned processing.

Opportunities
The consumats can use opportunities in order to satisfy their needs (e.g., consuming food) or to increase their abilities (e.g., work for money). Opportunities have predefined resource demands (RD), e.g., the financial costs or the effort to harvest them. Depending on the abilities being addressed in the simulation, more or less resource demands are being defined for each opportunity. In many cases these resource demands take the form of *operational costs*, that is, they require the use of resources. The availability of opportunities may be limited, e.g. in the case of a common renewable resource, where scarcity may emerge.

In the experiments described in this paper we defined a renewable resource R that functions as the artificial environment of the consumat. Consuming from this resource provides means for subsistence. CT denotes the total consumption of all the consumats. The resource grows every time step with factor λ, which is stochastic. This stochastic part allows including variation in the growth rate of the resource, thereby simulating natural variability of the resource (e.g., fluctuating weather conditions) in a very simple manner. The following formula 4 captures the size of the resource at time-step t as the growth factor times the resource size in the previous time-step, minus the total consumption in the current time-step.

(4) $R_t = \lambda_t * R_{t-1} - CT_t$

λ_a refers to the non-stochastical part of the growth factor λ. On average λ is equal to λ_a. A random selection from the normal distribution N with a standard deviation σ is used to simulate this stochastic variability, as is depicted in formula 5.

(5) $\lambda_t = \lambda_a + N(0,\sigma)$

In case of deterministic experiments λ_t is equal to λ_a (σ is set at 0). We set λ_a at 110%, and consequently without consumption the resource grows exponentially with 10% at every time step. A consumption level that consistently exceeds this 10% growth will result in the gradual depletion of the resource.

To satisfy both needs, subsistence and leisure, the consumat has to decide on how much time it should spend consuming from the resource. This consuming from the resource can be understood as harvesting behaviour, which we shortly notify as ‘working’. The consumat is allowed to work for a maximum of 16 hours a day, thus having a minimum of 8 hours a day for leisure activity. This minimum has been set to refer to the minimal time that is needed for sleeping and eating. The consumat decides how much to work on the basis of units of one hour. Consequently, the following 17 opportunity distributions are available:

Opportunity Distributions	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Hours of work	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Hours of leisure	24	23	22	21	20	19	18	17	16	15	14	13	12	11	10	9	8

Table 1: The 17 opportunity distributions the consumats can choose from

The level of need satisfaction for subsistence depends on how much the consumat is able to consume during one hour of work. This is one of the abilities of the consumat, and will be discussed in the next section.

The abilities of the consumat

The consumat has two abilities, namely a cognitive ability a_{ci} and a physical ability a_{hi}. The consumats' cognitive ability refers to the time-horizon (TH) it employs when elaborating on the expected outcomes. When the consumat is motivated to elaborate ($LNS_{it} < LNSmin$), and engages in deliberating or social comparison, it will calculate the outcomes of behaviour. The longer the TH the consumat employs here the earlier it detects a possible depletion of the resource. This allows the consumat to restrain its current consumption in order to sustain a higher consumption level in the long run.

The physical ability refers to the quantity of consumption-units the consumat can harvest from the resource R during one hour of work, and is expressed with a value ranging from 0 (no ability) to 1 (maximum ability). A physical ability of 1 implies that the consumat is able to harvest $1/16^{th}$ (0.0625) consumption-units of the resource per hour. Working for the maximum number of 16 hours adds up to a harvest of exactly 1 consumption-unit. These figures hold for resources that are always equally accessible for harvesting, no matter how abundant or depleted the resource may be. It is also possible to make the resource less accessible for harvesting the more depleted it is, thereby simulating that the more depleted the resource, the less one can harvest in one hour. In the depletion factor we calculate the resource size in the previous time-step (R_{t-1}) divided by the initial resource size (R_{t0}). We use a factor π to define the accessibility of the resource as depending on the difference between the initial and previous resource-size (formula 6). Setting π at 0 results in $(R_{t-1}/R_{t0})^{-\pi}$ being equal to 1. In this case, the resource is always equally accessible for harvesting. The harvest depends on the time spend working times the ability to harvest, provided the resource is not depleted. Increasing π results in a lower harvest-per-hour the more depleted the resource is. The factor π thus allows for the specification of the depletion dynamics of a resource.

On the basis of the resource development and its abilities the consumat calculates an expectation regarding its consumption in the next time-step. This expected individual consumption $E[CI]_it$ is equal to the amount of time spent on harvesting, times the consumats ability to harvest a_{hi} and the depletion dynamics. These depletion dynamics involve the resource-size at the previous time-step divided by the initial resource size.

(6) $$E[CI]_{it} = x_{it} * a_{hi} (R_{t-1}/R_{t0})^{-\pi}$$

This expected individual consumption is being used for the calculation of uncertainty.

Uncertainty
We operationalised the uncertainty index U_{it} , indicating for consumat i to what extent the outcomes of the previous behaviour (at t – 1) in terms of $LNS_{1..n}$ differ from what it expected at time t. In the experiments discussed in this paper the uncertainty refers to the difference between the actual consumption and the expected consumption. In the present time-step (t) there has to be decided how much to consume. Therefore the actual consumption refers to the previous time step (t – 1). This actual consumption of t – 1 is being compared with the expected consumption, which has been constituted at t – 2. Differences may occur due to changes in the resource depletion, which causes differences in harvesting efficiency.

(7) $U_{it} = ABS(E[CI]_{it-1}-CI_{it-1})$

We operationalised an uncertainty tolerance UT as the critical value that is being used to indicate above which level of U the consumat engages in social processing. UT ranges from 0 (always uncertain) to 1 (never uncertain). Consumat *i* is considered to be uncertain and engage in social processing at time-step *t* when $U_{it} > UT$.

UT can be defined for each consumat separately, thus allowing to operationalise consumats with different uncertainty tolerances. In our experiments all the consumats in a single simulation run will have identical UT's.

6.2: The State system

In the State system we operationalise the cognitive processes of the consumat, as well as the mental map that is being used.

The mental map
To operationalise cognitive processes, we first have to equip the consumat with a mental map that allows the memorising of experiences. First, the mental map memorises information on the consumats previous behaviours. This implies that the need-satisfying capacities and ability changing properties of opportunities are memorised. In the mental map is also memorised which other consumats serve as comparison-consumats, as well as the behaviour these consumats performed in the previous time step (t-1). Finally, the mental map contains the perception of the consumats' own abilities, e.g., what its financial budget is at a particular moment and how much money can be earned by a certain type of work. During the different cognitive processes the mental map may be the subject of information retrieval and updating. Four cognitive processes are being operationalised in the consumat, respectively deliberation, social comparison, repeating and imitation. The minimal level of need satisfaction (LNSmin) and uncertainty tolerance (UT) are the key variables that determine which of these cognitive strategies is being employed

Deliberation
Deliberation stands for reasoned individual processing, and relates to decision and choice theory and theory of reasoned action. Consumats engage in deliberation if the level of need satisfaction does not reach a minimum level ($LNS_{it} < LNSmin$), and uncertainty is not too high ($U_{it} < UT$). Deliberating starts with updating the mental map. This updating implies that information is gathered regarding the need satisfying capacities of the opportunities, the resource demands of the opportunities and the own abilities. This information is being used to calculate the behavioural control (BC) over the possible opportunities, and the expected outcomes in terms of

LNS of consuming possible opportunities. In calculating the expected outcomes the consumat uses a certain time-horizon (TH), which notifies its cognitive ability. The consumat will be motivated to consume the opportunity with the highest perceived multiple need satisfying capacity that is feasible in terms of BC. In our experiments the opportunities consist of different numbers of hours spend working versus leisure time. Working for more than 16 hours implies that the consumat would have less than 8 hours for leisure, which is an absolute minimum. Consequently, we can state that the behavioural control over these opportunities is negative. The deliberating consumat will choose that number of hours working that maximises the levels of need satisfaction for subsistence and leisure, provided that it's behavioural control over that opportunity is positive (formula 8).

(8) $MAX_{Xi}\ [LNSs_i^{\gamma i} * LNSl_i^{1-\gamma i}]$ for $BC_{ix} > 0$

This maximal level of need satisfaction is based on a maximisation of the weighted product of both needs as operationalised in equations 1 and 2. In deliberating on this maximal level of need satisfaction, the consumat takes into account what the other consumats are consuming from the resource.

On the basis of the desired consumption for all consumats *j*, the deliberating consumat calculates an expected total consumption of all agents which is necessary to project the resource depletion. For simplicities sake the consumat assume that the other consumats consume the same amount as in the previous period which is an amount equal to $CT_{t-1} - CI_{i,t-1}$. Multiplying this with the relative change in the depletion factor as introduced in formula 6 we derive the total desired consumption of the other consumats. The consumption of the consumat itself is equal to $x_{j,t} * a_{h,j} * (R_{t-1}/R_{t0})^{-\pi}$ as discussed in formula 6. This results into

(9) $CET_t = (CT_{t-1}-CI_{i,t-1})*(R_{t-1}/R_{t-2})^{-\pi} + x_{i,t} * a_{h,i} * (R_{t-1}/R_{t0})^{-\pi}$

This allows the consumat to calculate the expected resource size for the time-horizon it employs.

(10) $R_{t+ci} = R_{t-1+ci} * \lambda - CET_t$

Where ci = cognitive ability of consumat i, resembling the time-horizon in time-steps.

Social Comparison

Social comparison stands for reasoned social processing, and relates to social comparison theory, relative deprivation theory and theory of reasoned action (social norms). A consumat engages in social comparison if $LNS_{it} < LNSmin$ and $Unc_i > UT$, that is, it is dissatisfied and certain. While engaging in social comparison, the consumat first will update its' mental map. Then it will observe the consumptive behaviour of the other consumats with about the same abilities. When other consumats' abilities differ no more than a certain percentage from the own abilities those consumats are assumed to be comparable. The range within which other consumats are being considered as comparable is denoted with the comparison-factor ε. If ε is set at 0, only other consumats with exactly equal abilities are being considered as comparable, whereas when setting ε at 0.5, also consumats with half or twice as much abilities are being considered as comparable. In our experiments, only the ability to harvest (a_h) is taken into consideration in calculating the comparison-factor ε. Only when there is another comparable consumat *j* the consumat can engage in social processing, as is denoted in formula 11.

(11) $ABS(a_{hi} - a_{hj}) > \varepsilon$ then social processing

If the number of consumats is larger than 2, the comparison consumat is initially chosen random. After engaging in social comparison a comparable consumat is selected on the basis of similarity (equation 8). This comparable consumat is being memorised in the mental-map, and is being used in situations when the consumat engages in imitative processing.

Having selected a comparison consumat, the consumat will calculate the expected outcomes for reproducing the opportunity consumption of the other consumat. This calculation employs the full time-horizon the consumat is able to use. Also the behavioural control over this behaviour is being calculated. If the expected outcomes of reproducing are higher than the expected outcomes of not changing the opportunity consumption, and the behavioural control over this opportunity is positive, then the consumat will reproduce the other consumats opportunity consumption. The consumat thus will be motivated to consume either the other consumats' behaviour, or the own previous behaviour, depending on the highest perceived multiple need satisfying capacity of both opportunities (according to formula 8). In our experiments the consumats will compare which number of hours spent working yields the highest LNS, either reproducing the behaviour of the comparable consumat, or not changing the behaviour. In formula:

(12) $x_i = \max_{xcomp} LNS$

Repeating

Repeating stands for automatic individual processing, and relates to classical and operant conditioning theory. A consumat engages in repetition when $LNS_{it} > LNSmin$ and $Unc_i < UT$, that is, the consumat is satisfied and certain. Repeating implies that the consumat does not update its mental map. It will just repeat the previous behaviour. Thus, the consumat is motivated to consume the previous consumed opportunity. Only when it appears that the behavioural control over this opportunity has dropped below zero, the consumat will switch towards deliberating to find an opportunity that is both satisfying and feasible. In our experiments a repeating consumat *i* at time-step *t* spends the same number of hours on harvesting as it did in the previous time-step, as is notified in formula 13.

(13) $x_{it} = x_{it-1}$

Imitation

Imitation stands for automatic social processing, and relates to social learning theory and the theory of normative conduct. A consumat engages in imitation if $LNS_{it} > LNSmin$ and $Unc_i > UT$, that is, the consumat is satisfied and uncertain When the consumat engages in imitation, it will read the mental map and recall the consumat that functioned most recently as comparison-consumat. It will do what this consumat did in the previous time-step. The consumat is thus motivated to consume whatever the other similar consumat is consuming. Only when it appears that the behavioural control over this opportunity is below zero, the consumat will switch towards social comparison. In our experiments this implies that the consumat follows an agent with about similar harvesting abilities (a_h). If the number of consumats is larger than 2, the comparison consumat is initially chosen random. After engaging in social comparison a comparable consumat is being available in the mental-map. In the following formula 14 is stated that the time spend working of consumat *i* at time-step *t* is equal to the consumption of the comparison consumat *j* at t-1.

(14) $x_i = x_{j\ t-1}$

6.3: The Impact system

The impact system starts with the consumat performing behaviour following the processing rules of the state system. Performing this behaviour also results in behavioural outcomes, referring to changes in the level of need satisfaction ($LNS_{1..n}$), and consumption abilities. Moreover, their perception of opportunities may change. Finally, the opportunities themselves may change. For example, extensive consumption may result in the scarcity of a resource and an increase in its price (using a price-demand function).

In our simulation experiments the actual consumption of the individual consumat *i* at time-step *t* depends on the number of hours spent working times the ability to consume. This is being multiplied with the depletion dynamics to include the possible effect of the resource-size on the consumption per hour. Finally, this all is being multiplied by the total consumption at time-step *t* divided by the desired consumption at time-step *t*. In formula:

(15) $CI_{it} = x_{it} * a_{hi} (R_{t-1}/R_{t0})^{\pi} *(CT_t/CD_t)$

The total consumption of the population at time-step *t* (CT_t) depends on the maximum available resource and the sum of the expected individual consumption (CI_t) of all agents. As long as the resource is large enough to allow for the desired consumption to be realised, the total consumption will be equal to the desired consumption, resulting in (CT_t/CD_t) having a value of 1. However, if the desired consumption is larger than the resource allows for, this value becomes smaller than 1. Then the consumption is allocated over the consumats and the agents consume the whole resource. Formula 16 states that the total consumption at time-step *t* is the lowest value of either (1) the resource size at time-step *t* or (2) the sum of the expected individual consumption of all agents

(16) $CT_t = \min((1+\lambda)*R(t-1), \Sigma\ E(CI)_{it})$

Following the consumption, the levels of need satisfaction according to formula 1 and 2 and the resource-size will change, resulting in new values for the pressure variables.

6.4: The response system

For the consumat this implies that a policy measure is either affecting the consumption opportunity (its availability, need-satisfying capacity or the effort that is required for its consumption) or the consumats' abilities (e.g., its available budget, knowledge). A policy measure can be translated as a change of parameters during a simulation run. In our experiments it is in principle possible to change the resource characteristics (size, growth-function and depletion-dynamics), the abilities of the consumat, the shape of the function that relates the level of need satisfaction to consumption (factor α) and the relative weighting of both needs (the value of γ). However, in this first series of experiments we investigated the behavioural dynamics without experimenting with changes of these parameters. In later experiments we intend to experiment with different strategies to alter the behavioural dynamics.

In the following sections we will present the results of a series of experiments we performed with the consumats as circumscribed above. The first series of experiments as presented in section 7 is intended to demonstrate the performance of the different consumat rules. Section 8 presents a second series of experiments is intended to investigate the effects of environmental uncertainty and accessibility of the resource. These experiments are aimed at gaining a better understanding of the behavioural dynamics that provoke over-consumption.

7: Experimenting with the consumat rules

Now that we have discussed the conceptual model and the basic consumat rules involved, it is time to demonstrate how the consumats as operationalised in the previous section behave in an artificial world. Many experiments are possible with the consumat approach as sketched above. In this section we aim to demonstrate the various behavioural rules by presenting a series of simple experiments. Whereas later experiments will include two or even twenty-five consumats, the first experiment will be about only one consumat that is deliberating over its' consumption.

7.1: Varying the time horizon of a single, deliberating consumat

In the first simulation experiments we investigate how deliberation works in managing a resource. These experiments imply that we confront consumats with different time-horizons with a resource, and observe how deliberation affects the resource size and the consumats level of need satisfaction. To guarantee that the consumat is only deliberating, we set both LNSmin and UT at value 1. This implies that the consumat is never satisfied (LNS < LNSmin) and fully certain (U < UT), thus exclusively engaging in deliberating. Each time-step the consumat calculates what opportunity (i.e., amount of time spent working) results in the maximal need-satisfaction (LNS) for the time-horizon (TH) being considered.

Given a cornucopious resource (maximal consumption < resource growth per time-step) that is impossible to deplete by the single consumat, this consumat has complete consumptive freedom, because there is no risk of depleting the resource. In this situation we observe the consumat engaging in a stable behavioural pattern of working for 9 hours a day (consuming 0.5625 per time-step), and using the remaining 15 hours for leisure. This pattern results in the consumat experiencing a stable level of need satisfaction for subsistence (LNSs) of 0.94 and a level of need satisfaction for leisure (LNSl) of 0.89. The time horizon (TH) the consumat employs while deliberating has no effect on its behaviour, because it is not being confronted with a possible future depletion of the resource. Instead, the resource size is consistently increasing.

Next we make things less easy for the consumat. Setting the initial resource size at 2.5 results in a resource that is vulnerable to overexploitation but which, however, is large enough to allow for a sustainable consumption. We assume that an early anticipation of possible resource depletion is critical to arrive at sustainable behaviour. Consequently, if the consumat elaborates on its consumption using a long time horizon (TH), it will detect a possible resource depletion much earlier than in case of using a short time-horizon. Consequently, employing a long time-horizon enables the consumat to react in an early stage of resource depletion by moderating its consumption.

In the situation with an initial resource size of 2.5 we start with a consumat with a very short time perspective by setting the TH at 1. This implies that the consumat optimises its LNS for the current and the next time-step. This consumat, not being able to perceive the longer-term consequences of its behaviour, quickly increases its time spent working from 8 hours to 9 hours a day. The associated consumption increases from 0.5 to 0.56 units per time-step, at which level consumption remains stable for 5 time-steps. This level of consumption is quite satisfactory for the consumat (LNSs = 0.94 and LNSl = 0.89), and mirrors the situation of the abundant resource sketched before, until t = 6, when the resource has been depleted such that this consumption level can no longer be maintained (see Figure 5). At t = 6 the consumat can work for only three hours, consuming 0.18 of the resource and leaving the resource almost completely depleted at t = 8. By consequence of this depletion the LNSs drops to 0, whereas the LNSl goes to 1. At t = 18 the remains of the resource have grown to a volume that can be consumed in one hour of working, and thus the consumat then completely depletes the resource. Following that, the situation is completely stable, the consumat being completely dissatisfied for subsistence as the resource is empty, but being maximal satisfied regarding its leisure need.

Setting the TH at 10 makes a large difference. After the first consumption at the first time-step, the consumat perceives that continuation of this consumptive behaviour will lead towards a depletion of the resource. The consumat calculates which opportunity-use would yield the highest level of need satisfaction for the next ten time-steps. It concludes that moderating its time spent working down to 5 hours a day would be optimal, and so it does at t = 1. This implies a consumption of 0.31 units, resulting in a fair level of need satisfaction (LNSs of 0.80 and a LNSl of 0.97). For the next time steps, working for five hours a day remains the optimal solution, however, the resource is clearly depleting in the longer run. At t = 4 the consumat perceives that this level of consumption is too high to achieve a maximal need satisfaction for the next ten time-steps. The optimalisation now concludes that working should be decreased to 4 hours a day, resulting in a consumption of 0.25. This process repeats at t = 9, where the consumat further decreases its time spent working to 3 hours a day, consuming 0.19, and at t = 15, at which time it works 2 hours a day, consuming 0.13. This level is being sustained for quite some time.

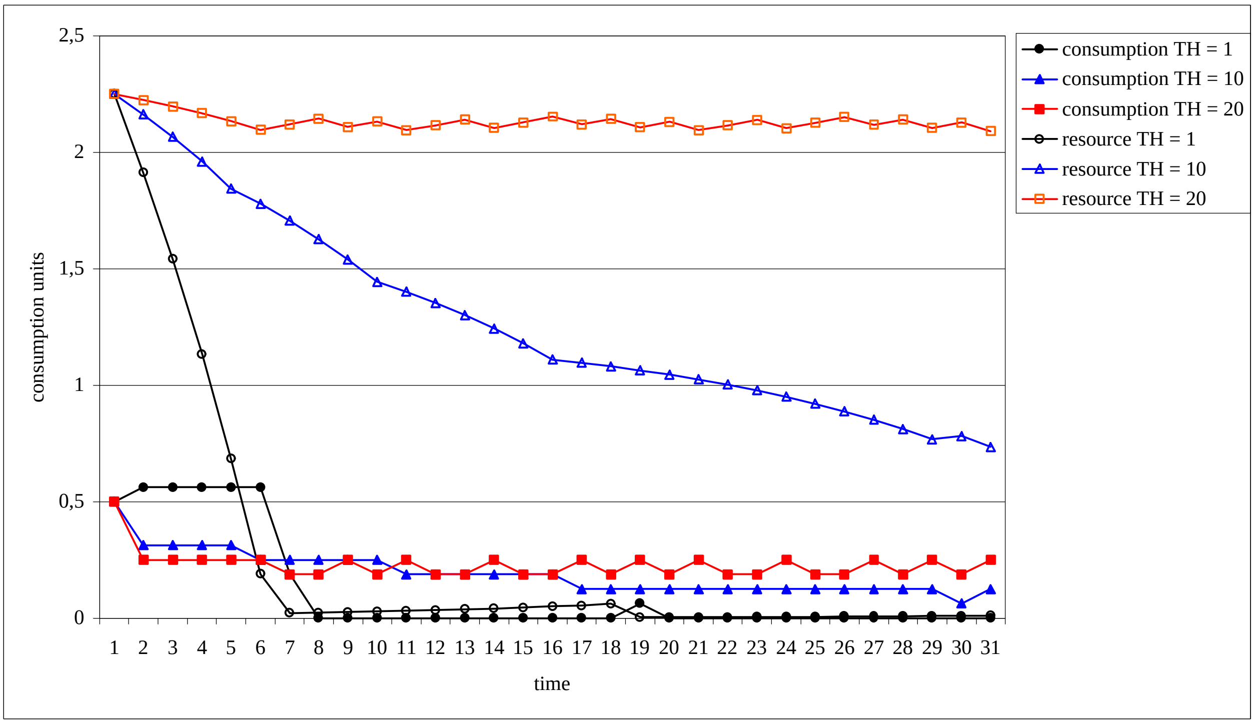

Figure5: Resource size and consumption level (vertical) for TH = 1, TH = 10 and TH = 20

However, we observe the resource further decreasing (Figure 5), and at t = 29 the consumat 'concludes' that it has to work for only one hour during one day in order to prevent the resource from depleting. From that moment on the consumat switches between one and two hours working, maintaining the resource level between 0.73 and 0.75. The consumat thus ends up sustaining its consumption, being not very satisfied regarding its subsistence need (LNSs switches between 0.46 and 0.27), but being very satisfied regarding its leisure needs (LNSi = 0.99).

Increasing the TH to 20 time steps further illustrates the importance of the time factor on the resource consumption. After the first consumption the consumat perceives that it should moderate its consumption now so as to guarantee optimal outcomes in the long run. At t = 1 the consumat thus reduces its time spent working to 4 hours a day. This implies a consumption of 0.25, resulting in a LNSs of about 0.71 and a LNSl of about 0.98. After t = 5 the consumat occasionally reduces its time spent working with one hour. As Figure 5 shows, this secures the resource to remain at a high level, thus allowing a satisfactory consumption level in the future.
During the periods of diminished consumption, which last for one or two time steps, consumption drops to 0.19 and the LNSs drops to about 0.61. These first experiments demonstrate that sustainable use of a resource by a single consumat is strongly affected by the time-horizon being used in deliberating its future level of need satisfaction. Neglecting future outcomes results in a large consumption and need satisfaction at first, causing a quick depletion of the resource, and a fully dissatisfied need for subsistence later on. Deliberating while using a longer TH results in a quick reduction of the consumption so as to avoid depletion of the resource. A longer TH (20) here proves to be far more efficient than a shorter TH (10) in achieving a high level of need satisfaction in the long run. *Ergo*, the longer the time-horizon the consumat employs, the more sustainable its consumption will be, because the resource is being maintained.

7.2: Introducing repetition as processing style

In the previous experiment we wanted the consumat to engage only in deliberation, which we accomplished by making it unsatisfiable (LNSmin = 1). However, it would be worthwhile to make the consumat satisfiable. This would imply that the consumat, when satisfied, engages in repetitive (habitual) behaviour. Introducing repetition as cognitive processing style enhances the realism of the consumat, since real people, when satisfied about their behaviour, do not tend to deliberate much about alternatives. During repetitive behaviour, the consumat does not update its mental map, thus it is not aware of a possibly depleting resource.

To allow repetitive behaviour to occur in the present experiment, we set the minimum level of need satisfaction LNSmin at 0.75. This implies that as long as both LNSs and LNSl are larger then 0.75, the consumat is satisfied and will engage in repetition. For the rest, we replicate the previous experiment with a TH of 20. In this experiment, it appears that in the first time-step the consumption level of 0.50 is high enough to keep LNS above the critical value of 0.75. The consumat is thus satisfied regarding its needs for subsistence and leisure. As a result of that, the consumat will continue with the repetitive processing style. Only when the resource has been depleted completely at t = 7, consumption will drop to zero and the LNSs will also drop to zero. Consequently, at t = 8 the consumat will engage in deliberation. However, there is nothing left to deliberate about.

This experiment demonstrates what looks like a very naive type of behaviour. As long as its needs are satisfied, the consumat remains totally unaware of what happens with the resource. One of the reasons for this naive behaviour can be attributed to the character of the resource, which is always equally accessible for harvesting. No matter if the resource is abundant or almost depleted, during one hour of work the consumat will always obtain 0.0625 consumption units. In the previous experiments the only factor that determined the consumption level was the consumat's ability to consume, that is, for as long the resource was not depleted. It would be more realistic to make the consumption level also depending on the size of the resource.

7.3: Introducing a less accessible resource

To improve the realism of the experiments, we introduce a less accessible resource that makes harvesting more difficult the more depleted the resource is. Such a resource would be more resistant against depletion and would alert the consumat earlier by means of decreasing harvests in case of a strong decline of the resource. Moreover, such a resource is more realistic. For example, when fishing, the harvest not only depends on one's fishing ability and the time spent fishing, but also on the available fish stock. We introduce a resource function that makes the harvest dependent on the time spent working and on the resource size. The smaller the resource gets, the less a consumat can harvest per unit of time. The depletion dynamics are being changed by setting the accessibility factor π at 2, causing that when the resource-size has been halved, one's harvest per hour will reduce to a quarter. Setting LNSmin for subsistence at 0.75, we observe that the consumat is engaging in repetition as processing style until t = 8, when LNS for subsistence drops below 0.75. At that moment the consumat starts deliberating. The consumat will then increase or decrease its proportion of time spent working, depending on the time-horizon (TH) it employs when deliberating (see Figure 6).

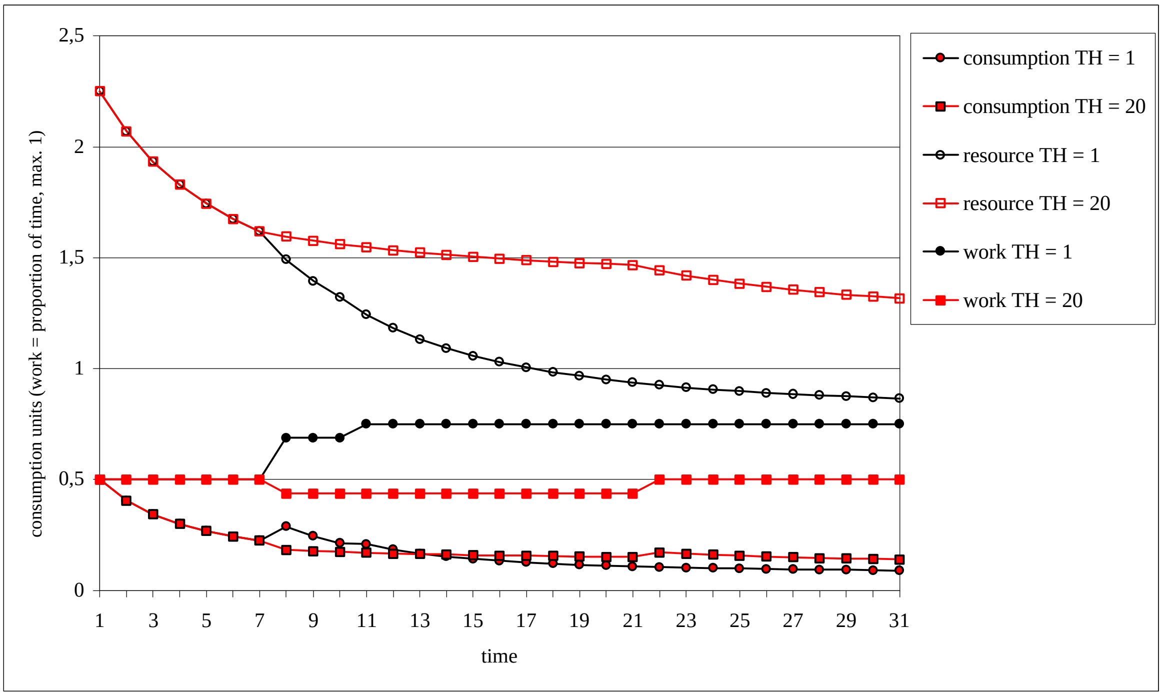

Figure 6: Resource size, consumption level and proportion of working time for TH = 1 and TH = 20.

At t = 8 the consumat with a TH of 1 immediately increases its time spent working to increase its LNSs. At t = 11 this consumat further increases its time spent working. The resulting increase in consumption yields a significant smaller resource and a lower consumption level in the longer run (t >13) compared with the consumat that employs a TH of 20. This latter consumat 'concludes' at t = 8 that it should moderate its time spent working as to guarantee the highest outcomes in the long run. As such it will more quickly reach a stable consumption pattern, as can be seen in Figure 6.

We also performed the same experiment with consumats having a LNSmin of .20, and a TH of 1 or 20. Under this condition the consumats are engaging only in repetition, thus the time-horizon (TH) has no effect on their behaviour. The consumats with LNSmin = .20 thus continue to work for 0.5 of the time, thus working equally or more than the consumat with LNSmin = 0.75 and TH = 20, and work equally or less than the consumat with LNSmin = 0.75 and TH = 1. Compared with the last consumat, the consumats with LNSmin = 0.20 will consume less, and thus not deplete the resource that much. Consequently, in the longer run, the consumats with LNSmin = 0.20 will obtain a higher level of need satisfaction than the consumat with LNSmin = 0.75 and TH = 1. This demonstrates that under the condition of a short time-horizon, habitual behaviour may outperform reasoned behaviour qua keeping LNS at a high level.

7.4: Experimenting with two consumats

The management of a resource starts being a dilemma when a second party also has access to the resource and may contribute to its depletion. The consumats here are interdependent because their individual consumption determines the size of the common resource. A consumat which is over-harvesting not only endangers its own future consumption, but it also risks the future of the other consumat. In the present set of simulation experiments we operationalised this situation by confronting two consumats with a resource that is initially twice as large (5.0) as in the previous experiments with a single consumat. Both consumats expect that, in the present time-step, the other consumat will consume the same as in the previous time-step. Using identical settings for the minimal level of need satisfaction and time horizon as in the previous experiment (LNSmin = 0.75, TH = 1) yields exactly the same outcomes as in the comparable single consumat with TH = 1 experiment (Figure 6). We observed the increase of the time spent working at t = 8 and t = 11. The only difference resided in the resource-size, which in this two-consumat experiment was exactly twice as large as in the comparable single consumat experiment.

The differences between the single-consumat experiments and the two-consumat experiments become apparent when the TH of both consumats is increased from 1 to 20. In the first time-steps we see (Figure 7) a stable proportion of time-worked of 0.5 due to the repetitive cognitive process. However, at t = 8, the LNSs has decreased so much (below 0.75) that both consumats start deliberating. Due to the large TH they are using, they decrease their proportion of time worked so as to prevent the resource from depleting.

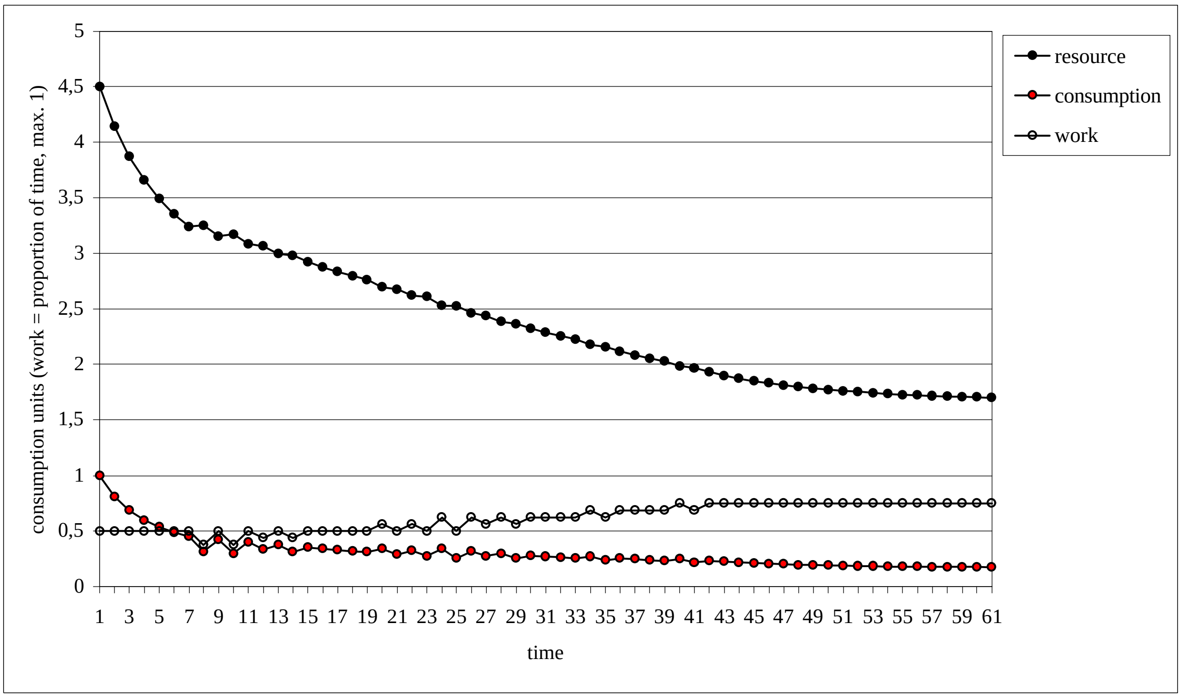

Figure 7: Resource size, consumption level and proportion of work for two consumats with a TH of 20

In Figure 7 we see several small short-term oscillations starting at t = 8, which are caused by the difference between how much each consumat expects the other to consume, and what the other actually consumes. For reasons of clarity, this does not involve social processing yet. When e.g. at t = 8 both consumats consume relatively little, they both deliberate on how much to consume in the next time step, thereby assuming that the other consumat will remain consuming at this low level. As a result, at t = 9 they both increase their consumption to a relatively high level. Deliberating about how much to consume in the next time-step, both assume that the other remains consuming at that relatively high level, resulting in both consumats decreasing their consumption at t = 10. The outcomes both consumats experience thus alternate between lower and higher than expected, and as a response the consumats adapt their behaviour in the opposite direction.

Thus far, the consumats have only engaged in individual processing styles (repetition and deliberation). This is because the uncertainty tolerance (UT) was set at 1, and the uncertainty (U) following from the difference between the expected outcomes and the actual outcomes never reached this maximal value. If the expected outcomes differ from the actual outcomes to a degree that exceeds the setting of UT, the consumat will engage in social processing. Because in the current simulation experiments we have not yet introduced a stochastic function in the resource growth-function (here $\lambda_t = \lambda_a$), the U will remain at a relatively low level. This implies that we have to set UT at a low level to initiate social processing in the consumats. Setting UT at a level between 0.0 and 0.1 implies that we can define a level of uncertainty tolerance (actual outcomes are different from expected outcomes) above which level the consumat will engage in social processing, whereas below that level the consumat will process individually.

Social processing involves the comparison with another, more or less similar consumat. To define the range wherein other consumats are considered as similar we introduced the variable ε (equation 8). If ε is set low, only consumats with about equal abilities will be accepted for social comparison, whereas a large ε implies that also more differing consumats will be accepted for social comparison. If a consumat is uncertain, and it perceives another consumat with abilities that fall within the range of acceptance of ε, the consumat will use this consumat as comparison other. While social processing, the consumat, will either imitate the comparison-others behaviour (when 'satisfied') or engage in social comparison (when 'dissatisfied'), thereby checking if adopting the behaviour of the comparison-other would yield higher outcomes.

The next experiment we performed was a replication of the previous experiment, only with an UT of 0.05 and a comparison-factor ε of 0.5. This implies that when the uncertainty becomes larger than the uncertainty tolerance (U >UT), the consumat will engage in social processing. Because the two consumats are identical, their equal ability implies that they always fall within the critical range of the comparison-factor. Running the simulation model with these settings showed that the consumats become uncertain only during the first two time-steps, because at t = 1 and t = 2 the resource decreases more than they expected. Because at that time both consumats are satisfied, they engage in imitation, copying the behaviour of the other consumat at t – 1. Because the consumats performed identical behaviour at t - 1, the outcomes of imitation do not differ from a situation where they engaged in repetition. After t = 2, the speed of the resource depletion decreases to such a degree that the resulting uncertainty never exceeds the uncertainty tolerance value (U < 0.05). The consumats thus engage in individual processing only. When the LNS of both consumats drops below the critical value at t = 7, both consumats engage in deliberation, just as in the previous experiment. Consequently, the outcomes of this experiment are exactly the same as plotted in Figure 7.

To avoid both consumats performing identical behaviour we operationalised two different consumats. Therefore we set the harvesting-ability of consumat 1 at 1 and the harvesting-ability of consumat 2 at 0.60. Moreover, to stimulate social processing we set UT at 0.0025. We use an extreme setting for UT as to invoke uncertainty in the consumats despite the absence of stochastic processes in the resource growth function. . Finally, we set LNSmin at 0.60 to stimulate automatic processing. What we can observe in Figure 8 is that consumat 2 is the first to change its proportion of time worked at t = 19. This is no surprise, as the lower ability of consumat 2 causes its LNS to drop below the critical level of 0.60 at t = 19. Consequently, consumat 2 starts deliberating, and decides to increase its time spent working. This causes its LNS to increases to above 0.60 again, inclining consumat 2 to repetition at t = 20, thus continuing the increase in time spent working. Both consumats are satisfied again, consumat 2 working somewhat more than consumat 1. The increase in working by consumat 2 results in an increase in consumption at t = 20, causing the resource to deplete at a higher rate. As a consequence, consumption decreases with a level that exceeds their expectations, and at t = 21 both consumats become uncertain. This uncertainty combined with their satisfaction (both consumats then have a LNS above 0.60) implies that both consumats engage in mutual imitation. For consumat 1 this implies an increase in its time spent working, to 'catch up' with consumat 2. This maintains its LNS above the critical level of 0.60. Consumat 2 decreases its consumption back to 0.50. However, this was and still is not enough to keep consumat 2 satisfied, and at t = 24, its LNS has dropped below the critical value which starts deliberation, and on the basis of this consumat 2 decides to increase its proportion of time working. This in turn increases uncertainty, resulting in imitative behaviour of consumat 1 at t = 26. The process repeats itself once more, and from t= 31 both consumats remain working for 0.75 of the time. It is interesting to see that consumat 1 works more than optimal, because working somewhat less yields a higher level of need satisfaction. On the basis of imitation it copied the behaviour of consumat 2. Because this was satisfactory, and uncertainty dropped, consumat 1 continued working for 0.75 on the basis of repetition, thus engaging in some sort of habitual over-harvesting. This effect may be called the *imitation-effect*. Because of its lesser abilities, consumat 2 is not capable of consuming enough to be satisfied. Despite continuous deliberation, it does not find a more satisfying behaviour than working for 0.75 of the time.

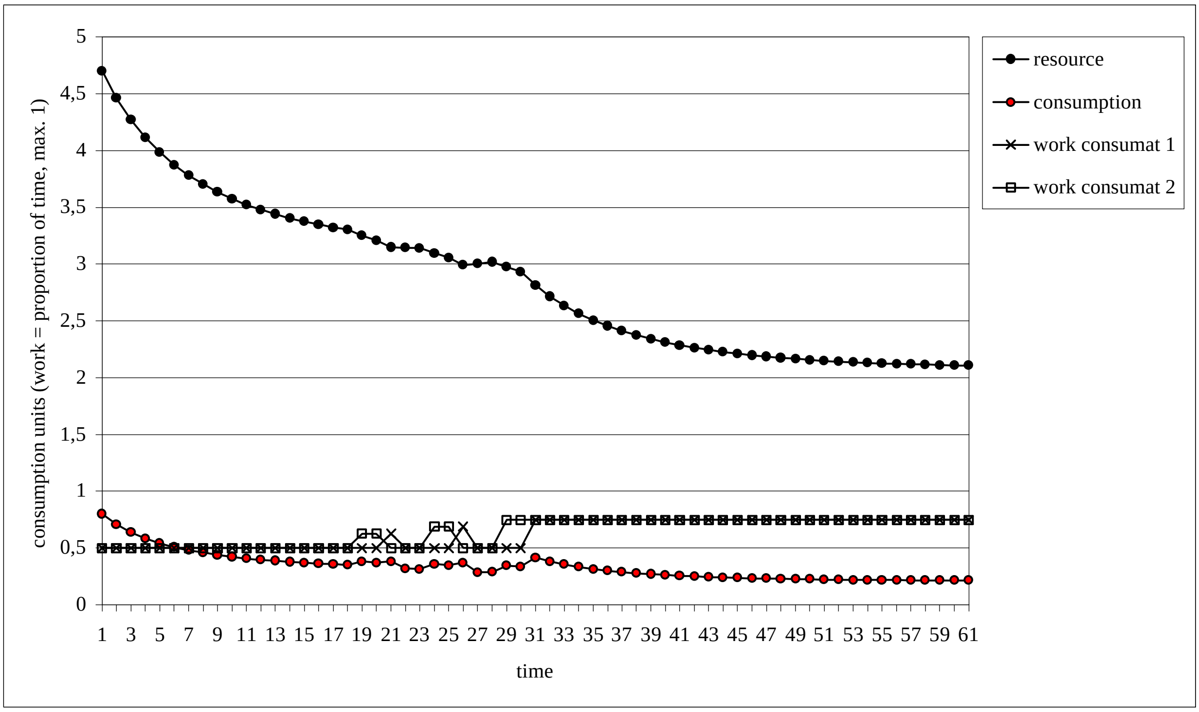

Figure 8: Resource size, consumption level and proportion of work for two different consumats with a TH of 20, including social processing

In the next experiment we replicate the previous experiment, setting the comparison-factor ε at 0.5., the harvesting-ability of consumat 1 at 1 and the harvesting-ability of consumat 2 at 0.60, and LNSmin at 0.60. The only difference with the previous experiment is that we set the uncertainty tolerance at the maximum level of 1 (UT = 1), so that social comparison does not occur. In Figure 9 we show the results of this experiments, depicting the resource size as found in the previous experiment with social processing as reference resource.

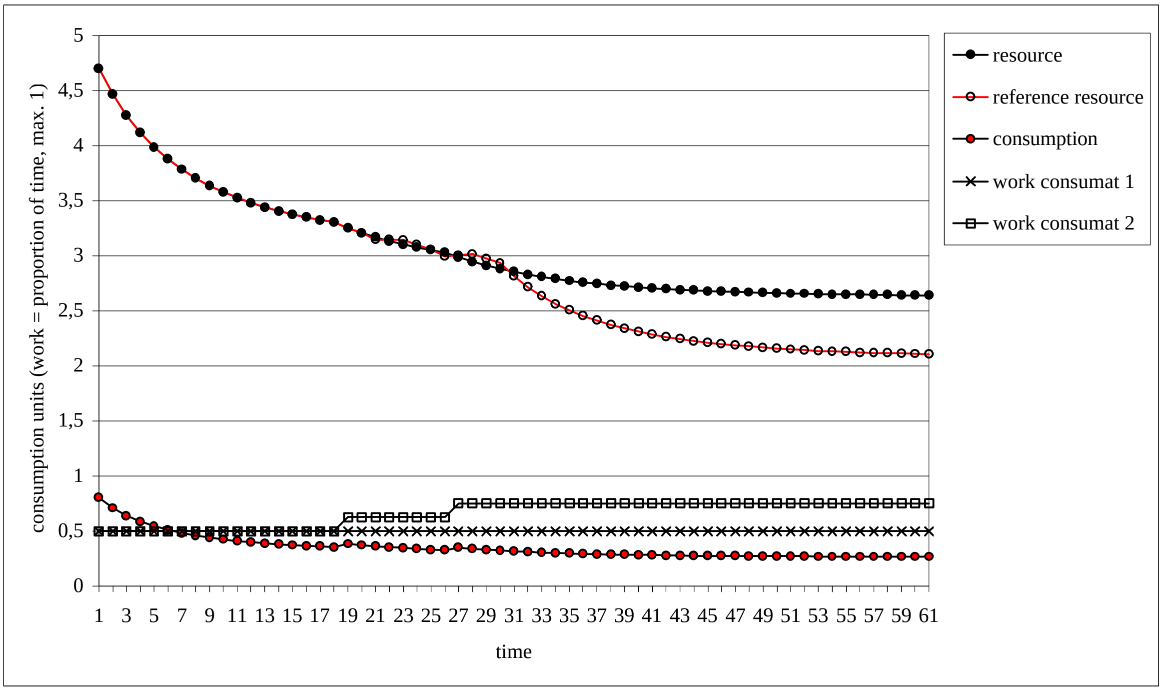

Figure 9: Resource size, consumption level and proportion of work for two different consumats with a TH of 20, excluding social processing

Because the consumats are not uncertain, they only engage in individual processing. Consumat 1 remains satisfied, and thus does not change its behaviour, while continuing to work for 0.5 of the time (8 hours). Consumat 2, having less ability, becomes dissatisfied at t = 19. As a result, it engages in deliberation, and calculates that increasing the proportion of working time to 0.625 (9 hours) is optimal. This causes consumat 2 to be satisfied until t = 27, where it again engages in deliberation and calculates that working for 0.75 (12 hours) of the time is optimal. This is satisfactory until t = 30, where LNS again drops below 0.60. However, consumat 2 does not find a more satisfying behaviour at t = 30, and it remains working for 0.75 of the time, yet being dissatisfied. Most interesting is that in the previous experiment, which included social comparison, the resource depleted more strongly (Figure 9, the reference resource) than in the last experiment without social comparison. The simulation experiments here provide insights regarding the dynamics of social behaviour. It appears that under the condition of a vulnerable resource, imitation may result in harvesting more at the cost of the achieved level of need satisfaction in the long run.

7.5: Experimenting with 25 consumats

In the next experiment, we investigated if the effect of social comparison also holds in a large group of consumats. Therefore we operationalised 25 consumats. We formed 5 subgroups, each group consisting of 5 consumats. These subgroups differed with respect to the harvesting ability of the consumats, respectively having a level of 1.0, 0.8, 0.6, 0.4 and 0.2. Just like in the previous experiment, LNSmin was set at 0.60 and ε at 0.5. The initial resource size was 2.5 units per consumat, thus a total of 62.5. The accessibility factor π was set at 1, implying that when the resource-size has been halved, one's harvest per hour will also be halved. The resource is thus more vulnerable for depletion than in the previous experiments where π was set at 2. The current setting will increase the difference between the different conditions of this experiment regarding the resource depletion. We varied the settings of uncertainty tolerance (UT), so that a condition was created where the consumats only engage in individual behaviour (no social: UT = 1), and a condition where the consumats engage in all four behavioural processing styles (social: UT = 0.0025). For both conditions we performed simulation-experiments with the consumats having a time horizon of 5 or 20 time-steps (TH = 5 or TH = 20). In Figure 10 we present the resource size for the resulting four conditions as a function of time.

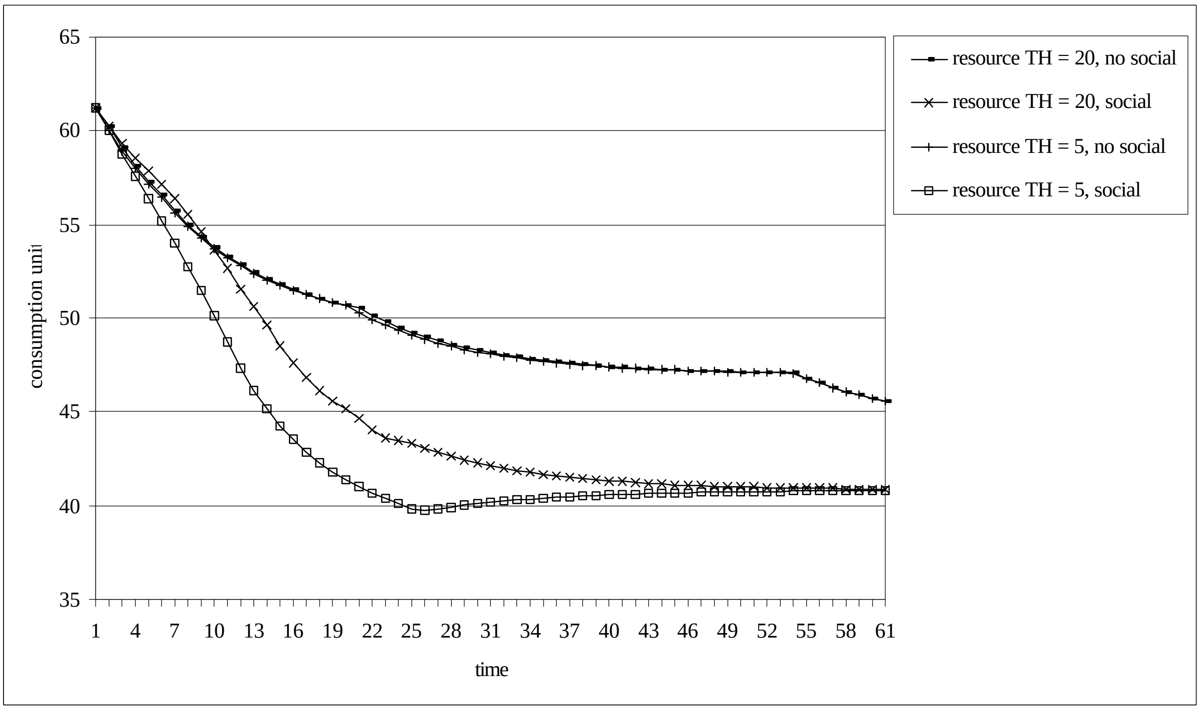

Figure 10: Resource size for 25 different consumats under 4 conditions

Figure 10 shows that in the two conditions where the consumats can perform social processing (TH = 20, social and TH = 5, social) the resource is depleting faster than in the two conditions where the consumats only process individually (TH = 20, no social and TH = 5, no social). This is in line with the effects found in the previous simulation experiment, which demonstrated that imitation stimulates an increase in harvesting at the cost of the level of need satisfaction in the long run. The groups of consumats with a lower harvesting ability will be the first to engage in deliberation because they are the first to become dissatisfied. As a consequence they increase their consumption, which in its turn seriously affects the resource size and thus yields uncertainty in the consumats. Only in the social condition (UT = 0.0025) this causes that the consumats with a higher ability, which are still satisfied at that moment in time, will engage in imitative behaviour. The increased time spend working thus spreads through the population, resulting in a faster depletion of the resource than had they engaged in repeating their previous behaviour.

Whereas the two social behaviour conditions (TH = 5, social, and TH = 20, social) show a remarkable difference regarding the development of the resource-size, the two no social behaviour conditions hardly show any difference between them (Figure 10). The similarity between the TH = 5 and TH = 20 conditions for no-social behaviour can be explained as a ceiling-effect. Once the consumats start deliberating, it hardly matters if they use a time-horizon of 5 or 20 time-steps because of the less accessible resource. In the TH = 5 condition the resource-size is only slightly lower.

Regarding the both social behaviour conditions, it appears that the use of a large time-horizon (TH =20) results in the resource being depleted at a slower rate than if a short time-horizon (TH = 5) is being used. Remarkably, in the latter condition (TH = 5, social) we see the resource being at the lowest level at t = 25, and afterwards growing slightly. This is being caused by the fact that at that time all the consumats engage in deliberating, and with a TH of 5 they calculate that a decrease of consumption is necessary to increase their level of need satisfaction. The difference between the two social behaviour conditions resides in the fact that the consumats do not elaborate on new behavioural options while engaging in social processing. Only when they deliberate they may find a new optimal behaviour. The consumats that are most likely to start deliberating are the consumats with the lowest ability, because their LNS will be the first to drop below the critical value. How much they will increase their time spent working as to increase consumption depends on the time-horizon they use in deliberating. Consumats with a TH of 5 will increase their time spent working more then consumats with a TH of 20. Consequentially, the consumats with a TH of 5 will cause a greater disturbance in the resource size, resulting in a larger uncertainty in the consumats. Moreover, the consumats having a TH of 5 provide a behavioural example that involves working for more hours than the behavioural example provided by the consumats with a TH of 20. Consequentially, the consumats with a higher ability to harvest are more likely to engage in imitation under the TH = 5 condition, and in that condition they have a higher chance of being confronted with high consumptive exemplary behaviour. Imitating this behaviour causes a rapid depletion of the resource, as can be seen in Figure 10. Summarising, it appears that a short time-horizon may create the conditions that facilitate the imitation effect to happen.

To further investigate the robustness of the effects of social comparison, we have to perform many more simulation experiments under varying conditions.

8: Experimenting with different types of resources

In the previous section we presented a series of experiments in which consumats were confronted with a resource with a non-stochastic growing function ($\lambda_t = \lambda_a$). In this section we want to investigate the effects of introducing a stochastic growing function of the resource (Formula 5: $\lambda_t = \lambda_a + N(0,\sigma)$). On the basis of the results of the previous experiments we expect that a higher value for σ will yield a higher uncertainty of the consumats, causing them to consume more from the resource. Moreover, we will experiment with the accessibility of the resource. We expect that a more accessible resource (lower value for the accessibility factor π) will be more vulnerable for depletion.

8.1: Introducing environmental uncertainty

In the previous section we observed the importance of uncertainty in the management of a renewable resource. In these experiments uncertainty resulted from a change in consumption that caused an irregularity in the resource growth. Only when the uncertainty tolerance (UT) was set very low this would incite social processing in the consumats. However, in real life the irregularities in the resource growth are not only caused by consumption, but are originating from the often very complex dynamics of the resource. For example, the growth of a fish-stock is not only depending on the catch of the fishermen, but also on weather conditions, sea temperature, the food situation in the sea and pollution, to name a few factors. In the experiments to come, we operationalise such irregularities in the resource growth in the most simple way by introducing a stochastic function in the resource growth. This implies that simulation-runs with the same initial settings may show different developments regarding the resource growth and the consumat behaviour. Consequentially, experiments that are aimed at revealing the effects of starting with different initial-settings require that for each initial-settings-condition several simulation-runs will be performed. This allows the comparison of the different conditions in an experiment. We are especially interested in the effects of different levels of uncertainty tolerance (UT) and minimum level of need satisfaction (LNSmin) on the management of the resource. For LNSmin we selected 10 values ranging from very easy to satisfy (LNSmin = 0.05) to very hard to satisfy (LNSmin = 0.95). For UT we selected 10 values between 0.005 and 0.095, which range appears to capture consumats that seldom engage in social processing (UT = 0.095) and consumats that very frequently engage in social processing (UT = 0.005). Pairing the ten values for LNSmin with the ten values for UT yields a design with 100 LNSmin-UT conditions. For each condition we perform 10 simulation runs, resulting in 1000 runs for the overall experiment. The conditions in the experiment are expected to show a difference regarding the prevailing cognitive processing rules. For example, setting UT and LNSmin both at a low level will increase the likelihood of the consumats engaging in imitation, as they are quickly uncertain (low UT) but easy to satisfy (low LNSmin).

Each run starts with an initial resource size of 5. The standard deviation σ in the resource growth-function is set at 0.02. The accessibility factor π is set at 1, effectuating that when the resource has been halved, it becomes two times as difficult to harvest. Two consumats are confronted with this resource. Both consumats have a time-horizon (TH) of 20. Consumat 1 has an ability to harvest of 1.0, whilst consumat 2 has an ability of 0.5. The LNSmin and UT of both consumats are being varied according to the discussed design, resulting in 100 conditions. In Figure 11 we show the resource size after 30 time-steps for the 100 LNSmin-UT conditions. We chose to present the resource size at t = 30 because at that time the effects of consumption are clearly visible. Each centre of a square in the landscape of Figure 11 represents the average resource size of 10 runs under that particular LNSmin-UT condition.

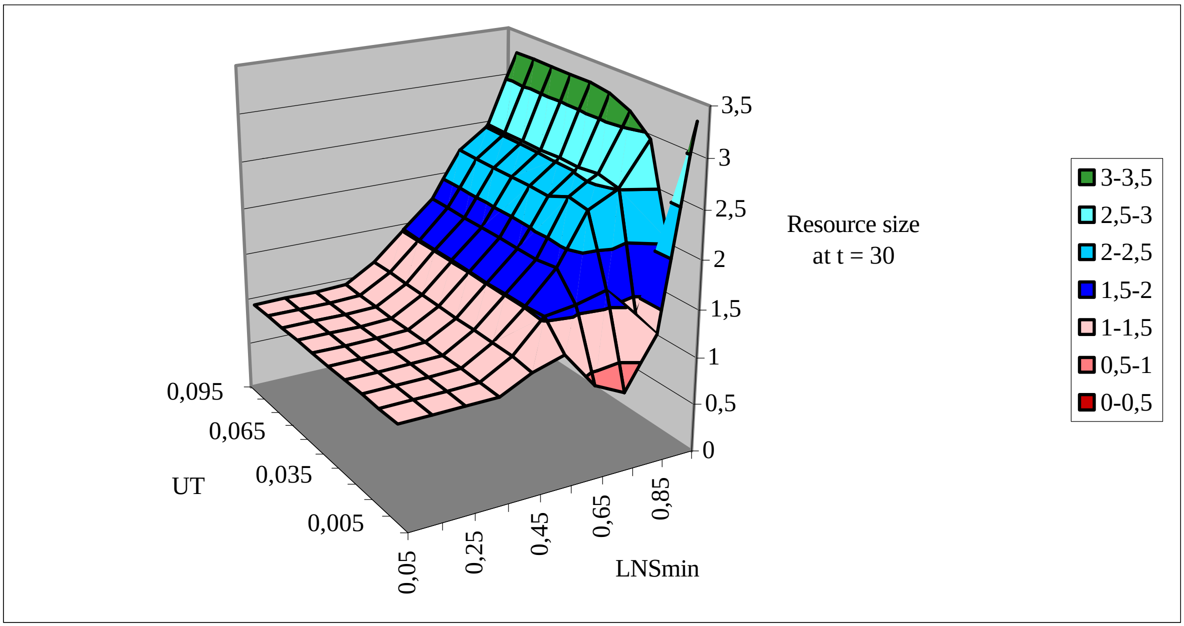

Figure 11: Resource size at t = 30 for different values of LNSmin and UT and two differing consumats, σ = 0.02

It appears that consumats that are easy to satisfy (low levels of LNSmin) have almost depleted the resource at t = 30. The higher the consumats' LNSmin is, the higher the resource-size at t = 30. This is no surprising result, because the more frequent the consumats deliberate (which is associated with higher levels of LNSmin), the earlier they reduce their consumption to prevent future resource depletion. Consumats with a low LNSmin are easier to satisfy, and thus are most likely to engage in automatic processing. As a consequence, they do not anticipate future resource depletion. Only when the resource has been depleted to a considerable extent, their behaviour is not satisfactory any more, forcing them to engage in reasoned processing. However, because of the substantial depletion of the resource at that moment in time, the consumats cannot find a satisficing behavioural opportunity. Consequentially, they remain dissatisfied, continuing to process in a reasoned manner (either engaging in deliberation or social comparison).

For consumats with a higher LNSmin (≥ 0.35), Figure 11 reveals an effect of uncertainty tolerance (UT). The higher the UT of the consumats, the less they engage in social processing. Consumats with an UT ≥ 0.045 rarely become uncertain for more than one time-step, because the uncertainty seldom exceeds their critical UT-level. Consequentially, these consumats engage almost exclusively in individual processing. It hardly matters if the consumat has an UT of 0.045 or 0.095, as can be seen in Figure 11.

For consumats with a relative low uncertainty tolerance (UT ≤ 0.035) and which are not too quickly satisfied (LNSmin ≥ 0.35) we observe that the lower UT, the more depleted the resource is at t = 30. This effect is particularly strong for relatively high levels of LNSmin (0.65 – 0.85) and an UT ≤ 0.015. Under these conditions consumat 1 (high ability) often engages in imitation, thus copying the higher proportion of time spent working of consumat 2. This usually causes consumat 1 to work more than is required to satisfy its needs. This effect thus resembles the *imitation-effect* that was found in the n = 1 experiment in section 5.4, Figure 8. Consumat 2, having a lower ability and thus more often being dissatisfied, is most likely to engage in social comparison. When consumat 1 engaged in imitation, this causes that both consumats engage in the same behaviour. In that case social comparison does not reveal alternative behavioural opportunities, and consumat 2 continues the high proportion spent working. Consequently, in this situation the consumats are not capable of finding a new behaviour, e.g. reducing their time spent working now as to preserve the resource and guarantee future outcomes. For as long both consumats experience an uncertainty larger than their uncertainty tolerance (U > UT), they are trapped in this high proportion of working. This period of over-harvesting can only come to an end if one of the consumats starts deliberating for one time-step. It appears that under conditions of uncertainty an increase in harvesting is the behaviour that is most likely to be imitated and sustained for a while, resulting in the resource being depleted to a larger extent

Remarkably, for UT = 0.005 and LNSmin = 0.95, Figure 11 reveals a high level of the resource at t = 30. Under this condition the consumats do not engage in automatic processing, but will often socially compare and occasionally deliberate. When this occasional deliberating occurs in the first time-steps, the resource has not been depleted to a large extent. Consequently, the consumat will be able to find a behavioural opportunity that that prevents the resource from further depletion, thereby obtaining a relative good harvest in the long run. In later social comparisons the consumats thus only consider this relatively sustainable behavioural opportunity.

Increasing environmental uncertainty

To further investigate the effects of uncertainty on resource management, we replicate the previous experiment. This time however, the stochastic function in the resource growth function is being doubled ($\sigma = 0.04$), causing the environmental uncertainty to be larger. We expect that this increased environmental uncertainty causes the resource to deplete more in comparison to the previous experiment (Figure 11). Figure 12 shows what the resource size is after 30 time-steps for varying levels of UT and LNSmin.

The most remarkable difference with the previous 1000-run experiment is the much smaller resource size at t = 30 for LNSmin = 0.45 – 0.85 (see Figure 11). For example, for LNSmin = 0.55 and UT = 0.055 the resource size at t = 30 dropped from 1.51 (Figure 11) to 1.25 (Figure 12). The fact that the lower resource size is equally large for middle and high levels of UT makes clear that this cannot be a pure social comparison effect. This lower resource size for LNSmin = 0.45 – 0.85 can be explained as follows. Environmental uncertainty may lead to optimistic and pessimistic expectations regarding the resource growth. Deliberating during a coincidental downward fluctuation in the resource growth ($N(0,\sigma) < 0$) causes the consumats to have ‘pessimistic’ expectations regarding resource growth. Consequently, the consumat will reduce its proportion of time working to prevent the depletion of the resource and to guarantee future outcomes. Because this behaviour is based upon a pessimistic expectation of the resource growth, the consumption may be denoted as under-harvesting. This under-harvesting causes the consumats to remain dissatisfied, thus sustaining them to reason about consumptive behaviour.

The chances are large that a following time-step shows an upward fluctuation in the resource growth ($N(0,\sigma) > 0$). An upward fluctuation results in the consumats having optimistic expectations regarding the resource growth, and thus they will increase their proportion of time spent working. The resulting over-harvesting usually results in a higher satisfaction, which stimulates the consumats to engage in automatic processing. However, this automatic processing

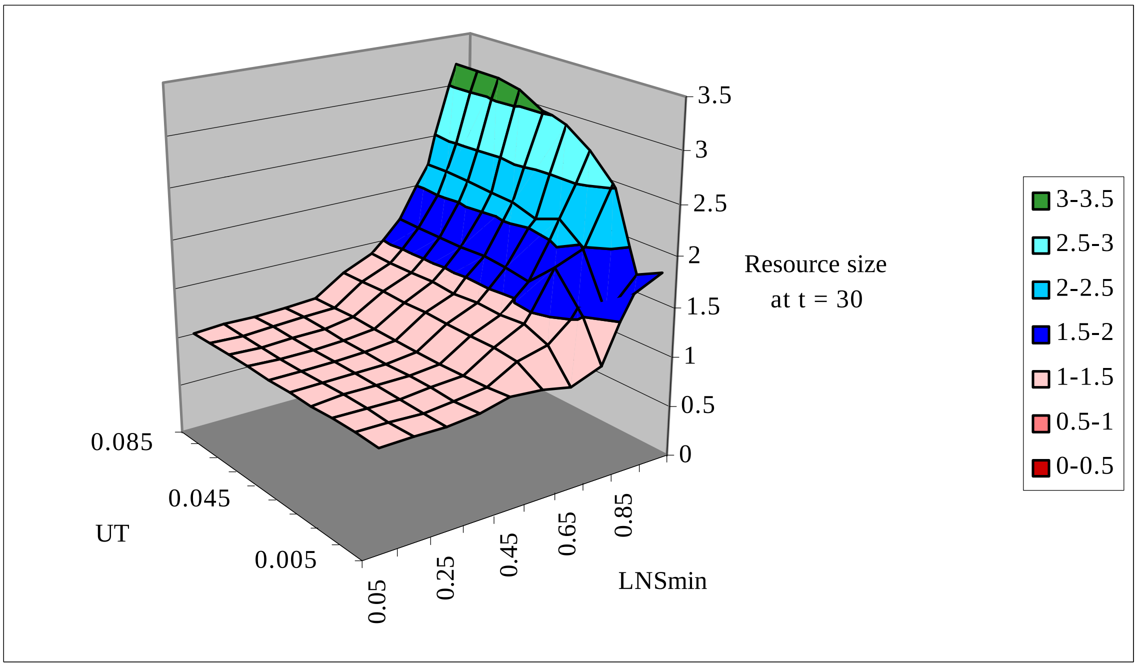

Figure 12: Resource size at t = 30 for different values of LNSmin and UT and two differing consumats, σ = 0,04

makes them insensitive for future negative fluctuations for as long as they are satisfied. The higher the environmental uncertainty, the more frequent consumats will be 'captured' in automatically over-harvesting on the basis of this *optimism-effect*. The optimism effect thus occurs only in situations where the consumats can engage both in reasoned and automatic processing. The optimism-effect does not occur for low and high levels of LNSmin. For low levels of LNSmin this effect does not occur because the consumats do not engage in reasoned processing, and thus never have (optimistic) expectations regarding future outcomes. For LNSmin = 0.95, this effect does not occur because the consumats do not engage in automatic processing, and thus cannot be 'captured' in automatically over-harvesting.

Regarding the *imitation-effect*, this second 1000-run experiment shows a larger effect than in the previous experiment. Whereas in the previous experiment the imitation-effect occurred for LNSmin (0.65 –0.85) and UT ≤ 0.015, here the effect manifests itself stronger for LNSmin (0.65 – 0.85) and UT ≤ 0.025, as can be seen from Figure 12. It appears that an increase in environmental uncertainty also increases the imitation effect.

For LNSmin = 0.95 we also see an effect for UT 0.005 – 0.075, however, this cannot be an imitation-effect because the consumats here engage purely in reasoned processing (either deliberating or social comparing). Close observation of these conditions showed that for consumats with a LNSmin of 0.95 holds that the more frequent they engage in social comparison, the slower they adapt their behaviour. This is caused by the fact that only when one of the consumats engages in deliberation, a new more sustainable behavioural opportunity can be found and be available for comparison. The effect that more social comparison causes behavioural adaptation to proceed at a slower rate is denoted as the *adaptation-effect*. Because the consumats with LNSmin = 0.95 and UT = 0.005 still engage in deliberation (about 20% of the time), they are still able to prevent the resource from collapsing. However, because they deliberate less frequently than in the previous 1000-run experiment, they do not succeed in keeping the resource at such a remarkably high level.

These two 1000-run experiments demonstrate that three differing effects cause the consumats to increase their harvesting under conditions of high environmental uncertainty. First there is the *optimism-effect.* This effect holds that deliberating consumats when confronted with a positive fluctuation in the resource growth are more likely to develop an over-harvesting habit. Second there is the *imitation-effect.* Just like in the previous deterministic (one-run) experiments, we here observe that while uncertain, Consumat 1 (higher ability) is prone to imitate the behaviour of the other consumat, even when this behaviour is less optimal than one's own previous behaviour. Third there is the *adaptation-effect*. The adaptation-effect holds that no new behavioural opportunities are introduced during social processing, and as a consequence the consumats are not capable of adapting their behaviour to changing circumstances, such as a depletion of the resource.

8.2: Experimenting with the accessibility of the resource

Accessibility here stands for the capacity the resource has to resist depletion. The previous 1000-run experiments were performed with a resource that was reasonably accessible, because when the resource had halved, it became twice as difficult to harvest (accessibility factor $\pi = 1$). Under this condition the consumats never completely depleted the resource. The question is how the consumats react to resources that are more or less accessible for harvesting. To answer this question, we performed simulation experiments with varying depletion rates.

A less accessible resource

The following experiment is a replication of the first 1000-run experiment, only the resource is made less accessible. Setting π at 2 effectuates that if the resource is halved, it becomes four times as difficult to harvest, making it very difficult to deplete the resource. In Figure 13 we graphically depict the results of this simulation experiment.

It appears immediately that this less accessible resource results in the resource remaining at a higher level. This is not surprising, because harvesting is made more difficult the smaller the resource size gets.

The most striking difference with the previous experiments lies in the “valley” in Figure 13. Whereas the previous experiment showed a monotonous increase in the resource size at t = 30 the larger LNSmin (starting from LNSmin = 0.35), here we observe the resource size at t = 30 decreasing when LNSmin increases from 0.55 to 0.75, except for UT = 0.005. This effect can be attributed to the *optimism-effect* discussed in the previous section. For LNSmin ≤ 0.45 both consumats always engage in automatic processing. For LNSmin = 0.55, consumat 2 (low ability) is the first to become dissatisfied. Engaging in deliberating combined with a positive fluctuation in the resource growth causes consumat 2 to increase its consumption. Being satisfied, it will engage in automatic processing, thereby sustaining this over-harvesting behaviour. For LNSmin = 0.65, the optimism-effect also applies to Consumat 1, and as a consequence the resource size at t = 30 is even smaller. Moreover, for a LNSmin of 0.65 the optimism-effect will happen earlier in time for Consumat 2, also causing the resource to be smaller at t = 30. For LNSmin = 0.75 the resource size at t = 30 is slightly smaller because both consumats become dissatisfied earlier in time and the optimism-effect will thus manifest earlier in time. For higher levels of LNSmin the consumats are so quickly dissatisfied that they do not sustain their over-consumptive behaviour for longer periods. Instead they will engage very frequently in deliberating, thereby adapting their

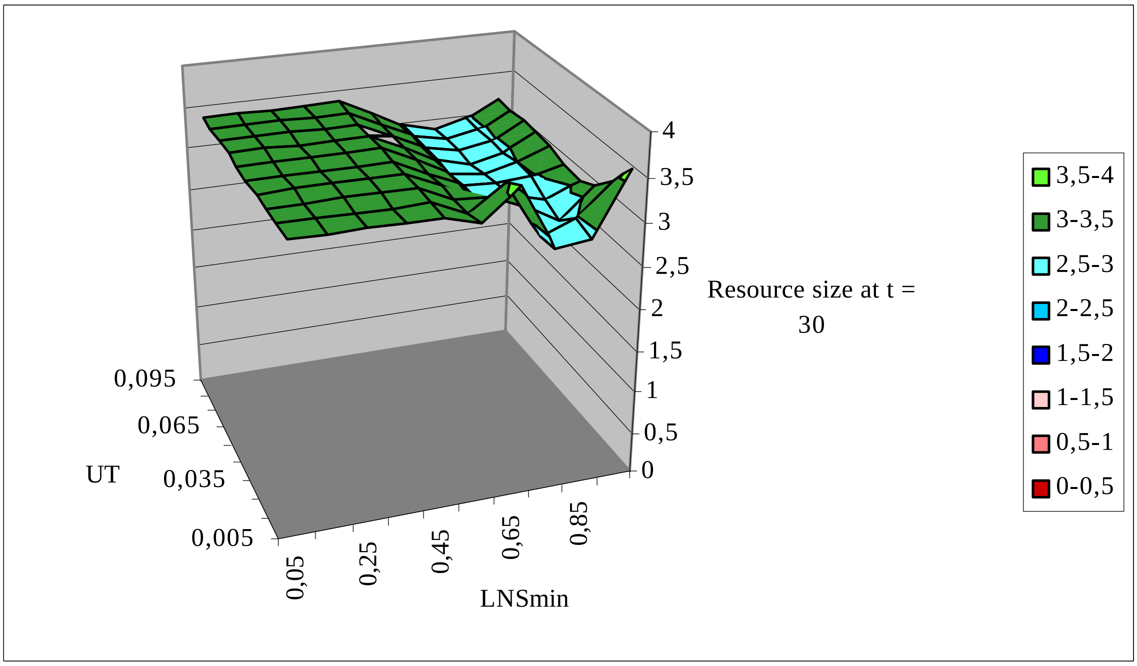

Figure 13: Resource size at t = 30 for different values of LNSmin and UT and two differing consumats, depletion rate = 2, σ = 0,02

behaviour to changes in the resource size. Remarkably, the consumats that always engage in reasoned processing (LNSmin = 0.95) have depleted the resource somewhat more than the consumats with a LNSmin ≤ 0.045. Because these latter consumats never deliberated on how much to work, they kept working for the same proportion of time whilst being satisfied. However, the consumats that engaged only in reasoned processing calculated that they could increase their consumption without depleting the resource. Apparently, the consumats with LNSmin ≤ 0.045 are under-harvesting.

For a low UT we observe some irregularities in the valley. This can be attributed to the fact that under these conditions the consumats are engaging in social processing for a considerable time. However, occasionally there may be periods of relative stability in the resource growth, resulting in individual processing. Scrutinising this experimental condition (low UT, LNSmin 0.65 – 0.85) we noticed that it mattered especially what behaviour Consumat 1 performed just before entering such a period. Was Consumat 1 working a lot (copied from Consumat 2), a period of automatic individual behaviour may result in habitual over-harvesting behaviour, depleting the resource to a value of 2.5 at t = 30. When Consumat 1 was working less before such a period, a less over-harvesting habit may persist for some time, resulting in a resource size at t = 30 of 4,5 and sometimes even about 5. These conditions thus appear to be more susceptible for coincidence, which is causing the irregularities in the valley as shown in Figure 13.

We replicated this experiment with a higher environmental uncertainty (σ = 0.04). Basically, the effects on the resource size were the same. Only the slope was a bit steeper for

LNSmin = 0.45, and the bottom of the valley was somewhat less regular for low values of UT, indicating that the effect of periods of relative stability as described before was even stronger.

A more accessible resource

In the next experiment, we made the resource more accessible. We again replicated the first 1000-run experiment, only here the difficulty to harvest was made independent of the resource size (accessibility factor $\pi = 0$). Consequently, it is always equally difficult to harvest, no matter how depleted the resource is. This resembles the resource dynamics that have been used in the experiments described in sections 7.1 and 7.2. In Figure 14 we depict the results obtained with this very accessible resource.

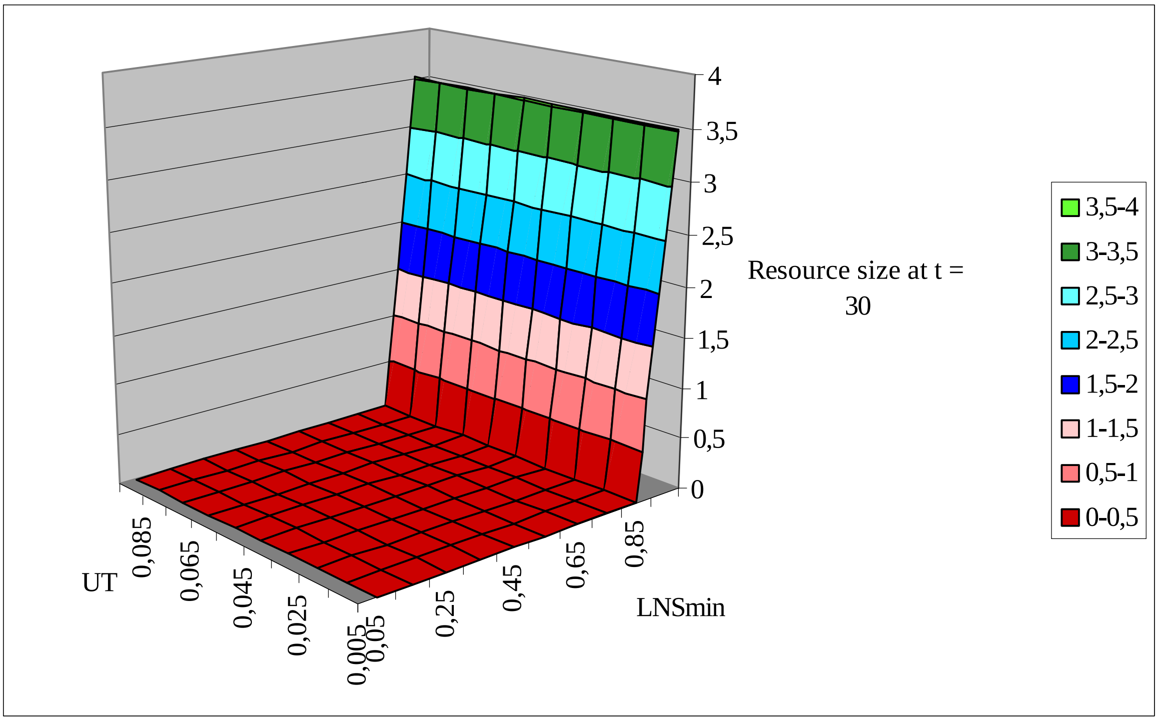

Figure 14: Resource size at t = 30 for different values of LNSmin and UT and two differing consumats, depletion rate = 0, σ = 0.02

What we observe is that for a LNSmin of 0.05 to 0.85 the resource completely depletes. Only when the consumats engage exclusively in reasoned behaviour (i.e., LNSmin = 0.95), they manage to prevent the resource from crashing, ending with a resource size of 3,5 at t = 30. The UT of the consumats appears to have no effect under this condition. This is explained by the fact that the accessibility of the resource is high, and the stochastic function in the growth function has no effect on the direct harvest of the consumats. Consequently, the consumats harvest what they expected to harvest, and thus they will not experience any uncertainty, despite the fluctuations in the resource growth-function. Even the consumats with a low UT are processing individually for as long as the resource is not fully depleted.

This dramatic effect mirrors the resource-crash in the n = 1 experiment (section 7.2), and can be explained as follows. The high accessibility of the resource causes at least Consumat 1 to engage in repeating as processing style for as long the resource is not completely depleted and

LNSmin < 0.95. Processing automatically, Consumat 1 does not perceive the depletion of the resource. Only when the resource is fully depleted, Consumat 1 starts deliberating, however, there is nothing left to reason about.

For conditions where LNSmin < 0.85, Consumat 2 engages in the same process as described above for Consumat 1. Only when LNSmin = 0.85, we observe that Consumat 2 starts with reasoned processing, and strongly decreases its consumption so as to preserve the outcomes in the long range. However, because Consumat 1 continues to over-harvest, this results in the resource being fully depleted only a bit later than had both consumats over-harvested.

We replicated this experiment with a larger environmental uncertainty ($\sigma = .04$), but the results were quite the same. Only the resource size was a bit smaller (3.28) for consumats with a LNSmin of 0.95. Consequently, the simulations show that the more accessible the resource, the smaller the effect of environmental uncertainty.

9: General conclusions and further research

In the previous sections we discussed the behavioural rules and presented some results obtained using the consumat approach. We are the first to admit that much more research has to be performed to further test and validate the consumat approach. Yet, we want to finish this paper with some preliminary conclusions on the behavioural rules and the effects that we observed using them in the consumat approach. We will end this section with suggestions for further research.

9.1 The behavioural rules

The behavioural rules that we have been using are very simple, and the behaviours of the consumats do not represent real human behaviour. Yet, the behavioural rules capture some basic behavioural processes, and as such allow experimentation with some simple behavioural dynamics. Not to our surprise, it appeared that deliberation was the cognitive process that resulted in the best possible outcome (LNS and resource size) in the long run. The introduction of repetition as a cognitive strategy revealed that the more accessible the resource, the more likely it is that consumats engage in habitual repetitive behaviour, thereby depleting the resource to a serious extent. The introduction of social processing (social comparison and imitation) yielded some remarkable effects. In the first place, social processing appeared to promote the spreading of over-harvesting behaviour. Second, it appeared that a higher proportion of social processing was associated with a slower behavioural adaptation to a depleting resource, because no new behaviours are being adopted during social processing. Third, it appeared that more social processing led towards less stable outcomes, making the process of resource management more susceptible for irregularities in the resource growth.

In the following sections, we will discuss the effects that several variables had on the management of a resource and the behavioural processing style of the consumats.

9.2: Time horizon as a cognitive ability

The first experiments, in which a single consumat was confronted with a resource, illustrated that the time-horizon the consumat is able to employ largely determines the degree to which the resource is being depleted. The longer the time-horizon, the earlier the consumat anticipates a possible resource depletion. The less frequent consumats engage in deliberation, the more important the time-horizon gets. If consumats are deliberating very frequently, a short time-horizon will suffice to prevent the resource from depleting. Flexibility is guaranteed because each time the consumats are deliberating they are capable of engaging in new behaviour. However, if the consumats rarely engage in deliberation this flexibility is lost. In such situations the time-horizon the consumat employs becomes very important, because it matters if the consumat occasionally looks forward for 20 time-steps or just 5. Here, employing a short time-horizon while deliberating may lead to the adaptation of a new behaviour that results in depletion occurring after the time-horizon, whereas the consumat with a long time-horizon has a better chance of finding a more sustainable consumption level. Consequently, the less frequent the consumat engages in deliberation, the more important the time-horizon of the consumat becomes.

9.3: Minimal level of need satisfaction

The minimal level of need satisfaction that satisfies the consumat (LNSmin) appears to be an important behaviour-determining factor. If the actual level of need satisfaction drops below the critical LNSmin, the consumats starts processing in a reasoned manner. Consequently, a consumat with a high value of LNSmin is hard to satisfy and thus will frequently engage in reasoned processing. In section 8 (Figures 11, 12 and 14) was demonstrated that reasoned processing results in a more sustainable use in case of a relative accessible resource. This causes the somewhat contradictory effect that the consumats that are the most easily to satisfy (low LNSmin) are the ones that are most likely to deplete a resource. For a less accessible resource (Figure 13) the effect turns around, showing that consumats with a higher LNSmin are less likely to under-harvest. We conclude that a higher LNSmin results in more frequent reasoned behaviour, thereby decreasing the likelihood of over-harvesting and of under-harvesting.

9.4: Uncertainty

In the 1000-run simulations we introduced a stochast ($N(0,\sigma)$) in the resource growth function that resembles environmental uncertainty. This environmental uncertainty causes that the actual outcomes the consumat gets often differ from what it expects to get. A difference between expected and actual outcomes causes the consumats to experience uncertainty (U). The uncertainty tolerance (UT) of the consumat expresses for what value of U the consumats engages in social processing. Uncertainty appears to be an important factor in the simulation experiments, because it stimulates social processing, which in its turn leads towards an increased consumption from the resource.

In the literature on resource dilemmas a distinction is made between environmental uncertainty and social uncertainty (Messick, Allison & Samuelson, 1988). Social uncertainty is associated with the absence of knowledge on the planned behaviour of others. Strictly spoken, our consumats do not experience social uncertainty because they expect the other consumat(s) to perform the same behaviour as they did in the previous time-step. This is not to say that these expectations always come true. Because our consumats do not experience social uncertainty, we can assume that all uncertainty in our simulations is environmental uncertainty. In the literature on social dilemmas, environmental uncertainty is operationalised as the lack of precise information regarding the resource-size (Wit & Wilke,1998; Hine & Gifford, 1996; Rapoport *et al.*, 1992; Messick *et al.*, 1988). This operationalisation of environmental uncertainty differs from our operationalisation of environmental uncertainty, which bears a more process-oriented character. In our definition, the uncertainty U depends on the difference between the actual and expected resource size development. If this difference exceeds the critical level of the uncertainty tolerance (UT), the consumat will engage in social processing. Unlike the experiments reported in the literature (Wit & Wilke ,1998; Hine & Gifford, 1996; Rapoport *et al.*, 1992; Messick *et al.*, 1988), here a (reasoned processing) consumat knows the exact resource-size and has a precise expectation regarding the resource-size. The resource size may have developed in an unexpected manner because of the consumptive behaviour of the other(s) and because of a stochastic part in the resource growth-function. Consequently, we state that uncertainty in our simulation experiments does not bear a pure environmental or social character, but rather notifies the state of the consumat. In our view this resembles real life situations, where the resource dynamics and behaviour of other people also interact and cannot be separated into pure types of uncertainties. Moreover, uncertainty is in the end a psychological construct that reflects the impossibility to predict outcomes accurately.

The simulation experiments reveal three different effects of uncertainty, respectively the optimism-effect, the imitation-effect and the adaptation-effect. To recapitulate, the optimism-effect holds that deliberating consumats, when confronted with a positive fluctuation in the resource growth, are more likely to develop an over-harvesting habit. 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. These three effects are all *process-effects*, that is, they describe the process that leads towards a certain outcome. To validate these effects empirically, it is necessary to observe if these effects also occur when real people are confronted with a resource management task.

Many experiments have been performed regarding the management of resources. Relative few of these have explored the effects of (environmental and social) uncertainty on people's harvesting behaviour. The behavioural processes the subjects engaged in have not been studied in these experiments. Consequentially, it is impossible to validate the process-effects as found in our simulation experiments on the basis of existing psychological experiments. To validate the process-effects we have found, we propose to observe the behavioural processes people engage in during resource management tasks. For the time being, we can check if our simulation results are at least in accordance with experimental research conducted with real people.

Despite the fact that our operationalisation of uncertainty is different, the effects of uncertainty we observed in our simulation experiments are pointing in the same direction as experimental research with human subjects. Several experiments showed that increased environmental uncertainty causes people to harvest more (Wit & Wilke ,1998; Hine & Gifford, 1996; Rapoport *et al.*, 1992; Messick *et al.*, 1988). Two explanations for this effect are discussed. First, is has been said that uncertainty leads towards an overestimation of the resource size. This 'environmental optimism' prompts individuals to harvest more (Rapoport, Budescu, Suleiman & Weg, 1992; Budescu, Rapoport & Suleiman, 1990). Rapoport *et al.* (1992) attribute this effect to the tendency of people to overweight the positive endpoint in a probability distribution. This would give rise to an optimistic estimate of the resource-size. Because the estimation of the resource took place before harvesting took place, this optimism effect is fundamentally different from the optimism-effect we discussed, which is a process-effect.

A second explanation of the increased consumption under conditions of environmental uncertainty states that the overestimation of the resource-size is no 'environmental optimism effect' but a post-experimental cognitive defence strategy to justify one's over-harvesting behaviour. Obviously this effect could not occur in our simulation experiments.

We suggest the optimism-effect and imitation-effect provide alternative explanations for these experimental results. We assume that in the experiments with human subjects the attendants were on the average not that motivated to engage in reasoned processing at every time-step, but not that unmotivated either to engage only in automatic processing. Switching between reasoned and automatic processing may cause the optimism-effect to occur. It might be that pre-experimental optimism actually has nothing to do with over-harvesting. Moreover, we expect that in experiments where the attendants had the possibility to communicate with each other, the attendants will engage in social processing more often. As a consequence, we expect that the imitation-effect may occur, thereby further contributing to resource depletion.

Both the imitation- and the optimism-effect stimulate over-harvesting, which may result in a higher satisfaction in the short run, but in a more depleted resource in the long run. This implies that only when the resource management task comprises a sufficient number of time-steps, these effects may manifest themselves to their full extent. Experiments that consider 10 time-steps, a number frequently reported in experimental studies on resource management, consider too short a period of time for the imitation- and the optimism-effect to unfold themselves to their full extent.

A next question is if the optimism, imitation and adaptation effects appear to have some practical relevance. If that is so, we could attribute some face-validity to these processes.

The optimism effect can be used to describe the process that occurs with fisheries. A fish-stock can be considered as a complex resource that has a random-like component in its grow function. Following a series of good catches, the fishermen are likely to have an optimistic expectation regarding the fish-stock. Consequently, they will harvest a lot, being satisfied and tending to ignore (scientific) information that suggests the resource may be depleting. However, after a series of bad catches, they may be convinced of the necessity to reduce their harvesting. Because they will be dissatisfied, the first news that the fish-stock is increasing will be elaborated and they will be very eager to increase their harvesting again.

The imitation effect can be exemplified with hoarding. When people are satisfied, but confronted with uncertainty regarding the availability of a certain good (e.g., food), they tend towards imitating the behaviour of others. This may lead to imitating people that are creating a private stock. The social spreading of such behaviour may lead towards hoarding. In the short run it may sustain the satisfaction in the hoarding people, but in the long run it may cause serious scarcity problems.

The adaptation-effect applies to situations where people are mainly engaging in social processing. Being a favourite conversation topic, the buying of a car appears to be a situation that incites much social processing. Because people are discussing quite a lot what other people do, really new behavioural options, such as new small cars or new public transportation services, are less likely to be discussed. This may be an important factor determining the speed at which a new product penetrates the market. It makes it obvious that it is a (intuitively) smart strategy of car-manufacturers to make surprising advertisements so as to incite discussion.

9.5: Accessibility of the resource

The effects of accessibility of the resource were quite straightforward: the more accessible the resource for harvesting, the quicker it depleted. A very accessible resource causes the consumats to be certain, because they actually harvest what they expected to harvest, until the resource is completely depleted. Because the consumats harvest what they expected, they are usually satisfied, until the resource is empty. Consequently, we found that a more accessible resource tends to provoke repetitive behaviour to be performed habitually, until the resource is empty. Empirical research is necessary to prove the existence and the size of such effects.

9.6: Further research

In this paper we applied the consumat approach to the well-known field of behaviour in commons dilemmas. We experienced that using our consumat approach we were able to perform many experiments under very well controlled situations. Consequently, we were able to find process-effects that are hard to find experimenting with human subjects. Moreover, in the previous sections several questions emerged regarding the validation of the effects that have been found using the consumats. This led to suggestions regarding empirical research using human subjects. In our opinion this exemplifies a fruitful simulation approach: simulation should make use of existing empirical research, and simulation should stimulate new empirical research. Behaviour simulation and empirical psychological research can be considered as research-tools that may be used in combination.

Regarding our research plans with the consumat approach, four lines of research are suggested.

Further developing the consumat approach

First we plan further experiments with the consumat approach. In order to increase our grip on the processes that evolve in the simulations, we intend to develop procedures for statistical analysis of simulation runs. This implies the manipulation of large data sets, because for large series of experiments containing time-series we want to study different variables, such as resource size, type of behavioural processing and level of need satisfaction. Moreover, we want to experiment with larger numbers of consumats, which would allow studying the effects of different patterns of heterogeneity in a population. For example, we would like to study the imitation effect for populations that differ with respect to the distribution of consumption abilities. Finally, we intend to develop variables that are useful in describing macro-level effects. The Gini-coefficient for example is a measure that indicates the skewness in a population regarding income. The question is if such measures can be developed for e.g., level of need satisfaction.

Empirical testing of the effects found with simulation

We propose to empirically test the imitation-effect in a laboratory-situation using human subjects. Before we do so, we have to perform many simulations so as to explore the conditions under which this effect occurs, and how this effect holds when larger groups of people are confronted with a commons dilemma. We suggest performing experiments in which the environmental uncertainty is being varied. Dependent variables are the behavioural process the subjects engage in, and the resource size. These dependent variables will be measured in a repeated-measurements design, because the resource management task will consider a substantial number of time steps (e.g., 30 time steps). We have to develop an appropriate method to measure the behavioural process the subjects engage in. Measuring how people retrieve different types of available information (e.g., via a computer display) may provide a promising method. Later experiments can be directed at the manipulation of minimal level of need satisfaction (LNSmin) and Uncertainty Tolerance (UT).

Application of the simulation to more complex situations

To apply the consumat approach to more realistic problems, we first intend to confront the consumats with a more complex ‘micro-world’. This would imply an integrated assessment exercise, because a behavioural model (the consumats) and an ecological economic model (the micro-world) will interchange data. For this, we have further developed Lakeland (De Vries & De Greef, 1991). Lakeland consists of a computerised micro-world containing a lake with fish and micro-organisms, a gold mine, a government that determines the fishing season and that may allow foreign fleets to fish in the lake, impose taxes on the consumats and the like. The complex dynamics of Lakeland allow us to study the concept of sustainability in a more realistic yet controllable context. Such an integrated assessment model makes it also possible to perform experiments with real people managing a simulated world. Distributing knowledge on different subsystems of the model across several people would create a situation where different specialists have to collaborate in a resource management task.

Subsequently, we intend to apply the consumat approach to a well-defined real world problem. It would, for example, be a challenge to try to model household consumption or personal transportation. This would require the collection of data on the need-satisfying aspects of various behavioural opportunities. Such an exercise would also have to operationalise the response-system as described in section 4. Operationalising the response-system would allow for the including of the supply side in the simulations (product manufacturers, service providers), and allows performing policy exercises with the model, testing various strategies to affect consumer behaviour.

Simulating of other empirically found effects:
We are convinced that many more behavioural factors and processes can be studied using the consumat approach. Whenever an effect or process is affected by personality factors, and the interactions between people are highly susceptible to what other people do, it may be very difficult to attribute an observed effect to a certain combination of variables. Especially where process-effects occur because of the interaction between individual and group factors, the consumat approach seems appropriate. Employing the consumat approach allows one to control for all the unwanted variance, and check under what precise conditions an effect may occur. A subsequent empirical study may be performed to validate the results of the simulation. Simulations thus help to identify effects that are hard to perceive in reality, but which may play important roles.

Examples of the investigation of other behavioural factors and effects are the effects of social orientations and the lock-in of consumer behaviour (Janssen & Jager, 1999). Within the commons-dilemma simulation we are currently working on the inclusion of social orientations, such as individualism, cooperation and competition. This allows for the simulation of the resource management task using consumats having different perspectives on the distribution of outcomes.

An example of a special behavioural effect is the lock-in effect, that describes how the process evolves that causes product A to conquer a large market share whilst product B, being equally good, only has a marginal market-share. In simulating this process, we discovered that two types of lock-in occur, depending on what needs are being satisfied by the products (Janssen & Jager, 1999). Besides the total lock-in, which describes the process in which one product is totally dominating the market, a spatial lock-in occurred in which different groups of consumats consuming the same product emerged. We hope that the consumat approach will prove to be fruitful for investigating these and other behavioural processes.

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