Modelling Greed of Agents in Economical Context

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Abstract. A classical debate in economics addresses the advantages and drawbacks of modelling from a macroeconomics perspective as opposed to modelling from a microeconomics perspective. Form the latter psychological aspects at an individual level can be taken into account in a differentiated manner. Within computer science and AI, a similar debate exists about the differences between agent-based and population-based modelling. This paper aligns both debates by exploring the differences and commonalities between population-based and agent-based modelling in economical context. A case study is performed on the interplay between individual greed as a psychological concept and global economical concepts. It is shown that under certain conditions agent-based and population-based simulations show similar results.

Keywords: economics, greed, agent-based and population-based modelling.

1 Introduction

Traditionally, macroeconomics addresses the behaviour of a world-wide, national or regional economy as a whole [3], whereas microeconomics investigates the economic behaviour and decision making of individual agents, for example, consumers, households or firms [11]. Since the latter aims to understand why and how agents make certain economic decisions, various social, cognitive, and emotional factors of human behaviour are studied. This has resulted in the emergence of the field of behavioural economics [14]. Although this may be very useful when one wants to analyse the behaviour of individual agents, there is some debate about the extent to which it is useful to incorporate these aspects when studying global processes in economics, e.g., [5]. Do personal factors such as risk avoidance, greed, and personal circumstances provide more insight in the global patterns, or can they simply be ignored or treated in a more abstract, aggregated manner? This paper provides some answers to these questions from a computational perspective.

In recent years, various authors have studied processes in economics by building computational models of them, and analysing the dynamics of these models using agent-based simulation techniques [15]. Ironically, also in the area of agent-based modelling, a debate exists about the pros and cons of two perspectives, namely agent-based and population-based modelling. Agent-based models are often assumed

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to produce more detailed, faithful behaviour, whereas population-based models abstract from such details to focus on global patterns (e.g., [2], [7], and [9]).

Given these similarities between the debate between macro- and microeconomics on the one hand, and the debate between population-based and agent-based modelling on the other hand, it makes sense to align the two debates. Hence, the goal of the current paper is to explore the differences and commonalities between population-based and agent-based modelling in an economical context. This will be done via a case study on the interplay between individual greed and the global economy.

This paper is structured as follows. In Section 2, the existing debate between agent-based and population-based modelling is briefly explained. In Section 3, both an agent-based and a population-based model are introduced for the example domain. In Section 4, a number of simulation results of both models are shown, and the similarities are discussed. Next, Section 5 provides a mathematical analysis on the models. Section 6 concludes the paper with a discussion.

2 Agent-Based versus Population-Based Modelling

The classical approaches to simulation of processes in which larger groups of agents are involved are population-based: a number of groups are distinguished (populations) and each of these populations is represented by a numerical variable indicating their number or density (within a given area) at a certain time point. The simulation model takes the form of a system of difference or differential equations expressing temporal relationships for the dynamics of these variables. Well-known classical examples of such population-based models address ecological processes, for example, predator-prey dynamics (e.g., [6], [12], [13] and [16]), and the dynamics of epidemics (e.g., [1], [6], and [8]). Such models can be studied by simulation and by using analysis techniques from mathematics and dynamical systems theory.

From the more recently developed agent system area it is often taken as a presupposition that simulations based on individual agents are a more natural or faithful way of modelling, and thus will provide better results (e.g., [2] and [7]). Although for larger numbers of agents such agent-based approaches are more expensive computationally than population-based approaches, such a presupposition may provide a justification of preferring their use over population-based approaches, in spite of the computational disadvantages. In other words, they are justified because the results are expected to deviate from the results of population-based simulation, and are considered more realistic. However, in contrast there is another silent assumption sometimes made, namely that for larger numbers of agents (in the limit), agent-based simulations approximate population-based simulations. This would indicate that for larger numbers of agents agent-based simulation just can be replaced by population-based simulation, which would weaken the justification for agent-based simulation discussed above. In, e.g., ([4; 9]), these considerations are explored for the domains of epidemics and crime displacement, respectively. The results put forward in these papers reveal several commonalities between both types of simulation, but also some differences. For example, for some specific parameter settings (concerning population size and rationality of the individual agents, among others), the results of population-based simulation seem to approximate those of agent-based simulation, whereas for other situations some differences can be observed. Furthermore, as could be expected, the computation time of the populations-based simulations is shown to be much lower than that of the agent-based simulation.

In the next sections, similar issues are explored, but this time for a domain within economics. Comparative simulation experiments have been conducted based on different simulation models, both agent-based and population-based.

3 The Agent-Based and Population-Based Simulation Model

In this section, the two simulation models are introduced. First, an agent-based perspective is taken. The main idea behind this model is that the state of the global (world) economy influences the level of greed of the individual agents in the population, which is supposed to relate to the risk level of their investment decisions: in case the economic situation is positive, then people are tempted to take more risk. Moreover, the investment decisions of the individual agents in turn influence the global economy: in case agents become too greedy [10], this is assumed to have a negative impact on the economic situation, for example, due to higher numbers of bankruptcy. In addition, the state of the economy is assumed to be influenced by technological development which is driven by innovation. Inspired by these ideas, the interplay between agents' greed and the global economy is modelled as a dynamical system, in a way that has some similarity to predator-prey models in two variations: agent-based, where each agent has its own greed level, and population-based, where only an average greed level of the whole population is considered.

The agent-based model assumes n heterogeneous agents, which all interact within a certain economy. For each agent k, the individual greed is represented using a variable y_k, and the global economic situation is represented using a variable x. The complete set of variables and parameters used in the model is shown in Table 1.

Table 1. Variables and parameters used in the agent-based model

Variables	x	World economy
	$y^{(1)}, ..., y^{(n)}$	Greed of individual agents
	z	Average greed of the agents (i.e., arithmetic mean of all $y^{(k)}$)
	TD	Technological development level
Parameters	a	Growth rate of the economy
	b	Decrease rate of the economy due to average greed
	$c_1, ..., c_n$	Growth rate of an agent's greed based on the economy
	$e_1, ..., e_n$	Decrease rate of an agent's greed
	inn	Innovation rate

Based on these concepts, a system of difference equations was designed that consists of $n+3$ formulae; here (2) specifies a collection of n equations for each of the n agents, where each agent has its individual values for $y^{(k)}$, c_k and e_k:

(1) Updating the world economy

$$x_{new} = x_{old} + (a*x_{old} - b*x_{old}* z_{old}) * \Delta t$$

(2) Updating the greed of the agents

$$y^{(k)}_{new} = y^{(k)}_{old} + (c_k*b* x_{old}*y^{(k)}_{old} *(2-y^{(k)}_{old}) / TD_{old} - e_k*y^{(k)}_{old}) * \Delta t \quad \text{(for all agents } k\text{)}$$

(3) Updating the technological development

$$TD_{new} = TD_{old} + inn * TD_{old} * \Delta t$$

(4) Aggregating greed

$$z_{old} = (\Sigma_k \ y^{(k)}_{old})/n$$

Table 2. Variables and parameters used in the population-based model

Variables	x	World economy
	y	Average greed of the population
	TD	Technological development level
Parameters	a	Growth rate of the economy
	b	Decrease rate of the economy due to population greed
	c	Growth rate of the population greed based on the economy
	e	Decrease rate of the population greed
	inn	Innovation rate

The population-based dynamical model is similar to the agent-based model, but the difference is that it abstracts from the differences of the individual agents. This is done by replacing the average greed z over all $y^{(k)}$ in formula (1) by one single variable y indicating the greed of the population as a whole, and using a single formula (2), which is only applied at the population level, in contrast to the collection of formulae (2) in the agent-based model, which are applied for all agents separately. The resulting population-based model is shown in Table 2 and in the formulae below.

(1) Updating world economy

$$x_{new} = x_{old} + (a*x_{old} - b*x_{old}* y_{old}) * \Delta t$$

(2) Updating the greed of the population

$$y_{new} = y_{old} + (c*b* x_{old}*y_{old} *(2-y_{old}) / TD_{old} - e*y_{old}) * \Delta t$$

(3) Updating the technological development

$$TD_{new} = TD_{old} + inn * TD_{old} * \Delta t$$

Note that in differential equation format the agent-based and population-based dynamical model can be expressed by n+2, respectively 3 differential equations as shown in Table 3. Moreover, as the innovation rate inn is assumed constant over time, for both cases the differential equation for TD can be solved analytically with solution $TD(t) = TD(0)\ e^{inn\ t}$.

Table 3. The two models expressed by n+2, respectively 3 differential equations

Agent-based model	Population-based model
$dx/dt = ax - bxz$	$dx/dt = ax - bxy$
$d\,y^{(k)} /dt = (c_k b\, xy^{(k)}(2- y^{(k)}) / TD) - e_k\, y^{(k)}$	$dy/dt =(cb\, xy(2-y) / TD) - ey$
$dTD/dt = inn\ TD$	$dTD/dt = inn\ TD$
$z = (\Sigma_k \ y^{(k)})/n$	

4 Simulation Results

Based on the model introduced above, a number of simulation experiments have been performed under different parameter settings (with population size varying from 2 to 400 agents), both for the agent-based and for the population-based case. Below, a number of them are described. First an agent-based simulation experiment is described. In this first experiment, 25 agents were involved. The initial settings used for the variables and parameters involved in the experiment are shown in Table 4.

Table 4. Initial settings for variables and parameters

Parameter	Value	Variable	Initial value
a	*1.5*	*x*	*5*
b	*5.8*	*y*	random in [*0.2, 0.3*]
c	random in [*0.0260, 0.0274*]	*TD*	*1*
e	random in [*0.85, 0.89*]		
inn	*0.01*	Δt	*0.1*

The results of the simulations are shown in Figure 1a and 1b. In Figure 1a, time is on the horizontal axis and the value of the world economy is represented on the vertical axis. It is evident from the graph that the economy grows as time increases (but fluctuating continuously). Figure 1b shows the individual greed values of all 25 agents. As can be seen they fluctuate within a bandwidth of about 25% with lowest points between about *0.1* and *0.15,* and highest points around *0.45*. The pattern of the average greed over all 25 agents is shown in Figure 1c.

For the population-based simulation, all the parameter settings are the same as in Table 4, except parameters *y*, *c* and *e*. The values for parameters *y*, *c* and *e* used in the population-based simulation were determined on the basis of the settings for the agent-based simulations by taking the average *y*, *c* and *e* for all fifty agents:

$$y = (\Sigma_k \, y_k)/n \qquad\qquad c = (\Sigma_k \, c_k)/n \qquad\qquad e = (\Sigma_k \, e_k)/n$$

The results of the population-based simulations are shown in Figure 2a (economy) and 2b (greed). As can be seen from these figures, the results approximate the results for the agent-based simulation. The difference of the world economy for the population-based and agent-based simulation (averaged over all time points) turns out to be 0.112, and the difference between the average greed of the 25 agents in the agent-based simulation and the greed for the population-based simulation is 0.005.

In addition, a number of simulation runs have been performed for other population sizes. Figure 3a displays the (maximum and average) difference between the world economy in the agent-based model and the world economy in the population-based model for various population sizes. Similarly, Figure 3b displays the difference between the average greed in the agent-based model and the greed in the population-based model for various population sizes. The red line indicates the maximum value and the blue line the average value over all time points. As the figures indicate, all differences approximate a value that is close to 0 as the population size increases. Although the results of these particular simulation experiments should not be over-generalised, this is a first indication that for higher numbers of agents, the results of the agent-based model can be approximated by those of the population-based model.

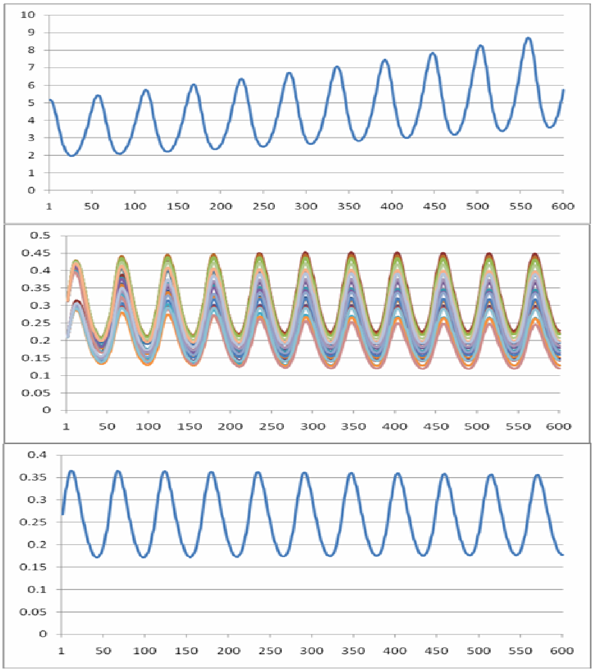

Fig. 1. Agent-based simulation results:
a) world economy, b) individual greed of 25 agents, and c) average greed (over 25 agents)

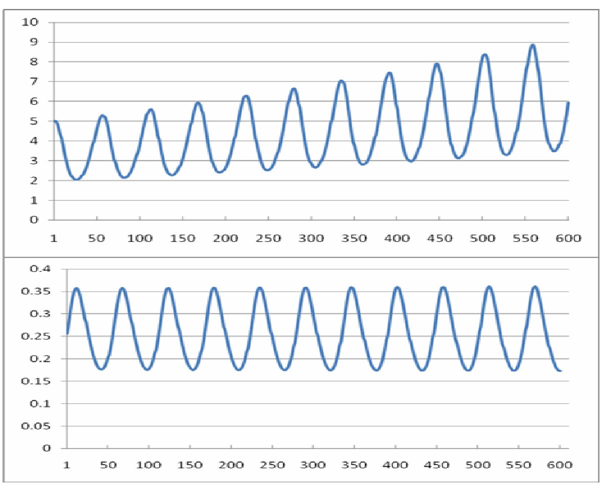

Fig. 2. Population-based simulation results: a) world economy, and b) greed

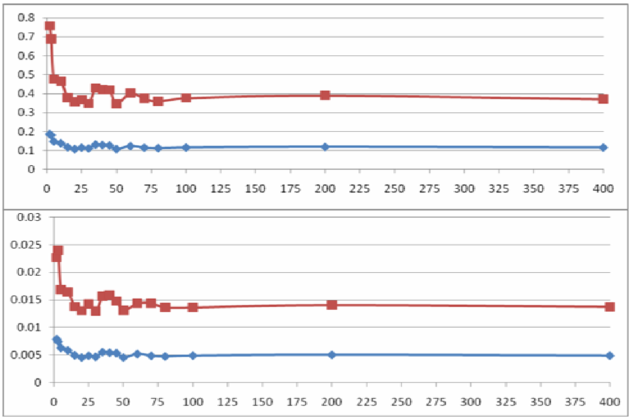

Fig. 3. Difference between both models for various population sizes:
a) world economy, and b) greed

5 Mathematical Analysis

In this section a mathematical analysis is presented concerning the conditions under which partial or full equilibria occur; it is assumed that the parameters *a, b, c* and *e* are nonzero. For an overview of the equilibria results, see Table 5.

Dynamics of the economy. The economy grows when $dx/dt > 0$ and shrinks when $dx/dt < 0$; it is in equilibrium when $dx/dt = 0$. Assuming x nonzero, according to equation (1) for the population-based model, this can be related to the value of the greed as follows

economy grows	$dx/dt > 0 \Leftrightarrow ax - bxy > 0 \Leftrightarrow a - by > 0 \Leftrightarrow y < a/b$
economy shrinks	$dx/dt < 0 \Leftrightarrow ax - bxy < 0 \Leftrightarrow a - by < 0 \Leftrightarrow y > a/b$
economy in equilibrium	$dx/dt = 0 \Leftrightarrow ax - bxy = 0 \Leftrightarrow a - by = 0 \Leftrightarrow y = a/b$

So, as soon as the greed exceeds a/b the economy will shrink (for example, due to too many bankruptcies), until the greed has gone below this value. This indeed can be observed in the simulation traces. For the agent-based model similar criteria can be derived, but then relating to the average greed z instead of y.

Full Equilibria for the Population-Based Model. The first issue to be analysed is whether (nonzero) equilibria exist for the whole population-based model, and if so, under which conditions. This can be analysed by considering that x, y and TD are constant and nonzero. For x constant above it was derived from (1) that the criterion is $y = a/b$. For TD constant the criterion is $inn = 0$ as immediately follows from (3). The criterion for $dy/dt = 0$ can be derived from (2) as follows

$$dy/dt = (cbxy(2-y) / TD - ey) = 0 \Rightarrow cbx(2-y) / TD = e \Rightarrow x = (e / ((2b-a)c))\, TD$$

This provides the conditions for a full equilibrium

$$(1)\ \ y = a/b \qquad (2)\ x = (e / ((2b-a)c))\, TD \qquad (3)\ inn = 0$$

It turns out that for any nonzero setting for the parameters a, b, c and e and for setting $inn = 0$ for the innovation parameter and for any value of TD a nontrivial equilibrium is (only) possible with values as indicated above. Note that this shows that for inn nonzero a nontrivial full equilibrium is not possible, as TD will change over time. However, partial equilibria for greed still may be possible. This will be analysed next

Equilibria for greed in the population-based model. Suppose that the innovation inn is nonzero. In this case it cannot be expected that technological development TD and economy x stay at constant nonzero values. However still for the greed variable y an equilibrium may exist. From the second equation (2) by putting $dy/dt = 0$ it follows

$$cbx\,(2\text{-}y)\,/\,TD = e \;\Rightarrow x = \alpha\, TD \qquad \text{with } \alpha = e\,/\,cb\,(2\text{-}y)$$

By filling this in differential equation (1) it follows

$$d\,\alpha\, TD\,/dt = a\alpha\, TD - b\alpha\, TD\, y \Rightarrow d\, TD\,/dt = (a - by)\, TD$$

By differential equation (3) it can be derived

$$d\, TD\,/dt = (a - by)\, TD = inn\, TD \;\Rightarrow\; (a - by) = inn \;\Rightarrow\; y = (a - inn)/b$$

Note that for $inn = 0$ this also includes the result for the full equilibrium obtained earlier. Moreover, as the equation for TD can be solved analytically, and $x = \alpha\, TD$, also an explicit solution for x can be obtained:

$$TD(t) = TD(0)\, e^{inn\, t} \qquad\qquad x(t) = \alpha\, TD(t) = \alpha\, TD(0)\, e^{inn\, t} = x(0)\, e^{inn\, t}$$

Here α can be expressed in the parameters as follows:

$$\alpha = e\,/\,cb\,(2\text{-}y) = e\,/\,cb\,(2\text{-}(a - inn)/b) = (e\,/\,c)\,/\,(2b - a + inn)$$

This shows that according to the model greed can be in an equilibrium $y = (a - inn)/b$, in which case the economy shows a monotonic exponential growth.

Full Equilibria for the agent-based model. Similar to the approach followed above:

(1) $dx/dt = (ax - bxz) = 0$
(2) $d\, y^{(k)}\,/dt = (c_k bx\, y^{(k)}\, (2\text{-}\, y^{(k)})\,/\,TD - e_k\, y^{(k)}) = 0$ (for all agents k)
(3) $dTD/dt = inn\, TD = 0$
(4) $z = (\,\Sigma_k\; y^{(k)}\,)/n$

A full equilibrium can be expressed by the following equilibria equations:

(1) $ax = bxz$ (2) $c_k bx\, y^{(k)}\, (2\text{-}\, y^{(k)})\,/\,TD = e_k\, y^{(k)}$
(3) $inn\, TD = 0$ (4) $z = (\Sigma_k\; y^{(k)}\,)/n$

It is assumed that a, b, c_k and e_k are nonzero. One trivial solution is $x = y^{(k)} = 0$. Assuming that x, $y^{(k)}$ and TD all are nonzero, the equations (1) to (3) are simplified:

(1) $a = bz$ (2) $c_k bx\, (2\text{-}\, y^{(k)})\,/\,TD = e_k$ (3) $inn = 0$ (4) $z = (\,\Sigma_k\; {}^{y(k)}\,)/n$

This provides

(1) $z = a\,/b$ (2) $y^{(k)} = {}^{2-}\, e_k\, TD/(c_k bx)$ (3) $inn = 0$ (4) $z = (\,\Sigma_k\; y^{(k)}\,)/n$

From the second, first and last equation it follows that

$$a/b = (\Sigma_k\ y^{(k)})/n = (\Sigma_k\ (2- e_k\ TD/(c_k bx)))/n = 2 - \Sigma_k\ (e_k\ TD/(c_k bx))/n =$$
$$2 - (TD/bx)(\Sigma_k\ (e_k/c_k))/n \ \Rightarrow\ x = TD\ \Sigma_k\ (e_k/c_k)/(2b - a)n$$

From this the values for the $y^{(j)}$ can be determined:

$$y^{(j)} = 2- e_j\ TD/(c_j bx) = 2- e_j\ TD/(c_j b\ TD\ \Sigma_k\ (e_k/c_k)/(2b - a)n)$$
$$= 2- e_j/(c_j b\ \Sigma_k\ (e_k/c_k)/(2b - a)n) = 2- e_j(2b - a)n/(c_j b\ \Sigma_k\ (e_k/c_k))$$
$$= 2- e_j(2 - (a/b))n/(c_j\ \Sigma_k\ (e_k/c_k)) = 2- (2 - (a/b))n/(\Sigma_k\ (e_k/e_j)(c_j/c_k))$$

It turns out that for any nonzero setting for the parameters a, b, c_k and e_k and for setting $inn = 0$ for the innovation parameter, and for any value of TD a nontrivial equilibrium is (only) possible with values as indicated above.

Equilibria for greed for the agent-based model. From the second equation $c_k bx\ (2-y^{(k)})/TD = e_k$ with $y^{(k)}$ constant it follows that $x = \alpha_k\ TD$ with α_k the constant $\alpha_k = e_k/c_k b\ (2-y^{(k)})$ which apparently does not depend on k, as both x and TD do not depend on k, so the subscript in α_k can be left out. Filling this in (1) provides:

$$d\ \alpha\ TD/dt = (a\alpha\ TD - b\alpha\ TD\ z) \ \Rightarrow\ d\ TD/dt = (a - bz)\ TD$$

By differential equation (3) it can be derived

$$dTD/dt = (a - bz)\ TD = inn\ TD \ \Rightarrow (a - bz) = inn \ \Rightarrow\ z = (a - inn)/b$$

Now the equilibrium values for $y^{(j)}$ can be determined as follows.

$$\alpha = e_k/c_k b\ (2-y^{(k)}) \ \Rightarrow\ \quad 2-y^{(k)} = e_k/\alpha\ c_k b \quad \Rightarrow \quad y^{(k)} = 2- e_k/c_k\ \alpha b$$

Next the value of α is determined $z = (\Sigma_k\ y^{(k)})/n = \Sigma_k\ (2- e_k/c_k\ \alpha b)/n = 2- (1/\alpha bn)\ \Sigma_k\ e_k/c_k$. Since $z = (a - inn)/b$ it follows

$$(a - inn)/b = 2- (1/\alpha bn)\ \Sigma_k\ e_k/c_k \quad \Rightarrow (1/n\alpha)\ \Sigma_k\ e_k/c_k = 2b- (a - inn) \quad \Rightarrow$$
$$\Sigma_k\ e_k/c_k = (2b- (a - inn))\ n\alpha \ \Rightarrow\ \alpha = \Sigma_k\ (e_k/c_k)/(2b- (a - inn))n$$

Given this value for α the equilibrium values for the greed $y^{(j)}$ are

$$y^{(j)} = 2- e_j/c_j\ \alpha b = 2- e_j/b\ c_j \Sigma_k (e_k/c_k)/(2b- (a - inn))n$$
$$= 2- (2- (a - inn)/b)\ n/\ \Sigma_k (e_k\ c_j/e_j\ c_k)$$

Table 5. Overview of the equilibria of the two models

	Agent-based model	**Population-based model**
Full equilibrium	$inn = 0$ $x = (1/(2b - a))\ (\Sigma_k\ (e_k/c_k)/n)\ TD$ $z = a/b$ $y^{(j)} = 2- (2 - (a/b))\ n\ /\ \Sigma_k\ (e_k/e_j)(c_j/c_k)$	$inn = 0$ $x = (1/(2b-a))(e/c))\ TD$ $y = a/b$
Partial equilibrium for greed	$TD(t) = TD(0)\ e^{inn\ t}$ $x(t) = (1/(2b- a + inn))\ (\Sigma_k (e_k/c_k)/n)\ TD(0)\ e^{inn\ t}$ $z = (a - inn)/b$ $y^{(j)} = 2- (2- ((a - inn)/b))\ n/\ \Sigma_k (e_k/e_j)(c_j/c_k)$	$TD(t) = TD(0)\ e^{inn\ t}$ $x(t) = (1/(2b - a + inn))\ (e/c)\ TD(0)\ e^{inn\ t}$ $y = (a - inn)/b$

6 Discussion

This paper discusses similarities and dissimilarities between agent-based models and population-based models in behavioural economics. Inspired by variants of predator prey models (e.g., [6], [12], [13], and [16]), a dynamic behavioral economical model was developed for the relationship between individual agents' greed and the global economy. Simulation experiments for different population sizes were performed for both an agent-based and a population-based model. For both cases the results show that the world economy grows in a fluctuating manner over time and the average greed of the agents fluctuates between *0.1* and *0.45*. A mathematical analysis was performed for both, showing the conditions under which equilibria occur.

It turned out that, in particular for large population sizes, the differences in the economy and average greed between agent-based and population based simulations are close to zero. In different domains, in [4] and [9], under certain conditions similar results were obtained. In literature on agent-based simulation such as in (e.g., [2] and [7]), it is argued that although agent-based modelling approaches are more expensive computationally than population-based modelling approaches, they are preferable due to more accuracy. In contrast to this, the results in the current paper indicate that for the considered domain the agent-based approaches can be closely approximated by population-based simulations. On the other hand, for cases with a rather small number n of agents the population-based approach may be inadequate. This may raise the question whether a more differentiated point of view in the debate can be considered, namely that for numbers of n agents exceeding a certain N, population-based models are as adequate as agent-based models, whereas for $n < N$ agent-based models are more adequate. A challenge may be to determine this number N for different cases.

For future work, more differentiated personality aspects will be included in the agent model, concerning risk profile and emotions (e.g., feeling insecure) involved, depending upon which decisions are made for the investment (in banking products or stock market). A further aim is to develop a web-based business application incorporating a virtual agent that will interact with a client and regulate the emotions.

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