Agent-based computer modeling for understanding organizational dynamics

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ABSTRACT

Although it has been argued that understandings of dynamic linkage between individuals (micro) and organizations (macro) is critical for explaining organizational phenomena, the traditional methods, such as survey and interview are limited in their ability to examine research questions to describe bottom-up effect by aggregating data. Here we propose agent-based modeling as a tool to elaborate theoretical and practical implications to understand organizational dynamics. Agent-based modeling is a computer simulation method that allows researchers to examine dynamic processes in which heterogeneous micro-level actors interact with other agents and environmental conditions, thereby giving rise to macro-level phenomena. This capability enables us to simulate coordination processes within organizations. In the current study, we show an example of such dynamics by applying the research setting of the evolution of cooperation to the organizational contexts. The results showed that the heterogeneity in capability is critical for the organizational effectiveness (or, high organizational performance). Further, a certain structural arrangement plays an important role to the coordination process to withdraw a high organizational performance. Implications for management research and practices are discussed.

***Keywords*:** Organizational dynamics, cooperation, heterogeneity, group formation, coordination

INTRODUCTION

Micro-Macro Dynamics of Organization

Organization is defined as a social unit of people that is structured and managed to pursue collective goals. All organizations have a management structure that determines relationships between the different activities and the members and subdivides. They also assign roles, responsibilities, and authority to carry out different tasks. The structures of an organization are not static. They are changing along with external environments and internal necessities. The consisting members of an organization are changing, too. The member changes are usually more frequent than structural changes.

Insert Figure 1 about here

Organizational researchers have tried to capture the dynamics of organization. In sociology, Coleman (1990) [1] shows a graphic representation of this dynamic relationship between individuals and society (Figure 1). Figure 1, also known as "boat," illustrates how macro and institutional factors affect conditions of individual actions (Arrow 1) leading to individual actions themselves (Arrow 2), and also how individual actions lead to social outcomes (Arrow 3), in addition to macro to macro relation (Arrow 4). In this figure, individual actions refer to "micro," while social facts and social outcomes refer to "macro." Felin, Foss, & Ployhart (2015) [2], quoting this figure as "a general model of social science explanation," claim that microfoundations are significant in the context of organizational analysis, especially in strategy and organizational theory.

Methodological Constraints to describe organizational dynamics

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Although organizational researchers are aware of the importance of analyzing micro-macro dynamics of organization, they have found difficulties to address appropriate methods to do it. (Ployhart & Hale, 2014 [3]; Kozlowski, Chao, Grand, Braun, & Kuljanin, 2013 [4]). One major problem is methodological limitation to handle multi-level unit of analysis ranging from individual to lager divisions or even subsidiaries in conglomerate. Kozlowski et al. (2013) [4] highlight two fundamental systems processes in organizations: top-down cross-level contextual effects and bottom-up emergence. They argue that remarkable research neglect shown to emergent phenomena. What they claim here is that researchers do not pay much attention to Arrow 3 in Figure 1 while Arrow 1, Arrow 2, and Arrow 4 are well focused by researchers.

A major reason why Arrow 3 is neglected refers to the constraint of methodologies in organizational study. Many of studies on organizations rely on the methodological individualism, which argues that organizational phenomenon can be described as accumulation of individuals' motivation and behaviors at least in principle. Researchers relying on this view usually conduct interviews, surveys, and experiments. These methods take individuals as the unit of analysis and, in most cases, have an assumption that a collective outcome would be caused by simple and/or linear accumulation of individual characteristics. These approaches are useful to analyze correlational and/or causal relationship from a social fact to conditions of individual action (Arrow 1), from conditions to individual actions (Arrow 2), and from social facts to another social outcome (Arrow 4). In fact, these methodological approaches have been made a number of significant contribution to acquire academic knowledge on organizations.

In fact, some recent organizational studies try to capture Arrow 3 processes by analyzing how individual, micro actions lead to organizational macro phenomena (Kouamé, & Langley, 2017 [5]; Salvato & Vassolo 2017 [6]). Salvato & Vassolo (2017) [6], for example, propose a new theoretical approach to explain emergent property of organizational outcome. Emergent property refers to mechanism of "unintentional collective outcome." Emergent property is not linear accumulation of micro movements, but non-linear or sometime unexpected-function-based collective state, which means reductionism is not working to explain a collective outcome (Elster, 2003 [7]). Salvato & Vassolo (2017) [6] point out the importance of explaining how individuals' capacity and interpersonal relationships could produce the organizational outcome as emergent property.

Agent-based Simulation and Prototyping for Organizational Study

In this paper, aiming to examine Arrow 3 process in the context of organizational study, we introduce an agent-based model (ABM) of computer simulation to describe dynamic interaction between organizational phenomenon (macro state) and individual behaviors (micro actions) in one model. Agent-based model has been a popular method in evolutionary biology (i.e., Nowak & Sigmund, 1998 [8]), economics (i.e., Schelling, 1971 [9]), and political science (i.e., Axelrod & Hamilton, 1981 [10]). ABM is one of computational models for simulating the actions and interactions of autonomous agents (in this study, they are individuals in organization) to assess their collective effects on the system as a whole (in this study, they are the effects on organizational performance). Most agent-based models are composed of: 1) a certain number of agents with several characteristics; 2) agents' decision-making rules; 3) learning rules or adaptive processes; 4) an interaction setting; and 5) an external environment. Typically, the implementation of ABM is computer simulation.

There have been actually several organizational researchers pointing out the importance of simulation study (Felin et al., 2015 [2]; Fioretti, 2012 [11]). However, researchers are still exploring to find the fundamental model to describe the nature of organizations (Puranam, Stieglitz, Osman, & Pillutla, 2015 [12]) and have not reach a consensus. In this study, we are proposing Public Goods Game (PGG), alternatively called Social Dilemma (SD), as a fundamental model of organization. Social Dilemma is, as Baron (2000) [13] notes, a situation where "each person benefits by consuming the fruits of others' labor and laboring himself as little as possible—but if everyone behaved this way, there would be no fruits to enjoy"(p. 434) PGG is the game theoretical version of SD, and the most major model to address how to achieve cooperation in a large-scale group in social and natural sciences such as political science (i.e., Riolo, Cohen, & Axelrod, 2001 [14]), evolutionary biology (i.e., Ohtsuki, & Iwasa, 2007 [15]), cultural anthropology (i.e., Henrich & Henrich, 2007 [16]), social psychology (i.e., Yamagishi, 1986 [17]), and economics (i.e., Fehr & Gächter, 2000 [18]). Theories and empirical findings on PPG in such areas indicate that cooperation cannot be achieved from laissez-faire. Many researchers agree that certain combination of psychological tendencies (i.e., strong reciprocity) (Bowles & Gintis, 2011 [19]) and institutional arrangement (i.e., collective punishment) (Sigmund, De Silva, Traulsen, & Hauert, 2010 [20]) are necessary to achieve sustainable cooperation.

A major reason for employing PGG with ABM for this study is that PGG always exists as a potential thread in organizations. Although contract and other institutional enforcement would facilitate cooperation and contribution from employees, each employee still has incentive for "free-riding," "social loafing," and "exploiting others." This incentive for individual collectively leads to non-cooperative group without solidarity, which represents emergent property of organization. Thus, existing organizations should somehow solve PGG to maximize cooperative behavior from employees.

Here, we would like to note that we do not intend to simulate actual organizations. Rather, we intend to propose prototypical models of organizational behavior. Since organizational structures are complex with multi-level subdivisions related with many different types of stakeholders, it is almost impossible to create "miniature copy of real organizations" in computer. What we should study with ABM is to focus on several key components of organizations to analyze how these components dynamically interact with each other to produce macro-organizational outcomes. In our study, by using PGG as a prototype of interaction, we will focus on those components interdependency among individuals and trade-off between group outcome and individual incentives.

If we find appropriate prototype of organizational simulations, the findings should have practical contribution, too. It would reveal certain structural characteristics of organization has emergent property via dynamic micro-macro interaction. Based on the findings, we expect how managers and leaders should make organizational coordination would suggested.

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Another advantage of simulation method is that this method enables us to analyze not only Arrow 3 but, also Arrow 1 and 2 simultaneously, resulting in that dynamic chronological change of macro outcome is also analyzable. For these reasons, we claim the contribution of simulation method to organizational study would be significant.

Heterogeneity of Competence in Organizations

According to the above argument, although we think PGG captures some of key features of organizations, this study proposes to modify the model with one additional important feature, heterogeneities of contributions to group task. Past studies with ABM, including the above studies, have strong assumption of homogeneity in individual contributions to group and, thus, overlooked heterogeneity or diversity within groups. While some studies have their focus on diversity of accessibilities in networks and spatial constraints (Santos, Santos, & Pacheco, 2008 [21]; Hauser, Hendriks, Rand, & Nowak, 2016 [22]; Wang, Szolnoki, & Perc, 2013 [23]) or opportunities outside group (Boyd & Mathew, 2007 [24]; Hauert, Traulsen, Brandt, Nowak, & Sigmund, 2007 [25]), they still have assumption of each individual's contribution to group in a PGG being constant among individuals.

In this study, we introduce another type of diversity in PGG, the heterogeneities in individual capabilities for contribution. Most body of previous research assumed that each individual can contribute the same amount with the same efficiency (ratio of cooperation cost to contribution) when contributing or cooperating. However, this assumption is critically implausible in the context of organizational study. Many organizational and management studies found that contributions to group task solving can differ among individuals depending on their knowledge, skills and ability, and other characteristics (KSAOs) (Felin et al, 2015 [2]; Ployhart & Hale, 2014 [3]). Further, these types of individual diversity in contribution are essential management component are fundamental as a basis of effective division of labor in groups and organizations (Durkheim, 2014 [26]).

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Although we introduce some important components of organizations in ABM above, our model is still not close to the ideal prototype model to describe organizational dynamics very efficiently. Since there has been no established and standard model commonly accepted by organizational researchers, we need to explore to build up better prototype step by step. Therefore, we would like to note that the present study is a preprimary work to seek a useful model for organizational study.

METHOD

In this study, we conducted a computational simulation introducing the heterogeneity in individual capability to make contribution to groups. To model a PGG with heterogeneity, we assume that if $N \geq 2$ individuals participate in the interaction, each can decide whether to contribute a fixed amount, $c > 0$, to the common pool. This amount will be multiplied by a factor of $r_i \geq 0$, and then divided among all of the N players in the interaction. The heterogeneity in contribution is represented as diversified r_i among individuals depending on their types. With $\frac{\sum_1^N r_i}{N} \succ 1$ this model represents the situation in which contribution to the common pool is socially desirable in terms of social welfare although contributing individuals need to personally incur the cost. Meanwhile, non-contributors are always better off than contributors in an interaction because any individuals in the interaction can enjoy distribution from the common pool regardless of their contribution.

In our model, we assume a finite population consisting of M players. Random samples of N individuals are faced with the opportunity of an interaction of PGG. In terms of heterogeneity, we consider four types of individuals. Let X denote the number of high-capable contributors who contribute with r_{HIGH}; Y the number of low-capable contributors who contribute with r_{LOW}; Z the number of high-capable non-cooperators who do not contribute regardless with r_{HIGH}; W the number of low-capable non-cooperators who do not contribute with. r_{LOW}

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We assume $r_{HIGH} \geq r_{LOW} \geq 0$. For the condition without heterogeneity in capabilities, we assume two types of individuals: contributors $(X+Y)$ and non-cooperators $(Z+W)$, both with r_{H0}.

With X, Y, Z and W, we also denote the number of players belonging to the corresponding type (and $M = X+Y+Z+W$ is the total population size, which we assume to be constant). We set it that the sequential T rounds make a generation. When the first generation begins, total population, M, is randomly divided to each four type, X, Y, Z, and W. From the population, N members of joint enterprise is set up by random pickup to play one round of PGG as explained in the above section, and after a PGG, the enterprise dismissed and the round ends. After repeating the T rounds, one generation ends.

At the end of each generation, two different updating processes are performed. The first process is on evolutionary dynamics, or replicator dynamics, which assumes that the change in frequency of an individual type is proportional to the difference between the fitness of that type and the average fitness of the population (Gao, Wang, Pansini, Li, & Wang, 2015 [27]), $\overline{f}$ Thus, the time evolution of the frequency of each type is given by

$$
\begin{aligned}
x(t+1) &= x(t)(f_x - \overline{f}),\\
y(t+1) &= y(t)(f_y - \overline{f}),\\
z(t+1) &= z(t)(f_z - \overline{f}), and\\
w(t+1) &= w(t)(f_w - \overline{f}),
\end{aligned}
$$

where the frequency of each type is given by $x(t)$, $y(t)$, $z(t)$, and $w(t)$, respectively, and the fitness of each type are given by f_x, f_y, f_z, and f_w, respectively. The average fitness of the individuals, $\overline{f}$, is

$$\overline{f} = xf_x + yf_y + zf_z + wf_w.$$

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For our model, we must resort to numerical simulation to study the time evolution because the dynamic equations become too complex.

The second updating process is on a mutation. A mutation occurs to keep the diversity of the individual types. Each type is replaced with a mutant player with a probability, m. The strategy of the mutant player is randomly chosen from the existing types: high-capable cooperator, low-capable cooperator, high-capable non-cooperator, and low-capable non-cooperator. Note that, through the simulation process, we set the total population size $(M = X + Y + Z + W)$ as constant.

We obtain their long-run frequencies by computer-based agent simulations. Each computational simulation has a number of generations, G, and five separate simulations run independently for each condition.

RESULTS

Let us first neglect the heterogeneities in individual capabilities by assuming the homogeneous r_i, or r_{H0} for all individuals. As previous research has repeatedly shown (Fehr & Gächter, 2000 [18]; Sigmund et al., 2010 [20]), the group performance falls and never comes up (Figure2, gray line). In contrast, when heterogeneities introduced, individuals have divergent r_i or r_{HIGH} and r_{LOW} where $r_{HIGH} \geq r_{LOW} \geq 0$. We set r_{HIGH}, r_{LOW}, and r_{H0} as $\frac{(r_{HIGH} + r_{LOW})}{2} = r_{H0} \succ 1$ so that the expected average of r_i is set as to be the same in two conditions. In fact, our simulations obtained the result of the same level of the group performance at the initial state and diverse as updating process progressed. The results are shown in Figure 2.

Insert Figure 2 about here

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With heterogeneity, the group performance improved and sustain at high level (Figure 2, blue line). Figure 2 clearly shows the effects of heterogeneity. Even though both with-heterogeneity and without heterogeneity starts with the same state, with-heterogeneity condition increases the sum of profit in a group over the generation, whereas without-heterogeneity decreases it. These results indicate that cooperators can drive out non-cooperators. In most of the past research without heterogeneity, researchers claim that exogenous mechanisms such as reputation or centralized body for punishment should be necessary (Boyd & Mathew, 2007 [24]; Hauert, et al., 2007 [25]; Hauser et al., 2016 [22]; Santos et al.,2008 [21]; Wang et al., 2013 [23]). However, Figure 2 shows that the cooperation is endogenously obtained through interactions without any further exogenous assumptions.

Insert Figure 3 about here

Figure 3 shows how much the entire group scores in the 200th generation improved it from the first generation by the different working group size. In this simulation, individuals are selected for a working group to play PGG and go back to the large group after PGG. Figure 3 indicates that the working group size needs to be small. As the model indicates, the increase of the participants for the interactions (N) leads to decrease the distribution amount for each person. Thus, it is no surprise that, with the multiplied factor (r_i) being given, the obtained level of group performance is a negative function of the size of a PGG interaction (N) since it ends up the decrease of the individual benefit for contribution. These results suggest that the group structure or formation process played important roles.

Insert Figure 4 about here

Next, we changed the entire group size instead of the working group size. Figure 4 shows how much the entire group scores in the 200th generation improved it from the first generation by the different population size with the fixed working group size with five.

Figure 4 indicates that not only interaction group size itself but the ratio to population size is also critical. As noted above, as typical PGGs, non-cooperators can be better off than cooperators at any single interaction. Thus, cooperation can be achieved when and only when cooperators win at the population level in spite of their loss at any working group level. It can happen through group formation process. In fact, our results show that forming relatively small group from larger population is essential to achieve group performance. That is, even with a small size of the interaction (N), the larger population size (M) is necessary for individual heterogeneities to make group performance remain high.

In group forming process, individuals are randomly picked up from population for the small enterprise to play a PGG. In some groups, there are more cooperators than non-cooperators and in other groups more non-cooperators than cooperators. Cooperators can enjoy the reasonable payoffs when same kinds gather while non-cooperators go into deadlock with other non-cooperators. Thus, the small-sized-group to population or large-sized-population to group is essential so that members for interactions can vary among interactions. For example, if the group size is the same as the population size, members of each interaction are as exactly the same as the population. If so, the loss at each interaction directly results to the loss at population level and cooperation cannot be evolve. In contrast, if the interaction size is fairly small compared with population size, the membership structure of each interaction can be different both among interactions and from population. If so, there should be fairly enough interactions in which cooperators or non-cooperators gathered and, through them, cooperators can be better off in total or at the population level. This leads to improve group performance.

DISCUSSION

Summary and Key Findings

This study aims to explore an appropriate prototype of organizational simulation to describe micro-macro dynamics. As the first step, we introduce ABM with PGG featuring heterogeneity of competence. In our simulations, individuals make decisions whether to cooperate or not for groups to complete a group task, which represents strong interdependency among members. Through interactions among individuals, macro status, which is captured as the level of cooperation or group performance in this study, was observed. By using ABM, we make it possible to examine how individual factors (heterogeneities in contribution in this study) affect macro outcome.

As to findings from our simulation, we found that heterogeneity in individual capability to make contribution to groups can help higher individual performance level emerge and become sustainable, and, therefore, improve overall collective performances. Also, the results indicated that only a group formation structure matters to achieve cooperation and individual behavioral rules do not have to change. Especially, it is revealed that smaller group formation from larger population is essential.

Contributions

Our prototyping of organizations and applications of ABM have theoretical contributions on organizational research in that micro-macro dynamics between individuals and organizational state (group performance) was captured.

Also, the results of our study show an example of plausible prototype of organizational simulation to shed a new light on a key institutional arrangement, which can achieve mutual cooperation under heterogeneity of individual contribution. In addition, the results of our simulation indicate that heterogeneity is critical to achieve mutual cooperation to achieve high organizational performance under the condition of appropriate structural arrangement (dividing a large organization into small groups with a certain size. Our findings are in line with the argument in management and organizational literature that individual diversity needs to be treated explicitly and connected to more macro level theory such as organizational theory and business strategy.

As a practical contribution, this study gives an evidence for justification of small-project-team-based division of labor. As a matter of fact, Kazuo Inamori, the founder of Kyocera and KDDI, and the chairman of JAPAN AIRLINES, has achieved a lot of successes by practicing this small-project-team-based division of labor called “Amoeba Management” (Adler, & Hiromoto, 2012[28]).

Limitation and Future Direction

While showing possibilities for groups and organizations to endogenously overcome social dilemmas, we left out several important issues. “Evolutionability” or “copiablity” of capability (Lazear,1995 [29]) should be carefully examined to see if this is justified as a core organizational characteristic. We also left out important key characteristics of organization such as leadership, organizational hierarchical order, multiple stakeholders inside and outside of organization and so on. These keys factors should be included in the future research.

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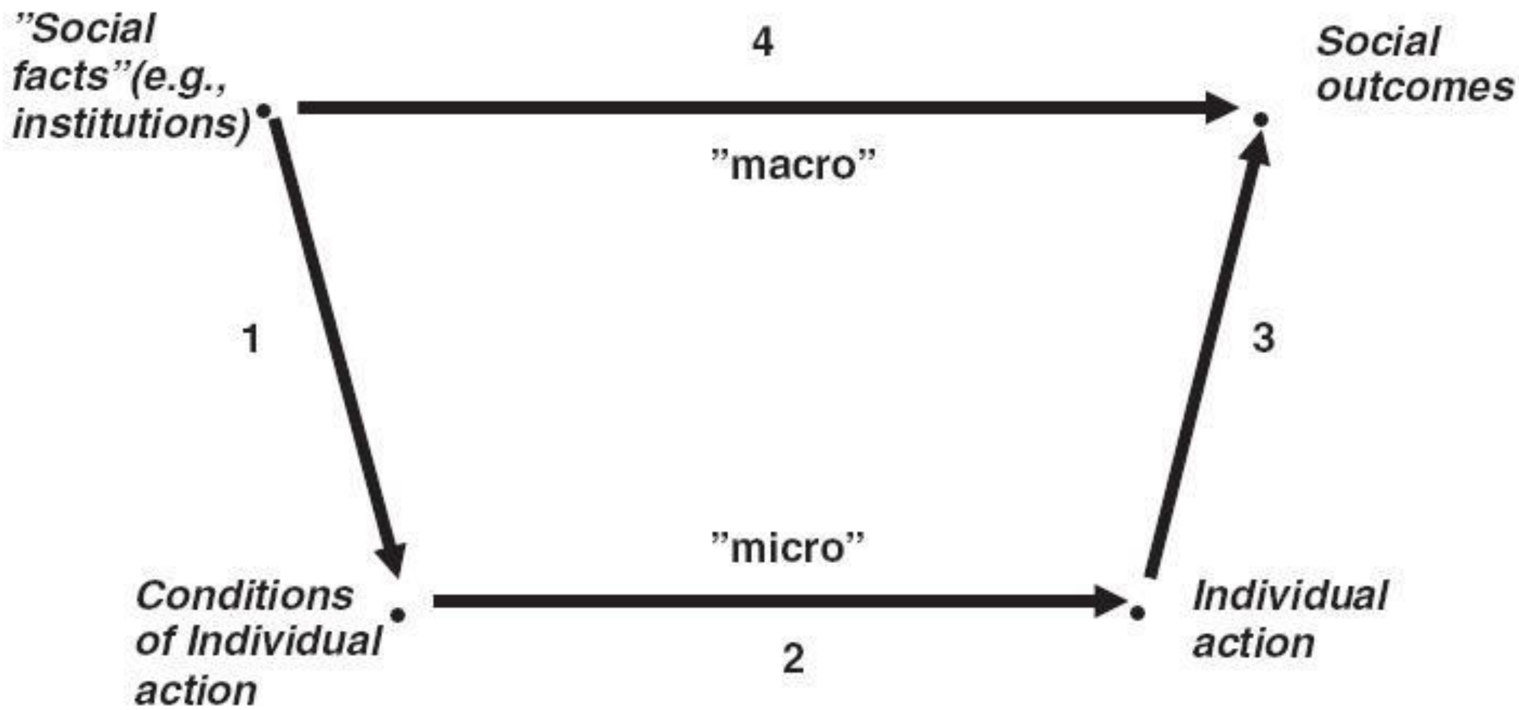

Figure1: Theoretical Model of Micro-Macro dynamics in Social Science (quoted from Colman (1990))

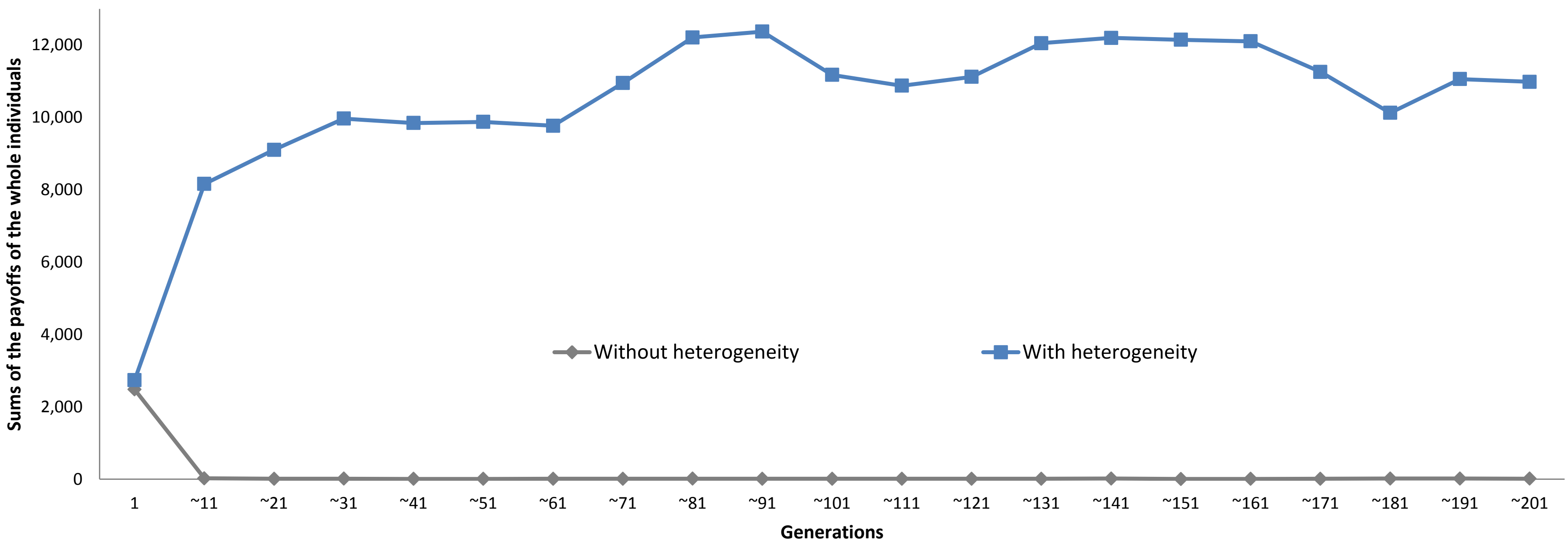

Figure 2: Time evolution of the overall performance of PGGs

We ran the same simulation 5 times with and without individual heterogeneity in capabilities and take average scores. Figure 2 shows the sums of the payoffs of the whole individuals in a group (the vertical axis) through the generations (the horizontal axis) with individual heterogeneity (blue line) and without individual heterogeneity (back line) in capabilities. Parameters are N =5, c =1, M =100, T =500, G =200, and $m = 5\times 10^{-3}$, and $r_{H0} = 3$ without heterogeneity, and $r_{LOW} = 0$, and $r_{HIGH} = 6$ without it. The overall performance begins at the same level at initial state, and declines without heterogeneities in capabilities, but improved with them.

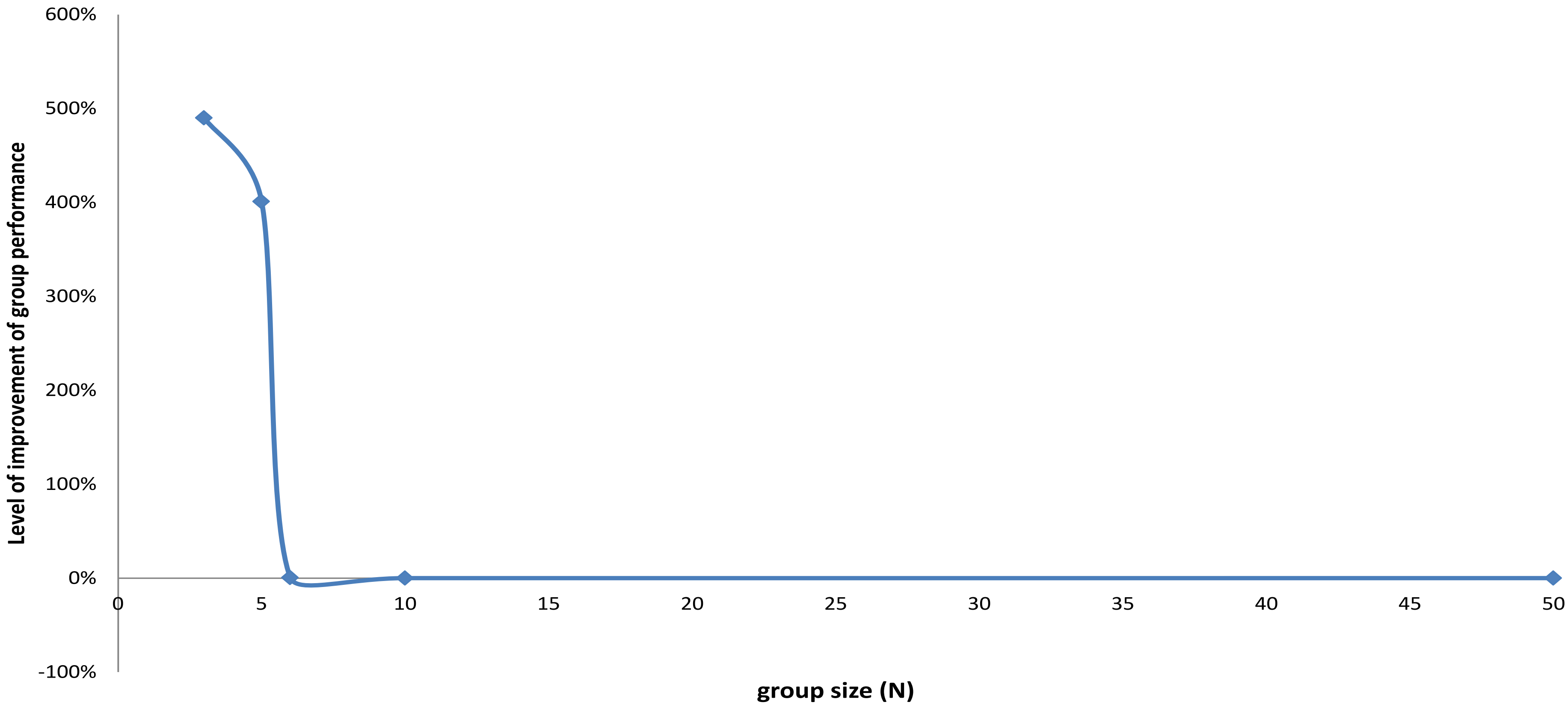

Figure 3: The improved level of group performance as various working group size (N), with fixed population size (M)

Figure 3 shows the level of improvement of group performance after 200 generation from the beginning with individual heterogeneities, as the function of group size (N) . All other parameters are as in Figure 2. High performance can be achieved only when the size of enterprise (N) is reasonably small (smaller than 5, with the given parameters).

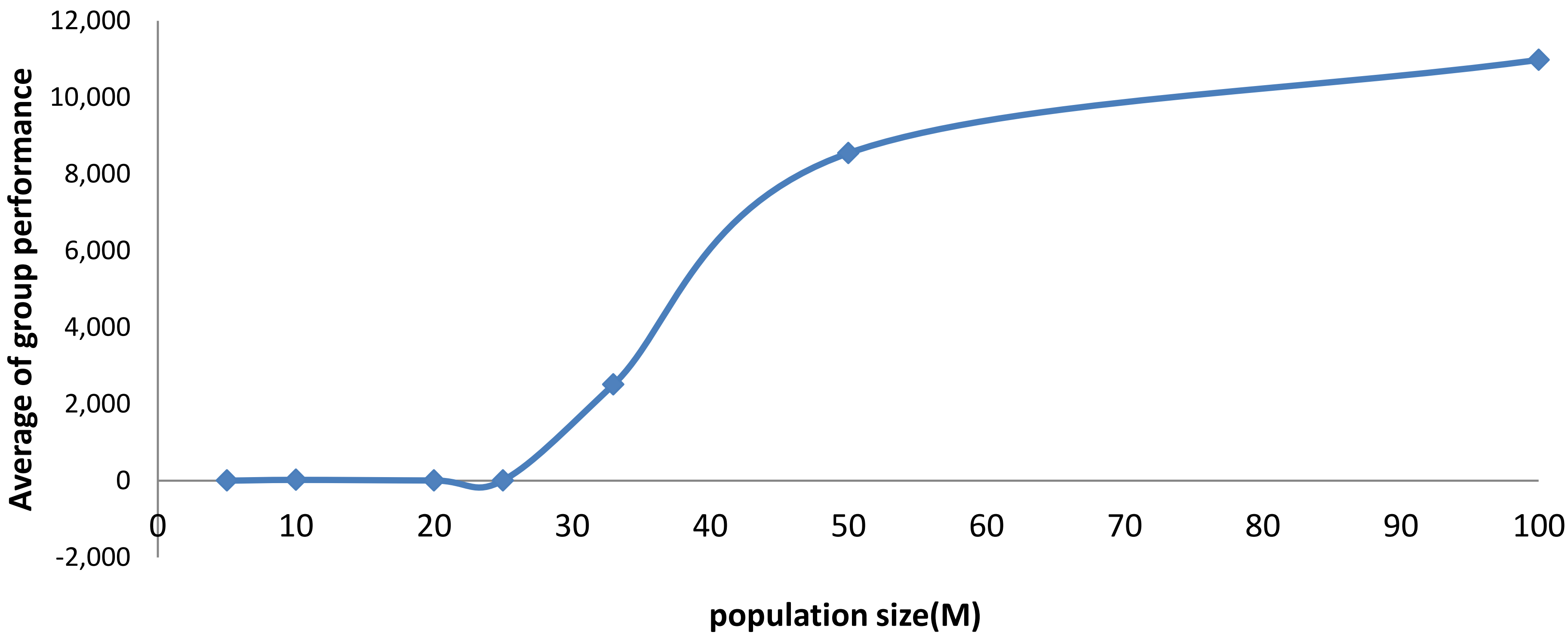

Figure 4: The obtained level of group performance as various population size (M), with fixed working group size (N)

Figure 4 shows the average of group performance with individual heterogeneities after 200 generations from 5 simulations, as the function of population size (M). N is fixed at 5, and all other parameters are as in Figure 2 and 3. High level of group performance can be achieved only when the population size becomes relatively large (i.e., the group size ratio to population size is small).