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Agent-based Simulations for Examining Stability and Efficiency of Societies with Respect to Partnership Structures

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Abstract: In this paper, we deal with partnership among agents in an economic situation with different production skills and abilities where they are free to form coalitions, alliances or partnerships. And from the viewpoints of stability and efficiency we examine the resulting partnership structure. To take into account restrictions on partner selection, various production skills, and environmental changes, we employ an artificial social model in which such aspects can be incorporated in a relatively easy way, and perform the agent-based simulations for analyzing the partnership structure. From the experimental results, we find that the stability and the efficiency of the partnership structures depend on cost, production function, or number of agent types.

Keywords: Partnership structure, Stability, Efficiency, Agent-based simulation

JEL Classifications: C51, E27, E37

1. Introduction

There are many economic situations such that multiple agents with different production skills and abilities are required to form coalitions to achieve an aim. In this paper, we discuss stability and efficiency of societies with partnerships formed by multiple agents with different production skills and abilities to achieve undertakings, and from a viewpoint of adaptive behavior of agents under various environments, we employ agent-based simulations for analyzing partnership structures arising from interaction among artificial agents.

In our model, there are multiple types of agents which have different production skills and different grades of ability of them. Namely, each agent has a certain production skill, and there exist differences of ability for the skill among a group of the agents which have the same skill. Agents can select members to form a production coalition which is called a partnership in this paper. The partnership can produce an output which yields some payoff and divide the obtained payoff among its members. Equal profit-sharing is frequently employed in partnerships (Sherstyuk, 1998), and then we assume that the payoff is shared equally among the members. Through agent-based simulations in the artificial social system, we demonstrate what structure of partnerships will be formed and examine the stability and efficiency of the societies with partnership structures.

In studies on efficiency in partnership structures, the moral hazard and incomplete information are dealt with and conditions that partnership structures are efficient are given (Holmstrom, 1982; Farrell and Scotchmer, 1988; Legros and Matsushima, 1991; Legros and Matthews, 1993; Miller, 1997; Sherstyuk, 1998). Matching in partnerships is also considered from the aspects of marriage markets (Becker, 1981), the two-sided and the multisided assignments problems (Shapley and Shubik, 1971; Quint, 1991), and rankings of university departments (Conroy et al., 1995).

In particular, Sherstyuk (Sherstyuk, 1998) considers the issue of stability and efficiency in partnership structures through a game theoretic approach, and shows that under the equal profit-sharing rule, a consecutive partnership structure is stable, that is, agents with the same grade of ability form a partnership, and it is efficient if the production function is super-modular.

In the Sherstyuk model, any agent has no restriction and no cost for choosing partners, and the influence of the variety of production skills on the structure of partnerships is not taken into account. Moreover, it is assumed that the performance of agents depends on their abilities, that is, agents can fulfill their potential completely no matter how severe surroundings may be. From a realistic viewpoint, the above mentioned aspects should not be disregarded, but in a mathematical model such as the Sherstyuk model, it is difficult to incorporate these aspects.

In this paper, to deal with such aspects, we employ an artificial society model, in which restrictions on selection of partners, variety of production skills, and variations in the environment can be easily implemented. Through simulations using this artificial society model, we attempt to analyze stability and efficiency of the structure of partnerships.

With respect to the efficacy and effectiveness of agent-based simulation models, Holland and Miller (1991) point out that since many of economic systems can be recognized as complex adaptive systems, artificial models consisted of selfadaptable agents are more effective in analyzing such economic systems. Axelrod (1997) argues importance of simulation in social sciences, and adverts to diversity of aims of simulation. Artificial models and multi-agent systems for analyzing social behaviors of people and social phenomena have been developed. For the iterated prisoner's dilemma game, Axelrod (1987) examines the effectiveness of strategies generated in an artificial social system, in which agents endowed with strategies are adaptively evolved by using a genetic algorithm. Dorsey et al. (1994) employ an artificial decision making mechanism using neural networks to imitate decision making of auctioneers, and compare artificial agents' behavior with that of real auctioneers which often deviate from the Nash equilibria. To estimate bid functions of bidders, i.e., to establish the appropriate weights of a neural network, they employ the genetic adaptive neural network algorithm based on genetic algorithms instead of the error backpropagation algorithm which is the most commonly used method. Andreoni and Miller (1995) use genetic algorithms to model decision making in auctions. In a way similar to the approach of Dorsey et al. (1994), they compare decisions of artificial adaptive agents with decisions observed in the experiments with human subjects, and find that they resemble each other. Erev and Rapoport (1998) investigate a market entry game by using an adaptive learning model based on reinforcement learning proposed by Roth and Erev (1995). Rapoport et al. (2002) also deal with market entry games. They compare decisions observed in experiments with human subjects with decisions of artificial adaptive agents with a learning mechanism based on reinforcement learning, and analyze behavioral patterns on the aggregate level. Leshno et al. (2002) consider equilibrium problems in market entry games through agent-based simulations with a decision making mechanism based on neural networks, and the neural networks are trained not by some teacher signals but by the outcomes of games. They compare the results of the simulations with those of the experiments with human subjects conducted by Sundali et al. (1995), and find some similarities in experimental data between the simulations and the experiments. Nishizaki et al. (2005) investigate the effectiveness of a socio-economic system for preserving the global commons by simulation analysis. A number of attempts have been made for performing multi-agent based simulations and developing the related techniques underlying the ideas from distributed artificial intelligence and multiagent systems (Epstein and Axtell, 1996; Conte et al., 1997; Chellapilla and Fogel, 1999; Downing et al., 2001; Moss and Davidsson, 2001; Banerje and Sen, 2002; Niv et al., 2002; Parsons et al., 2002; Sichman et al., 2003).

In our artificial society system, which is based on the Sugarscape model developed by Epstein and Axtell (1996), the restrictions on partner selection are represented by "vision" of an agent, and it is also easy to change the number of production skills of agents. Moreover, variations in the environment can be expressed by a distribution and a recovery rate of the resources. To express production skills, we provide multiple kinds of resources and each resource can be exclusively collected by the specific type of agents. We assign each agent a different ability level to collect the corresponding resource in order to express diversity of abilities, and introduce a rule of exchanging members between two partnerships.

2. Sugarscape Model for Analyzing Partnership Structures

In this section, we give fundamental concepts of the Sugarscape model and describe a simulation system on the Sugarscape for analyzing structures of partnerships.

2.1 Sugarscape model

To analyze stability and efficiency of partnership structures, we develop a simulation system with autonomous artificial agents on an artificial social model. Spatial models are appropriate to implement behavior of several types of agents which have different production skills and abilities and form partnerships in the artificial society model. Especially, the Sugarscape model developed by Epstein and Axtell (1996) satisfies such requirements, and then we develop an agent-based simulation system employing the framework of the Sugarscape model.

Epstein and Axtell (1996) develop the Sugarscape and show that fundamental social structures and group behaviors emerge from the interaction of individual agents operating under the given rules on the Sugarscape. We can investigate structures and mechanisms of social phenomena through simulations on the Sugarscape which consists of three main elements: environments, agents, and rules.

2.1.1 Agents and environments

The Sugarscape is represented by a two-dimensional lattice plane and it forms a torus. On the Sugarscape, there are a large number of agents which have internal states and behavioral rules. The vision and the metabolic rate are internal states and they does not change in lifetimes of agents. Each agent's individual payoff is also an internal state but it changes through interaction with environments, depending on the volumes of the resources gathered by members of a partnership. The metabolic rate means the amount of resources spent by an agent within one period of time.

Multiple kinds of resources corresponding to the types of agents are initially arranged on the Sugarscape, and they are regenerated after some agents have taken them. Any point on the Sugarscape has two parameters: a current amount of the resource and the maximal limit of the regenerated resource.

2.1.2 Rules

For the above mentioned agents and environments, rules are provided to prescribe themselves and to connect these two elements. Each agent autonomously behaves according to the rules under the influence of the other agents and the environment. We give rules newly adopted for analyzing partnership structures as follows.

Each agent has an attribute of a type representing its own production skill. A partnership is formed by all types of agents, and it includes exactly one agent from each type. Resources corresponding to the types of agents are arranged on the Sugarscape, each agent tries to find the corresponding resource within the scope of its vision, and the agent moves to a point with the largest amount of the resource that the agent can pick up.

The production of the partnership is determined by a production function which is a function of a vector of the volumes of the resources gathered by all the members of the partnership. Ability of an agent is represented by the collection rate of the resource, and only a part of the resource arranged on the Sugarscape can be picked up in proportion to the collection rate of the agent.

The value of the production function is thought to be a payoff to the partnership, and it is equally divided among the members of the partnership. The accumulated individual payoff of an agent increases by the payoff allocated from the partnership and decreases by the payoff corresponding to the metabolic rate in one period. Therefore, the payoff of the agent can be interpreted also as provisions.

An agent in the partnership may be swapped with the same type of an agent in the other partnership when there exists the same type of agents within the sight of the agent after the agent has gathered the resource. If the payoff of the agent increases by swapping and the payoffs of the rest of the members of the partnership that the agent would join also increase compared to the amount of the resources gathered by them in the previous period, the agent is swapped with the counter-agent.

2.2 A simulation model

Taking into account the restriction on partner selection, various agent types (production skills), and the environmental changes in our artificial society system, we analyze the influence of them on the structure of partnerships from the viewpoints of stability and efficiency.

The restriction on partner selection is represented by choosing a swapping pair within the sight of an agent. For a given number of agent types, a partnership includes exactly one agent for each type, and therefore we can vary the scale of partnerships by changing the number of agent types. By adjusting a distribution of the resources and the recovery rate of the resources, we can vary situations of the environment. In a certain situation of the environment, even an agent with high ability may gather only a small amount of the resource off its stroke.

We summarize the artificial social model on the Sugarscape as follows. Each partnership includes exactly one agent for each type, and there does not exist any isolated agent which does not belong to a partnership. Therefore, any partnership has the fixed member of agents. Exchange of members between partnerships is executed at most once a period. There are 100 agents for each type and they possess different abilities of the production skills. The best agent with the maximum ability can collect 100% of the resource on a point on the Sugarscape, and the second and the third agents can collect 99.5% and 99.0% of the resource, respectively. The worst agent with the minimum ability can collect only 50% of the resource. Namely, grades of ability of agents are given from 100% to 50% by a decrement of 0.5%. At the beginning of the simulation, members of partnerships are grouped together at random, and all the types of the resources are randomly arranged on the Sugarscape.

In this paper, since we focus on analysis of the partnership structure, the limitation of life span of agents and mating between agents are not necessary to be introduced, and all the agents have the same initial endowment and the same metabolic rate. Each agent has 1,000 units of payoff at the beginning of simulations, and it spends 3 units of payoff in one period. Although vision of an agent can be also interpreted as the agent's grade of the ability, we utilize vision of agents as restrictions on the selection of partners because aside from vision we express the agent's ability by the collection rate of the resource.

In our simulations, we deal with five values for vision of agents: 5, 10, 15, 20, and 25; and three values for the number of production skills (agent types): 2, 3, and 4. Moreover, the following four situations of the environment of the Sugarscape are implemented.

Environment MM (Maximal resource/Maximal recover) The maximal volume (500 units) of the resources is placed at each point on the Sugarscape, and the resource is recovered up to the maximum in one period.

Environment MP (Maximal resource/Partly recover) The maximal volume of the resources is placed at each point, and the resource is limitedly recovered by 100 units in one period.

Environment RM (Random resource/Maximal recover) The initial volume of the resource at each point on the Sugarscape is randomly determined from 0 unit to 500 units by an increment of 100 units, and the resource is recovered up to the initial volume in one period.

Environment RP (Random resource/Partly recover) The initial volume of the resource is randomly determined at each point, and the resource is limitedly recovered by 100 units in one period.

The several types of resources are randomly arranged on the Sugarscape for each situation of the environment. In Environment MM, it is most likely for agents to collect the resources according to their abilities, namely agents with high ability gather a large volume of the resource. Conversely in Environment RP, even agents with high ability may gather only a small amount of the resource. Environments MP and RM are intermediate situations between Environments MM and RP.

Consider a society for production activities with k types of agents. Let $K = \{1, \dots, k\}$ denote a set of agent types. Assume that there exist n agents for each type $l \in K$ and their abilities are ranked. Let N^k be the set of all agents, and then the total number of agents is nk. An agent can be denoted by li_l; it means that the agent is of type l and its ability is the i_l-th highest in the group of type l agents. A partnership B is a subset of agents where exactly one agent is included from each type. Therefore, the number of members in any partnership is k, and the number of partnerships in a society is n. A set of partnership is interpreted as a partnership structure. Let $P = \{B^1, \dots, B^n\}$ be a partnership structure, and then $\bigcup_{r=1}^{n} B^r = N^k$ holds.

Let $v(li_l^r)[t]$ denote a collected amount of the resource by the agent li_l^r in the partnership $B^r \in P$ at period$t$. For given numbers k and n of agent types and partnerships, respectively, the super-modular production function for the partnership B^r is represented by

$$f(B^r) \equiv f(v(1i_1^r)[t], \dots, v(ki_k^r)[t]) = \min\{v(1i_1^r)[t], \dots, v(ki_k^r)[t]\} \tag{1}$$

Also, the submodular production function for the partnership B_r is represented by

$$f(B^r) \equiv f(v(1i_1^r)[t], \dots, v(ki_k^r)[t]) = \left\{\sum_{l=1}^{n} v(li_l^r)[t]\right\}^{1/\rho}, \tag{2}$$

where $0 < 1/\rho < 1$ holds. The supermodular and the submodular production functions are related to economic notions of complementarity and substitutability, respectively. Namely, complementarity is interpreted as situations in which two or more different things improve each other's payoff, and substitutability is interpreted as situations in which one thing acts or serves in place of another.

Various simulations are carries out by changing the size of vision of agents, the number of agent types, the situations of the environment, and the type of production functions. The maximal period of simulations is set at 500, and the number of runs is 10.

2.3 Evaluation methods of the results

We consider methods for evaluating the results of the simulations from the viewpoints of stability and efficiency. After showing the definitions of stability and efficiency by Sherstyuk (1998), we give evaluation methods of stability and efficiency in our artificial social system.

Let $P = \{B^1, \dots, B^R\}$ be a partnership structure, w_{li_l} be an allocated payoff of an agent li_l which is of type l and has the i_l-th ability, and f be a production function. The set of equal-sharing payoffs is given by

$$W^e(P) = \{\boldsymbol{w} \in \mathbb{R}_+^{kn} | w_{li_l} = f(B^r) \setminus |B^r|, \forall li_l \in B^r, r = 1, \dots, R\}, \tag{3}$$

where $\mathbb{R}_+^{kn}$ is the set of kn-dimensional vectors of nonnegative real numbers. For any equal-sharing payoff $\boldsymbol{w}$, if

$$f(B^r) \setminus |B^r| > w_{li_l}, \forall li_l \in B^r, \tag{4}$$

it is said that a partnership B^r improves equitably upon $\boldsymbol{w}$. Then, the stability of the partnership structure P is defined as follows.

Definition 1 (Stability). A partnership structure P is stable under the equal-sharing rule if the corresponding equal-sharing payoff $\boldsymbol{w} \in W^e(P)$ cannot be improved equitably upon by any partnership B^r.

Based on the above definition of stability, we provide an evaluation criterion of stability for a partnership structure in our artificial society system. Considering that an agent can move into another partnership once in each period, we define a degree of the stability as a quotient of the number of exchanges of agents which can improve payoffs to the number of all possible exchanges of agents. It is called the local stability, LS, when exchanges of agents are limited in their sights, and it is also called the global stability, GS, if there does not exist any limitation. Let i_L and i_G be the numbers of exchanges of agents which can improve payoffs locally and globally, respectively, and n_L and n_G the numbers of possible local and global exchanges of agents, respectively. Then

$$LS = i_L / n_L \tag{5}$$

$$GS = i_G / n_G \tag{6}$$

are the degrees of local and global stability of the partnership structure, respectively. From these definitions, the partnership structure with small values of LS and GS is more stable than that with large values.

Let F^* be the maximal social wealth, i.e., $F^* = \max_{P \in \Pi} \sum_{r=1}^{R} f(B^r)$, where Π is the set of all partnership structures.

Definition 2 (Efficiency). A partnership structure $P = \{B^1, \dots, B^R\}$ is efficient if the social wealth is maximized, i.e.,

$$\sum_{r=1}^{R} f(B^r) = F^*. \tag{7}$$

Based on the above definition of efficiency, we also provide an evaluation criterion of efficiency for a partnership structure in our artificial society system. We define a degree of the efficiency as a quotient of the social wealth in the current partnership structure to the maximal social wealth among all possible partnership structures. It is called the local efficiency, LE, when exchanges of agents are limited in their sights, and it is also called the global efficiency, GE, if there does not exist any limitation. Let F_L^* and F_G^* be the local and the global maxima of the social wealth, and $P = \{B^1, \dots, B^R\} \in \Pi$ be a current partnership structure. Then

$$LE = \sum_{r=1}^{R} f(B^r) / F_L^* \tag{8}$$

$$GE = \sum_{r=1}^{R} f(B^r) / F_G^* \tag{9}$$

are the degrees of local and global efficiency of the partnership structure, respectively. From these definitions, partnership structures with larger values of LE and GE are more efficient than those with smaller values.

The social wealth is maximized, namely the maximum F_G^* is actualized if a partnership structure is consecutive and the production function is supermodular (Sherstyuk, 1998). For the submodular case, it is maximized if the productions of all partnerships are the same. The local maximum F_L^* of the social wealth is calculated by exchanging agents limitedly in their sights.

While Sherstyuk (1998) shows that a consecutive partnership structure is stable under the equal-sharing rule through a game theoretic approach, we employ an artificial society model and analyze the stability and efficiency of partnership structures in the artificial society under various environments.

3. Results of the Simulations

We carried out the simulations for examining the influence of (i) the restrictions on selection of partners, (ii) the variety of production skills, (iii) the variations of the environment, and (iv) the types of the production function on the stability and efficiency of the artificial society which depend on the partnership structures formed by artificial agents. In this section, we show the results of the simulations.

3.1 Restrictions on selection of partners

By varying the vision of agents from 5 to 25 at intervals of 5, we examine the influence of the restrictions on selection of partners on the stability and efficiency of the partnership structures. It follows that agents with smaller vision are more restricted on gathering the resources. In this simulation, the number of agent type is two; environment MM (Maximal resource/Maximal recover) is employed; and the production function is supermodular. The result of the simulation is shown in Table 1, and each value of GS and LS is an average of 10 runs. Note that the simulation starts with randomly generated coalitions, and the agents make decision for reconstructing coalitions and searching the appropriate partnership structure in the initial periods of time. The experimental results not involving the initial periods of time are shown in the following Tables.

For the global stability (GS) at period 50 in Table 1, which is in the early periods of the simulation, as the restriction on partner selection becomes hard, namely the vision of agents becomes small, the value of GS grows large. Therefore, it follows that the partnership structure becomes unstable.

In general, as time goes on, the value of GS becomes small and the partnership structure grows stable. For the stability of partnership structures of the societies with agents whose visions are larger than or equal to 15, the value of GS is small even in the early periods of the simulations and consequently the value of LS is also small. Namely, if partner selection is not restrictive, the partnership structure is relatively stable. For those of visions of 5 and 10, the values of GS are relatively large but because the values of LS is small, the partnership structure is stable locally.

Table 1 Influence of restrictions on partner selection on stability and efficiency Stability

Stability						
	period	vision				
		5	10	15	20	25
GS	50	0.0352	0.0108	0.0054	0.0038	0.0022
	100	0.0171	0.0028	0.0008	0.0003	0.0001
	200	0.0063	0.0002	0.0000	0.0000	0.0000
LS	50	0.0054	0.0019	0.0009	0.0017	0.0006
	100	0.0018	0.0013	0.0000	0.0002	0.0000
	200	0.0009	0.0002	0.0000	0.0000	0.0000
Efficiency						
	period	vision				
		5	10	15	20	25
GE	50	0.9874	0.9956	0.9975	0.9981	0.9988
	100	0.9935	0.9986	0.9995	0.9998	0.9999
	200	0.9972	0.9998	1.0000	1.0000	1.0000
LE	50	0.9997	0.9999	0.9999	0.9999	0.9999
	100	0.9999	0.9999	0.9999	0.9999	1.0000
	200	0.9999	0.9999	1.0000	1.0000	1.0000

For the efficiency, we also observe features similar to the stability. Namely, the partnership structure with a smaller vision of agents in the early periods of simulations is relatively inefficient, but in general the partnership structure becomes efficient as time goes on.

As an index for measuring a difference between a given partnership structure and the consecutive partnership structure, we calculate the total sum of differences of abilities among members of a partnership in the society. The partnership structure is consecutive if the total sum of differences of abilities is equal to zero, and becomes stable as time goes on. This index is relevant to the value of GS, and actually in partnership structures of societies with agents whose visions are larger than or equal to 15, when the value of GS becomes zero after around period 200, the index also becomes zero. In such a situation, then, it follows that the complete consecutive partnership structure is formed in our artificial society system.

From the above facts, when the production function is supermodular, the partnership structure becomes stable and efficient in the long run, but as the restriction on partner selection is severe, the stability and the efficiency get worse.

3.2 The variety of production skills

Developing three types of artificial societies differing in the number of agent types, we examine the influence of the number of production skills on the stability and efficiency of the partnership structure. In this simulation, the number of agent types is 2, 3, or 4. The value of vision of agents is set at 25; environment MM (Maximal resource / Maximal recover) is employed; and the production function is supermodular. The result of the simulation is shown in Table 2.

Table 2 Influence of the variety of production skills on stability and efficiency

Stability				
	period	the number of agent types		
		2	3	4
GS	50	0.0022	0.01090	0.02015
	100	0.0001	0.00266	0.00771
	200	0.0000	0.00018	0.00177
LS	50	0.0006	0.00519	0.00751
	100	0.0000	0.00081	0.00243
	200	0.0000	0.00000	0.00078
Efficiency				
	period	the number of agent types		
		2	3	4
GE	50	0.9988	0.99306	0.98662
	100	0.9999	0.99766	0.99396
	200	1.0000	0.99968	0.99747
LE	50	0.9999	0.99993	0.99968
	100	1.0000	0.99997	0.99997
	200	1.0000	0.99999	0.99999

As shown in the first row of the table of ‘Stability’ in Table 2, at period 50, the value of GS becomes large as the number of agent types increases. This is because it is supposed that exchanges of agents in one period give the partnership structure in societies with a larger number of agent types a relatively small amount of influence. However, even in the society where the number of agent types is 4, as time goes on, the values of GS and LS become small, and then the partnership structure becomes stable. At period 50 in the society where the number of agent types is 4, although the value of GS is the largest, the value of LS is small. Namely, it is found that the partnership structure is quiet stable locally. Concerning the efficiency of the partnership structure, features similar to the stability can be observed and it follows that the partnership structure becomes efficient as time goes on, but it is less efficient in societies with a larger number of agent types.

3.3 Variations in the environment

From a practical viewpoint, activities of agents may depend on situations of the environment surrounding agents. To examine such influences of environments on stability and efficiency of partnership structures, we provide four types of situations of the environment on our artificial society system. As shown in the previous section, we implement environment MM (Maximal resource/Maximal recover), environment MP (Maximal resource/Partly recover), environment RM (Random resource/Maximal recover), and environment RP (Random resource/Partly recover) on the Sugarscape. In this simulation, the number of agent types is two; the value of vision of agents is set at 25; and the production function is supermodular. The result of the simulation is shown in Table 3.

Environments MM and MP in which the resources are fully and uniformly arranged are more stable and efficient, compared with environments RM and PR in which the resources are not fully provided and a volume of the resource at each point is determined randomly. Although we do not find obvious differences with respect to stability and efficiency between environments MM and MP, there exists a large difference between environments RM and RP. Therefore, it can be said that stability and efficiency are affected mainly by the recovery rate of resources under environments with insufficient resources. Moreover, we find that environment RP does not grow stable and efficient even in the long run. Although in environments RM and RP partnership structures are not stable and not efficient globally, they are stable and efficient locally.

Table 3 Influence of the variety of production skills on stability and efficiency

Stability					
	period	environment			
		MM	MP	RM	RP
GS	50	0.0022	0.0019	0.0631	0.2056
	100	0.0001	0.0001	0.0564	0.2061
	200	0.0000	0.0000	0.0528	0.2029
LS	50	0.0006	0.0009	0.0262	0.0554
	100	0.0000	0.0008	0.0222	0.0540
	200	0.0000	0.0000	0.0203	0.0510
Efficiency					
	period	environment			
		MM	MP	RM	RP
GE	50	0.9988	0.9989	0.9866	0.9339
	100	0.9999	0.9999	0.9882	0.9359
	200	1.0000	1.0000	0.9896	0.9342
LE	50	0.9999	0.9999	0.9995	0.9948
	100	1.0000	1.0000	0.9997	0.9955
	200	1.0000	1.0000	0.9997	0.9956

While, for the simulation shown in Table 3, a difference between results of environments MM and MP is not obviously seen, we observe that there exists a clear difference between them in a simulation where the vision of agent is set at 5 and the other setting are the same as the case shown in Table 3.

From the above facts, when the production function is supermodular, the partnership structure is likely to be stable and efficient under environments where the resources are fully provided, and therefore agents can be easy to fulfill their potential.

3.4 Submodular production functions

So far, we have shown the results of the simulations with the supermodular production functions. In this subsection, we will give a summary of the results of the simulations in which the production function is submodular.

We perform simulations with the submodular production function changing the three parameters: the vision of agents, the number of agent types, and the situations of the environment. For the stability of partnership structures, we observe tendencies similar to the results of the simulations with the supermodular production function, but the maximal value of the global stability (GS) is smaller than that of the submodular case and the minimal value of it does not become zero unlike the supermodular case.

For the efficiency, even if the partnership structure is enough stable, it is not efficient. As the restriction of partnership selection is released, the performance of the society becomes inefficient. Concerning the number of agent types, the society with a small number of agent types is stable and inefficient in the early periods of simulations compared to the society with a larger one, and the influence of the variety of agent types is not exerted on the efficiency even in the long run. Moreover, the partnership structure is likely to be inefficient under environments such that the resources are fully provided.

4. Conclusions

Through the agent-based simulations, we have verified that the consecutive partnership structure is constructed and the society becomes stable if the cost for searching a better partner is low, the number of production skills is small and the resources are fully provided. Moreover, for the efficiency of the partnership structure, we have found that it depends on the type of production functions. However, in cases where the above conditions are not enough satisfied, the achievement of the stability and the efficiency is relatively lower in proportion to the cost or the number of agent types. In particular, under situations of the environment difficult to bring agents' abilities into full play, even in the long run the partnership structure does not become consecutive completely, and then we have observed that the society does not become fully stable.

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