Communication Modeling with Face-to-face Contacts — A Theoretical Perspective —

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Executive Summary

Supported by the highly advanced technologies of information/communication and transportation, the new knowledge society has been emerging. Newly developed transportation and communication technologies are diffused in the society, resulting in the rapid increase in the flexibility and the degree of freedom of human communication behaviours. The technological innovation of communications in the society does not only mean more rapid and efficient transmission of information and knowledge, it also expands the possibility of interactions of various types of activities in the spatially distant areas. The increased opportunity of communications in the society, greatly affecting the communication behaviours, brings about the structural evolution of social systems themselves. In most communication behaviours, the decisions made by travel agents cannot be independent of the decision and/or intention of other agents. One's decision on his/her communication behaviour is more or less affected by the others' will. Especially, in face-to-face communication (referred to as 'meetings' hereafter), the agreement with the other party to have a meeting is the prerequisite for the meeting.

The study aimed at formulating communication processes with face-to-face contacts. The objectives and scopes of the study were organized into four parts. The first part formulated face-to-face communication processes with agreement for meeting. The second part aimed at developing a theoretical model for communication processes by face-to-face contacts. The third party presented communication model with heterogeneous agent. The fourth part modeled communication processes with bounded memory.

In chapter 2, a random matching model was elaborated to characterize bilateral interregional human face-to-face contacts. The bilateral contacts can be realized only when both parties agree to meet each other. Thus, mutual agreement is the core of our contact modeling. Spatial distribution of bilateral contacts can be described as the results of random matching by potential meeting partners. The failure in agreement for meeting is the major source of inefficiency in human contacts among regions. The chapter provided a random matching scheme to describe the generation mechanism of inter-regional human contacts. The chapter concluded by illustrating some numerical examples showing how changes in transportation costs can modify the inter-regional interactability in terms of the face-to-face contacts.

Chapter 3 focused on two person meetings that is the simplest but also most fundamental form of meetings. The meeting behaviors are formulated as the two stage decision problems with 1) to find a meeting partner and 2) to agree (or disagree) on the meeting. The process that individuals repeat meetings with different partners was described.

It is then shown that the long term 'meeting equilibrium' can be modeled as the rational expectations equilibrium. In this chapter, we pointed out that the face-to-face communication was composed of the search behavior for the meeting partners and the agreement formation behavior. The individual meeting behavior was then expressed by using Bellman's principle of optimality. Moreover, the meeting equilibrium to realize in the long-term was described as the rational expectations equilibrium. The properties of the meeting behavior and meeting equilibrium were then clarified. One important result obtained in this study was that the better transportation and communication technologies bring about not only the increased volume of traffic demands but also the qualitative change of increased additive value of meetings.

The face-to-face communications in the society with heterogeneous agents are accompanied by inefficiency that is inherent to the coordination failure of meetings. Availability of exogenous information in order to recognize types of potential meeting partners has substantial impact on the resulting meeting equilibrium. In chapter 4, a meeting process in which two types of agents repeat meetings in the society was described as a random matching game. The meeting equilibria were defined as evolutionary stable states formed by meeting offer/acceptance interactions in the society. It showed that there exist multiple equilibria in the random matching game, and which specific equilibrium realizes depends on the path of social learning process. The relationship between availability of information for each agent to 'sort' his/her potential meeting partners and the resulting meeting equilibrium was also investigated. It is showed that in many cases the meeting equilibrium tends to be locked into inefficient states, and sorting information cannot rescue the agents from this coordination failure.

In chapter 5, assuming heterogeneous individuals and their bounded memory, we analyzed communication process among individuals and its simulation. This chapter focused on two person meetings that was the simplest but also most fundamental form of meetings. If different individuals want to communicate with the same agent, information pollution appeared. If rational individuals had bounded memory about the meeting history, they wanted repeated meetings with some individual within the group. So the phenomenon of sorting appeared. Chapter 5 focused on modeling heterogeneous individuals' repeated meetings with bounded memory and analyzed the mechanism of information pollution and sorting.

Contents

Chapter 1

Introduction

1.1 General Introduction

Supported by the highly advanced technologies of information/communication and transportation, the new *knowledge society* has been emerging. Newly developed transportation and communication technologies are diffused in the society, resulting in the rapid increase in the flexibility and the degree of freedom of human communication bahaviors. The technological innovation of communications in the society does not only mean more rapid and efficient transmission of information and knowledge, it also expands the possibility of interactions of various types of activities in the spatially distant areas. The increased opportunity of communications in the society, greatly affecting the communication behaviours, brings about the structural evolution of social systems themselves.

The *agora* in ancient Athens was a meeting facility. People in Athens had gathered in the agora and had exchanged goods and ideas. In many cities in Europe, the plazas had functioned as meeting places/facilities. *Fin-de-Siécle Vienna* has had the cultural meeting facility called *café*. These meeting facilities had played important roles in formation of urban structures and the growth of creativity in the cities. In modern cities, huge amount of ideas and knowledge have been accumulating. The smooth and easy transmission of ideas facilitates the agglomeration externality of the cities. The meeting facilities have significant meaning in the society, acting as the media to fulfill efficiently the expanding demand for the knowledge exchange in the spatially-limited urban systems.

In most communication behaviours, the decisions made by travel agents cannot be independent of the decision and/or intention of other agents. One's decision on his/her communication behaviour is more or less affected by the others' will. Especially, in face-to-face communication(referred to as 'meetings' hereafter), the agreement with the other party to have a meeting is the prerequisite for the meeting. In various aspects of daily life, mankind organizes meetings. People who make business trips, such as those for negotiation, collecting money and preconcert, and association trips with friends and loved ones, aim at the meetings themselves. Many institutional conditions and conventions which rule daily trips such as going to school, hospital, work and shopping have stemmed from the need for meetings. In addition, there is a tremendous amount of meetings at home within the familiy, and the relationships among the family members affect in many ways the occurrence of their trip/traffic behaviours.

Table 1.1: The Church Time System

matines	midnight
laudes	around 3:00
prime	around 3:00
tierce	around 3:00
sixte	around 3:00
none	around 3:00
vêpres	around 3:00
complies	around 3:00

1.2 Rediscovering the Existence of the Meeting 'Partner'

The major tenet of this chapter is to rediscover the 'partner' or 'opponent' in human communications, and to provide a new perspective on human contacts modeling. Let us first investigate the social role of meetings, by briefly referring to the historical facts, that the discovery of the 'opponent' in human communications had brought about the *time revolution* in Europe in the Middle Ages.

The promotion of commerce in Europe in the Middle Ages had allowed the present day time system to see the light - the so-called *time revolution*. Since the acceptance of Christianity by the emperor *Constantinus*, the "Church time system" had governed the human behaviour in the Middle Ages. The Church time system was originally introduced to gather monasteries and church councilor members and to organize choirs. The noontime was divided into three. Though the Church time system is a very irregular time clock system, it was rather rational for farmers' work patterns.

The time system is very conservative and rarely changes. In medieval Europe the machinery clock with which the public can realize time had not yet been innovated and only the bell ring by the church for sacred affairs was available for them. Farmers and workers had depended their “time to start working”, “time to have lunch”, “time to go back to work” and “time to finish work”, on the bell ring by lunch.

In the thirteenth century, the time system underwent a dramatic change caused by the emergence of the “time of merchants”. The merchants needed to have meetings with customers and trade opponents all the time. For them, the Church time system with only three hour units was extremely inconvenient. It was incompatible with the merchants’ rhythm. Churches had been gradually changing its time system based on the requirement by the merchants and workers in the town. J.Le Goff states that “during the period between tenth and thirteenth centry, only time system in noon have evolved. Time on *nine* was originally around three o’clock p.m in current system, but had moved backwards gradually, and stopped around the noon (this explains why the word ‘noon’ come from ‘nine’). The *noon*, that brings people working in the city about time to have a rest under the holy time told by the bell”(Le Goff,1980). After all, the time system that divides labour times into two, morning and afternoon, appeared; this is the emergence of the time evolution.

The time revolution provides a reasonable material for understanding meetings. The Church time system is the system for people to have holy communications with ‘God’. The moring-afternoon halving time system had appeared in order to communicate not with ‘God’ but ‘Partners’. This is not a system made up artificially by the man of power at the time. It is rather self-organized through the repetition of meetings by mankind. The essence of meeting is the discovery of the existence of the ‘opponent’. Meeting never happens by one individual. The necessity of agreement with opponents had formed the halving of working time, commercial conventions, work system, holidays and others over the long time.

Table 1.2: The Types of Meetings

	High Frequency	Low Frequency
Direct	Meeting with high frequency in high density space (daily contacts; friends intercourse)	Meeting with multi-persons at limited time and space (business meeting; preconcert)
Indirect	Information to be consumed very frequently in short time; quick acquisition of goods (stock market, etc.)	Transmission of highly insepa-rable and conservative knowledge and service (conferences)

1.3 Roles of Meetings

1.3.1 Meeting Types

T.Palander, an economist, focuses on the role of negotiation in the modern cities and points out the importance of communication costs in location decision in the city activities beyond the scope of the pioneering works by Thünen and other earlier works in location theory (Palander, 1935). As he reveals, one of the conspicuous characteristics of the modern city activities is the frequent and wide-range communications with activities of other cities. The amount of knowledge produced and concentrated in the big cities is increasing remarkably.

While the types of meeting vary, they can be categorized as given in Table 1.2 by focusing on the spatial and temporal characteristics. Human beings exchange their scientific ideas (such as knowledge and information), psychological services (such as friendship and affection), and goods via meetings. If the thing to be exchanged differs, the frequency and characteristic also differ. The one-to-one communication is the elemental form of meeting and the way to exchange ideas in the most condensed manner. Especially, when exchanging psychological services such as friendship and affection, this kind of communication form takes places. Similarly, in the case of scientific ideas, one-to-one communication allows people to exchange ideas with high concentration. The one-to-one meeting is, however, not always the most effective way of knowledge exchange. The progress of the society towards the knowledge one and activation of research and development lead to the increase in the variety of scientific ideas and also the frequency of knowledge exchange. If all the knowledge exchanges are done by one-to-one contacts, then the total number of exchanges should increase exponentially. If the large number of people gather at the same places such as conferences and conventions, the efficiency of knowledge exchange would be improved extensively. The scale of meeting increases, the probability that one can get to know the persons who hold the same knowledge that he/she seeks increases. Once came to know the person, one can have personal meetings and communications with him/her afterwards.

1.3.2 Duality of communication networks

The traffic and communication behaviours expand on two kind of networks: "the human networks" and "the physical network". Except for traffic behaviours conducted independently from other decision makers, these two networks play important roles in the realization of traffic and communications. Table 1.3 clarifies the characteristic

TABLE 1.3: The Comparision of Network Characteristics

	Transportation Network	Human Network
Node	Origin;Destination	Individual
Link	Roads;Railway	Meeting;Communication
Input	Trip Demand	Idea; Friendship,etc
Output	Realized Trips	Evolution of Ideas; Deepening of Friendships,etc.
Observable Variable	Transportation Trip	The Number of Meeting State
Variable(s)	Transportation Conditions	Function of Ideas, Friendship and others
Objective Variable(s)	Travel Time;Costs	Exchange of Knowledge and Ideas
Medium	Transportation Methods	Discussion
Activity Reachability	Long Distance	Short Distance

differences of the transportation network and the human network both of which play substantial roles in the face-to-face communication aspect(Beckmann, 1994).

The human network is the network on which the scientific ideas, psychological services and other ideas flow. One remarkable characteristic of the human network is that the individual human functions as a node which accumulates ideas, and the meeting as a link at which ideas are exchanged. In the human network, "whether to meet or not", "where to meet and when", and others are determined. Here, the "agreement by all participants" is a fundamental principle, and the decision making by multi persons takes part in the formation of a meeting. The meeings would vary in their decision making processes and manners; sometimes a meeting is organized compulsorily by a specific leader in power such as many formal business meetings, and sometimes a meeting is determined in its contents by the intention of the person who has the lowest incentive to meet, such as voluntary meeting and man-woman intimacy. It is, however, clear that the decisions by the multitudinous persons is concerned in the formation of meetings.

The physical network basically consists of the "telecommunication network" and the "transportation network". In the telecommunication network, the network itself functions are the medium so as to realize the meetings, such as the television meeting and facsimile. In this case, the monetary and temporal resources to be consumed by the communicating agents are relatively low. Though the parties concered communicate with each other while implicitly taking for granted the formation of communication, it does not require mutual agreement by parties very much. This type, with fewer requirements and conditions for pre-agreement on communication and meeting, is utilized as an efficient method to organize meetings that often require a tremendous amount of energy. The transportation network is always different from the human network in characteristics. A node and a link in the communication network do not always correspond to a node and a link in the human network. Individuals, that are nodes in the human network, move on the links in the transportation network. Many meetings use meeting facilities (nodes) such as hotels, convention halls, and cafés in town. The household, a most important link in the human networks, is also a node in the transportation network. The consultation during the transit in a mean of transportation and the unexpected chat with unknowns represent the cases where the link in the transportation network is utilized as a link in the human network.

One remarkable characteristic of the transportation network is the point that decision making on usage of the network is entrusted to the discretion of the persons who make trips in the network. The transportation network is the place which many trip makers use simultaneously, and each individual decision is affected by the 'results' from the decision making by others. Therefore, the point in concern here is the 'results' of the decision making by many and unspecific persons, and no agreement among the participating individuals is formed. In the transportation network without agreement, individuals have to make decisions under uncertain conditions. The decisions under uncertainty may not lead to the socially preferable, efficient and effective state. The transportation and traffic information provided by public sectors may induce individual behaviours, resulting in the more desirable decisions as a whole.

1.3.3 Issues in traffic behaviour modeling

Research on traffic behaviours stands on the viewpoint of metholological individualism in which the behaviour of trip makers is modeled separately from others' behaviours. The methodological individualism, the expression Schumpeter first used, means the scientific approach to clarify and understand a phenomenon in social or economic system by reducing it into independent individual behaviours and then aggregating them. While recognizing the operational handifulness and usefulness of this paradigm, he criticizes it as having the essential difficulty to understand the social phenomena caused by the interactions of composing individuals (Schumpeter, 1908). So far, traffic behaviour modelings have neglected the interactions of individual decision making on mutual adjustment in time schedule and on (same) meeting/gathering location and time, under the paradigm of the methodological individualism. To model the meeting behaviour, the mutual effects among individuals must be considered explicitly.

The decision making on the human network and the transportation network are closely connected. Meetings in the human network appear in the transportation network. The meeting properties such as 'where', 'when', 'who' and 'how' are determined by the potential meeting participants collectively. While there may be exceptional cases where the results of individual decisions on the transportation network affect the decision making processes regarding meetings, such as those on the accessibility of the location, the contents of meetings are essentially determined by the human network. Therefore, the decision on meeting has the Stackelberg-game like structure with the decision making in the human network as upper problem and the decision making in the transportation network as a lower problem. The development of behavioural models for meeting formation will be one of the most important and promising research topic.

Due to the transition of the society to become knowledge-oriented, many social and economic fundamental structures are reorganizing. For example, the standardization of the five-day-week system and the progress of research and development change the structure of and decisions in the human network. This may lead to the change of individual traffic behaviour. The person trip survey designed based on the fundamental paradigm of the methodological individualism had contributed to the clarification of the individual traffic behaviour. It is, however, a survey to investigate traffic behaviour in the transportation network, and therefore brings about highly limited and fragmental information on the meeting behaviour on the human network. There is still a long way before one can fully grasp the whole picture of meeting, which is one of the most fundamental communication form in the modern knowledge society.

1.4 Issues on Refinement of Transportation Infrastructure in Knowledge Society

A huge amount of research has been accumulated on traffic behaviour. The discret choice modeling based on the random utility theory has accelerated the development of more flexible and various traffic behaviour models (refer to, for example, Finney (1971), McFadden (1974), Domencich and McFadden (1975), Daganzo (1979) and Ben-Akiva and Lerman (1987)). There is no doubt that the transportation and communication networks are the compounds consisting of the nodes and links. Traditionally, the consolidation of the network infrastructure has concentrated on the refinement of its funtion on links. In the knowledge society, however, the function of the nodes will increasingly play more important roles. Especially, it is noteworthy that in the human network the meeting functions as the fundamental linkage. The spatially fixed meeting facilities are important network factors constituting the nodes of the physical network. On the contrary, the human network is not spatially fixed in its location. Sometimes we can have a meeting in the transportation means. The TV conference utilizing virtual reality is the technology that links spatially distant locations as if they are in the same node.

The nodes connect different links systematically. In order to fulfill the complicated meeting demand in the human network, it is necessary to construct and reinforce the elaborate the complex network with various nodes. Also, the marketing strategies to provide a new type of traffic services made of the combination of information services and the various conventional traffic services is indispensable. The city is the accumulated place of the nodes constituting various physical networks, and of the nodes connecting the city to other outside worlds. The density and efficiency of the nodes are primary conditions for expansion of the networks in the knowledge society.

The future of the cities in the knowledge society age relies on the urban development strategy of "how we can realize the mutual effects of the human networks and physical networks". In the short run, the human network determines the city potential. The structure of this human network is, however, very vulnerable and unstable. It is possible that one decision making in the human network metamorphoses the fundamental structure of the network in a moment. The examples are the founding, separation and discontinuance of scientific societies and associations. The hub structure of the network may also change drastically. The human network, however, is dependent on the structure of the physical network in the long run. The physical networks evolve slowly. Thus, the physical networks can be regarded as being constant or stable in the short run. On this physical network, the human networks self-organize. When the physical network gradually evolves and approaches and eventually exceeds a certain threshold, however, the human networks in the short term may possibly have catastrophical changes. A node at the comparatively disadvantageous position has a possibility to recover its potentials in the long run, if it holds a highly advanced accessibility in the physical network.

In the knowledge society, the importance of face-to-face communication is increasing. While playing an important role in the development of society, economy and culture, this kind of communication inherently holds the conflict that the increase in the time value makes it more difficult to self-organize. The technological innovation of information, telecommunication and transportation systems provide the society with the fundamental means to hold face-to-face communications in the era of increased time value. we will propose one promising direction of research on traffic behaviour modeling based on "communication with others", and attempt to abstract about the methodological individualism in the current traffic research paradigm, is still far apart from the position to scrutinize and develop a new comprehensive and systematized methodology.

1.5 Structure of Dissertation

This dissertation is structured into 6 chapters. Chapter 1 services as introductory part of the whole study. It provides basic framework and overview of the dissertation.

In chapter 2, a random matching model is elaborated to characterzie bilateral interregional human face-to-face contacts. The bilateral contacts can be realized only when both parties agree to meet each other. Thus, mutual agreement is the core of our contact modeling. Spatial distribution of bilateral contacts can be described as the results of random matching by potential meeting partners. The failure in agreement of meeting is the major source of inefficiency in human contacts among regions. This chapter provides a random matching scheme to describe the generation mechanism of inter-regional human contacts. This chapter concludes by illustrating some numerical examples showing how changes in transportation costs can modify the inter-regional interactability in terms of the face-to-face contacts.

Chapter 3 focuses on two person meetings that is the simplest but also most fundamental form of meetings. The meeting behaviors are formulated as the two stage decision problems with 1) to find a meeting partner and 2) to agree (or disagree) on the meeting. The process that individuals repeat meetings with different partners is described. It is then shown that the long term ”meeting equilibrium” can be modeled as the rational expectations equilibrium.

The face-to-face communications in the society with heterogeneous agents are accompanied by inefficiency that is inherent to the coordination failure of meetings. Availability of exogenous information in order to recognize types of potential meeting partners has substantial impact on the resulting meeting equilibrium. In chapter 4, a meeting process in which two types of agents repeat meetings in the society is described as a random matching game. The meeting equilibria are defined as evolutionary stable states formed by meeting offer/acceptance interactions in the society. This chapter shows that there exist multiple equilibria in the random matching game, and which specific equilibrium realizes depends on the path of social learning process. The relationship between availability of information for each agent to ‘sort’ his/her potential meeting partners and the resulting meeting equilibrium is also investigated. It is shown that in many cases the meeting equilibrium tends to be locked into inefficient states, and sorting information cannot rescue the agents from this coordination failure.

For chapter 5, if different individuals want to communicate with the same agent, information pollution appear. If rational individuals have bounded memory about the meeting history, they may want repeated meetings with some individual within the group. So the phenomenon of sorting appears. Chapter 5 focuses on modeling heterogenous individuals' repeated meetings with bounded memory and analysis the mechanism of information pollution and sorting.

The dissertation is ended with conclusion remarks in chapter 6. The chapter summarizes all the results in preceding chapters and notes the limitations of the study. In the end, the chapter highlights potential ideas for future research on the same area of study.

References

Beckmann, M. J., (1994) On knowledge networks in science: collaboration among equals. Ann Reg Sci, 28:233-242.

Ben-Akiva, M. and Lerman, S. R., (1987) Discrete Choice Analysis: Theory and Application to Travel Demand. The MIT Press, Cambridge.

DeCanio, S., (1979) Rational expectations and learning from experience. Quarterly Journal of Economics, 370:47-57.

Domencich, T. A. and McFadden, D., (1975) Urban Travel Demand: A Behavioral Analysis. North-Holland, Amsterdam.

Finney, D., (1971) Probit Analysis. Cambridge University Press, Cambridge.

Kobayashi, K., (1993) Incomplete information and logistical network equilibria. The Cosmo-Creative Society, Berlin:Springer-Verlag.

Kobayashi, K., Sunao, S. and Yoshikawa, K., (1993) Spatial equilibria with knowledge production with meeting facilities. The Cosmo-Creative Society, Berlin:Springer-Verlag.

Kobayashi, K., (1994) Information, rational expectations and network equilibria. The Annals of Regional Science, 28:369-393.

Le Goff, J., (1980) Time, Culture in the Middle Ages. The Univeristy of Chicago Press, Chigago.

McFadden, D., (1974) Conditional logit analysis of qualitative choice behavior. In: Zarembka, P., (ed.) Frontiers in Econometrics. Academic Press, New York.

Palander, T., (1935) Beiträge zur Standortstheorie. Uppsala:Almqvist Wiksell.

Schumpeter, J. A., (1908) Das Wesen und der hauptinhalt der Theoretichen Nationalökonomie. Leipzig:Duncker Humblot.

Chapter 2

Face-to-face Communication Modeling with Agreement for Meeting

2.1 Introduction

As a result of the accelerating diffusion and popularization of new high-tech information transmission and transportation technologies, the degree of and opportunities for human communications have increased dramatically. While new communication media such as the Internet enable us to transmit information more efficiently, human face-to-face communications (or 'meetings') may remain the primary means of communication in a knowledge society, in order to exchange, share, and create (new) ideas effectively. The meeting, as a core communication medium in the knowledge society, however, is accompanied by an inefficiency inherent to the meeting process; a meeting is realized only when all potentially participating individuals agree to having it. While being supported by active face-to-face communications, the knowledge society may inherently increase its inefficiency due to the increased meeting activities and correspondingly increased meeting failures.

In the last two decades, a huge amount of research has been accumulated on travel behavior. Discrete choice modeling based on random utility theory has accelerated the development of more flexible and varied travel behavior models (refer to, for example Finney, 1971; McFadden, 1974; Domencich and McFadden, 1975; Daganzo, 1979; Ben-Akiva and Lerman, 1987). Most of these modelings use the methodology in which the transportation phenomena of concern are reduced to the independent behavior of individual trip makers, with these then being aggregated. In such an approach, the mutual interactions allowing individuals to negotiate and adjust to meet at the same place and at the same time are totally ignored. In order to model human interactions, this mutual matching of individual behavior should be modeled explicitly (Kobayashi, 1995).

When one decides one's meeting behavior, the decisions of others intervene. In extreme cases, one may be required to attend a meeting at the behest of someone else. When an individual's decision is altered by others' intentions, the resulting equilibrium of the travel behavior is unlikely to be efficient. This kind of inefficiency causes the problem of over-supply and/or under-supply of trips. For example, the frequency of interactions with friends would tend to be less than the socially optimal level, as Scitovsky cleverly manifested (Scitovsky 1976). On the other hand, many business trips governed by institutional and/or mandatory arrangements may be realized with more than optimal frequency. Among these, some trips might not occur due to increased telecommunication activity. Surprisingly, these kinds of externalities on travel behavior have not been so often debated in the literature. Once the existence of the economic externalities associated with interactions among individual decisions are recognized, one realizes that many research issues remain to be addressed.

A meeting is organized through a negotiation process by its potential participants. In the formation of a convention, a private session, or any other meeting, there is always a proposer/originator who calls for the potential meeting of participants. With the agreement to have a meeting, the size, place, time and other details are then determined. While some are simultaneously determined, adjustment and feedback based on each individual's private affairs may also take place during the process. The meeting agreement formation process can be, in general, expressed as a sequential decision process consisting of 1) a decision on the purpose of the meetings and whether to have it, and 2) a decision on the details of the meetings.

The critical concern in the modeling of meeting behavior is the "meeting agreement" (Beckmann 1994). To systematize this idea into a new methodology for human contact modeling, there are many issues to be addressed. First, it is necessary to develop a model that can explicitly consider both the meeting formation and the travel behavior at the same time. Further research on and modeling of the random matching method presented briefly in this chapter may be beneficial. Secondly, the development of techniques for the aggregation of meeting behavior is needed. When there exists a strong dependency between the behavior of individuals, the simple 'summing-up' type of aggregation technique cannot be employed. In urban areas, individuals with various potential meeting demands look for and find the meeting partners who match their purposes, and repeat the meetings. The meeting processes are like the chemical reaction of molecules that meet incidentally and create a new material. The mathematical formalization of the meeting process is still a fundamental issue required to clarify the whole aspect of face-to-face communications in urban areas.

In this study, the focus is on the behavior of two-person meetings. This generation mechanism is modeled and analyzed under the behavioural assumptions: the individuals, who are all *homogenous*, form meetings by the history-independent *random matching technology*. With these rather simple behavioral assumptions on meetings, the process by which two individuals mutually agree to have face-to-face communication and then generate a meeting is modeled by explicitly considering "the opportunity to join meetings" ('matching'), followed by the meeting agreement decision by the matched partners. This chapter also gives some simple numerical examples and concludes by mentioning some future research topics and directions in the study of meeting behavior.

2.2 Matching and Agreement for a Meeting

In general, the term "matching" refers to mechanisms by which persons are combined to form distinguishable entities with some common purpose that these persons cannot accomplish alone (Roth and Sotomayor 1990). Problems of interest for this chapter are those in which meetings, as consequences of matchings, take place voluntarily; substitution possibilities exist in the sense that no individual is an essential member of any meeting, and the value of the joint activity engaged in at the meetings can be assessed by their participants in many ways. In this view of meetings, there arise two questions of interest: for a given environment described by a set of individuals; how are they matched and coupled in order to realize these meetings, and by what technological means does the matching take place; what is the value of each possible meeting, and how do people agree jointly to form meetings.

In order to realize a meeting, potential partners must be coordinated to decide whether the meeting should be taking place or not. In this chapter, the term *matching* specifically refers to the process by which potential meeting partners come to be coordinated for negotiations. For individuals, the activity of being matched as potential partners for a meeting does not necessarily mean the realization of the meeting. The meeting is realized only when the matched pairs come up with an agreement through the negotiation process. In other words, a meeting is realized via two distinct processes: 1) formation of partner pairs (*matching pairs*) to start the negotiations over meetings, and 2) formation of an agreement to have a meeting by the matching pairs. In this chapter, the former process, in which matching pairs are chosen from individuals, is called the *matching process*, while the latter, in which the matching pair considers the meeting realization, is called the *agreement process*. The term referring to coordinating both the matching and agreement processes is called the *meeting process*.

In general, meetings can consist of any number of participants. Among other issues, this chapter highlights the relatively simple problem of bilateral meetings, consisting of two persons (two-person meetings based on two-person matching) as the most fundamental meeting type. The *matching technology* which regulates the bilateral matching process in which two individuals are coupled as possible partners for a meeting, is fundamental in describing the whole process of meetings, and varies widely depending on the characteristics of the meetings of concern.

This study assumes that the most simple matching rule of *random matching technology* is appropriate. With this rule, at any discrete point in time, some (or all) matching pairs are randomly chosen from the set of all possible combinations of matching pairs. The proposed matching process is mechanistic, with agreement decisions by potential participants being the only control variables. Nevertheless, the model, with its simple random matching technology seems to be rich enough for depicting one of the basic features of human contact with mutual agreement.

In the meeting formation processes in real world, the agreement process involves negotiations over the conditions of the meetings between matched partners. In this study, no such negotiation and bargaining aspects are explicitly considered. The agreement process is, however, solely represented by the mechanism that each in the matched pair agrees or not to have a meeting.

The value of a meeting depends on its participants, and the willingness of the members to participate in the meeting depends on the sharing of that value. In this chapter, the share of the surplus of a meeting that its participants can gain is supposed to be exogenously pre-determined. No bargaining for the dividends between meeting partners is allowed. The agreement process is also assumed to be governed by a voluntary rule. That is, the meeting is realized only when two potential individuals simultaneously agree to having it, based on their own individual motives. In what follows, using a random matching model with identical individuals, the processes by which meetings are coordinated by both the simple random matching technology and the voluntary agreement rule are formulated.

2.3 Modeling

2.3.1 Assumption

Consider a spatial system consisting of M cities. In city i ($i = 1, \ldots, M$), there live N_i distinguishable individuals with homogeneous preferences. There holds $\sum_i^M N_i = N$, where N is the total population of the system. The spatial system is characterized by $\Omega = (N_1, \ldots, N_M)$. All individuals of the system are motivated to have meetings with others in order to obtain goods, services, knowledge, and/or information in so far as they acknowledge the value of meetings. At each discrete point in time, a certain number of matching pairs are randomly chosen from the set of all possible pair-wise combinations of individuals by the simple random matching technology. In other words, matching pairs are exogenously determined by their own nature. The matching formation itself is taken as costless. These assumptions somewhat limit the scope of investigation of this chapter, but sufficient remain to describe the essential properties of face-to-face communications as discussed in the previous. An extension of the model can be made by incorporating individual search behavior, and this is being considered for future study.

Two individuals in a matching pair will consider the formation of a meeting and if an agreement is reached, the meeting will be realized. The particular agreement for a meeting is assumed to be independent from other meeting agreements. The probability that a match will form in a short time interval is also independent of the number of matching pairs. Once the agreement for a pair is attained, the two jointly determine the place where the meeting will take place. In order to physically realize the meeting, either 1) one of the two in the matching pair goes to meet the other, or 2) both in the matching pair go to a certain (common) place to meet each other. In what follows, for simplicity, either of the two in the matching pair is simply assumed to visit the other. The roles of the 'visitor' and 'host' are assumed to be assigned by nature when two individuals are matched, and the probability that a person in the matching pair will be chosen as either a host or a visitor is equal. At the end of each point in time, all meetings will be dissolved and all individuals will wait for the next allocation of matchings. Thus, the matching process is repeated for infinite rounds.

2.3.2 Modeling of the matching process

Define the probability distribution of the number of matching pairs used to model the matching process. Let the total number of distinct pairs of individuals in city i and city j ($i \neq j$) be denoted by $H_{ij} = N_i N_j$. For city pair (i, i), it is given by $N_i(N_i - 1)/2$. Then, the total number of distinguishable pairs in the whole system is then given by $\sum_{i,j} H_{ij} = H$ where $H = N(N-1)/2$. Let x_{ij} indicate the number of the matching pairs realized for city pair (i, j), which varies from period-to-period, and let q_{ij} be the probability that any pair of individuals in city i and j is chosen as a matching pair. All individual pairs in city pair (i, j) are subject to both an identical and independent probability of being chosen as a matching pair, denoted by q_{ij}. This implies that individuals are allowed to be simultaneously involved in several different matchings. If all individual pairs in cities i and j have identical and independent probability q_{ij}, the probability that x_{ij} matching pairs are achieved for city pair (i, j) is given by the following binomial distribution,

$$\begin{aligned} p(x_{ij}) &= B(H_{ij}, x_{ij}; q_{ij}) \\ &= {}_{H_{ij}}C_{x_{ij}} q_{ij}^{x_{ij}} (1 - q_{ij})^{H_{ij} - x_{ij}}. \end{aligned} \tag{2.1}$$

For x_{ij} matching pairs, all partners of the respective matching pairs start negotiations as to whether they agree to have a meeting or not. The meetings will fail to be realized for those matching pairs where either (or both) partners disagree to organize them.

2.3.3 Probability of meeting occurrence

Suppose that x_{ij} pairs are matched for city pair (i, j). For each matching pairs the results of the agreement process can be classified into the following mutually exclusive states:

(State 1): Both agree to have a meeting;

(State 2): The person in city i agrees but the person in city j disagrees on having a meeting;

(State 3): The person in city j agrees but the person in city i disagrees on having a meeting;

(State 4): Both disagree on having a meeting.

Let $m_{ij}^{(k)}$, $(k = 1, \cdots, 4)$ be the number of pairs whose negotiations result in state k. Obviously, there holds:

$$\sum_{k=1}^{4} m_{ij}^{(k)} = x_{ij}. \tag{2.2}$$

Let $p_{ij}^{(k)}$, $(k = 1, \cdots, 4)$, be the probability that state k is realized as a consequence of the agreement process, and also let $\hat{p}_i^j$ indicate the probability that a person in city i agrees to meet a person in city j (hereafter, referred to as *agreement probability*). By assuming the independence of individual agreement probabilities, the probability that each state is realized can be defined as follows:

$$\begin{array}{ll} \textbf{(State 1)} & p_{ij}^{(1)} = \hat{p}_i^j \hat{p}_j^i, \\ \textbf{(State 2)} & p_{ij}^{(2)} = \hat{p}_i^j (1 - \hat{p}_j^i), \\ \textbf{(State 3)} & p_{ij}^{(3)} = (1 - \hat{p}_i^j) \hat{p}_j^i, \\ \textbf{(State 4)} & p_{ij}^{(4)} = (1 - \hat{p}_i^j)(1 - \hat{p}_j^i). \end{array} \tag{2.3}$$

In order for a meeting to take place, state 1 implies that the two individuals in the matching pair agree to meet each other and that the meeting is thus realized. Accordingly, the probability that a meeting takes place for a matching pair, denoted by p_{ij}, is given by

$$p_{ij} = p_{ij}^{(1)} = \hat{p}_i^j \hat{p}_j^i. \tag{2.4}$$

This probability of meeting realization is called the *probability of meeting formation* throughout this chapter. The equation above clearly represents the fact that a meeting is realized only after both parties of the matching pair agree simultaneously to meet each other. The following describes the precondition of meeting formation; this is called the *characteristics of mutual agreement.*

2.3.4 Modeling the probability of meeting formation

The probability that the meeting will take place is modeled based on a random utility model. The meeting will take place in the city of either of its participants. Consider the matching pair consisting of individuals from city i and j. To realize the meeting, either one of the individuals in a matching pair visits the other, or both in the matching pair agree on another place to meet and go to that place. In this chapter, we assume the simplest case, where one visits the other. Moreover, the role assignment between the two over which one will be a visitor or a host of the meeting is determined randomly, and no negotiations over this role assignment occur.

Consider the matching pair that consists of individual k in city i and individual l in city j. The indirect utility of the individual k in city i who will visit individual l in city j is given as follows:

$$U_{ij}^k = Y_i + v_{ij} + \varepsilon_{ij}^k \tag{2.5}$$

where Y_i is income and v_{ij} is the deterministic part of the indirect utility, both of which are assumed to be common for all individuals in city i. The term ε_{ij}^k is the stochastic utility obtained from the meeting. The stochastic term can be interpreted as representing a change of the meeting utility from situation to situation, time to time and also meeting to meeting. Notice that the utility does not depend on l. This reflects the fact that under the random matching technology, individual k can be assumed to have no information about individual l except for the city where he/she lives.

Now, specify the deterministic term of the indirect utility as follows:

$$v_{ij} = V_{ij} - c_{ij} \tag{2.6}$$

where V_{ij} is the utility obtained from the meeting characteristics, and c_{ij} is the transportation cost (moving cost) between cities i and j, which is common to everybody for moving between the same cities. Here, the utility v_{ij} can be expressed, for example, as the weighted linear indirect utility model as one of the simplest specification case, by which the parameters are estimated.

Each individual is assumed to be a utility maximizer and agree to the meeting as far as he/she derives more utility than his/her threshold utility level (the utility level when no meeting is realized):

$$\bar{U}_i = Y_i + \bar{V}_i \tag{2.7}$$

The threshold utility is assumed to be exogenous and identical across all individuals in each city. Then, the probability of agreement when k in city i visits l in city j is defined by

$$\begin{aligned} {}^k\hat{p}_i^j &= \text{Prob}\{U_{ij}^k \geq \bar{U}_i\} \\ &= \text{Prob}\{Y_i + V_{ij} - c_{ij} + \varepsilon_{ij}^k \geq Y_i + \bar{V}_i\} \\ &= \text{Prob}\{\varepsilon_{ij}^k \geq \bar{V}_i - V_{ij} + c_{ij}\}. \end{aligned} \tag{2.8}$$

In the same manner, the partner's probability to agree to the meeting is given by

$$\begin{aligned} {}^{l}\hat{p}_j^i &= \text{Prob}\{U_{ji}^l \geq \bar{U}_j\} \\ &= \text{Prob}\{Y_j + V_{ji} + \varepsilon_{ji}^l \geq Y_j + \bar{V}_j\} \\ &= \text{Prob}\{\varepsilon_{ji}^l \leq \bar{V}_j - V_{ji}\}. \end{aligned} \tag{2.9}$$

If the stochastic terms are independently and identically distributed with $N(0,1)$, the probabilities of reaching an agreement between an individual in city i and one in city j depends only on the cities themselves and are respectively given by

$$\begin{aligned} \hat{p}_i^j &= \Phi(\bar{V}_i - V_{ij} + c_{ij}), \\ \hat{p}_j^i &= \Phi(\bar{V}_j - V_{ji}), \end{aligned} \tag{2.10}$$

where $\Phi(\cdot)$ is the normal distribution. From the assumption of independence of the stochastic utility terms, the probability that the meeting between an individual in city i and one in city j will take place, denoted by p_{ij}, is given as follows:

$$\begin{aligned} p_{ij} &= \hat{p}_i^j \hat{p}_j^i \\ &= \Phi(\bar{V}_i - V_{ij} + c_{ij}) \cdot \Phi(\bar{V}_j - V_{ji}) \end{aligned} \tag{2.11}$$

Accordingly, the probability of meeting formation p_{ij}, which is expressed as a product of the probability of agreement for each individual, is much less than the probability of agreement for each person $\hat{p}_i^j or \hat{p}_j^i$. As society progresses, and the consequent value of time increases, the threshold utility level is expected to increase with it. Eventually, people will need more incentive to organize meetings to account for the increase in the value of time. This is partially explained by some well-known economic puzzles: human contacts in developed societies are increasingly sought but decreasingly attained (Scitovsky 1976, Hirsch 1976).

2.3.5 Probability distribution of meeting occurrence

When the number of matchings is x_{ij}, the conditional probability that each state $m_{ij}^{(k)}$ $(k = 1, \cdots, 4)$ occurs, denoted by $p(\boldsymbol{m}_{ij}|x_{ij})$, can be described by the multinomial distribution:

$$\begin{aligned} p(\boldsymbol{m}_{ij}|x_{ij}) &= M(\boldsymbol{m}_{ij}; \boldsymbol{p}_{ij}, x_{ij}) \\ &= x_{ij}! \prod_{k}^{4} \frac{\left(p_{ij}^{(k)}\right)^{m_{ij}^{(k)}}}{m_{ij}^{(k)}!}, \end{aligned} \tag{2.12}$$

where $\boldsymbol{m}_{ij} = (m_{ij}^{(1)}, \cdots, m_{ij}^{(4)})$, $\boldsymbol{p}_{ij} = (p_{ij}^{(1)}, \cdots, p_{ij}^{(4)})$. The probability that x_{ij} matching pairs decide to explore meeting is given by equation (2.1). The probability that each state occurs is given by combining the multinomial distribution (2.12) with the binomial distribution (2.1). The resulting distribution can be approximated by using a Poisson distribution.

$$\begin{aligned} p(\boldsymbol{m}_{ij}) &= \sum_{x_{ij}=0}^{H_{ij}} p(\boldsymbol{m}_{ij}|x_{ij})p(x_{ij}) \\ &= H_{ij}! \prod_{k}^{4} \frac{(p_{ij}^{(k)} q_{ij})^{m_{ij}^{(k)}}}{m_{ij}^{(k)}!} \\ &\simeq \prod_{k=1}^{4} \frac{(\lambda_{ij}^{(k)})^{m_{ij}^{(k)}}}{m_{ij}^{(k)}!} \exp(-\lambda_{ij}), \end{aligned} \tag{2.13}$$

where $\lambda_{ij}^{(k)} = H_{ij} q_{ij} p_{ij}^{(k)}$, $\lambda_{ij} = \sum_k \lambda_{ij}^{(k)}$.

Among the four possible states of matching pairs, meetings occur only in state 1. Consequently, states can be categorized into two cases: 1) meetings take place (i.e., state 1) or 2) matchings are realized but no meeting takes place (i.e., states 2, 3, and 4). Moreover, let us redefine the frequency of meeting formation for city pair (i, j) by using the number of meetings n_{ij}. The conditional probability of meeting frequency when the number of matching pairs for city pair (i, j) is x_{ij}, is expressed by the binomial distribution and is given as follows:

$$\begin{aligned} p(n_{ij}|x_{ij}) &= B(x_{ij}, n_{ij}, p_{ij}) \\ &= {}_{x_{ij}}C_{n_{ij}} p_{ij}^{n_{ij}} (1 - p_{ij})^{x_{ij} - n_{ij}}. \end{aligned} \tag{2.14}$$

From equations (2.1) and (2.14), the probability of meeting occurrence for city pair (i, j) is then expressed by

$$\begin{aligned} p(n_{ij}) &= \sum_{x_{ij}=0}^{H_{ij}} p(n_{ij}|x_{ij})p(x_{ij}) \\ &= {}_{H_{ij}}C_{n_{ij}} {r_{ij}}^{n_{ij}} (1 - r_{ij})^{H_{ij} - n_{ij}}, \end{aligned} \tag{2.15}$$

where $r_{ij} = p_{ij} q_{ij}$. The expected value of the total number of meeting formations for city pair (i, j) is described by the following equation:

$$E[n_{ij}] = \sum_{n_{ij}=0}^{H_{ij}} n_{ij} \cdot p(n_{ij}). \tag{2.16}$$

2.4 Social Welfare of Meetings

2.4.1 Economic benefits of meetings

Not surprisingly, the meeting process that is induced by both the random matching technology and the voluntary agreement rules is generally inefficient in the sense that another possibility exists which would leave individuals better off. The simple random matching technology does not necessarily generate socially optimal matching pairs. Even worse, since the negotiations are coordinated by the voluntary agreement rules, there are essentially no economic mechanisms by which the individuals who wish to realize the meetings can compensate for a partners' reluctance to attend the meetings. Thus, those who wish to but fail to have a meeting will always lose the surplus to be gained if the meeting were to take place. The lost surplus due to the failure of the meeting originates from the basic characteristics of mutual agreement.

When the economic benefits derived from the meeting processes are estimated based upon the random matching model, there exist two sources of risk: 1) the stochastic allocation of matching pairs over the spatial system, 2) the individual idiosyncratic valuation of the meetings. The former uncertainty is generated in the matching process, while the latter is generated in the agreement process. As discussed in the previous, the individual preferences for the meetings vary from period-to-period, and this variation causes a fluctuation of matching agreements. In the random matching model, the matching-specific variation in the individual utility can be collectively expressed by a single stochastic variable ε_{ij}^{k}. One plausible interpretation of stochastic utility is that individuals have idiosyncratic and state-dependent preferences toward the meetings, with the specified partners of matching pairs varying from period-to-period. Irrespective of how individual preferences vary through the periods, these preferences become deterministic at the instant each makes a decision. This means that the individuals know the value of the meeting with certainty before agreements for the meetings are made; however they do not know their partners' preferences.

The economic benefits of the meeting process can be measured by taking the long-run average of the aggregated individual expected consumer's surplus defined at each point in time. The individual consumer's surplus can be evaluated based on the individuals' utility levels when all uncertainty is resolved. At each instance of matching, there is no uncertainty for the individual. Thus, when matching pairs are allocated to individuals, all matched individuals can calculate the expected surplus of the respective matchings, given their belief about the probability that their partners agree to the meetings. Once the expected consumer's surplus is properly defined, the expected economic benefits of the meeting process can be calculated by aggregating the expected consumers' surplus for a particular matching over all the possible matchings, as long as the meeting processes are operated in a stationary environment.

The individuals who participate in the meetings will have greater utility than their threshold levels, while the utility level of those who have no meetings stays at the threshold levels. Now, let $E[U_{ij}^k|U_{ij}^k \geq \bar{U}_i]$ represent the average conditional utility of individual k in city i when he/she participates in a meeting with an individual in city j. Considering that the probability of being a visitor (or a host) is 0.5, the average conditional utility $E[U_{ij}^k|U_{ij}^k \geq \bar{U}_i]$ can be given by

$$\begin{aligned} E[U_{ij}^k|U_{ij}^k \geq \bar{U}_i] &= \frac{1}{2}\left\{\frac{\int_{\bar{V}_i - V_{ij} + c_{ij}}^{\infty}(Y_i + V_{ij} - c_{ij} + \varepsilon_{ij}^k)\mathrm{d}\phi(\varepsilon_{ij}^k)}{\mathrm{Prob}\{V_{ij} - c_{ij} + \varepsilon_{ij}^k \geq \bar{V}_i\}}\right. \\ &+ \left.\frac{\int_{\bar{V}_i - V_{ij}}^{\infty}(Y_i + V_{ij} + \varepsilon_{ij}^k)\mathrm{d}\phi(\varepsilon_{ij}^k)}{\mathrm{Prob}\{V_{ij} + \varepsilon_{ij}^k \geq \bar{V}_i\}}\right\}, \end{aligned} \tag{2.17}$$

where $\phi(\varepsilon_{ij}^k)$ is the normal density function. Then, the expected consumers' surplus that an individual in city i can gain from a matching with an individual in city j is given by

$$EU_i^j = p_{ij}E[U_{ij}^k|U_{ij}^k \geq \bar{U}_i] + (1 - p_{ij})\bar{U}_i, \tag{2.18}$$

where p_{ij} is the probability of meeting formation and is given by equation (2.11). Then, the conditional aggregated consumers' surplus for city i when n_{ij} meetings are realized from x_{ij} matching pairs, $EW(n_{ij}|x_{ij})$, can be defined as the sum of individual expected consumers' surplus. In other words, this is the aggregate sum of expected consumers' surplus for when "a meeting is organized", "no meeting is organized" and "no matching is organized".

$$\begin{aligned} EW(n_{ij}|x_{ij}) &= n_{ij}E[U_{ij}^k|U_{ij}^k \geq \bar{U}_i] + (x_{ij} - n_{ij})\bar{U}_i \\ &\quad + (N_i - x_{ij})\bar{U}_i \\ &= (E[U_{ij}^k|U_{ij}^k \geq \bar{U}_i] - \bar{U}_i)n_{ij} + N_i\bar{U}_i \\ &= EW(n_{ij}) \quad ([when]\ i \neq j) \end{aligned} \tag{2.19}$$

$$\begin{aligned} EW(n_{ii}|x_{ii}) &= 2n_{ii}E[U_{ii}^k|U_{ii}^k \geq \bar{U}_i] + 2(x_{ii} - n_{ii})\bar{U}_i \\ &\quad + (N_i - 2x_{ii})\bar{U}_i \\ &= 2(E[U_{ii}^k|U_{ii}^k \geq \bar{U}_i] - \bar{U}_i)n_{ii} + N_i\bar{U}_i \\ &= EW(n_{ii}) \quad ([when]\ i = j), \end{aligned} \tag{2.20}$$

where N_i is the number of individuals in city i. This equation shows that the (conditionally) aggregated expected consumers' surplus does not depend on the number of matching pairs x_{ij}. Next, by using $p(n_{ij})$ in equation (2.15), the (unconditionally) aggregated expected consumers' surplus generated in city i, EW_i, can be expressed as follows.

$$\begin{aligned} EW_i =& \sum_{\{j|j\neq i\}} \sum_{n_{ij}=0}^{H_{ij}} p(n_{ij}) \cdot EW(n_{ij}) + \sum_{n_{ii}=0}^{H_{ii}} p(n_{ii}) \cdot EW(n_{ii}) \\ =& \sum_{\{j|j\neq i\}} \sum_{n_{ij}=0}^{H_{ij}} p(n_{ij}) \cdot \{(E[U_{ij}^k|U_{ij}^k \geq \bar{U}_i] - \bar{U}_i)n_{ij} + N_i\bar{U}_i\} \\ &+ \sum_{n_{ii}=0}^{H_{ii}} p(n_{ii}) \cdot \{2(E[U_{ii}^k|U_{ii}^k \geq \bar{U}_i] - \bar{U}_i)n_{ii} + N_i\bar{U}_i\} \end{aligned} \tag{2.21}$$

The (unconditionally) aggregated expected consumers' surplus in city i, EW_i, is also independent of the number of matching pairs x_{ij}. The same formulation can be also applied to city j. Finally, the total consumers' surplus over the spatial system, EW, is given as follows.

$$EW = \sum_i EW_i \tag{2.22}$$

2.4.2 Lost surplus by failed meetings

A meeting will take place only after a mutual agreement by the matched individuals is made. Even if one party seeks a meeting, it cannot take place without the agreement of the partner. If a meeting fails to be realized due to the lack of agreement from either one of the partners, potential benefits will be lost. The loss of benefits due to meetings that fail to take place can only be generated in the case where one wishes to have the meeting, but the partner does not. This is the case corresponding to states 2 and 3 defined in Section 2.3.3. If we look at the particular city, e.g., city i, state 2 is the only case exhibiting a loss of benefits. Let the lost benefits ΔL_{ij} be defined by the expected value of the utility surplus that would have been obtained by the meetings as follows:

$$\Delta L_{ij} = p_{ij}^{(2)}(E[U_{ij}^k|U_{ij}^k \geq \bar{U}_i] - \bar{U}_i), \tag{2.23}$$

where $p_{ij}^{(2)}$ is the probability that state 2 occurs, which is defined by equation (2.3). $E[U_{ij}^k|U_{ij}^k \geq \bar{U}_i]$ is the average conditional utility of individual k in city i when a meeting with an individual in city j is realized. The total loss of benefits from city i, denoted by $\Delta\bar{L}_i$, is then given by

$$\Delta\bar{L}_i = \sum_{\{j|j\neq i\}} \sum_{x_{ij}=0}^{H_{ij}} x_{ij} p(x_{ij}) \Delta L_{ij} + \sum_{x_{ii}=0}^{H_{ii}} 2x_{ii} p(x_{ii}) \Delta L_{ii}, \tag{2.24}$$

where the first term, $p(x_{ij})$, is the probability that x_{ij} matching pairs are organized (see equation (2.1)), and the second term is the lost benefits from city i. The total loss of benefits for the system, ΔL, is given as follows.

$$\Delta L = \sum_i \Delta\bar{L}_i \tag{2.25}$$

2.5 Numerical Examples

2.5.1 Settings

This study aims to propose a framework to describe, model, and analyze face-to-face communications. In order to develop a practical face-to-face communication model, the probability of matching formation q_{ij} and the probability of agreement in equation (2.11) need to be expressed in specified functional forms. For example, the agreement model can be expressed as the more elaborate random matching model (Kobayashi *et al.*, 1996). The elaboration of the practical models represent very important studies. In the numerical example, the probability of matching formation q_{ij} and the probability of agreement p_{ij} are assumed to be modeled already. Given that, through some simple numerical examples, we will present a method of describing individual meeting formation behavior and evaluating the social welfare state based upon the individual consumers' surplus.More precisely, the effects of upgrading of transportation facilities between cities on meetings will now be analyzed.

Consider the spatial system consisting of two cities $1, 2$ (1: local city, 2: central city). City 1 has population $N_1 = 100,000$, while city 2 $N_2 = 1,000,000$. The deterministic part of the meeting utility for individuals living in city 1 and city 2, are assumed to be constant, i.e., $V_{ij} = 1.0$, and also the threshold utility levels are also constant, i.e., $\bar{U}_1 = \bar{U}_2 = \bar{U} = 0.1$. For simplicity, we neglect income terms, i.e., $Y_i = 0$. The probability of matching occurrence is set as $q_{12} = 5 \times 10^{-5}$.

TABLE 2.1: Probability of Meeting Formation

c_{12}	0.2	0.4	0.6	0.8	1.0
Average($\times 10^6$)	3.3069	3.2846	3.2619	3.2388	3.2154
Standard Deviation	1818.5	1812.3	1806.1	1799.7	1793.1

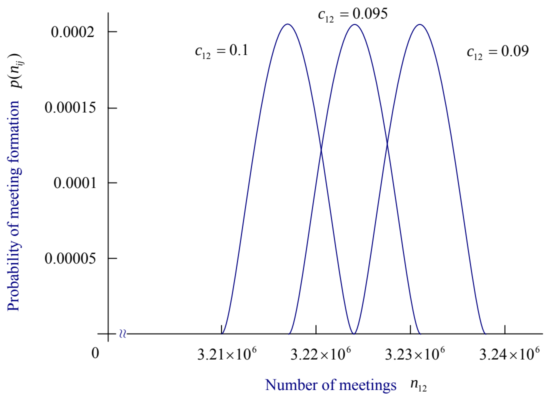

FIGURE 2.1: Occurence distribution of meeting formation

2.5.2 Occurrence distribution of meeting formation

First, let us derive the occurrence of meeting formation and meeting distribution. Using the agreement formation model (2.11), the probability of meeting formation p_{12} can be calculated. Next, by using equation (2.15), the occurrence distribution of meeting formation can be obtained. Figure 2.1 shows the occurrence distribution of meeting formation between the two cities. The decrease in the transportation cost c_{12} brings about an increase in meeting formation. Table 4.2 also shows the effects of change in transportation cost on the meeting distribution (average and standard deviation). The decrease in transportation costs between two cities c_{12} leads to an increase in meeting formation n_{12}, and consequently, an increase in the average number of meetings, as well as in the variance of meeting occurrence.

2.5.3 Examination on social welfare

From equation (2.21) the aggregated expected consumers' surplus for each city, EW_1 and EW_2, are obtained, and from equation (2.24) the lost benefits, $\Delta\bar{L}_1$ and $\Delta\bar{L}_2$, are also derived. The results are depicted in Figures 2.2 and Figure 2.3. In these figures, the horizontal axes are transportation costs between cities, c_{12}. Figure 2.3 shows the relationship between transportation cost and the per capita expected consumers' surplus. The increase in transportation cost c_{12} results in a

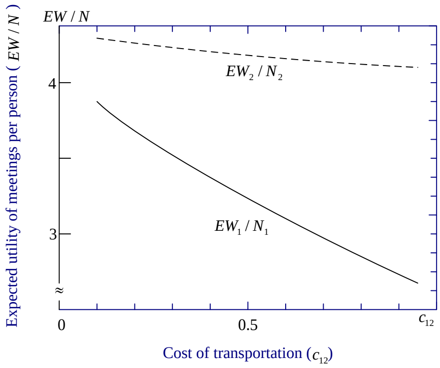

FIGURE 2.2: Average of expected utility of meetings(per person)

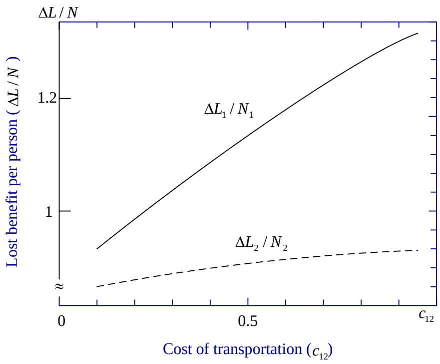

FIGURE 2.3: Lost benefit

decrease in expected consumers' surplus. Figure 2.3 shows the relationship between the cost of transportation and the lost benefit per capita for each city. The increase in transportation cost c_{12} yields a decrease in the expected consumers' surplus and an increase in the lost benefits.These tendencies are more remarkable for city 1 with less population.In this numerical example, the population in city 1 is small and a large portion of meetings held by persons in city 1 take place with persons in city 2. Therefore, the deterioration of the transportation facilities between cities means more difficult face-to-face communication and increased inefficiency of attending meetings for city 1 residents. On the other hand, city 2, which has the relatively larger population, suffers less damage in the case of an increase in transportation costs, because of the existence of more potential meeting partners in the same city. As a result, smaller population cities will benefit relatively more than large population cities from the refinement and consolidation of transportation facilities in the form of increased face-to-face communication.

2.6 Summary and Recommendations

One of the most important characteristics of face-to-face communication is that in order for individuals to communicate, they have to agree to meet first. By focusing on this characteristic, this study describes the meeting formation using a random matching model, specialized to the all-important two person meeting. The meeting occurrence is expressed by a probability distribution. Moreover, the methodology to measure the economic benefits of the meetings, as well as the benefits that are lost due to acceptance of potential meetings by just one partner is presented.

The model described here is limited in scope. One cannot draw policy conclusions directly from such a model. There are two purposes for its construction. One is to form a basis for further generalization. In particular, it would be interesting to introduce a search à la Diamond to examine how individuals can coordinate the matching process (Diamond and Maskin 1979; Diamond 1982).The second proposal is to provide an example to contrast with traditional travel behavior models that assume, unrealistically, the absence of mutual agreements and interactions in making decisions about face-to-face communications. Recently, travel demand modeling has been shifting its focus from the traditional trip-based modeling to the activity-based modeling approach (Spear 1996) in which the trip is regarded as one of several options for satisfying the activity, recognizing interpersonal dependencies. In corporation this activity-based approach into the meeting modeling may be beneficial.While the construction of realistic models of human contacts is needed for good communications policy analysis, the existence of this simple model indicates the possibility of constructing consistent behavioral models based on the existence of mutual agreements.

So far very little research has been done on the meeting mechanisms, and many study topics remain to be tackled in the future. First, the matching technology should be studied from the viewpoint of meeting efficiency. In the real world, various matching technologies are utilized in order to efficiently create meetings. Repeated meetings with the same partners is one example of efficient matching technology, and organizing conferences is another. The knowledge society can be sustained only with efficient matching technologies. Another study direction would be the inclusion of the heterogeneity of individual preferences and meeting technologies. When differences in individuals exist, meetings may not be organized at both cities with equal probability, as we assumed in this study. The meeting place and time may be determined by negotiations between the matched partners. For example, if the meeting takes place at the city where the matched partner with the smaller meeting benefit lives, the meeting cities and consequently, the distribution of meeting benefits over the system of cities, will have some systematic characteristics. The agglomeration merit of having meetings in the same city where other meetings are also frequently organized would also encourage the meetings to take place in the bigger city.

References

Beckmann, M. J., (1994) On knowledge networks in science: collaboration among equals. Ann Reg Sci, 28:233-242.

Ben-Akiva, M. and Lerman, S. R., (1987) Discrete Choice Analysis: Theory and Application to Travel Demand. The MIT Press, Cambridge.

Diamond, P. A. and Maskin, M., (1979) An equilibrium analysis of search and breach of contract, I: steady states. Bell J Econ, 10:282-316.

Diamond, P. A., (1982) Aggregate demand management in search equilibrium. J Poli Econ, 90: 881-894.

Domencich, T. A. and McFadden, D., (1975) Urban Travel Demand: A Behavioral Analysis. North-Holland, Amsterdam.

Finney, D., (1971) Probit Analysis. Cambridge University Press, Cambridge.

Hirsch, F., (1976) Social Limits to Growth. Harvard University Press, Cambridge.

Kobayashi, K., (1995) Transportation behavior in knowledge society. Infra Plan 12:1-13.

Kobayashi, K., Kita, K. and Tatano, H., (1996) A random matching model for joint trip production within households. J Infra Plan Man 536/IV31: 49-58 (in Japanese)

McFadden, D., (1974) Conditional logit analysis of qualitative choice behavior. In: Zarembka, P., (ed.) Frontiers in Econometrics. Academic Press, New York.

Roth, A. E. and Sotomayor, MAO (1990) Two-Sided Matching: a study in game-theoretic modeling and analysis. Cambridge University Press, New York.

Scitovsky, T., (1976) The Joyless Economy. Oxford University Press, New York.

Spear, B. D., (1996) New approaches to transportation forcasting models: A synthesis of four research proposals. J Trans 23: 215-240.

Wilson, A. G., (1970) Entrop in Urban and Regional Modelling. Pion, London.

Chapter 3

A Theoretical Model for Communication Processes by Face-to-face Contacts

3.1 Introduction

With the advance of micro econometrics, modeling methodology has gained remarkable ability to express various traffic behaviors. These modeling studies are ground on the presumption that traffic phenomena can be reduced to independent individual behaviors; they can be aggregated to explain the phenomena. In many situations, however, no traffic agent can decide his every behavior independently from the others' will. Especially, in face-to-face communications, the interdependence among individuals' decisions, that has been totally ignored in modeling, are essential.

When ones travel decisions are affected by the others' will, the meeting processes in a city can be no longer described by a simple aggregation of individual separate choices. Many search for and find meeting partners; they build up the agreement on meetings; then dissolve the meetings; and restart to search for new partners. The utility derived from repetition of meetings is also regulated by the others' characteristics and decisions. Whether a meeting realizes or not is also hinged by some exogenous contingent events. The deep understanding of face-to-face communications requires investigation of the process where meetings are repeated in a random fashion.

Of cause the effects of one's decision on the other's behavior has not totally ignored in transportation modeling. For example, in stochastic network equilibrium

(Daganzo 1977) and rational expectation equilibrium (Kobayashi 1994), the individuals' choices affect on the others' behavior in an aggregated fashions (via aggregated performances on transportation networks). Recently, several authors try to directly investigate the interdependence among individuals' choices. For instance, Kobayashi *et al.* (1996) propose a random matching model to investigate joint trip production by multiple persons. In these approaches, modeling efforts are only for description of interactions in individual decisions. No theoretical advancement has been made to define the equilibrium of the whole system.

Regarding with search behaviors, there already exists extensive literature both in Operation Research (McMillan *et al.* 1994) and in Economics. For example, Diamond (1984) and Mortensen (1982) investigate search for trading partners both on demand and supply sides, and analyze the inefficiency of equilibrium states. Howitt (1990) analyzes the market with search costs and clarifies the externalities caused by the scarcity of trading partners. Recently, there emerge new arenas in game theory with the heading of "two-sided matching games" (Roth and Sotomayor 1990). The major characteristic of these games is that market trading is made between distinct differentiated agents both of two different sides of demand and supply. However, in meeting markets, everyone can be a demander or supplier depending on situations. Consequently, face-to-face communication modeling requires a new framework describing 'no-sided matching game'.

This chapter focuses on two person meetings that is the simplest but also most fundamental form of meetings. The meeting behaviors are formulated as the two stage decision problems with 1) to find a meeting partner and 2) to agree (or disagree) on the meeting. The process that individuals repeat meetings with different partners is described. It is then shown that the long term 'meeting equilibrium' can be modeled as the rational expectations equilibrium.

3.2 Modeling of Meeting Process

3.2.1 Meetings

In order to realize a two person meeting, two persons should intend to have a meeting. They have to agree with having a meeting. The process of meeting formation (in brief, meeting process) is composed of 1) the process to find a potential meeting partner and 2) the process to negotiate whether they have a meeting or not. The former is called "the matching process", while the later "the agreement formation process". The meeting can be categorized into two: "spontaneous meetings" and "forced meetings", depending on whether it is formed by someone's order or by their spontaneous intentions. The former includes private meetings such as the one with friends and many business meetings by participants' free choices. The spontaneous meetings can be classified by "how potential meeting partners come to know each other" and "how they start their negotiation over meeting formation"(the matching technology). The later, on the other hand, is the meeting where one of the meeting members or the third party forces persons in concern to participate. In the forced meetings the person or the organization in power decides details of meeting formation. This chapter focuses on "the spontaneous meetings" to be realized by the people's free choices.

3.2.2 Assumption

Consider a city where $2m+1$ persons reside and search for meeting partners based on their private information. Each person decides whether to have a meeting or not when he finds a meeting partner or when he receives the meeting offer. When the both in concern agree to have a meeting, they stop their searching and the meeting forms instantaneously. When the agreement cannot be reached, both restart to search for their new partners. When the meeting ends, the meeting partners separate each other and restart to search for their new partners. During the meeting, search is temporally stopped and any arrived offers for meetings are rejected. Re-meetings with old partners are allowed. Persons do not distinguish the old partners from the new ones. In the next section, the process where all individuals repeat this kind of meeting formation is described as a birth/death stochastic process.

3.2.3 Modeling of meeting process

Assume that at time t, $2n+1$ persons are having no meetings, while $2(m-n)$ are doing meetings. Each person having no meeting has $2n$ (excluding himself) potential partners to initiate negotiations over meetings. The probability that more than two meetings start (or more than two meetings end, or both of these two events occur) in sufficiently small time interval of Δt can be neglected. The possible state changes between the time interval t and $t+\Delta t$ is either 1) one meeting starts, 2) one meeting ends, or 3) neither occurs. Let $a(n)$ denote the average instantaneous rate at which a new meeting forms and $b(n)$ denote the average instantaneous rate at which one meeting ends. These rates are conditional to the number of the persons having no meeting $2n+1$ $(0 \leq 2n \leq 2m)$. The probability that at time $t + \Delta t$ $2n + q$ persons have no meetings, $P_{t+\Delta t}(n)$ $(n = 0, 1, \cdots, m)$, is defined by

$$P_{t+\Delta t}(0) = a(1)\Delta t P_t(1) + (1 - b(0)\Delta t)P_t(0) + o(\Delta t)!, \tag{3.1-a}$$

$$P_{t+\Delta t}(n) = a(n+1)\Delta t P_t(n+1) + b(n-1)\Delta t \cdot P_t(n-1) + [1 - a(n)\Delta t - b(n)\Delta t]P_t(n) + o(\Delta t)!, \quad (n = 1, 2, \cdots, m-1) \tag{3.1-b}$$

$$P_{t+\Delta t}(m) = b(m-1)\Delta t P_t(m-1) + [1 - a(m)\Delta t] \cdot P_t(m) + o(\Delta t)!, \tag{3.1-c}$$

$$\sum_{n=0}^{m} P_t(n) = 1 \tag{3.1-d}$$

where $o(\Delta t)!$ is the higher order terms and $o(\Delta t)!/\Delta t \to 0$ as $\Delta t \to 0$. By dividing equations (3.1-a)-(3.1-c) by Δt and taking limit of $\Delta t \to 0$, the following equations hold.

$$\dot{P}(0) = a(1)P(1) - b(0)P(0), \tag{3.2-a}$$

$$\dot{P}(n) = a(n+1)P(n+1) + b(n-1)P(n-1) - [a(n) + b(n)]P(n), \quad (n = 1, 2, \cdots, m-1) \tag{3.2-b}$$

$$\dot{P}(m) = b(m-1)P(m-1) - a(m)P(m) \tag{3.2-c}$$

$$\sum_{n=0}^{m} P(n) = 1, \tag{3.2-d}$$

where $\dot{P}(n) = \lim_{\Delta t \to 0}\{P_{t+\Delta t}(n) - P_t(n)\}/\Delta t$. When $a(n) \geq 0$ and $b(n) \geq 0$ hold, at the limit of $t \to \infty$ the system (3.2-a)-(3.2-c) converges to the steady state. At the steady state, $\dot{P}(n) = 0$ $(n = 0, \cdots, m)$, and

$$a(n+1)P(n+1) + b(n-1)P(n-1) = [a(n) + b(n)]P(n), \quad (n = 1, 2, \cdots, m-1) \tag{3.3-a}$$

$$b(0)P(0) = a(1)P(1), \tag{3.3-b}$$

$$b(m-1)P(m-1) = a(m)P(m) \tag{3.3-c}$$

From equations (3.3-a),(3.3-b),and (3.3-c), the following equation is hold inductively.

$$a(n+1)P(n+1) = b(n)P(n) \quad (n = 1, \cdots, m-1) \tag{3.4}$$

By solving the equation (3.4) with the boundary conditions (3.3-b) and (3.3-c) and the condition (3.2-d), the stable probability is given as follows.

$$P(0)=\frac{\prod_{i=1}^{m}a(i)}{\prod_{i=1}^{m}a(i)+\sum_{k=2}^{m}\left\{\prod_{i=k}^{m}a(i)\prod_{j=0}^{k-2}b(j)\right\}+\prod_{j=0}^{m-1}b(j)} \tag{3.5-a}$$

$$P(n)=\prod_{l=1}^{n}\frac{b(l-1)}{a(l)}P(0),\ \ (n=1,\cdots,m-1) \tag{3.5-b}$$

$$P(m)=\frac{\prod_{j=0}^{m-1}b(j)}{\prod_{i=1}^{m}a(i)+\sum_{k=2}^{m}\left\{\prod_{i=k}^{m}a(i)\prod_{j=0}^{k-2}b(j)\right\}+\prod_{j=0}^{m-1}b(j)} \tag{3.5-c}$$

3.2.4 Birth/Death rates of meetings

At time t, $2n+1$ persons are searching for their meeting partners. Each of them has $2n$ potential partners to initiate negotiation over meetings. However, they cannot know a priori who does and does not have a meeting at each instant of time, and has to search for their meeting partners against all $2m$ persons. For them there are two ways to find the negotiation opponents: 1) to find the partner via their efforts and 2) to be offered a meeting by someone else. Now, let us describe the individual search effort by the probability that one can find a partner in a unit time, α_i (if brief, search strength). Assume that the probability that a person finds a negotiation partner by his search depends on the rate of the persons having no meetings to all persons at that point in time, $2n/2m$. The probability that one finds a partner in $[t, t+\Delta t]$, $s_i\Delta t$, is given by $s_i\Delta t = \alpha_i(n/m)\cdot\Delta t$, where s_i is the probability that one finds a partner to negotiate over meeting in a unit time. All individuals are supposed to be symmetric and to have exactly same search strength. Let the search strength of the individuals other than the person in concern i be denoted by α^i. The probability that one of the $2n$ searchers with the search strength α^i find the person in concern in $[t, \Delta t]$ is given by $(\alpha^i/2m)\Delta t$. Consequently, the probability that one in concern receives negotiation offer from someone else in $2n$, $s^i\Delta t$, is given by $s^i\Delta t = \alpha^i(n/m)\cdot\Delta t$. Thus, the probability that the person i is matched with a negotiation partner in $[t, t+\Delta t]$ is given by $h_i(n) = (\alpha_i + \alpha^i)(n/m)\Delta t$. Let the probability that in the matching pair both agree on having a meeting and the meeting realizes by π_i. With the assumption that the agreement and/or disagreement on meeting forms instantaneously, the probability that the meeting forms in a short time period of $[t, t + \Delta t]$ is given as follows.

$$\xi_i(n)\Delta t = \pi_i(\alpha_i + \alpha^i)\frac{n}{m}\Delta t \tag{3.6}$$

In the meeting process, if two of the matched pair agree to have a meeting, then the searches are promptly stopped and the meeting forms. On the other hand, when the agreement fails, they start to search again. Now assume that at the symmetric steady states, there hold $\xi_i(n) = \xi(n)$, $\pi_i = \pi$, $\alpha_i = \alpha$, and $\alpha^i = \hat{\alpha}$. Then, the probability that new meeting forms in a city in period Δt, when $2n + 1$ persons search for meeting partners independently at time t, is given as follows:

$$a(n)\Delta t = \frac{\xi(n)(2n + 1)\Delta t}{2} = \pi(\alpha + \hat{\alpha})\frac{n(2n + 1)}{2m}\Delta t. \tag{3.7}$$

Assume that meeting length is subject to an exponential distribution with a mean of β^{-1}. The probability that one meeting among $m - n$ meetings occurring at t will end in a period Δt, $b(n)\Delta t$ is given by

$$b(n)\Delta t = \beta(m - n)\Delta t. \tag{3.8}$$

3.3 Modeling of Individual Meeting Behaviour

3.3.1 Agreement over meetings

The search for a meeting partner is performed on information networks. Once the agreement for a new meeting is made, the meeting is organized and face-to-face communications are taken place on transportation networks. Irrespective of having a meeting or not, the search for a meeting partner always require the searching (information) cost. On the other hand, the transportation cost is imposed only when the meeting realizes.

Consider the situation where individuals i and j are matched by some manners and decide whether to have a meeting or not. They have two pure strategy of 'have a meeting' or 'not have a meeting'. The meeting realizes only when both choose the strategy of 'have a meeting'. While place, time, cost sharing, and others are also important agreement items to negotiate, these items are not considered in what follows. The negotiation over these items can be handled in the bargaining game approach.

Assume that individual i starts a meeting with individual j at time t. Let the utility of the meeting with length T evaluated as the present value at time t be expressed by the following random utility model.

$$\begin{aligned} U_i^j(t:T,\varepsilon) &= \int_t^T (\bar{v}_i^j + \varepsilon_i^j)\exp\{-r(\tau - t)\}d\tau - c_i^j \\ &= \frac{\bar{v}_i^j + \varepsilon_i^j}{r}\{1 - \exp[-r(T-t)]\} - c_i^j \end{aligned} \tag{3.9}$$

where r is the discount rate, v_i^j is the instantaneous utility level that individual i gets from the meeting with j, ε_i^j is the stochastic part of the instantaneous utility, which is assumed to be constant during the meeting, and c_i^j is the meeting cost (transportation cost) and is paid at the beginning of the meeting. Though the share of the meeting cost between the two participants varies depending on which one first offers a meeting, here the constant meeting cost for an individual is assumed for the shake of simplicity. The meeting length is not determined by the meeting negotiation but it is known that it follows the exponential distribution with the average β^{-1}. The expected utility evaluated as the present value at time t, $EU_i^j(t)$, is given by

$$EU_i^j(t:\varepsilon_i^j) = \int_t^\infty \{U_i^j(t:T,\varepsilon_i^j)\beta\exp\{-\beta(T-t)\}dT = \gamma(\bar{v}_i^j + \varepsilon_i^j) - c_i^j \tag{3.10}$$

where $\gamma = 1/(r+\beta)$. The individual i agrees to have a meeting with j when the expected meeting utility $EU(t:\varepsilon_i^j)$ is greater than his reservation utility level H_i. The probability that individual i agrees to have a meeting with j is expressed by

$$p_i^j = \text{Prob}\{EU_i^j(t:\varepsilon_i^j) \geq H_i\} = \text{Prob}\{\gamma(\bar{v}_i^j + \varepsilon_i^j) - c_i^j \geq H_i\}. \tag{3.11}$$

Assume that ε_i^j follows the normal distribution with average 0 and variance 1. By indicating the normal distribution function by $\Phi(\cdot)$, the agreement probability over meetings by i and j is given by the following equations.

$$p_i^j = \text{Prob}\{\gamma(\bar{v}_i^j + \varepsilon_i^j) - c_i^j \geq H_i\} = \Phi(\bar{v}_i^j - \delta(c_i^j + H_i)) \tag{3.12-a}$$

$$p_j^i = \text{Prob}\{\gamma\bar{v}_j^i - c_j^i + \varepsilon_j^i \geq H_j\} = \Phi(\bar{v}_j^i - \delta(c_j^i + H_j)) \tag{3.12-b}$$

where $\delta = \gamma^{-1}$. As the results of negotiation over meetings by i and j, the four possible states exist: 1) both agree to have a meeting (State Ω_1), 2) the individual i agrees to have a meeting but the individual j disagrees (State Ω_2j, 3) the individual j agrees to have a meeting but the individual i disagrees (State Ω_3), 4) both reject a meeting (State Ω_4). Now, assume that the random utility terms ε_i^j in (3.12-a) and

(3.12-b) are mutually independent. Then, the probability that each state occurs, $P(\Omega_i)$ $(i = 1, \cdots, 4)$, is given by $P(\Omega_1) = p_i^j p_j^i$, $P(\Omega_2) = p_i^j(1-p_j^i)$, $P(\Omega_3) = (1-p_i^j)p_j^i$, $P(\Omega_4) = (1-p_i^j)(1-p_j^i)$, respectively. The probability that a meeting realizes, π_{ij}, is given by $P(\Omega_1)$. Assume that individual's behavior is symmetric among all, and for arbitrary i it holds that $H_i = H$, $\bar{v}_i^j = \bar{v}\mathrm{C}c_i^j = c$, $\varepsilon_i^j = \varepsilon$, $p_i^j = p$, and $EU_i^j = EU$. The probability that both in a negotiation agree to have a meeting is given by

$$\pi(H, \hat{H}) = \{\Phi(\bar{v} - \delta(c + H))\}\{\Phi(\bar{v} - \delta(c + \hat{H}))\}, \tag{3.13}$$

where $\hat{H}$ is the reservation utility level and is determined by the meeting partner, and the probability that both agree, π, depends on the reservation utilities of both himself and the negotiating partner, $(H, \hat{H})$. From the fact that for the normal distribution $\phi(\varepsilon)$, $\int \varepsilon\phi(\varepsilon)d\varepsilon = -\phi(\varepsilon)$ and $\phi(\varepsilon) = \phi(-\varepsilon)$ hold, the average of expected utility of the meeting, EV, is given as follows.

$$EV = \frac{\int_{\delta(H+c)-\bar{v}}^{\infty} EU(t:\varepsilon)\phi(\varepsilon)d\varepsilon}{\int_{\delta(H+c)-\bar{v}}^{\infty} \phi(\varepsilon)d\varepsilon} = \gamma\bar{v} - c + \gamma\frac{\phi(\bar{v} - \delta(c+H))}{\Phi(\bar{v} - \delta(c+H))} \tag{3.14}$$

where $\phi(\cdot)$ is the normal density function.

3.3.2 Optimal search

No body can precisely know the total number of meetings taken place in a city at a certain point in time. Thus, no one is accessible to information of the exact rate of n/m. Assume that each individual can form rational expectations on the average rate of the number of potential negotiators to the total population in the city through repeated learning. In the rational expectations equilibrium, the subjective probability of matching that he expects is congruent with the objective average of the rate in the long run:

$$q(\alpha; \hat{\alpha})\Delta t = (\alpha + \hat{\alpha})E\left[\frac{n}{m}\right]\Delta t \tag{3.15}$$

where $\hat{\alpha}$ is the search strength of others. With the symmetry of individuals, there holds $\alpha = \hat{\alpha}$. As equation (3.15) shows, the probability of matching formation depends not only on the search strength of himself but also the one of the others.

Let $V(t)$ indicate the expected lifetime utility of an individual who searches for a meeting partner at time t. Let $U(t:T,\varepsilon)$ be the discounted utility of the meeting of length T started at t. The expected lifetime utility when the meeting of length

T is started at time t is defined by the sum of the meeting utility and the expected lifetime utility at time $t+T$ discounted for the present value at time t:

$$\bar{U}(t:T,\varepsilon) = U(t:T,\varepsilon) + V(t+T)\exp\{-r(T-t)\}$$

When the meeting length, T, follows the exponential distribution with average β^{-1}, the expected lifetime utility is rewritten to

$$\overline{EU}(t,\varepsilon) = \int_t^\infty \{\bar{U}(t:T,\varepsilon)\beta\exp\{-\beta(T-t)\}dT. \tag{3.16}$$

Since ε is a stochastic variable, the expected lifetime utility with a meeting started at time t, $R(t)$, is given as follows.

$$R(t) = \frac{\int_{\delta(c+H)-\bar{v}}^\infty \overline{EU}(t,\varepsilon)\phi(\varepsilon)d\varepsilon}{\int_{\delta(c+H)-\bar{v}}^\infty \phi(\varepsilon)d\varepsilon} \tag{3.17}$$

The states which may occur in $[t, t+\Delta t]$ are 1) a meeting starts (Sates ω_1), 2) a matching occurs but a meeting does not occur (State ω_2), and 3) matching fails (State ω_3), and they have a probability of occurrence, $p(\omega_1)$, $p(\omega_2)$, and $p(\omega_3)$, respectively: i.e., $p(\omega_1) = \pi(H)q(\alpha;\hat{\alpha})\Delta t, p(\omega_2) = \{1-\pi(H)\}q(\alpha;\hat{\alpha})\Delta t, p(\omega_3) = \{1-q(\alpha;\hat{\alpha})\}\Delta t$. Consider a representative person who searches at time t. He gains the expected lifetime utility of $R(t+\Delta t)$ with the probability $p(\omega_1)$, and the expected lifetime utility of $V(t+\Delta t)$ with $p(\omega_2)+p(\omega_3)$ at time $t+\Delta t$. By applying Bellman's principle of optimality, the optimal search effort is characterized by

$$V(t) = \max_{\alpha\geq 0,H}\left\{-C(\alpha)\Delta t + \frac{\pi q\Delta t}{1+r\Delta t}R(t+\Delta t) + \frac{1-\pi q\Delta t}{1+r\Delta t}V(t+\Delta t)\right\}, \tag{3.18}$$

where $V(t)$ is the optimal expected lifetime utility at time t, r is the time discount rate and $q = q(\alpha;\hat{\alpha})$. $C(\alpha)$ is the search cost function and has the following neoclassical properties: i.e., $\partial C(\alpha)/\partial\alpha > 0, \partial^2 C(\alpha)/\partial\alpha^2 > 0$. The right hand side of (4.4) consists of, from right to left, 1) the search cost, 2) the present value of the expected lifetime utility when a meeting realizes, and 3) the present value of the expected lifetime utility when a meeting fails. If at the steady state $V(t) = V(t+\Delta t) = V$ holds, then

$$rV = \max_{\alpha\geq 0,H}\{-C(\alpha) + \pi q[EV - \rho V]\} \tag{3.19}$$

where $\rho = r/(r+\beta)$Cand EV is the average of expected utility of the meeting (3.14) and is the function of H. Given $\hat{H}$ and $\hat{\alpha}$ as well as myopic conjectures satisfying $\partial E[n/m]/\partial\alpha = 0$, the optimal reservation utility level, H^*, is defined by

$$\frac{\partial \pi(H,\hat{H})q\{EV(H)-\rho V\}}{\partial H}=0, \tag{3.20}$$

where $EV(H)-\rho V$ is the expected lifetime utility when a matching is made. From (3.13) and (3.14), the optimal condition (3.20) can be rewritten to $(\rho V - H)q\phi(\bar{v}-\delta(c+H))=0$. From $q\phi(\bar{v}-\delta(c+H))>0$, the optimal reservation utility level, H^*, is given by

$$H^*=\rho V \tag{3.21}$$

where ρV is the average opportunity cost of a meeting and is expressed as the time value of the average meeting length evaluated by the expected lifetime utility. When individuals are symmetric, $H^*=\hat{H}^*$ holds. Substituting H^* into (3.13) and (3.14), the probability of meeting agreement, $\pi^*(V)$Cand the expected utility, $EV^*(V)$, are expressed as the functions of the expected lifetime utility, V.

$$\pi^*(V)=\Phi(\bar{v}-\delta c-rV)^2 \tag{3.22}$$

$$EV^*(V)=\gamma\bar{v}-c+\gamma\frac{\phi(\bar{v}-\delta c-rV)}{\Phi(\bar{v}-\delta c-rV)} \tag{3.23}$$

The optimal strategy of each individual, α^*, can be defined by the following first order condition:

$$\frac{\partial C}{\partial \alpha^*}=\pi^* E\left[\frac{n}{m}\right][EV^*-\rho V] \tag{3.24}$$

where $\pi^*=\pi^*(V)$ and $EV^*=EV^*(V)$. From (3.24), the optimal search is determined in order that the marginal expected benefit equals to the marginal cost.

3.4 Meeting Equilibrium

3.4.1 Meeting process

In the meeting process, search for partners and agreement with the matched partners are repeated. One cannot know the exact utility obtained from the meeting before one starts negotiations with the matched partner. The meetings are repeated with randomly selected partners with no memory. The individuals behave with bounded rationality in the sense that they adjust their subjective expectations through their private experiences. No individual can be accessible to a certain information on the utility level that he may obtain from the meeting to realize and the true probability of meeting formation. The types of information that one can gain are the expected utility of the meeting as well as long-term frequency of meetings occurrence. One chooses the best strategies based upon his subjective beliefs of the probability of meeting occurrence. When all individuals' subjective expectations are converged upon the rational ones, their strategy will also converges to the long-term steady solution. In what follows, the optimal steady strategy is formulated as the stable Nash equilibrium with the rational expectations.

3.4.2 Rational expectations equilibrium

When the birth/death rates of meetings in a shot time interval are given by (3.7) and (3.8), the probability that a matched partner is not having a meeting (call hereafter 'probability of encounter') is given by

$$E\left[\frac{n}{m}\right] = \frac{\sum_{n=0}^{m} n x^n \Gamma(n)}{\sum_{n=0}^{m} m x^n \Gamma(n)} = f(x), \tag{3.25}$$

where $x = \beta/2\pi\alpha$ and $\Gamma(n) = \prod_{i=1}^{n} m(m-i)/\{i(2i+3)\}, \Gamma(0) = 1$. If m is large enough, $f(x)$ can approximate to

$$f(x) = \frac{1}{2}\sqrt{x^2 + 4x} - \frac{x}{2} \tag{3.26}$$

where $f(x)$ is increasing and concave function with $f(0) = 0$ and $f(\infty) = 1$. One forms his rational expectation on the probability of encounter through his daily meeting experience. From (3.24), it is clear that different subjective expectation on the probability of encounter means the different search strategy to choose. One adjusts his search strategy through repetitive leaning on the probability of encounter. This kind of learning process can, for example, be formalized by Bayesian learning model (Kobayashi 1994). Now, assume that people's subjective expectation has converged to the rational expectation from which none have incentive to change his subjective expectation. This rational expectations equilibrium is defined as $(\alpha^*, \cdots, \alpha^*; V^*, \cdots, V^*)$ satisfying

$$\frac{\partial C}{\partial \alpha^*} = \pi^*(EV^* - \rho V^*) f\left(\frac{\beta}{2\pi^*\alpha^*}\right) \tag{3.27-a}$$

$$rV^* = -C(\alpha^*) + 2\pi^*\alpha^*(EV^* - \rho V^*) \cdot f\left(\frac{\beta}{2\pi^*\alpha^*}\right) \tag{3.27-b}$$

where EV^* is the expected utility (3.23) defined by the equilibrium utility V^*. Equation (3.27-a) characterizes the optimal search. Equation (3.27-b) defines the equilibrium utility level, implying that at the rational expectations equilibrium the present value of the reservation utility equals to the net profit obtained from the search of the meeting partners. From (3.27-a) and (3.27-b), the following holds at the rational expectations equilibrium.

$$rV^* = (2\eta - 1)C(\alpha^*) \tag{3.28}$$

where $\eta = \{\partial C(\alpha)/\partial\alpha\}/\{C(\alpha)/\alpha\} > 1$ is the elasticity of the cost function and the equilibrium utility equals to the search information cost multiplied by the markup rate of $2\eta - 1$.

3.5 Comparative Static Analyses

Let us investigate the impacts of improvement of transportation technology on the meeting equilibrium. Suppose temporally that the value of V is fixed. The meeting cost, cCand the reservation utility level, H, have the following effects on the agreement formation.

[**Proposition 1**] For a fixed expected lifetime utility, V, it holds that

$$\left.\frac{\partial \pi}{\partial c}\right|_{V=\text{const.}} < 0, \quad \left.\frac{\partial \pi}{\partial H}\right|_{V=\text{const.}} < 0, \quad \left.\frac{\partial EV}{\partial c}\right|_{V=\text{const.}} < 0, \quad \left.\frac{\partial EV}{\partial H}\right|_{V=\text{const.}} > 0$$

Proposition 1 shows that the increase in meeting costs decreases both the probability of meeting agreement and the expected utility of meetings. The increase in the reservation utility level decreases the probability of agreement formation but increases the expected utility of meetings. As the reservation utility increases, people tends to choose meetings with higher utility, resulting in the increase in the expected utility of meetings EV.

Now, consider the case when the expected utility of meeting is not fixed. The change of meeting cost affects the individual search behavior and the lifetime utility level and frequency of meeting occurrence. The effects of meeting cost on the meeting equilibrium are summarized as the following property.

[**Proposition 2**] Given the search cost function $C(\alpha)$, there holds that

$$\frac{\partial V}{\partial c} < 0 \quad \frac{\partial \alpha}{\partial c} < 0 \quad \frac{\partial E[n/m]}{\partial c} \geq\leq 0$$

Proposition 2 holds for an arbitrary $m > 0$. The increase of meeting cost decreases the equilibrium utility and the search effort. The effect of the meeting cost on the expected frequency of meeting occurrence $1 - E[n/m]$ is undecided.

Next, investigate the impacts of the improvement of information technology on the meeting equilibrium. Introduce a parameter η indicating technology levels into the cost function. Then, $C(\alpha : \zeta)$ is supposed to satisfy: $\partial C(\alpha : \zeta)/\partial\zeta \leq 0, \partial^2 C(\alpha : \zeta)/\partial\zeta\alpha \leq 0, \partial\eta(\zeta)/\partial\zeta \leq 0$. The advance in information technology is represented by the decrease in η. Then, the following property holds.

[Proposition 3]

$$\frac{\partial V}{\partial \eta} \geq 0 \quad \frac{\partial \alpha}{\partial \eta} < 0 \quad \frac{\partial E[n/m]}{\partial \eta} \geq\leq 0$$

In words, the advance of information technology brings about the decrease of the search effort α. The decrease in ζ does not affect on the agreement probability when the equilibrium utility is constant. The decrease of search efforts brings about the decrease in the frequency of meeting occurrence but increases the probability of encounter. The increase in the probability of encounter has, as a result, effects to increase the expected utility of matching. The impacts of decrease in ζ on the equilibrium utility level and frequency of meeting occurrence are therefore indecisive.

3.6 Summary and Recommendations

In this chapter, we point out that the face-to-face communication is composed of the search behavior for the meeting partners and the agreement formation behavior. The individual meeting behavior is then expressed by using Bellman's principle of optimality. Moreover, the meeting equilibrium to realize in the long-term is described as the rational expectations equilibrium. The properties of the meeting behavior and meeting equilibrium are then clarified. One important result obtained in this study is that the better transportation and communication technologies bring about not only the increased volume of traffic demands but also the qualitative change of increased additive value of meetings.

While this chapter focuses on the two-person meeting process, various face-to-face communication behaviors can be tacked by expanding our model. First, the heterogeneous of individuals' preferences and meeting technologies should be taken into consideration. When there exists differences in labor productivity and preference among individuals, there is a possibility that too much meeting offers go to some specific individuals. This kind of inefficiency problem caused by information pollution should be tackled. Secondly, conventions and symposiums organized by academic societies and other organizations contributes to increase efficiency of meeting. The development of organizations and institutions saves information search cost. The formation mechanism of various kinds of human networks can be analyzed based on the externalities of the information search cost. Third, the meeting process can be modeled as an evolutionary game. When discussing the development process of institutions and organizations, evolutionary game approach is necessary. Forth, model should be able to express the spatially distributed cities. finally, with some extension of the model, social problems caused from the existence of information search costs, such as reservation of transportation modes, can be tackled by the approach proposed in this study.

Appendix

A Deduction of the recursive equations

Assume that under the stable state it holds that $V(t+\Delta t+T)\exp\{-r(T-t-\Delta t)\} = V(t+\Delta t)(T>0)$. by integrating (3.17), it holds that $R(t+\Delta t) = EV + \upsilon V(t+\Delta t)$, where $\upsilon = \beta/(r+\beta)$. from (3.18), we get the following.

$$\begin{aligned}\frac{r\Delta t}{1+r\Delta t}V(t) = \max_{\alpha\geq 0,H}\Big\{&-C(\alpha)\Delta t\\&+\frac{\pi q\Delta t}{1+r\Delta t}[EV+(\upsilon-1)V(t+\Delta t)]\\&+\frac{1}{1+r\Delta t}\{V(t+\Delta t)-V(t)\}\Big\}.\end{aligned}$$

By dividing the both sides of the equation above by $\Delta t/(1+r\Delta t)$, it holds that

$$\begin{aligned}rV(t) = \max_{\alpha\geq 0,H}\Big\{&-C(\alpha)(1+r\Delta t)+\pi q[EV\\&+(\upsilon-1)V(t+\Delta t)]+\frac{V(t+\Delta t)-V(t)}{\Delta t}\Big\}\end{aligned}$$

Because under the stable state, it holds that $\lim_{\Delta t\to 0}V(t+\Delta t) = V(t) = V$, $\lim_{\Delta t\to 0}\{V(t+\Delta t)-V(t)\}/\Delta t = 0$, at the limit of $\Delta t \to 0$ the following equation holds.

$$rV = \max_{\alpha\geq 0,H}\{-C(\alpha)+\pi q(\alpha)(EV-\rho V)\}$$

where $\rho = r/(r+\beta)$.

B Deduction of $E[n/m]$

Because $P(m+1)=0$, it holds that $E[n^2] = \sum_{n=0}^{m}(n+1)^2P(n+1)$ and $E[n] = \sum_{n=0}^{m}(n+1)P(n+1)$. Also, obviously $E[n(2n+1)] = 2E[n^2]+E[n]$. on the other hand, from (3.4), (3.7), and (3.8), we get the following.

$$\begin{aligned}E[n(2n+1)] &= \sum_{n=0}^{m}(n+1)(2n+3)P(n+1)\\&= \sum_{n=0}^{m}(n+1)(2n+3)\frac{2m\beta(m-n)}{\bar{\alpha}\pi(n+1)(2n+3)}P(n)\\&= \frac{2m\beta}{\bar{\alpha}\pi}\sum_{n=0}^{m}(m-n)P(n) = \frac{2m\beta}{\bar{\alpha}\pi}\{m-E[n]\}\end{aligned}$$

where $\overline{\alpha} = \alpha + \hat{\alpha}$. therefore, we get the following.

$$E[n^2] = -\frac{E[n]}{2} + \frac{m\beta}{\overline{\alpha}\pi}\{m - E[n]\}$$

By dividing the both side of the equation by m^2 and take limitation of $m \to \infty$, the following holds.

$$E\left[\left(\frac{n}{m}\right)^2\right] = \frac{\beta}{\overline{\alpha}\pi}\left\{1 - E\left[\frac{n}{m}\right]\right\} \tag{3.29}$$

On the other hand, differentiating the both sides of (3.25) with respect to x, we get the following.

$$\frac{dE\left[\frac{n}{m}\right]}{dx} = \frac{m}{x}Var\left[\frac{n}{m}\right] \tag{3.30}$$

where $Var[n/m] = E[(n/m)^2] - E[n/m]^2$ is the variance. For some m, it holds that $0 \leq E[n/m] \leq 1$ and $0 \leq E[(n/m)^2] \leq 1$Cand the variance, $Var[n/m]$, satisfies $0 \leq Var[n/m] \leq 1$. $E[n/m]$ is the function of x, $0 \leq f(x) \leq 1$. From (3.30), $\lim_{x\to 0} \partial f(x)/\partial x = \infty$ and $\lim_{x\to\infty} \partial f(x)/\partial x = 0$. By Intermediate Value Theorem, for arbitrary $\infty > u > 0$, there exists X such that $dE[n/m]/dx = u$. For arbitrary m, in order that $dE[n/m]/dx = u$ holds, it must be $\lim_{m\to\infty} Var[n/m] = 0$. Therefore, for a number m which is large enough, the following holds.

$$\left\{E\left[\frac{n}{m}\right]\right\}^2 + \frac{\beta}{\overline{\alpha}\pi}E\left[\frac{n}{m}\right] - \frac{\beta}{\overline{\alpha}\pi} = 0 \tag{3.31}$$

From (3.31), we get the following.

$$E\left[\frac{n}{m}\right] = \frac{1}{2}\sqrt{\left(\frac{\beta}{\overline{\alpha}\pi}\right)^2 + 4\frac{\beta}{\overline{\alpha}\pi}} - \frac{1}{2}\frac{\beta}{\overline{\alpha}\pi}$$

C Proofs of propositions

(Proposition 1) from the definition of π, it is obvious that $\partial\pi/\partial c \leq 0$ and $\partial\pi/\partial H \leq 0$. define $y = \bar{v} - \delta(c + H)$. $\delta\gamma = 1$. From (3.14) $\partial EV/\partial c = -1 + (y\phi/\Phi + \phi^2/\Phi^2)$. From Mill's ratio (Mills, 1926), for arbitrary y it holds that $1 \geq y\phi/\Phi + \phi^2/\Phi^2 \geq 0$ (Maddala, 1983). From this, $\partial EV/\partial c \leq 0$. With same manner, we get $\partial EV/\partial H = y\phi/\Phi + \phi^2/\Phi^2 \geq 0$. **(Proposition 2)** First, evaluate the sign of the following derivatives. i) from (3.30), $\partial E[n/m]/\partial x \geq 0$. ii) from Proposition 1, $\partial(EV - \rho V)/\partial c = y\phi/\Phi + \phi^2/\Phi^2 - 1 \leq 0$ iii) from the assumption, $\partial C/\partial\alpha \geq 0$, $\partial^2 C/\partial\alpha^2 \geq 0$, and $\partial\eta/\partial\alpha \geq 0$Div) because $f(x)$ is the monotone increasing convex function and also because $f(0) = 0$, it holds that $f - (\partial f/\partial x)x \geq$

0. By differentiating (3.27-a) and (3.28) at the equilibrium x^*, α^*, V^*, we get

$$\begin{aligned} &\Xi^a_c dc + \Xi^a_V dV - \Xi^a_\alpha d\alpha = 0 \\ &r dV - \Xi^b_\alpha d\alpha = 0 \end{aligned} \tag{3.32}$$

where $\Xi^a_c = \{f^* - (\partial f^*/\partial x^*)x^*\}(\partial \pi^*/\partial c)(EV^* - \rho V^*) + \pi^* f^* \{\partial(EV^* - \rho V^*)/\partial c\} \leq 0$, $\Xi^a_\alpha = \partial^2 C^*/\partial \alpha^2 + \pi^*(EV^* - \rho V^*)(\partial f^*/\partial x^*)(x^*/\alpha^*) \geq 0$, $\Xi^a_V = \pi^* f(x^*)\partial(EV^* - \rho V^*)/\partial V^* + (\partial \pi^*/\partial V^*)(EV^* - \rho V^*)\{f^* - (\partial f^*/\partial x^*)x^*\} \leq 0$, $\Xi^b_\alpha = (2\partial \eta^*/\partial \alpha^*)C^* + (2\eta^* - 1)(\partial C^*/\partial \alpha^*) \geq 0$. From (3.32),

$$\begin{aligned} \frac{d\alpha}{dc} &= \frac{\Xi^a_c}{\Xi^a_\alpha - \Xi^a_V \Xi^b_\alpha / r} \leq 0 \\ \frac{dV}{dc} &= \frac{\Xi^b_\alpha}{r}\frac{d\alpha}{dc} \leq 0. \end{aligned}$$

On the other hand, $dE[n/m]/dc = -(\partial f^*/\partial x^*)x^*\{(d\alpha^*/dc)/\alpha^* + (\partial \pi^*/\partial c)/\pi^* + (\partial \pi^*/\partial V^*)(dV^*/dc)/\pi^*\}$. From $d\alpha^*/dc \leq 0$, $\partial \pi^*/\partial c \leq 0$, $dV^*/dc \leq 0$, $\partial \pi^*/\partial V^* < 0$, the sign of $dE[n/m]/dc$ is undecided. **(Proposition 3)** Near the equilibrium, it holds that

$$\begin{aligned} &\Xi^{a'}_\eta d\zeta - \Xi^{a'}_V dV - \Xi^{a'}_\alpha d\alpha = 0 \\ &r dV - \Xi^{b'}_\zeta d\zeta - \Xi^{b'}_\alpha d\alpha = 0 \end{aligned} \tag{3.33}$$

Here, from the assumptions, $\Xi^{a'}_\zeta = \partial^2 C^*/\partial \alpha \partial \zeta \geq 0$, $\Xi^{a'}_\alpha = -\pi^*(EV^* - \rho V^*)(\partial f^*/\partial x^*)(x^*/\alpha^*) - \partial^2 C^*/\partial \alpha^2 \leq 0$, $\Xi^{a'}_V = \pi^* f(x^*)\partial(EV^* - \rho V^*)/\partial V^* + (\partial \pi^*/\partial V^*)(EV^* - \rho V^*)\{f^* - (\partial f^*/\partial x^*)x^*\} \leq 0$, $\Xi^{b'}_\zeta = 2(\partial \eta/\partial \zeta)C^* + (2\eta - 1)\partial C^*/\partial \zeta \geq 0$, $\Xi^{b'}_\alpha = (2\eta - 1)\partial C^*/\partial \alpha \geq 0$. From (3.33), we get the following equation.

$$\begin{aligned} \frac{d\alpha}{d\zeta} &= \frac{\Xi^{a'}_\zeta - \Xi^{a'}_V \Xi^{b'}_\zeta / r}{\Xi^{a'}_\alpha + \Xi^{a'}_V \Xi^{b'}_\alpha / r} \geq 0 \\ \frac{dV}{d\zeta} &= \frac{\Xi^{a'}_\zeta \Xi^{b'}_\alpha + \Xi^{a'}_\alpha \Xi^{b'}_\zeta}{r\Xi^{a'}_\alpha + \Xi^{a'}_V \Xi^{b'}_\alpha} 0. \end{aligned}$$

By applying the similar method used for Proposition 2, it can be shown that the sign of $dE[n/m]/d\eta$ is undecided.

References

Daganzo, C. F. and Sheffi, Y., (1977) On stochastic models of traffic assignment. Transportation Science, Vol. 11: 253-255.

Diamond, P. A., (1984) A Search Equilibrium Approach to the Micro Foundation of Macroeconomics, MIT Press.

Howitt, P., (1990) Costly Search Recruiting, in: Howitt, P.. The Keynesian Recovery and Other Essays, 177-196, Philip Allan.

Kobayashi, K., (1994) Information, rational expectations and network equilibria. The Annals of Regional Science, Vol. 28: 369-393.

Kobayashi, K., Kita, H. and Tatano, H., (1996) A random matching model for joint trips production within households. Journal of Infrastructure Planning and Management, No. 536/IV-31:49-58(in Japanese).

Maddala, G. S., (1983) Limited-Dependent and Qualitative Variables in Econometrics. pp.165-170, Cambridge University Press.

McMillan, J. and Rothschild, M., (1994) Search, in: Aumann, R. J. and Hart, S. (eds.). Handbook of Game Theory, Vol.2:905-927, North-Holland.

Mills, J. F., (1926) Table of the ratio: Area to bounding ordinate for any portion of normal curve. Biometrica, Vol.18:395-400.

Mortensen, D. T., (1982) The matching process as a noncooperative bargaining game, In J. J. McCall (ed.). The Economics of Information and Uncertainty, 233-258, University of Chicago Press.

Roth, A. and Sotomayor, M. A. O., (1990) Two-Sided Matching, A Game-Theoretic Modeling and Analysis. Cambridge University Press.

Chapter 4

Communication Modeling with Heterogenous Agents

4.1 Introduction

In modern cities, huge amount of ideas and knowledge have been accumulating. The smooth and easy transmission of ideas facilitates the agglomeration externality of the cities. The face-to-face communication (referred to as 'meeting' hereafter) is an important means for human being to exchange ideas and knowledge. The meeting, as a core communication medium in the knowledge society, is accompanied by inefficiency inherent to the meeting coordination; a meeting is realized only when all potentially participating agents agree to having it (Kobayashi, Roy and Fukuyama, 1998). When an agent's decision is altered by others' will, the resulting equilibrium of the meetings is unlikely to be efficient. While being supported by active meetings, the knowledge society may inherently increase its inefficiency due to the increased meeting activities and correspondingly increased coordination failures of meetings.

In order to realize a meeting, potential partners must be 'matched' to negotiate whether or not the meeting should be taking place. In this paper, the term 'matching' refers to a mechanism by which agents are combined to form distinguishable opportunities with some common purpose that these agents cannot accomplish alone. Problems of interest for this paper are those in which meetings take place voluntarily. Possibility of substitution exists in the sense that no agent is an essential member of any meeting. The value of the joint activity engaged in the meetings can be assessed by their participants in many ways. In principle, meetings can consists of any number of participants. Among other issues, this paper highlights the relatively simple problem of bilateral meetings, consisting of two persons (two-person meetings based on two-person matchings) as the most fundamental meeting type.

For agents, the activities of being matched as potential meeting partners for a meeting does not necessarily mean the realization of the meeting. The meeting is realized only when the matched pairs come up with an agreement through negotiation. In other words, a meeting is realized via two distinct processes: 1) formation of pairs of agents (matching pairs) to start the negotiation over meetings, and 2) formation of an agreement to have a meeting by matching pairs. In a meeting process, each agent has two basic strategies: 1) whether to search for meeting partners, and 2) whether to accept a meeting offer made by a potential meeting partner (Kobayashi, Roy, and Fukuyama, 1998). People repeat meetings with different partners by adopting their best suitable strategy noncooperatively. Individuals are matched for meetings at random, and decide their own strategy by referring to their expected payoffs driven by the meetings as well as their expectations on others' strategies.

In a meeting process, search for meeting partners (matching of potential partners) has substantial impact on resulting meeting equilibrium. Search in market transactions has been studied extensively (for example, Diamond, 1984; Mortensen, 1982; Howitt, 1990; McMillan and Rothschild, 1994). A group of papers on random-matching games (first introduced in Rosenthal (1979)) shows that players may be able to cooperate or coordinate their actions even in settings where they play with changing partners. For example, Rosenthal and Landau (1979) demonstrate that for a particular bargaining game, players can avoid costly conflict through the evolution of reputations for players, or through suitable social norms that prescribe their behavior based on these reputations. A recent paper by Kandori (1992) greatly generalizes results on random matching games.

Social learning in random matching games has been an important topic of research in recent years. A significant part of this literature has pursued an evolutionary game approach where agents are assumed only boundedly rational when adjusting their behavior over time on the basis of relatively simple rules. The evolutionary game theory that is originally developed by Maynard-Smith (1982) in the contexts of the evolutionary biology is now actively applied in economics (see, for example, Friedman, 1991; Young, 1993, Kandori *et al.*, 1993; Weibull, 1995; Vega-Redondo, 1996). These models share one common setting; they assume that agents have access to relevant payoff information which is used to guide their behavioral adjustments. It is typically supposed that agents can either compute a best response to the current situation, or they can imitate those actions with highest payoff performance. In these studies, the main focus is on analyzing the strategic equilibrium of groups that are formed by the exogenously determined random matching, and the process that explains how such random matchings arise is not argued explicitly. In the face-to-face communications, however, random matchings arise as results of agents' search strategies, and, therefore, patterns of the random matching should be explained explicitly.

The most of research related to random matching games with evolutionary perspectives typically assume, and their results heavily rely on, the homogeneity of agents' characteristics. There is a relatively small literature that studies matching problems in which a set of heterogeneous agents is mapped into a set of heterogeneous objects with the payoffs from each match depending on some characteristic(s) of both sides of the match, (Becker, 1973; Cole, Mailath and Postlewaite, 1992; Sattinger, 1995; Burdett and Coles, 1996). Our contribution, departing from the previous literature, consists of the analysis of the implications of asymmetric information among agents, and also of effects of information availability (which is governed by information mechanism) on resulting meeting equilibrium. The introduction of asymmetric information complicates the model considerably since it introduces an additional source of heterogeneity to the usual unidimensional matching problem.

The asymmetry of information among agents is best represented by a parameter representing the value of meeting realized at each period. Suppose two distinct information mechanisms: 1) to provide null information about partners' type, and 2) to provide all agents complete information about partners' type. In the former mechanism, an agent, when being matched with a new partner, is assumed not to be accessible to the relevant information of the partner's type. Through repetition of meetings, the agents are motivated to learn their expected payoffs driven by participating in the meeting process. Thus, with the null information mechanism, one cannot differentiate one's strategies on search and agreement formation against the opponents' types, resulting in the *pooling equilibrium.* On the other hand, when the complete information mechanism available, one can know the type of potential partners while searching, and one can also judge the opponent's type while receiving meeting offers. In addition, one can also form expectations on whether or not the partners of the respective type will accept his/her offers through the long-term learning. Eventually, given their expectations, the agent can differentiate his/her search strategies according to the type of partners. Thus, with the complete information mechanism, one can distinguish search and agreement strategy depending on the type of meeting partners, resulting in the *separating equilibrium.*

The meeting process with heterogeneous agents can be, most typically, characterized by coordination failure, in which the agents fail to be coordinated the matches with the relevant meeting partners. The availability of exogenous information sorting the opponents' types has substantial impact on resulting meeting equilibrium. In this paper, a meeting process in which population with two types of agents repeat meetings is described in the framework of random matching game. The meeting equilibrium can be defined as an evolutionary stable state that forms as a result of meeting offer/acceptance interactions among the agents. The paper shows that there exist, quite naturally, multiple equilibria, and which equilibrium realizes is path dependent in social learning process. The relationship between information mechanisms (that governs information availability for each type of agents) and the resulting meeting equilibrium is also investigated. In what follows, the meeting equilibrium with null information mechanism is investigated in Section 4.2. Section 4.3 focuses upon the meeting equilibrium with complete information mechanism. In section 4.4, the relationship between information mechanisms and meeting equilibrium is investigated. In Section 5.5, conclusions and remaining research issues on the meeting analyses are mentioned.

4.2 Communication Equilibrium without Information

4.2.1 Assumption

Consider a society consisting of two types of agents. Which type each agent belongs to is private information and others cannot know prior to the meeting. There exists no information mechanism which transmits the potential meeting partners' type, but the meeting process itself transmits some of the macro statistics on the values of the meeting process to the agents. In other words, through repetition of meetings, each agent is motivated to learn their expected payoffs driven by participating in the meeting process. With the null information mechanism, no agent can differentiate its strategies on search and agreement formation against the opponents' types.

To address this question, we use a simple model with the following features. There are two populations of agents: The market operates over time. The agents repeat bilateral meetings with different partners. They are allowed to hold meetings with the same partners, but they have no memory about the types of the partners. It is assumed that the history of the meeting process has no impact upon the meeting process in the future. At each occasion, the agents decide 'whether to search for a meeting partner' and 'whether to accept a meeting offer by others'. If no information to sort the opponents' types is available, the agents cannot differentiate their strategies on search and agreement formation against the opponents' types. The agents should search for, if they wish to do so, meeting partners from the whole population. They should also decide whether to accept the opponent's offer whereby offerer's type is not revealed. If two matched agents agree to have a meeting, the meeting realizes. We consider a specific market where the payoff of each agent from a meeting only depends on the types of the partner. There are no utility transfers between partners in a match. Given an experience of a new meeting, the agents will revise their strategies on search and agreement formation. The expected payoffs in the game are supposed to represent the reproductive value from the social interactions in question. In a given strategic environment, the fittest strategy that maximizes the agent's expected payoffs essentially depends upon the strategies of others. Hence, there are feedback routes from the set of individual strategies to individual expectations on expected payoffs, by which the agents' strategies are guided to converge upon evolutionary stable ones in the long run. In this paper, we do not explain how a population arrives at such a strategies. Instead, it asks whether, once reached, a strategy is robust to evolutionary pressures.

The evolutionary stability is a robustness test against a single mutation at a time. In other words, it is as if mutations are rare in the sense that the population has time to adjust back to status quo before the next mutation occurs. The evolutionary stability requires that any small group of individuals who try some alternative strategy do less well than those who stick the status quo strategy. Consequently, individuals who use the prevailing strategy have no incentive to change their strategy, since they do better than the experimenters, and the latters have an incentive to return to the incumbent strategy. An evolutionarily stable strategy in such a social setting may be thought as social conventions (habits).

4.2.2 Meeting formation

Assume that N agents of two types with different preferences repeat meetings. Population of type 1 and type 2 agents are N_1 and N_2, respectively ($N_1+N_2=N$). Pure strategies of a type i agent, ρ_i^k ($i = 1,2; k = 1,\cdots,4$), are defined by a combination of two decision variables, s_i^k and θ_i^k. s_i^k is a dummy variable, indicating whether a type i agent searches for partners or not, while θ_i^k represents whether he/she accepts the opponents offers or not. More concretely, $s_i^k = 1$

means *search for meeting partners* and $s_i^k = 0$ means *not search*; $\theta_i^k = 1$ means *accept meeting offers* and $\theta_i^k = 0$ means *refuse them*. For the respective agent, four pure strategies are available, each of which is described by a pair of dummy variables, (s_i^k, θ_i^k), (see Table 4.1).

TABLE 4.1: Pure Strategies under Null Information

ρ_i^k	Contents	(s_i^k, θ_i^k)
ρ_i^1	(search,accept)	(1,1)
ρ_i^2	(search,refuse)	(1,0)
ρ_i^3	(not search,accept)	(0,1)
ρ_i^4	(not search,refuse)	(0,0)

The expected frequency of meetings per unit time duration that a certain type of agent can enjoy is fully conditional to the whole set of the strategies that all agents have chosen. Suppose an equilibrium situation where all agents in type 1 and type 2 adopt pure strategies, ρ_1^k and ρ_2^l, respectively. Also, suppose that if an agent in type i is motivated to search for meeting partners, he/she can find α (> 0) potential partners per a unit period on average regardless of their types. Suppose that he/she finds an agents in type j $(j = 1, 2)$ as his/her meeting partner. If the agent of type j accepts his/her offer (if $\theta_j^k = 1$), a meeting will form between the agents in type i and j. When $\theta_j^k = 0$, on the other hand, a meeting will not form. The probability that an agent in type 1 finds an agent in type 1 (or alternatively, in type 2) is given by $\beta_{11} = (N_1 - 1)/(N - 1)$ (or alternatively, $\beta_{12} = N_2/(N-1)$). Similarly, that of the type 2 finds an agent in type 1 (or alternatively, 2) is represented by $\beta_{21} = (N_1 - 1)/(N - 1)$ (or alternatively, $\beta_{22} = N_2/(N - 1)$). When N is large enough, the approximations, $\beta_{11} \cong N_1/N$, $\beta_{21} \cong N_1/N$, $\beta_{12} \cong N_2/N$, and $\beta_{22} \cong N_2/N$ hold. Now, use the notations of $\beta_1 = N_1/N$ and $\beta_2 = N_2/N$. If the average number of agents to be found by a search in a unit period, α, is assumed to be independent for each agent, the expected frequency that an agent in both types finds an agent of type i $(i = 1, 2)$ is $\alpha\beta_i$. When all agents in the same type choose the same pure strategies, ρ_1^k and ρ_2^l, the expected number of the meetings with agents in type j $(j = 1, 2)$ that an agent in type i can realize by his/her own search in a unit period, denoted by $\overline{a}_i^j$ $(i, j = 1, 2)$, is given as follows:

$$\left.\begin{aligned}
\overline{a}_1^1 &= \alpha\beta_1 s_1^k \hat{\theta}_1^k \\
\overline{a}_1^2 &= \alpha\beta_1 s_1^k \hat{\theta}_2^l \\
\overline{a}_2^1 &= \alpha\beta_2 s_2^l \hat{\theta}_1^k \\
\overline{a}_2^2 &= \alpha\beta_2 s_2^l \hat{\theta}_2^l
\end{aligned}\right\} \tag{4.1}$$

where the symbol $\hat{\theta}_j^k$ represents the strategy that is chosen by the partner.

Notice that the probability that the agent in concern is chosen as a potential partner by a single agent is $1/(N-1)$. Consider a situation where all N_i agents in type i search for partners independently with the common search intensity α. Then, an agent in type i will receive $\alpha N_i - 1/(N-1)$ offers on average in a unit period from the agents in the same type. Similarly, an agent in type j receive $\alpha N_i/(N-1)$ offers from type i. When N is large enough, there hold $N_i/(N-1) \cong \beta_i$ and $(N_i-1)/(N-1) \cong \beta_i$. Suppose that all agents in the same type choose the same pure strategies, ρ_1^k and ρ_2^l, the expected number of meetings that an agent in type i accepts offers from agents in type j in a unit period, denoted by $\underline{a}_i^j$ $(i,j=1,2)$, is described as follows:

$$\left.\begin{aligned} \underline{a}_1^1 &= \alpha\beta_1\hat{s}_1^k\theta_1^k \\ \underline{a}_1^2 &= \alpha\beta_2\hat{s}_2^l\theta_1^k \\ \underline{a}_2^1 &= \alpha\beta_1\hat{s}_1^k\theta_2^l \\ \underline{a}_2^2 &= \alpha\beta_2\hat{s}_2^l\theta_2^l \end{aligned}\right\} \tag{4.2}$$

where $\hat{s}_i^k$ is the strategy that the potential partner chooses, being out of control by the agent in concern. Assume that all agents in type 1 choose the same pure strategy ρ_1^k, and those in type 2 adopt ρ_2^l. Notice that the meetings that an agent enjoy are arranged both by his/her own search efforts and by accepting the others' offers. Hence, the expected number of meetings, denoted by $n_i^j(\rho_1^k,\rho_2^l)$, is conditional to a set of pure strategies (ρ_1^k,ρ_2^l) that an agent in type i can realize with agents in type j in a unit period, and can be defined as follows:

$$\left.\begin{aligned} n_1^1(\rho_1^k,\rho_2^l) &= \alpha\beta_1(s_1^k\hat{\theta}_1^k + \hat{s}_1^k\theta_1^k) \\ n_1^2(\rho_1^k,\rho_2^l) &= \alpha\beta_2(s_1^k\hat{\theta}_2^l + \hat{s}_2^l\theta_1^k) \\ n_2^1(\rho_1^k,\rho_2^l) &= \alpha\beta_1(s_2^l\hat{\theta}_1^k + \hat{s}_1^k\theta_2^l) \\ n_2^2(\rho_1^k,\rho_2^l) &= \alpha\beta_2(s_2^l\hat{\theta}_2^l + \hat{s}_2^l\theta_2^l) \end{aligned}\right\} \tag{4.3}$$

4.2.3 Meeting payoffs

Now we model the payoffs that agents in type 1 and type 2 can get when they adopt pure strategies, ρ_1^k and ρ_2^l, respectively.

Let $\bar{V}_i^j$ be the payoff that an agent in type i $(i=1,2)$ acquires when holding a meeting with an agent in type j $(j=1,2)$. Without loss of generality, let us normalize the reserved payoff when no meetings are arranged as $\bar{V}_i^0=0$. The search cost is normalized to 1, and the acceptance cost is supposed to take sufficiently small value of $\varepsilon(>0)$. When all agents in the same type adopt the same pure strategies, ρ_1^k and ρ_2^l, respectively, the payoff that an agent in type i can gain from the meetings, $v_i(\rho_1^k, \rho_2^l)$, is given by

$$v_1(\rho_1^k, \rho_2^l) = -(s_1^k + \varepsilon\theta_1^k) + \beta_1(s_1^k\hat{\theta}_1^k + \hat{s}_1^k\theta_1^k)\bar{v}_1^1 + \beta_2(s_1^k\hat{\theta}_2^l + \hat{s}_2^l\theta_1^k)\bar{v}_1^2, \quad (4.4)$$

$$v_2(\rho_1^k, \rho_2^l) = -(s_2^l + \varepsilon\theta_2^l) + \beta_1(s_2^l\hat{\theta}_1^k + \hat{s}_1^k\theta_2^l)\bar{v}_2^1 + \beta_2(s_2^l\hat{\theta}_2^l + \hat{s}_2^l\theta_2^l)\bar{v}_2^2 \quad (4.5)$$

where $\bar{v}_i^j = \bar{V}_i^j/\alpha$ is the meeting payoff measured in terms of matching cost (the expense to be matched with a partner for a meeting). The first terms of right hand side of eqs. (4.4) and (4.5) represent search cost. The second and third terms represent expected sub-payoffs of meeting with agents in type 1 and 2, respectively. Consider the case that the single agent in type 1 adopts a pure strategy $\rho_1^{k'}$, while all other agents in each type adopt the common pure strategies, ρ_1^k and ρ_2^l, respectively. In this situation, the agent deviating from the common strategies will acquire the following payoff:

$$v_1(\rho_1^{k'}; \rho_1^k, \rho_2^l) = -(s_1^{k'} + \varepsilon\theta_1^{k'}) + \beta_1(s_1^{k'}\hat{\theta}_1^k + \hat{s}_1^k\theta_1^{k'})\bar{v}_1^1 + \beta_2(s_1^{k'}\hat{\theta}_2^l + \hat{s}_2^l\theta_1^{k'})\bar{v}_1^2 \quad (4.6)$$

Similarly, the payoff of the single agent in type 2 who adopts a pure strategy $\rho_2^{l'}$ different from the common one, ρ_2^l, can be given as follows:

$$v_2(\rho_2^{l'}; \rho_1^k, \rho_2^l) = -(s_2^{l'} + \varepsilon\theta_2^{l'}) + \beta_1(s_2^{l'}\hat{\theta}_1^k + \hat{s}_1^k\theta_2^{l'})\bar{v}_2^1 + \beta_2(s_2^{l'}\hat{\theta}_2^l + \hat{s}_2^l\theta_2^{l'})\bar{v}_2^2 \quad (4.7)$$

4.2.4 Equilibrium and stability

In order to formalize the payoff of the agent taking an strategy against the rest of the population, we define the distribution of strategies that realizes in the population. Let $\sigma_i(\rho_i^k)$ be the rate of the agents in type i who adopt pure strategy ρ_i^k in the population, where there holds $\sum_{k=1}^4 \sigma_i(\rho_i^k) = 1$. Define a vector $\boldsymbol{\sigma}_i = \{\sigma_i(\rho_i^1), \cdots, \sigma_i(\rho_i^4)\}$. The expected payoff for the single agent in type 1 or 2 that adopts pure strategy $\rho_1^{k'}$ or $\rho_2^{l'}$, given the behavior profile of the rest of the population, is defined by

$$v_1(\rho_1^{k'}; \boldsymbol{\sigma}_1, \boldsymbol{\sigma}_2) = \sum_{k=1}^4 \sum_{l=1}^4 \sigma_1(\rho_1^k)\sigma_2(\rho_2^l)v_1(\rho_1^{k'}; \rho_1^k, \rho_2^l)$$

$$v_2(\rho_2^{l'}; \boldsymbol{\sigma}_1, \boldsymbol{\sigma}_2) = \sum_{k=1}^4 \sum_{l=1}^4 \sigma_1(\rho_1^k)\sigma_2(\rho_2^l)V_2(\rho_1^{l'}; \rho_1^k, \rho_2^l),$$

respectively. If the single agent in type 1 or 2 adopts a mixed strategy $\boldsymbol{\sigma}'_i = \{\sigma'_i(\rho_1^i), \cdots, \sigma'_i(\rho_4^i)\}$, given the strategy profile of the rest of the population, his/her payoff is given by

$$v_1(\boldsymbol{\sigma}'_1; \boldsymbol{\sigma}_1, \boldsymbol{\sigma}_2) = \sum_{k=1}^{4} \sigma'_1(\rho_1^k) v_1(\rho_1^k; \boldsymbol{\sigma}_1, \boldsymbol{\sigma}_2) \tag{4.8}$$

$$v_2(\boldsymbol{\sigma}'_2; \boldsymbol{\sigma}_1, \boldsymbol{\sigma}_2) = \sum_{l=1}^{4} \sigma'_2(\rho_2^l) v_2(\rho_2^l; \boldsymbol{\sigma}_1, \boldsymbol{\sigma}_2). \tag{4.9}$$

There are two implicit assumptions in the formalization of these payoffs. First, it is assumed that the population is so large that every given individual has an insignificant weight. Second, the influence of the population on the payoff of any given individual is contained in the anonymous description of the frequencies with which each strategy is being played by the population.

The essential postulate underlying evolutionary game theory is that current payoffs determine the relative viability of the different strategies, thus affecting short-run evolution of their corresponding population frequencies. When any agent is not accessible to information on the types of potential partners, the social configuration of individual strategies will evolve, via natural selection, into one of pooling equilibria in which every agent in the respective type adopts the common nondiscriminatory strategy against opponent types. In order to find out the candidates for evolutionary stable pooling equilibria, let us count up all possible Nash equilibria in which all agents adopt optimal (best reply) meeting strategy noncooperatively. Nash equilibria, as the group equilibria, is then defined as a set of $\boldsymbol{\sigma}_1^*$ and $\boldsymbol{\sigma}_2^*$, that satisfy

$$\left.\begin{array}{l} v_1(\boldsymbol{\sigma}_1^*; \boldsymbol{\sigma}_1^*, \boldsymbol{\sigma}_2^*) \geq v_1(\boldsymbol{\sigma}_1; \boldsymbol{\sigma}_1^*, \boldsymbol{\sigma}_2^*) \\ v_2(\boldsymbol{\sigma}_2^*; \boldsymbol{\sigma}_1^*, \boldsymbol{\sigma}_2^*) \geq v_2(\boldsymbol{\sigma}_2; \boldsymbol{\sigma}_1^*, \boldsymbol{\sigma}_2^*) \end{array}\right\} \tag{4.10}$$

for any mixed strategies, $\boldsymbol{\sigma}_1$ and $\boldsymbol{\sigma}_2$. In order to examine the evolutionary stability of the respective Nash equilibria, it should be tested whether or not the patterns of strategies prevailing in the equilibrium states can be invaded by any mutation which is better fit. Notice that each agent's payoff is linear function of his strategies, $\boldsymbol{\sigma}_1$ or $\boldsymbol{\sigma}_2$. For any strategy of type 1, $\boldsymbol{\sigma}_1$, that satisfies $v_1(\boldsymbol{\sigma}_i^*; \boldsymbol{\sigma}_1^*, \boldsymbol{\sigma}_2^*) = v_1(\boldsymbol{\sigma}_1; \boldsymbol{\sigma}_1^*, \boldsymbol{\sigma}_2^*)$ against Nash equilibrium strategies, $\boldsymbol{\sigma}_1^*$ and $\boldsymbol{\sigma}_2^*$, they are evolutionary stable in piece-wise scene against any mutants of type 1 (Weibull, 1995), if the following holds.

$$\left.\begin{array}{l} v_1(\boldsymbol{\sigma}_1^*; \boldsymbol{\sigma}_1, \boldsymbol{\sigma}_2^*) > v_1(\boldsymbol{\sigma}_1; \boldsymbol{\sigma}_1, \boldsymbol{\sigma}_2^*) \\ v_2(\boldsymbol{\sigma}_2^*; \boldsymbol{\sigma}_1, \boldsymbol{\sigma}_2^*) > v_2(\boldsymbol{\sigma}_2^*; \boldsymbol{\sigma}_1, \boldsymbol{\sigma}_2^*) \end{array}\right\} \tag{4.11}$$

The evolutionary stable conditions to all mutants of type 2 can be defined in the same way. When equilibrium strategies $\boldsymbol{\sigma}_1^*$ and $\boldsymbol{\sigma}_2^*$ are 'piece-wise' stable to any mutants of both types, they are defined as 'evolutionary piece-wise stable'(or E.P.W. stable). The E.P.W. stability criterion rules out the simultaneous invasion of multiple mutants. The refinement of evolutionary stability is requested to scrutinize stronger concepts that can block simultaneous invasion of multi-mutants.

4.2.5 Pooling equilibrium

The agents' preferences towards meetings have substantial impacts upon the patterns of pooling equilibria. In this section, the relationship between the combinations of agents' payoffs and the resulting pooling equilibria is analyzed. Let us suppose that the shares of respective type population, (β_1, β_2), are fixed, and satisfy $\beta_1 \geq \beta_2$. Given the opponents' strategies, ρ_1^k and $\hat{\rho}_2^l$, eqs. (4.6) and (4.7) can be rewritten as follows:

$$\begin{aligned} v_1(\rho_i^{k'}; \rho_1^k, \hat{\rho}_2^l) &= \Phi_1(\hat{\theta}_1^k, \hat{\theta}_2^l) s_1^{k'} + \Psi_1(\hat{s}_1^k, \hat{s}_2^l)\theta_1^{k'} \\ v_2(\rho_i^{l'}; \rho_1^k, \rho_2^l) &= \Phi_2(\hat{\theta}_1^k, \hat{\theta}_2^l) s_2^{l'} + \Psi_2(\hat{s}_1^k, \hat{s}_2^l)\theta_2^{l'}, \end{aligned}$$

where

$$\begin{aligned} \Phi_1(\hat{\theta}_1^k, \hat{\theta}_2^l) &= -1 + \beta_1 \hat{\theta}_1^k \bar{v}_1^1 + \beta_2 \hat{\theta}_2^l \bar{v}_1^2 \\ \Phi_2(\hat{\theta}_1^k, \hat{\theta}_2^l) &= -1 + \beta_1 \hat{\theta}_1^k \bar{v}_2^1 + \beta_2 \hat{\theta}_2^l \bar{v}_2^2 \\ \Psi_1(\hat{s}_1^k, \hat{s}_2^l) &= -\varepsilon + \beta_1 \hat{s}_1^k \bar{v}_1^1 + \beta_2 \hat{s}_2^l \bar{v}_1^2 \\ \Psi_2(\hat{s}_1^k, \hat{s}_2^l) &= -\varepsilon + \beta_1 \hat{s}_1^k \bar{v}_2^1 + \beta_2 \hat{s}_2^l \bar{v}_2^2. \end{aligned}$$

Figure 4.1 defines the possible combinations of the utility levels that an agent in type i can gain from a meeting with agents in type j $(j = 1, 2)$. Solid lines in the figure correspond to the set of utility profiles combinations that make $\Phi_i = 0$ $(\Psi_i = 0)$, and the arrows indicate the half space where $\Phi_i \geq 0$ $(\Psi_i \geq 0)$ holds. While Figure 4.1 is drawn with $\beta_1 = \beta_2 = 0.5$, the values of β_1 and β_2 do not influence on the topological pattern of domain partition; it only shifts border lines between domains. The combination spaces of agents in each type can be divided into mutually exclusive utility domains in the same fashion. Hence, by combining the distinct utility domains of the different types of agents, the set of random matching games which have the same equilibrium patterns can be defined. Table 4.3 describes the whole set of Nash equilibrium patterns which can be obtained by considering all possible combinations of distinct utility domains of the respective types of agents.

As summarized in Table 4.3, 25 kinds of equilibrium pattern exist with various combination of the meeting utility levels, $\bar{v}_i^k$. Equilibria of pattern A to J are that of pure strategies, while those of K to Y are composed of mixed strategies. In this table, s_i and θ_i are given by $s_i = \sum_k \sigma_i(\rho_i^k)s_i^k$ and $\theta_i = \sum_k \sigma_i(\rho_i^k)\theta_i^k$, indicating the search probability and the accept probability, respectively. Since four pure strategies are available in the game, multiple independent combinations of pure strategies that express the same search probability and accept probability, (s_i, θ_i), exist. This means that there exist many different combinations that realizes the same probability combination (s_i, θ_i). Accordingly, in Table 4.3 only search and accept probabilities are given and the corresponding (many possible) strategies are omitted. In patterns A, K, L, M, N, and Y, all agents search for partners and accept every offer. In patterns B, C, U, V, W, and X, all agents accept any offers but only one type of agents searches. In other words, in these patterns agents of one type free-ride on other type's searching. In patterns D, E, O, P, Q, and R, both types search for partners but only one type refuses any offers. Especially in patterns D and E, where agents of one type always refuses the offer, offerers can distinguish the opposite type ex post by referring whether he accepts the offers. In pattern F and G, persons of only one type meet each other. In pattern H, I, S, and T, on the other hand, meetings are formed only between different types. In pattern J all agents neither search meeting partners nor accept offers, and therefore no meeting realizes. This pattern can exist in any utility profile. Finally, in patterns $D, E, F, G, H, I, O, P, Q, R, S$, and T, agents of one type always refuses meeting offers.

Nash equilibria given in Table 4.3 exist for each combination of utility profiles for both types given in Figure 4.1, but not all of them are E.P.W. stable. In Nash equilibrium under patterns K, O, Q, U and X, agents in type 2 get $v_2 = 0$ payoff. In other words, though they search or accept in these cases, payoff from these actions is canceled out by the cost for the actions. In these cases, the strategy of type 2 cannot block the mutants with $(s_2, \theta_2) = (0, 0)$ strategy, because their payoff decrease sub zero by the invasion of this type of mutants. Similarly, in patterns L, P, R, V and W, agents in type 1 that acquire 0 payoff resulting from the canceling-out the meeting benefit and the costs, cannot block the mutants with $(s_1, \theta_1) = (0, 0)$ strategy. In patterns S, T and Y, agents of both type get 0 payoffs and again they cannot block mutants with $(s_i, \theta_i) = (0, 0)$ $(i = 1, 2)$. Consequently, pure strategy equilibrium in pattern A to J and mixed strategy equilibria in patterns M and N are E.P.W. stable that are indicated by putting the asterisk, $*$, at the upper-right side of pattern symbols in Table 4.3.

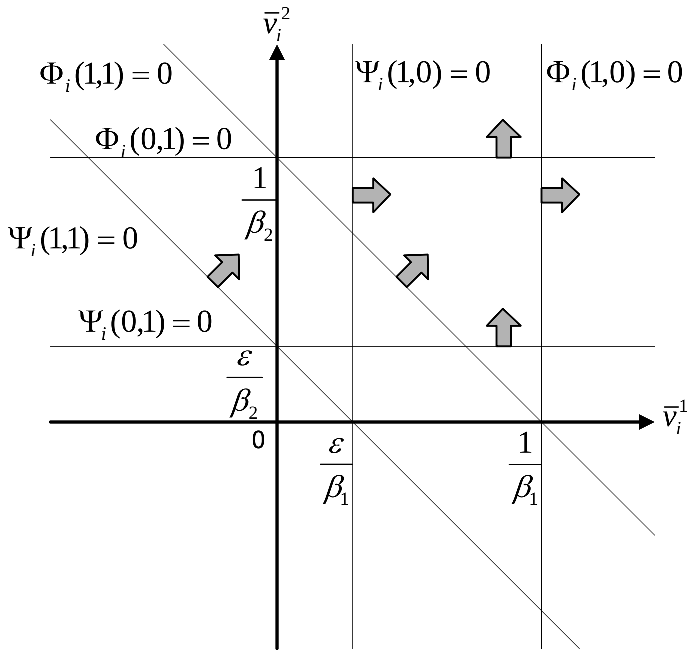

FIGURE 4.1: Domains division of utility profile in pooling equilibrium

4.3 Communication Equilibrium with Complete Information

4.3.1 Meeting strategies

In this section, let us consider the case where complete information mechanism is available, and each agent can perfectly distinguish the type of potential meeting partners beforehand. This assumption represents, for example, that one may have 'a receiving machine' by which he/she can distinguish offerers' type automatically and offers only from the selected type of people are forwarded to him/her. In real, it may be difficult for agents to distinguish offerers' type perfectly. In this section, the extreme situation where they can use complete information is assumed and the influence that availability of complete information on the meeting equilibrium are analyzed. Under complete information, all agents can recognize type of meeting partners *ex ante*. Accordingly, they are able to search for the specific partners with whom they want to have meetings. Moreover, as they can recognize the type of meeting offerers beforehand, they can distinguish offerers whether or not to accept them. There exist 16 different pure strategies, η_i^k, $(k = 1, \ldots, 16)$, shown in Table 4.2, that can be defined as the combinations of four decision making patterns, namely, 'whether or not to search for type 1', 'whether or not to search for type

2', 'whether or not accept offers from type 1', and 'whether or not accept offers from type 2'.

Let us introduce the dummy variables for type i, (u_i^k, w_i^k) and (ϕ_i^k, ψ_i^k), representing whether 'search' and 'accept' are chosen, respectively; $u_i^k = 1$ means 'search for partners of type 1', while $u_i^k = 0$ means 'not search for partners of type 1'. Similarly, w_i^k is also a dummy variable representing whether searching meeting partners of type 2. Also ϕ_i^k is the dummy variable describing whether accepting meeting offers from those of type 1 and ψ_i^k is the one representing whether accepting meeting offers from those of type 2. Then, the pure strategy, η_i^k, can be represented by dummy variables $(u_i^k, w_i^k, \phi_i^k, \psi_k)$ as given in Table 4.2.

TABLE 4.2: Pure Strategies under Complete Information

η_i^k	Contents	$(u_i^k, w_i^k, \phi_i^k, \psi_i^k)$
η_i^1	(search,search,accept,accept)	$(1,1,1,1)$
η_i^2	(search,search,accept,refuse)	$(1,1,1,0)$
η_i^3	(search,search,refuse,accept)	$(1,1,0,1)$
η_i^4	(search,search,refuse,refuse)	$(1,1,0,0)$
η_i^5	(search,not search,accept,accept)	$(1,0,1,1)$
η_i^6	(search,not search,accept,refuse)	$(1,0,1,0)$
η_i^7	(search,not search,refuse,accept)	$(1,0,0,1)$
η_i^8	(search,not search,refuse,refuse)	$(1,0,0,0)$
η_i^9	(not search,search,accept,accept)	$(0,1,1,1)$
η_i^{10}	(not search,search,accept,refuse)	$(0,1,1,0)$
η_i^{11}	(not search,search,refuse,accept)	$(0,1,0,1)$
η_i^{12}	(not search,search,refuse,refuse)	$(0,1,0,0)$
η_i^{13}	(not search,not search,accept,accept)	$(0,0,1,1)$
η_i^{14}	(not search,not search,accept,refuse)	$(0,0,1,0)$
η_i^{15}	(not search,not search,refuse,accept)	$(0,0,0,1)$
η_i^{16}	(not search,not search,refuse,refuse)	$(0,0,0,0)$

4.3.2 Meeting formation

When each agent has complete information about the type of potential meeting partners, he/she can specify his/her search intensity to agents based on their types. Suppose that all agents of both types adopt same pure strategies, η_1^k and η_2^l. Under complete information the type of all others are known *ex ante*, and therefore, those who search meeting partners of type 1 always succeed to meet them whenever searching for them. The average meeting frequency for an agent in type i to offer and realize the meeting with agents in type j within a fixed unit period of time is expressed as follows.

$$\left.\begin{aligned} \overline{a}_1^1 &= \alpha u_1^k \hat{\phi}_1^k \\ \overline{a}_1^2 &= \alpha w_1^k \hat{\phi}_2^l \\ \overline{a}_2^1 &= \alpha u_2^l \hat{\psi}_1^k \\ \overline{a}_2^2 &= \alpha w_2^l \hat{\psi}_2^l \end{aligned}\right\} \tag{4.12}$$

where α means the average matching frequency realized as a result of searching. Similarly, the average meeting frequency by accepting offers is given as follows.

$$\left.\begin{aligned} \underline{a}_1^1 &= \alpha \hat{u}_1^k \phi_1^k \\ \underline{a}_1^2 &= \alpha \hat{u}_2^l \psi_1^k \\ \underline{a}_2^1 &= \alpha \hat{w}_1^k \phi_2^l \\ \underline{a}_2^2 &= \alpha \hat{w}_2^l \psi_2^l \end{aligned}\right\} \tag{4.13}$$

Then the expected frequency of meeting that an agent of type i meets with agents in type j is given by

$$\left.\begin{aligned} n_1^1 &= \alpha(u_1^k \hat{\phi}_1^k + \hat{u}_1^k \phi_1^k) \\ n_1^2 &= \alpha(v_1^k \hat{\phi}_2^l + \hat{u}_2^l \psi_1^k) \\ n_2^1 &= \alpha(u_2^l \hat{\psi}_1^k + \hat{w}_1^k \phi_2^l) \\ n_2^2 &= \alpha(v_2^l \hat{\psi}_2^l + \hat{w}_2^l \psi_2^l) \end{aligned}\right\}. \tag{4.14}$$

4.3.3 Meeting payoffs

In this subsection, the payoffs of both types are formulated when all agents in each type use pure strategies of η_1^k and η_2^l. In the same manner as the case under null information, the utility level that an agent in type i ($i = 1, 2$) can get when he/she has a meeting with an agent in type j ($j = 1, 2$) is expressed as $\bar{V}_i^j$. Without loss of generality, let the utility level of no meeting, $\bar{V}_i^0$, be standardized as 0. Suppose also that the expense for searching behavior is 1, and that for acceptance behavior is ε. Assume that the 'who's who' list for each type are available and charge is levied as the searching cost when using it. Similarly, there is a receiving machine for each type and it charges 'the rental fee' as the accepting cost when using it. When all agents of both types adopt the same pure strategies, η_1^k and η_2^l, the payoffs that an agent in types 1 and 2 can acquire are expressed as follows:

$$v_1(\eta_1^k, \eta_2^l) = -(u_1^k + w_1^k) + \varepsilon(\phi_1^k + \psi_1^k) + (u_1^k \hat{\phi}_1^k + \hat{u}_1^k \phi_1^k)\bar{v}_1^1 + (w_1^k \hat{\phi}_2^l + \hat{u}_2^l \psi_1^k)\bar{v}_1^2 \tag{4.15}$$

$$v_2(\eta_1^k, \eta_2^l) = -(u_2^l + w_2^l) + \varepsilon(\phi_2^l + \psi_2^l) + (u_2^l \hat{\psi}_1^k + \hat{w}_1^k \phi_2^l)\bar{v}_2^1 + (w_2^l \hat{\psi}_2^l + \hat{w}_2^l \psi_2^l)\bar{v}_2^2 \tag{4.16}$$

where $\bar{v}_i^j = \bar{V}_i^j/\alpha$ is meeting utility level per matching unit. The first terms of right hand of eqs. (4.15) and (4.16) represent search cost, while the second and the third terms are the expected utility levels of meetings with type 1 and 2, respectively. Consider that only one agent adopts a different pure strategy, $\eta_1^{k'}$, when all other agents adopt the same pure strategies of η_1^k and η_2^l. In this case from equation (4.15) his payoff is given by

$$v_1(\eta_1^{k'};\eta_1^k,\eta_2^l) = -(u_1^{k'}+w_1^{k'}) + \varepsilon(\phi_1^{k'}+\psi_1^{k'}) + (u_1^{k'}\hat{\phi}_1^k + \hat{u}_k^1\phi_1^{k'})\bar{v}_1^1 + (w_1^{k'}\hat{\phi}_2^l + \hat{u}_2^l\psi_1^{k'})\bar{v}_1^2 \tag{4.17}$$

In the same way the payoff that an agent of type 2 can get when he/she adopts a different pure strategy, $\eta_2^{l'}$, when others use η_1^k and η_2^l

$$v_2(\eta_2^{l'};\eta_1^k,\eta_2^l) = -(u_2^{l'}+w_2^{l'}) - \varepsilon(\phi_2^{l'}+\psi_2^{l'}) + (u_2^{l'}\hat{\psi}_1^k + \hat{w}_1^k\phi_2^{l'})\bar{v}_2^1 + (w_2^{l'}\hat{\psi}_2^l + \hat{w}_2^l\psi_2^{l'})\bar{v}_2^2. \tag{4.18}$$

4.3.4 Equilibrium and stability

Let $\xi_i(\eta_i^k)$ be the relative frequencies that agents of type i adopt pure strategy η_i^k, where there holds $\sum_{k=1}^{16}\xi_i(\eta_i^k) = 1$. Thus, define a vector $\boldsymbol{\xi}_i = \{\xi_i(\eta_i^1),\cdots,\xi_i(\eta_i^{16})\}$. The expected payoffs that agents of types 1 and 2 can get when they adopt pure strategies $\eta_1^{k'}$ and $\eta_2^{l'}$ are given as follows:

$$v_1(\eta_1^{k'};\boldsymbol{\xi}_1,\boldsymbol{\xi}_2) = \sum_{k=1}^{16}\sum_{l=1}^{16}\xi_1(\eta_1^k)\xi_2(\eta_2^l)v_1(\eta_1^{k'};\eta_1^k,\eta_2^l)$$
$$v_2(\eta_2^{l'};\boldsymbol{\xi}_1,\boldsymbol{\xi}_2) = \sum_{k=1}^{16}\sum_{l=1}^{16}\xi_1(\eta_1^k)\xi_2(\eta_2^l)v_2(\eta_1^{l'};\eta_1^k,\eta_2^l)$$

The payoffs that the agent of type i in concern can obtain when he/she adopts the mixed strategy, $\boldsymbol{\xi}_i' = \{\xi_i'(\eta_i^1),\cdots,\xi_i'(\eta_i^{16})\}$, are given as follows:

$$v_1(\boldsymbol{\xi}_1';\boldsymbol{\xi}_1,\boldsymbol{\xi}_2) = \sum_{k=1}^{16}\xi_1'(\eta_1^k)v_1(\eta_1^k;\boldsymbol{\xi}_1,\boldsymbol{\xi}_2) \tag{4.19}$$
$$v_2(\boldsymbol{\xi}_2';\boldsymbol{\xi}_1,\boldsymbol{\xi}_2) = \sum_{l=1}^{16}\xi_2'(\eta_2^l)v_2(\eta_2^l;\boldsymbol{\xi}_1,\boldsymbol{\xi}_2) \tag{4.20}$$

Nash equilibria in which all agents adopt meeting strategies non-cooperatively are obtained as the combinations of mixed strategies, $\boldsymbol{\xi}_1^*$ and $\boldsymbol{\xi}_2^*$, that satisfy the following for arbitrary $\boldsymbol{\xi}_1$ and $\boldsymbol{\xi}_2$.

$$\left.\begin{array}{l} v_1(\boldsymbol{\xi}_1^*;\boldsymbol{\xi}_1^*,\boldsymbol{\xi}_2^*) \geq v_1(\boldsymbol{\xi}_1;\boldsymbol{\xi}_1^*,\boldsymbol{\xi}_2^*) \\ v_2(\boldsymbol{\xi}_2^*;\boldsymbol{\xi}_1^*,\boldsymbol{\xi}_2^*) \geq v_2(\boldsymbol{\xi}_2;\boldsymbol{\xi}_1^*,\boldsymbol{\xi}_2^*) \end{array}\right\} \tag{4.21}$$

Equilibrium strategies, $\boldsymbol{\xi}_1^*$ and $\boldsymbol{\xi}_2^*$, are evolutionary stable against any mutants of type 1, when to all strategies of type 1, $\boldsymbol{\xi}_1$, that satisfy the equation $v_1(\boldsymbol{\xi}_i^*;\boldsymbol{\xi}_1^*,\boldsymbol{\xi}_2) = v_1(\boldsymbol{\xi}_1;\boldsymbol{\xi}_1^*,\boldsymbol{\xi}_2^*)$ for Nash strategies, $\boldsymbol{\xi}_1^*$ and $\boldsymbol{\xi}_2^*$, the following inequalities hold:

$$\left.\begin{array}{l} v_i(\boldsymbol{\xi}_1^*;\boldsymbol{\xi}_1,\boldsymbol{\xi}_2^*) > v_1(\boldsymbol{\xi}_1;\boldsymbol{\xi}_1,\boldsymbol{\xi}_2^*) \\ v_2(\boldsymbol{\xi}_2^*;\boldsymbol{\xi}_1,\boldsymbol{\xi}_2^*) > v_2(\boldsymbol{\xi}_2^*;\boldsymbol{\xi}_1,\boldsymbol{\xi}_2^*) \end{array}\right\} \tag{4.22}$$

When Nash equilibrium strategies are piece-wisely stable against all mutants' strategies of types 1 and 2, separating equilibrium strategies, $\boldsymbol{\xi}_1^*$ and $\boldsymbol{\xi}_2^*$, are E.P.W. stable.

4.3.5 Separating equilibrium

When agents are accessible to complete information about the type of meeting partners, each agent can distinguish his search and acceptance strategies according to the type of partners. Consequently, the separating equilibrium in which the strategies are differentiated according to the partners is achieved. The patterns of separating equilibria are crucially conditional to the profiles of meeting payoffs of two type agents. From eqs. (4.17) and (4.18), under others' pure strategies, η_1^k and $\hat{\eta}_2^l$, the payoff of an agent of each type is given as follows:

$$v_1(\eta_i^{k'};\eta_1^k,\eta_2^l) = \Xi_1^1(\hat{\phi}_1^k)u_1^k + \Xi_1^2(\hat{\phi}_2^l)w_1^{k'} + \Omega_1^1(\hat{u}_1^k)\phi_1^k + \Omega_1^2(\hat{w}_2^l)\psi_1^{k'} \tag{4.23}$$

$$v_2(\eta_2^{l'};\eta_1^k,\eta_2^l) = \Xi_2^1(\hat{\psi}_2^l)u_2^l + \Xi_2^2(\hat{\psi}_2^l)w_2^{l'} + \Omega_2^1(\hat{w}_1^k)\phi_2^l + \Omega_2^2(\hat{w}_2^l)\psi_2^{l'}, \tag{4.24}$$

where

$$\begin{array}{l} \Xi_1^1(\hat{\phi}_1^k) = -1 + \hat{\phi}_1^k\bar{v}_1^1,\ \Omega_1^1(\hat{u}_1^k) = -\varepsilon + \hat{u}_1^k\bar{v}_1^1 \\ \Xi_1^2(\hat{\phi}_2^l) = -1 + \hat{\phi}_2^l\bar{v}_1^2,\ \Omega_1^2(\hat{u}_2^l) = -\varepsilon + \hat{u}_2^l\bar{v}_1^2 \\ \Xi_2^1(\hat{\psi}_1^k) = -1 + \hat{\psi}_1^k\bar{v}_2^1, \Omega_2^1(\hat{w}_1^k) = -\varepsilon + \hat{w}_1^k\bar{v}_2^1 \\ \Xi_2^2(\hat{\psi}_2^l) = -1 + \hat{\psi}_2^l\bar{v}_2^2,\ \Omega_2^2(\hat{w}_2^l) = -\varepsilon + \hat{w}_2^l\bar{v}_2^2. \end{array}$$

Using these, Nash equilibria satisfying eq. (4.21) can be obtained. The patterns of Nash equilibria are fully characterized by combinations of the meeting utility, $\bar{v}_i^j$. Figure 4.2 illustrates the possible combination of utility profiles that an agent in type i can gain from a meeting with agents in types j ($j = 1, 2$). The dotted

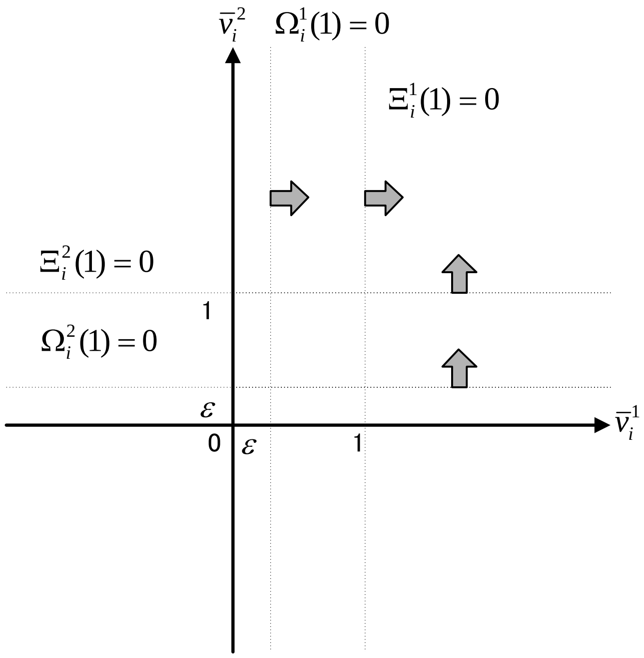

Figure 4.2: Domains division of utility profile in separating equilibrium

lines indicate the combinations of utility profiles satisfying $\Xi_i^k = 0$ ($\Omega_i^k = 0$), and the arrows show the half-space satisfying $\Xi_i^k \geq 0$ ($\Omega_i^k \geq 0$). For the possible combinations of these areas, Nash equilibria can be obtained as shown in Table 4. In this table, u_i, w_i, ϕ_i, and ψ_i are given by $u_i = \sum_k \xi_i(\eta_i^k)u_i^k, w_i = \sum_k \xi_i(\eta_i^k)w_i^k, \phi_i = \sum_k \xi_i(\eta_i^k)\phi_i^k$, $\psi_i = \sum_k \xi_i(\eta_i^k)\psi_i^k$, and $\theta_i = \sum_k \sigma_i(\rho_i^k)\theta_i^k$, respectively, and they mean the search probability against type 1 and 2, and the accept probability against type 1 and 2, respectively. Every Nash equilibrium consists of pure strategies. They all satisfy condition (4.22), and therefore are E.P.W. stable. Similarly to the pooling equilibria, the separating equilibria in which no one holds meetings exists in all combinations of utility profiles. As information about the type of potential meeting partners is available, those who are requested to hold a meeting always accept it in all equilibria. With complete information mechanisms all persons search for only partners who accept the requests, since they can know whether their offer is accepted by the partners in advance. Consequently, the agents can avoid unnecessary search for the partners who are revealed to reject their offers for meetings with them.

4.4 Information Mechanisms and Meeting Equilibria

4.4.1 Comparison of meeting equilibria

In this section, equilibrium patterns under null information and complete information are compared. The utility profile domains for the type 1 and types 2 are depicted in Figure 4.1 and Figure 4.2, respectively, that are put together in Figure 4.3. The full set of E.P.W. stable pooling and separating equilibria in the combination of utility profile domains are summarized in Table 5. A symbol $A \succ B$ior, alternatively $A \succeq B$jindicates that social welfare in the equilibrium A is larger (or alternatively 'not smaller') than that in the equilibrium B. The welfare orderings among equilibrium patterns within the same symbol $\{\cdot\}$ are not uniquely determined, which are dependent upon the values of β_1 and β_2. Table 5 fully counts up the possible equilibrium patterns. From this table, we can conclude the following properties on the relationship between meeting equilibria and information availability. First, we see that when there exists an equilibrium with no communications (the type J for the pooling equilibrium and the type P for the separating equilibrium), it is always dominated, in the Pareto sense, by another equilibrium with communications. This means that communications always Pareto-improves social welfare when E.P.W. stable equilibria with communications exist.

The second property is that in separating equilibria the social welfare is always improved as the number of agents who accept meeting offers increases. The socially preferable ordering among multiple equilibria can be uniquely defined for each combination of utility profile domains, when complete information is available. More the number of agents who accept meeting offers increases, more social efficiency of meeting equilibrium increases. On the other hand, when no information about the type of meeting partners is available, the relationship between the social welfare of meeting equilibria and the number of agents in each type is complicated and general properties cannot be easily found in comparison of social efficiency among multi equilibria. It is not necessarily true that the increase in the number of agents who accept offers makes meeting equilibria more efficient.

The social welfare differs among equilibria, if multiple ones exist. When there are multi meeting equilibria, which equilibrium would be selected in the society totally depends upon the history. However, once social system evolves into one of stable equilibria, it becomes very hard to move away from the current position and shift to another equilibrium. This is what is called *lock-in effect* (Arthur, 1994; Krugman,

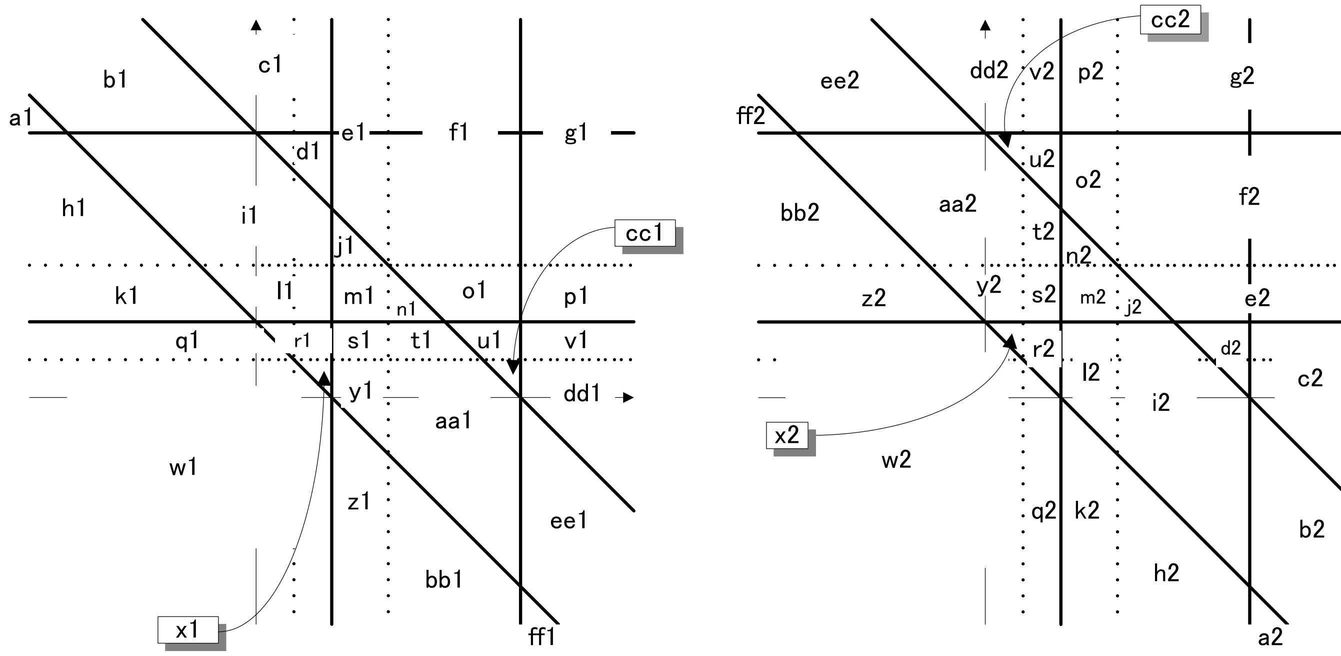

Figure 4.3: Jointing domains of utility profile in both case

1991). It suggests that the social system may has reached inefficient equilibrium and may not be able to escape from there by its own evolutionary mechanisms. As concerned in subsection 3.5, the system may be locked in a separating equilibrium in which agents neither search meeting partners nor accept offers by others, though all the agents could improve their welfare if they were simultaneously motivated to start to communicate with those whom they can gain positive payoffs by any means. In pooling equilibrium, on the other hand, it is not necessarily true that the agents can improve their individual welfare by starting communications though the expected payoffs of meetings is certainly positive. However, it is not guaranteed that the opening up a new channel to transmit information about types of meeting partners by itself can always better off individual welfare. Even with complete information mechanisms, the communications equilibrium may remain inefficient. Hence, we can post the third property that while information about types of meeting partners can certainly increase the efficiency of the individual behavior, does not always solve the inefficiency problems caused by the natural selection mechanisms. The society may possibly evolve into an inefficient equilibrium as a result of natural selection driven by locally improved individual behavior.

4.4.2 Policy implication

The properties of meeting equilibria clarified above provide insights about the future of face-to-face communications in the knowledge society. First, no communication equilibrium is always dominated by other meeting equilibria in which the agents are encouraged to have meetings. When the society is not equipped with sorting information mechanisms, the increase in the number of meetings does not always improve social efficiency. This is especially true if the agents are forced to accept the meetings that they gain negative utility to realize the meeting with the partners who convey large utility to them. On the other hand, with sorting information mechanisms, the agents can recognize the type of partners before they start negotiations whether or not to realize the meeting. Hence, it is always guaranteed that more communication-intensive equilibria are always efficient than the less ones.

When considering the future of communications in the knowledge society, more essential problem is expressed intensively in the last property. As information technologies advance, more minute information about meeting partners becomes available. Our results summarized in Table 5, however, suggest us that the number of meeting equilibria will be dramatically increasing as the society is equipped with more advanced mechanisms that can reveal more precise information of potential partners. These results also imply that if the population are fragmented with heterogeneous agents, it becomes more plausible that the agents are motivated to communicate only with a limited types of partners. This may explain that we may want face-to-face communications more than ever in the knowledge society, yet we cannot, individually and separately, express that want in a way that secures it. This analysis may cast doubts upon a prevailing belief that human communications, especially face-to-face communications, could be continuously improved associated with lasting progress of information technologies. In order to rescue the agents from meeting coordination failures, some policy means should be implemented to modify natural selection mechanisms, by which the society can evolve into more communication-activated equilibrium. The social institutional arrangements, that are designed to inject the society with sufficiently large amount of mutants to activate new evolutionary processes, are promising policy means. They are most typically exemplified by conventions, conferences, internet exhibitions, scientific societies, and other organized meetings.

4.5 Summary and recommendations

We have presented a model of pair wise face-to-face communications within a large population of heterogeneous agents, and investigated the resulting meeting equilibrium. We have shown that the meeting equilibrium patterns depends highly upon the heterogeneity of agents' preferences and also information availability. We find that while information about types of meeting partners can certainly increases the efficiency of the individual behavior, it does not always improve the natural selection mechanisms. We also show that in order to rescue the agents from meeting coordination failures, policy means by which the society can evolve into more communication-activated equilibrium should be implemented to modify natural selection mechanisms.

This paper have succeeded in characterizing one of important properties of face-to-face communication equilibrium, but there still remain many research topics to be tackled. First, we do not analyze the economic value of information about meeting partners' type. Also, the first-best match arrangement for meetings under the heterogeneous preferences of agents is not investigated. These issues should be scrutinized to discuss policy means for more socially efficient meetings in the society. Second, this paper has focused upon the meeting equilibrium with two rather extreme information mechanisms. The discussions on how information is provided to the agents is totally neglected. Information is supposed to be free goods. The signaling issues of how agents are motivated to reveal their types are left for the future research. Third, in real people may establish long-term relationships with fixed partners. In order to investigate this issue, we should depart from a simple framework of random matching games. Finally, if some (or all) agents are strongly motivated to purchase information on meeting partners, the information markets could emerge endogenously. Market formation should be also investigated.

TABLE 4.3(1): Pooling Equilibria and their Conditions

	Strategy of Type 1F(s_1, θ_1)	Strategy of Type 2F(s_2, θ_2)	Conditions
A^*	(1,1)	(1,1)	$\Phi_1(1,1) > 0, \Phi_2(1,1) > 0, \Psi_1(1,1) > 0, \Psi_2(1,1) > 0$
B^*	(1,1)	(0,1)	$\Phi_1(1,1) > 0, \Phi_2(1,1) < 0, \Psi_1(1,0) > 0, \Psi_2(1,0) > 0$
C^*	(0,1)	(1,1)	$\Phi_1(1,1) < 0, \Phi_2(1,1) > 0, \Psi_1(0,1) > 0, \Psi_2(0,1) > 0$
D^*	(1,1)	(1,0)	$\Phi_1(1,0) > 0, \Phi_2(1,0) > 0, \Psi_1(1,1) > 0, \Psi_2(1,1) < 0$
E^*	(1,0)	(1,1)	$\Phi_1(0,1) > 0, \Phi_2(0,1) > 0, \Psi_1(1,1) < 0, \Psi_2(1,1) > 0$
F^*	(1,1)	(0,0)	$\Phi_1(1,0) > 0, \Phi_2(1,0) < 0, \Psi_1(1,0) > 0, \Psi_2(1,0) < 0$
G^*	(0,0)	(1,1)	$\Phi_1(0,1) < 0, \Phi_2(0,1) > 0, \Psi_1(0,1) < 0, \Psi_2(0,1) > 0$
H^*	(1,0)	(0,1)	$\Phi_1(0,1) > 0, \Phi_2(0,1) < 0, \Psi_1(1,0) < 0, \Psi_2(1,0) > 0$
I^*	(0,1)	(1,0)	$\Phi_1(1,0) < 0, \Phi_2(1,0) > 0, \Psi_1(0,1) > 0, \Psi_2(0,1) < 0$
J^*	(0,0)	(0,0)	
K	(1,1)	$\left(\frac{\varepsilon-\beta_1\bar{v}_2^1}{\beta_2\bar{v}_2^2}, \frac{1-\beta_1\bar{v}_2^1}{\beta_2\bar{v}_2^2}\right)$	$\Phi_1\left(1, \frac{1-\beta_1\bar{v}_2^1}{\beta_2\bar{v}_2^2}\right) > 0, \Phi_2\left(1, \frac{1-\beta_1\bar{v}_2^1}{\beta_2\bar{v}_2^2}\right) = 0$ $\Psi_1\left(1, \frac{\varepsilon-\beta_1\bar{v}_2^1}{\beta_2\bar{v}_2^2}\right) > 0, \Psi_2\left(1, \frac{\varepsilon-\beta_1\bar{v}_2^1}{\beta_2\bar{v}_2^2}\right) = 0$
L	$\left(\frac{\varepsilon-\beta_2\bar{v}_1^2}{\beta_1\bar{v}_1^1}, \frac{1-\beta_2\bar{v}_1^2}{\beta_1\bar{v}_1^1}\right)$	$(1,1)$	$\Phi_1\left(\frac{1-\beta_2\bar{v}_1^2}{\beta_1\bar{v}_1^1}, 1\right) = 0, \Phi_2\left(\frac{1-\beta_2\bar{v}_1^2}{\beta_1\bar{v}_1^1}, 1\right) > 0,$ $\Psi_1\left(\frac{\varepsilon-\beta_2\bar{v}_1^2}{\beta_1\bar{v}_1^1}, 1\right) = 0, \Psi_2\left(\frac{\varepsilon-\beta_2\bar{v}_1^2}{\beta_1\bar{v}_1^1}, 1\right) > 0$
M^*	$\left(1, \frac{1-\beta_2\bar{v}_2^2}{\beta_1\bar{v}_2^1}\right)$	$\left(\frac{\varepsilon-\beta_1\bar{v}_1^1}{\beta_2\bar{v}_1^2}, 1\right)$	$\Phi_1\left(\frac{1-\beta_2\bar{v}_2^2}{\beta_1\bar{v}_2^1}, 1\right) > 0, \Phi_2\left(\frac{1-\beta_2\bar{v}_2^2}{\beta_1\bar{v}_2^1}, 1\right) = 0$ $\Psi_1\left(1, \frac{\varepsilon-\beta_1\bar{v}_1^1}{\beta_2\bar{v}_1^2}\right) = 0, \Psi_2\left(1, \frac{\varepsilon-\beta_1\bar{v}_1^1}{\beta_2\bar{v}_1^2}\right) > 0,$
N^*	$\left(\frac{\varepsilon-\beta_2\bar{v}_2^2}{\beta_1\bar{v}_2^1}, 1\right)$	$\left(1, \frac{1-\beta_1\bar{v}_1^1}{\beta_2\bar{v}_1^2}\right)$	$\Phi_1\left(1, \frac{1-\beta_1\bar{v}_1^1}{\beta_2\bar{v}_1^2}\right) = 0, \Phi_2\left(1, \frac{1-\beta_1\bar{v}_1^1}{\beta_2\bar{v}_1^2}\right) > 0,$ $\Psi_1\left(\frac{\varepsilon-\beta_2\bar{v}_2^2}{\beta_1\bar{v}_2^1}, 1\right) > 0, \Psi_2\left(\frac{\varepsilon-\beta_2\bar{v}_2^2}{\beta_1\bar{v}_2^1}, 1\right) = 0$
O	$\left(1, \frac{1}{\beta_1\bar{v}_2^1}\right)$	$\left(\frac{\varepsilon-\beta_1\bar{v}_1^1}{\beta_2\bar{v}_1^2}, 0\right)$	$\Phi_1\left(\frac{1}{\beta_1\bar{v}_2^1}, 0\right) > 0, \Phi_2\left(\frac{1}{\beta_1\bar{v}_2^1}, 0\right) = 0$ $\Psi_1\left(1, \frac{\varepsilon-\beta_1\bar{v}_1^1}{\beta_2\bar{v}_1^2}\right) = 0, \Psi_2\left(1, \frac{\varepsilon-\beta_1\bar{v}_1^1}{\beta_2\bar{v}_1^2}\right) < 0$
P	$\left(\frac{\varepsilon-\beta_2\bar{v}_2^2}{\beta_1\bar{v}_2^1}, 0\right)$	$\left(1, \frac{1}{\beta_2\bar{v}_1^2}\right)$	$\Phi_1\left(0, \frac{1}{\beta_2\bar{v}_1^2}\right) = 0, \Phi_2\left(0, \frac{1}{\beta_2\bar{v}_1^2}\right) > 0,$ $\Psi_1\left(\frac{\varepsilon-\beta_2\bar{v}_2^2}{\beta_1\bar{v}_2^1}, 1\right) < 0, \Psi_2\left(\frac{\varepsilon-\beta_2\bar{v}_2^2}{\beta_1\bar{v}_2^1}, 1\right) = 0$
Q	(1,0)	$\left(\frac{\varepsilon-\beta_1\bar{v}_2^1}{\beta_2\bar{v}_2^2}, \frac{1}{\beta_2\bar{v}_2^2}\right)$	$\Phi_1\left(0, \frac{1}{\beta_2\bar{v}_2^2}\right) > 0, \Phi_2\left(0, \frac{1}{\beta_2\bar{v}_2^2}\right) = 0$ $\Psi_1\left(1, \frac{\varepsilon-\beta_1\bar{v}_2^1}{\beta_2\bar{v}_2^2}\right) < 0, \Psi_2\left(1, \frac{\varepsilon-\beta_1\bar{v}_2^1}{\beta_2\bar{v}_2^2}\right) = 0$
R	$\left(\frac{\varepsilon-\beta_2\bar{v}_1^2}{\beta_1\bar{v}_1^1}, \frac{1}{\beta_1\bar{v}_1^1}\right)$	$(1,0)$	$\Phi_1\left(\frac{1}{\beta_1\bar{v}_1^1}, 0\right) = 0, \Phi_2\left(\frac{1}{\beta_1\bar{v}_1^1}, 0\right) > 0,$ $\Psi_1\left(\frac{\varepsilon-\beta_2\bar{v}_1^2}{\beta_1\bar{v}_1^1}, 1\right) = 0, \Psi_2\left(\frac{\varepsilon-\beta_2\bar{v}_1^2}{\beta_1\bar{v}_1^1}, 1\right) < 0$
S	$\left(0, \frac{1}{\beta_1\bar{v}_2^1}\right)$	$\left(\frac{\varepsilon}{\beta_2\bar{v}_1^2}, 0\right)$	$\Phi_1\left(\frac{1}{\beta_1\bar{v}_2^1}, 0\right) < 0, \Phi_2\left(\frac{1}{\beta_1\bar{v}_2^1}, 0\right) = 0,$ $\Psi_1\left(0, \frac{\varepsilon}{\beta_2\bar{v}_1^2}\right) = 0, \Psi_2\left(0, \frac{\varepsilon}{\beta_2\bar{v}_1^2}\right) < 0$
T	$\left(\frac{\varepsilon}{\beta_1\bar{v}_2^1}, 0\right)$	$\left(0, \frac{1}{\beta_2\bar{v}_1^2}\right)$	$\Phi_1\left(0, \frac{1}{\beta_2\bar{v}_1^2}\right) = 0, \Phi_2\left(0, \frac{1}{\beta_2\bar{v}_1^2}\right) < 0,$ $\Psi_1\left(\frac{\varepsilon}{\beta_1\bar{v}_2^1}, 0\right) < 0, \Psi_2\left(0, \frac{\varepsilon}{\beta_1\bar{v}_2^1}\right) = 0$

TABLE 4.3(2): Pooling Equilibria and their Conditions

	Strategy of Type 1F(s_1, θ_1)	Strategy of Type 2F(s_2, θ_2)	Conditions
U	$(0, 1)$	$\left(\frac{\varepsilon}{\beta_2 \bar{v}_2^2}, \frac{1-\beta_1 \bar{v}_2^1}{\beta_2 \bar{v}_2^2}\right)$	$\Phi_1\left(1, \frac{1-\beta_1 \bar{v}_2^1}{\beta_2 \bar{v}_2^2}\right) < 0, \Phi_2\left(1, \frac{1-\beta_1 \bar{v}_2^1}{\beta_2 \bar{v}_2^2}\right) = 0,$ $\Psi_1\left(0, \frac{\varepsilon}{\beta_2 \bar{v}_2^2}\right) > 0, \Psi_2\left(0, \frac{\varepsilon}{\beta_2 \bar{v}_2^2}\right) = 0$
V	$\left(\frac{\varepsilon}{\beta_1 \bar{v}_1^1}, \frac{1-\beta_2 \bar{v}_1^2}{\beta_1 \bar{v}_1^1}\right)$	$(0, 1)$	$\Phi_1\left(\frac{1-\beta_2 \bar{v}_1^2}{\beta_1 \bar{v}_1^1}, 1\right) = 0, \Phi_2\left(\frac{1-\beta_2 \bar{v}_1^2}{\beta_1 \bar{v}_1^1}, 1\right) < 0,$ $\Psi_1\left(\frac{\varepsilon}{\beta_1 \bar{v}_1^1}, 0\right) = 0, \Psi_2\left(\frac{\varepsilon}{\beta_1 \bar{v}_1^1}, 0\right) > 0$
W	$\left(0, \frac{1-\beta_2 \bar{v}_2^2}{\beta_1 \bar{v}_2^1}\right)$	$\left(\frac{\varepsilon}{\beta_2 \bar{v}_2^2}, 1\right)$	$\Phi_1\left(\frac{1-\beta_2 \bar{v}_2^2}{\beta_1 \bar{v}_2^1}, 1\right) < 0, \Phi_2\left(\frac{1-\beta_2 \bar{v}_2^2}{\beta_1 \bar{v}_2^1}, 1\right) = 0,$ $\Psi_1\left(0, \frac{\varepsilon}{\beta_2 \bar{v}_1^2}\right) = 0, \Psi_2\left(0, \frac{\varepsilon}{\beta_2 \bar{v}_1^2}\right) > 0$
X	$\left(\frac{\varepsilon}{\beta_1 \bar{v}_2^1}, 1\right)$	$\left(0, \frac{1-\beta_1 \bar{v}_1^1}{\beta_2 \bar{v}_1^2}\right)$	$\Phi_1\left(1, \frac{1-\beta_1 \bar{v}_1^1}{\beta_2 \bar{v}_1^2}\right) = 0, \Phi_2\left(1, \frac{1-\beta_1 \bar{v}_1^1}{\beta_2 \bar{v}_1^2}\right) < 0,$ $\Psi_1\left(\frac{\varepsilon}{\beta_1 \bar{v}_2^1}, 0\right) > 0, \Psi_2\left(\frac{\varepsilon}{\beta_1 \bar{v}_2^1}, 0\right) = 0$
Y	$\left(\frac{(\bar{v}_2^2 - \bar{v}_1^2)\varepsilon}{\beta_1(\bar{v}_1^1 \bar{v}_2^2 - \bar{v}_1^2 \bar{v}_2^1)}, \frac{\bar{v}_2^2 - \bar{v}_1^2}{\beta_1(\bar{v}_1^1 \bar{v}_2^2 - \bar{v}_1^2 \bar{v}_2^1)}\right)$	$\left(\frac{(\bar{v}_2^1 - \bar{v}_1^1)\varepsilon}{\beta_2(\bar{v}_1^2 \bar{v}_2^1 - \bar{v}_1^1 \bar{v}_2^2)}, \frac{\bar{v}_2^1 - \bar{v}_1^1}{\beta_2(\bar{v}_1^2 \bar{v}_2^1 - \bar{v}_1^1 \bar{v}_2^2)}\right)$	$\Phi_1\left(\frac{\bar{v}_2^2 - \bar{v}_1^2}{\beta_1(\bar{v}_1^1 \bar{v}_2^2 - \bar{v}_1^2 \bar{v}_2^1)}, \frac{\bar{v}_2^1 - \bar{v}_1^1}{\beta_2(\bar{v}_1^2 \bar{v}_2^1 - \bar{v}_1^1 \bar{v}_2^2)}\right) = 0,$ $\Phi_2\left(\frac{\bar{v}_2^2 - \bar{v}_1^2}{\beta_1(\bar{v}_1^1 \bar{v}_2^2 - \bar{v}_1^2 \bar{v}_2^1)}, \frac{\bar{v}_2^1 - \bar{v}_1^1}{\beta_2(\bar{v}_1^2 \bar{v}_2^1 - \bar{v}_1^1 \bar{v}_2^2)}\right) = 0,$ $\Psi_1\left(\frac{(\bar{v}_2^2 - \bar{v}_1^2)\varepsilon}{\beta_1(\bar{v}_1^1 \bar{v}_2^2 - \bar{v}_1^2 \bar{v}_2^1)}, \frac{(\bar{v}_2^1 - \bar{v}_1^1)\varepsilon}{\beta_2(\bar{v}_1^2 \bar{v}_2^1 - \bar{v}_1^1 \bar{v}_2^2)}\right) = 0,$ $\Psi_2\left(\frac{(\bar{v}_2^2 - \bar{v}_1^2)\varepsilon}{\beta_1(\bar{v}_1^1 \bar{v}_2^2 - \bar{v}_1^2 \bar{v}_2^1)}, \frac{(\bar{v}_2^1 - \bar{v}_1^1)\varepsilon}{\beta_2(\bar{v}_1^2 \bar{v}_2^1 - \bar{v}_1^1 \bar{v}_2^2)}\right) = 0$

TABLE 4.4: Separating Equilibria and their Conditions

	Strategy of Type 1 $(u_1, w_1, \phi_1, \psi_1)$	Strategy of Type 2 $(u_2, w_2, \phi_2, \psi_2)$	Conditions
A^*	$(1, 1, 1, 1)$	$(1, 1, 1, 1)$	$\Xi_1^1(1) > 0, \Xi_1^2(1) > 0, \Xi_2^1(1) > 0, \Xi_2^2(1) > 0,$ $\Omega_1^1(1) > 0, \Omega_1^2(1) > 0, \Omega_2^1(1) > 0, \Omega_2^2(1) > 0$
B^*	$(1, 1, 1, 1)$	$(1, 0, 1, 0)$	$\Xi_1^1(1) > 0, \Xi_1^2(1) > 0, \Xi_2^1(1) > 0, \Xi_2^2(0) \leq 0,$ $\Omega_1^1(1) > 0, \Omega_1^2(1) > 0, \Omega_2^1(1) > 0, \Omega_2^2(0) = 0$
C^*	$(1, 1, 1, 0)$	$(0, 1, 1, 1)$	$\Xi_1^1(1) > 0, \Xi_1^2(1) > 0, \Xi_2^1(0) \leq 0, \Xi_2^2(1) > 0,$ $\Omega_1^1(1) > 0, \Omega_1^2(0) = 0, \Omega_2^1(1) > 0, \Omega_2^2(1) > 0$
D^*	$(1, 0, 1, 1)$	$(1, 1, 0, 1)$	$\Xi_1^1(1) > 0, \Xi_1^2(0) \leq 0, \Xi_2^1(1) > 0, \Xi_2^2(1) > 0,$ $\Omega_1^1(1) > 0, \Omega_1^2(1) > 0, \Omega_2^1(0) = 0, \Omega_2^2(1) > 0$
E^*	$(0, 1, 0, 1)$	$(1, 1, 1, 1)$	$\Xi_1^1(0) \leq 0, \Xi_1^2(1) > 0, \Xi_2^1(1) > 0, \Xi_2^2(1) > 0,$ $\Omega_1^1(0) = 0, \Omega_1^2(1) > 0, \Omega_2^1(1) > 0, \Omega_2^2(1) > 0$
F^*	$(1, 1, 1, 0)$	$(0, 0, 1, 0)$	$\Xi_1^1(1) > 0, \Xi_1^2(1) > 0, \Xi_2^1(0) \leq 0, \Xi_2^2(0) \leq 0,$ $\Omega_1^1(1) > 0, \Omega_1^2(0) = 0, \Omega_2^1(1) > 0, \Omega_2^2(0) = 0$
G^*	$(1, 0, 1, 1)$	$(1, 0, 0, 0)$	$\Xi_1^1(1) > 0, \Xi_1^2(0) \leq 0, \Xi_2^1(1) > 0, \Xi_2^2(0) \leq 0,$ $\Omega_1^1(1) > 0, \Omega_1^2(1) > 0, \Omega_2^1(0) = 0, \Omega_2^2(0) = 0$
H^*	$(1, 0, 1, 0)$	$(0, 1, 0, 1)$	$\Xi_1^1(1) > 0, \Xi_1^2(0) \leq 0, \Xi_2^1(0) \leq 0, \Xi_2^2(1) > 0,$ $\Omega_1^1(1) > 0, \Omega_1^2(0) = 0, \Omega_2^1(0) = 0, \Omega_2^2(1) > 0$
I^*	$(0, 1, 0, 1)$	$(1, 0, 1, 0)$	$\Xi_1^1(0) \leq 0, \Xi_1^2(1) > 0, \Xi_2^1(1) > 0, \Xi_2^2(0) \leq 0,$ $\Omega_1^1(0) = 0, \Omega_1^2(1) > 0, \Omega_2^1(1) > 0, \Omega_2^2(0) = 0$
J^*	$(0, 1, 0, 0)$	$(0, 1, 1, 1)$	$\Xi_1^1(0) \leq 0, \Xi_1^2(1) > 0, \Xi_2^1(0) \leq 0, \Xi_2^2(1) > 0,$ $\Omega_1^1(0) = 0, \Omega_1^2(0) = 0, \Omega_2^1(1) > 0, \Omega_2^2(1) > 0$
K^*	$(0, 0, 0, 1)$	$(1, 1, 0, 1)$	$\Xi_1^1(0) \leq 0, \Xi_1^2(0) \leq 0, \Xi_2^1(1) > 0, \Xi_2^2(1) > 0,$ $\Omega_1^1(0) = 0, \Omega_1^2(1) > 0, \Omega_2^1(0) = 0, \Omega_2^2(1) > 0$
L^*	$(1, 0, 1, 0)$	$(0, 0, 0, 0)$	$\Xi_1^1(1) > 0, \Xi_1^2(0) \leq 0, \Xi_2^1(0) \leq 0, \Xi_2^2(0) \leq 0,$ $\Omega_1^1(1) > 0, \Omega_1^2(0) = 0, \Omega_2^1(0) = 0, \Omega_2^2(0) = 0$
M^*	$(0, 1, 0, 0)$	$(0, 0, 1, 0)$	$\Xi_1^1(0) \leq 0, \Xi_1^2(1) > 0, \Xi_2^1(0) \leq 0, \Xi_2^2(0) \leq 0,$ $\Omega_1^1(0) = 0, \Omega_1^2(0) = 0, \Omega_2^1(1) > 0, \Omega_2^2(0) = 0$
N^*	$(0, 0, 0, 1)$	$(1, 0, 0, 0)$	$\Xi_1^1(0) \leq 0, \Xi_1^2(0) \leq 0, \Xi_2^1(1) > 0, \Xi_2^2(0) \leq 0,$ $\Omega_1^1(0) = 0, \Omega_1^2(1) > 0, \Omega_2^1(0) = 0, \Omega_2^2(0) = 0$
O^*	$(0, 0, 0, 0)$	$(0, 1, 0, 1)$	$\Xi_1^1(0) \leq 0, \Xi_1^2(0) \leq 0, \Xi_2^1(0) \leq 0, \Xi_2^2(1) > 0,$ $\Omega_1^1(0) = 0, \Omega_1^2(0) = 0, \Omega_2^1(0) = 0, \Omega_2^2(1) > 0$
P^*	$(0, 0, 0, 0)$	$(0, 0, 0, 0)$	$\Xi_1^1(0) \leq 0, \Xi_1^2(0) \leq 0, \Xi_2^1(0) \leq 0, \Xi_2^2(0) \leq 0,$ $\Omega_1^1(0) = 0, \Omega_1^2(0) = 0, \Omega_2^1(0) = 0, \Omega_2^2(0) = 0$

TABLE 4.5(1): Pooling and Separating Equilibria

No.	Pooling	Separating	utility domains
1	H ≻ I ≻ J	I ≻ N ≻ M ≻ P	$(a1 \cup b1, a2 \cup b2), (a1 \cup c2)$
2	H ≻ J	I ≻ N ≻ M ≻ P	$(a1 \cup d2), (a1 \cup b1, h2 \cup i2 \cup j2), (c1, h2 \cup j2)$
3	C ≻ H ≻ J	I ≻ N ≻ M ≻ P	$(a1 \cup b1, e2)$
4	C ≻ H ≻ J	E ≻ K ≻ J ≻ O	$(a1, f2)$
5	C ≻ J	E ≻ K ≻ J ≻ O	$(a1 \cup b1 \cup h1 \cup i1 \cup j1, g2), (h1 \cup j1, f2)$
6	H ≻ J	M ≻ P	$(a1 \cup b1, k2 \cup l2 \cup m2), (c1, k2 \cup m2)$
7	H ≻ J	J ≻ O	$(a1 \cup b1 \cup c1, n2)$
8	C ≻ H ≻ J	J ≻ O	$(a1, o2)$
9	C ≻ J	J ≻ O	$(a1 \cup h1, p2 \cup u2 \cup v2), (b1 \cup i1, p2 \cup v2), (h1 \cup j1, o2)$
10	J	M ≻ P	$(a1 \cup b1 \cup c1 \cup d1 \cup e1 \cup h1 \cup i1 \cup j1, q2 \cup s2), (a1 \cup b1 \cup h1 \cup i1 \cup j1, r2)$
11	J	J ≻ O	$(a1 \cup b1 \cup c1 \cup e1, t2), (d1 \cup h1 \cup i1 \cup j1, n2 \cup t2)$
12	J	P	$(a1 \cup b1 \cup c1 \cup d1 \cup e1 \cup h1 \cup i1 \cup j1 \cup k1 \cup l1 \cup m1 \cup q1 \cup r1 \cup s1 \cup w1 \cup x1 \cup y1 \cup z1, y2 \cup w2), (a1 \cup b1 \cup h1 \cup i1 \cup j1 \cup k1 \cup l1 \cup m1 \cup q1 \cup r1 \cup s1 \cup w1 \cup x1 \cup y1 \cup z1, x2 \cup z2), (k1 \cup l1 \cup m1 \cup q1 \cup r1 \cup s1, k2 \cup l2 \cup m2 \cup q2 \cup r2 \cup s2 \cup w2 \cup x2 \cup y2 \cup z2), (a1 \cup b1 \cup e1 \cup h1 \cup i1 \cup j1, w2 \cup x2 \cup y2 \cup z2), (c1 \cup d1, w2 \cup y2)$
13	J	O	$(aa1 \cup bb1, aa2 \cup bb2), (c1 \cup d1 \cup e1, aa2), (k1 \cup l1 \cup m1 \cup r1 \cup x1 \cup y1, n2 \cup t2 \cup aa2 \cup bb2), (q1 \cup s1 \cup w1 \cup y1, n2 \cup o2 \cup t2 \cup u2 \cup aa2 \cup bb2 \cup cc2), (h1 \cup i1 \cup j1, aa2 \cup bb2), (h1 \cup j1 \cup k1 \cup m1, ee2 \cup ff2), (a1, ff2), (e1, ee2)$
14	C ≻ J	O	$(a1 \cup h1 \cup j1, cc2), (a1 \cup b1 \cup h1 \cup i1 \cup j1, dd2), (k1 \cup m1, o2 \cup u2 \cup cc2), (k1 \cup l1 \cup m1, p2 \cup v2 \cup dd2)$
15	E ≻ J	O	$(a1, ee2)$
16	{HIM} ≻ J	I ≻ N ≻ M ≻ P	$(b1, c2)$
17	{HM} ≻ J	I ≻ N ≻ M ≻ P	$(b1, d2)$
18	{CHM} ≻ J	E ≻ K ≻ J ≻ O	$(b1, f2)$
19	{CHM} ≻ J	J ≻ O	$(b1, o2)$
20	{CM} ≻ J	J ≻ O	$(b1, u2)$
21	{CM} ≻ J	O	$(b1, cc2)$
22	M ≻ J	O	$(b1, ee2 \cup ff2), (x1 \cup z1, f2 \cup o2 \cup u2 \cup cc2)$
23	H ≻ I	I ≻ N ≻ M ≻ P	$(c1, a2)$
24	{HIN} ≻ J	I ≻ N ≻ M ≻ P	$(c1, b2)$
25	{AHIMN} ≻ J	I ≻ N ≻ M ≻ P	$(c1, c2)$
26	{AHMN} ≻ J	I ≻ N ≻ M ≻ P	$(c1, d2)$
27	{AHM} ≻ J	I ≻ N ≻ M ≻ P	$(c1, e2)$
28	{AHM} ≻ J	E ≻ K ≻ J ≻ O	$(c1, f2)$
29	A ≻ J	E ≻ K ≻ J ≻ O	$(c1 \cup d1 \cup e1, g2), (e1, f2)$
30	{HN} ≻ J	I ≻ N ≻ M ≻ P	$(c1, i2)$
31	{HN} ≻ J	M ≻ P	$(c1, l2)$
32	{AHM} ≻ J	J ≻ O	$(c1, o2)$
33	A ≻ J	J ≻ O	$(c1 \cup d1 \cup e1, p2 \cup v2), (e1, o2 \cup u2 \cup cc2)$
34	N ≻ J	M ≻ P	$(c1 \cup d1 \cup e1, r2)$
35	{AM} ≻ J	J ≻ O	$(c1 \cup d1, u2)$
36	N ≻ J	P	$(c1 \cup d1 \cup e1, x2 \cup z2)$
37	N ≻ J	O	$(c1 \cup d1 \cup e1, bb2), (e1, ff2)$
38	{AM} ≻ J	O	$(c1 \cup d1, cc2)$
39	A ≻ J	O	$(c1 \cup d1 \cup f1, dd2)$
40	N ≻ M ≻ J	O	$(c1 \cup d1, ff2)$
41	I ≻ J	I ≻ N ≻ M ≻ P	$(d1, a2), (h1 \cup i1 \cup j1, a2 \cup b2), (h1 \cup j1, c2)$
42	{IN} ≻ J	I ≻ N ≻ M ≻ P	$(d1, b2)$

TABLE 4.5(2): Pooling and Separating Equilibria

No.	Pooling	Separating	Utility Domains
43	{AIMN} ≻ J	I ≻ N ≻ M ≻ P	$(d1, c2)$
44	{AMN} ≻ J	I ≻ N ≻ M ≻ P	$(d1, d2)$
45	J	I ≻ N ≻ M ≻ P	$(d1, h2), (h1 \cup i1 \cup j1, h2 \cup i2)$
46	N ≻ J	I ≻ N ≻ M ≻ P	$(d1, i2 \cup j2)$
47	{AM} ≻ J	I ≻ N ≻ M ≻ P	$(d1, e2)$
48	{AM} ≻ J	E ≻ K ≻ J ≻ O	$(d1, f2)$
49	B ≻ J	I ≻ N ≻ M ≻ P	$(e1, h2 \cup j2)$
50	{BN} ≻ J	I ≻ N ≻ M ≻ P	$(e1, i2)$
51	{AN} ≻ J	I ≻ N ≻ M ≻ P	$(e1, d2)$
52	A ≻ J	I ≻ N ≻ M ≻ P	$(e1, e2)$
53	B ≻ J	M ≻ P	$(e1, k2 \cup m2)$
54	{MN} ≻ J	M ≻ P	$(e1, l2)$
55	B ≻ J	J ≻ O	$(e1, n2)$
56	B ≻ J	B ≻ G ≻ F ≻ L	$(f1, h2 \cup j2), (g1, a2 \cup b2 \cup h2 \cup i2 \cup j2)$
57	{BN} ≻ J	B ≻ G ≻ F ≻ L	$(f1, i2)$
58	{AN} ≻ J	B ≻ G ≻ F ≻ L	$(f1, d2)$
59	A ≻ J	B ≻ G ≻ F ≻ L	$(f1, e2), (g1, c2 \cup d2 \cup e2)$
60	A ≻ J	A ≻ C ≻ D	$(f1 \cup g1, f2 \cup g2)$
61	B ≻ J	F ≻ L	$(f1, k2 \cup m2), (g1, k2 \cup l2 \cup m2)$
62	{BN} ≻ J	F ≻ L	$(f1, l2)$
63	B ≻ J	C ⪰ H	$(f1 \cup g1, n2)$
64	A ≻ J	C ⪰ H	$(f1, o2 \cup p2 \cup u2 \cup v2), (g1, o2 \cup p2 \cup u2)$
65	J	F ≻ L	$(f1, q2)$
66	N ≻ J	F ≻ L	$(f1, r2 \cup s2)$
67	J	C ⪰ H	$(f1, t2)$
68	N ≻ J	L	$(f1, x2 \cup z2), (o1 \cup u1 \cup cc1, r2 \cup x2 \cup z2)$
69	N ≻ J	H	$(f1 \cup o1, bb2 \cup ff2), (u1 \cup cc1, bb2)$
70	F	F ≻ L	$(g1, q2 \cup r2 \cup s2)$
71	J	L	$(f1, w2 \cup y2), (n1 \cup t1, k2 \cup l2 \cup m2 \cup q2 \cup r2 \cup s2 \cup w2 \cup x2 \cup y2 \cup z2), (o1 \cup u1, q2 \cup s2 \cup w2 \cup y2), (aa1, bb1, a2 \cup b2 \cup e2 \cup h2 \cup i2 \cup j2 \cup k2 \cup l2 \cup m2 \cup q2 \cup r2 \cup s2 \cup w2 \cup x2 \cup y2 \cup z2), (aa1, c2 \cup d2), (cc1, q2 \cup s2 \cup w2 \cup y2), (ee1, e2 \cup h2 \cup j2 \cup k2 \cup m2), (ff1, a2 \cup h2 \cup j2 \cup k2 \cup m2)$
72	J	H	$(f1, aa2 \cup ee2), (n1, n2 \cup t2 \cup aa2 \cup bb2 \cup ee2 \cup ff2), (o1, t2 \cup aa2 \cup ee2), (t1 \cup aa1, n2 \cup o2 \cup t2 \cup u2 \cup aa2 \cup bb2), (u1 \cup cc1, t2 \cup aa2), (t1, f2), (bb1, n2 \cup t2 \cup aa2 \cup bb2)$
73	A ≻ J	H ≻ P	$(f1, cc2 \cup dd2), (o1, o2 \cup p2 \cup u2 \cup v2 \cup cc2 \cup dd2), (p1, o2 \cup p2), (u1 \cup v1, o2), (cc1 \cup dd1, f2 \cup o2)$
74	F	C ⪰ H	$(g1, t2)$
75	A	C ⪰ H	$(g1, v2)$
76	F	L	$(g1, w2 \cup x2 \cup y2 \cup z2), (p1 \cup v1 \cup dd1, q2 \cup r2 \cup s2 \cup w2 \cup x2 \cup y2 \cup z2), (ee1 \cup ff1, q2 \cup s2 \cup w2 \cup y2)$
77	F	H	$(g1, aa2 \cup bb2 \cup ee2 \cup ff2), (p1 \cup v1 \cup dd1, t2 \cup aa2 \cup bb2 \cup ee2 \cup ff2), (ee1, t2 \cup u2 \cup aa2 \cup cc2), (ff1, t2 \cup aa2)$
78	A	H	$(g1, cc2 \cup dd2), (p1 \cup u1 \cup v1 \cup cc1 \cup dd1, p2 \cup u2 \cup v2 \cup cc2 \cup dd2), (cc1 \cup dd1, g2)$
79	C ≻ J	I ≻ N ≻ M ≻ P	$(h1 \cup i1 \cup j1, e2)$
80	{IM} ≻ J	I ≻ N ≻ M ≻ P	$(i1, c2)$
81	M ≻ J	I ≻ N ≻ M ≻ P	$(i1, d2)$
82	{CM} ≻ J	E ≻ K ≻ J ≻ O	$(i1, f2)$
83	{CM} ≻ J	J ≻ O	$(i1, o2 \cup u2)$
84	{CM} ≻ J	O	$(i1, cc2), (l1, o2 \cup u2 \cup cc2)$
85	M ≻ J	O	$(i1, ee2 \cup ff2), (r1, o2)$
86	I ≻ J	N ≻ P	$(k1 \cup m1, a2 \cup b2 \cup c2), (l1, a2 \cup b2)$
87	J	N ≻ P	$(k1 \cup m1, d2 \cup h2 \cup i2 \cup j2), (l1, h2 \cup i2 \cup j2), (q1 \cup s1, a2 \cup b2 \cup c2 \cup d2 \cup e2 \cup h2 \cup i2 \cup j2), (r1, a2 \cup b2 \cup e2 \cup h2 \cup i2 \cup j2)$
88	C ≻ J	N ≻ P	$(k1 \cup l1 \cup m1, e2)$
89	G ≻ J	K ≻ O	$(k1 \cup m1, f2 \cup g2), (l1, g2)$
90	{IM} ≻ J	N ≻ P	$(l1, c2)$

TABLE 4.5(3): Pooling and Separating Equilibria

No.	Pooling	Separating	Utility Domains
91	$M \succ J$	$N \succ P$	$(l1, d2), (r1, c2 \cup d2)$
92	$\{CM\} \succ J$	$K \succ O$	$(l1, f2)$
93	$I \succ J$	$G \succ L$	$(n1, a2 \cup b2 \cup c2)$
94	J	$G \succ L$	$(n1, d2 \cup h2 \cup i2 \cup j2), (t1, a2 \cup b2 \cup c2 \cup d2 \cup e2 \cup h2 \cup i2 \cup j2)$
95	$C \succ J$	$G \succ L$	$(n1, e2)$
96	$C \succ J$	$D \succeq H$	$(n1, f2 \cup g2)$
97	$C \succ J$	$H \succ P$	$(n1, o2 \cup p2 \cup u2 \cup v2 \cup cc2 \cup dd2)$
98	$B \succ J$	$G \succ L$	$(o1 \cup u1, h2 \cup j2 \cup k2), (p1 \cup v1, a2 \cup b2 \cup h2 \cup i2 \cup j2 \cup k2 \cup l2)$
99	$\{BN\} \succ J$	$G \succ L$	$(o1 \cup u1, b2 \cup i2)$
100	$\{AN\} \succ J$	$G \succ L$	$(o1 \cup u1, c2 \cup d2))$
101	$A \succ J$	$G \succ L$	$(o1 \cup u1, e2), (p1 \cup v1, c2 \cup d2 \cup e2)$
102	$A \succ J$	$D \succeq H$	$(o1 \cup p1 \cup u1 \cup v1, f2 \cup g2)$
103	$B \succ J$	$H \succ P$	$(o1 \cup p1 \cup u1 \cup v1 \cup cc1 \cup dd1, n2)$
104	$\{BN\} \succ J$	L	$(o1 \cup u1, l2), (cc1, b2 \cup i2 \cup l2)$
105	J	$K \succ O$	$(q1 \cup s1, f2)$
106	G	$K \succ O$	$(q1 \cup r1 \cup s1, g2)$
107	G	O	$(q1 \cup s1 \cup w1 \cup y1, p2 \cup v2 \cup dd2 \cup ee2 \cup ff2), (r1 \cup x1 \cup z1, p2 \cup v2 \cup dd2), (w1 \cup x1 \cup y1 \cup z1, g2)$
108	$M \succ J$	$K \succ O$	$(r1, f2)$
109	$M \succ J$	O	$(r1, u2 \cup cc2)$
110	{GM}	O	$(r1 \cup x1, ee2 \cup ff2)$
111	J	$D \succeq H$	$(t1, f2)$
112	G	$D \succeq H$	$(t1, g2)$
113	G	H	$(t1, p2 \cup v2 \cup dd2 \cup ee2 \cup ff2), (aa1, g2 \cup p2 \cup v2 \cup dd2 \cup ee2 \cup ff2), (bb1, g2 \cup p2 \cup v2 \cup dd2), (ee1 \cup ff1, g2 \cup p2), (u1, ee2), (cc1, ee2)$
114	{GN}	H	$(u1 \cup cc1, ff2)$
115	{FG}	H	$(v1 \cup dd1, ee2 \cup ff2), (ee1, v2 \cup dd2 \cup ee2), (ff1, v2 \cup dd2)$
116	$M \succ J$	P	$(x1 \cup z1, c2 \cup d2)$
117	$M \succ J$	L	$(bb1, c2 \cup d2)$
118	$M \succ J$	H	$(bb1, f2 \cup o2 \cup u2 \cup cc2), (ff1, f2 \cup o2)$
119	{GM}	H	$(bb1, ee2 \cup ff2)$
120	$B \succ J$	L	$(o1 \cup p1 \cup u1 \cup v1, m2), (cc1, a2 \cup h2 \cup j2 \cup k2 \cup m2), (dd1, a2 \cup b2 \cup h2 \cup i2 \cup j2 \cup k2 \cup l2 \cup m2)$
121	$\{AN\} \succ J$	L	$(cc1, c2 \cup d2)$
122	$A \succ J$	L	$(cc1, e2),(dd1, c2, d2, e2)$
123	$D \succ J$	L	$(ee1, a2)$
124	$N \succ J$	L	$(ee1, b2 \cup c2 \cup d2 \cup i2 \cup l2), (ff1, b2 \cup i2 \cup l2)$
125	{FN}	L	$(ee1 \cup ff1, r2 \cup x2 \cup z2)$
126	J	H	$(ee1, f2 \cup n2 \cup o2), (ff1, n2)$
127	{FN}	H	$(ee1 \cup ff1, bb2)$
128	{FGN}	H	$(ee1, ff2)$
129	$N \succ M \succ J$	L	$(ff1, c2 \cup d2)$
130	$M \succ J$	L	$(ff1, e2)$
131	{FGM}	H	$(ff1, ee2)$
132	{FGMN}	H	$(ff1, ff2)$
133	$B \succ I \succ J$	$I \succ N \succ M \succ P$	$(e1, a2)$
134	$\{BIN\} \succ J$	$I \succ N \succ M \succ P$	$(e1, b2)$
135	$\{AIN\} \succ J$	$I \succ N \succ M \succ P$	$(e1, c2)$
136	$\{B\} \succ I \succ J$	$B \succ G \succ F \succ L$	$(f1, a2)$
137	$\{BIN\} \succ J$	$B \succ G \succ F \succ L$	$(f1, b2)$
138	$\{AIN\} \succ J$	$B \succ G \succ F \succ L$	$(f1, c2)$
139	$B \succ I \succ J$	$G \succ L$	$(o1, a2)$
140	$\{BIN\} \succ J$	$G \succ L$	$(o1, b2)$
141	$\{AIN\} \succ J$	$G \succ L$	$(o1, c2)$

References

Arthur, W. B., (1994) Increasing Returns and Path Dependence in the Economy. The University of Michigan Press, Michigan.

Becker, G., (1973) A theory of marriage: Part I. Journal of Political Economy, 91:813-846.

Burdett, K. and Coles, M., (1997) Marriage and class. Quarterly Journal of Economics, 112:141-168.

Cole, H., Mailath, G. and Postlewaite, A., (1992) Social norms, saving behavior, and growth. Journal of Political Economy, 100: 1092-1125.

Diamond, P. A., (1984) A Search Equilibrium Approach to the Micro Foundation of Macroeconomics. The MIT Press, Cambridge, Massachusetts.

Friedman, D., (1991) Evolutionary games in economics. Econometrica, 59:637-666.

Howitt, P., (1990) Costly Search Recruiting. In: Howitt P (ed.) Keynesian Recovery and Other Essays, 177-196. University of Michigan Press, Ann Arbor, Michigan.

Kandori M, Mailath G. J., Rob, R., (1993) Learning, mutation, and long run equilibrium in games. Econometrica, 61:29-56.

Kobayashi, K., Roy, J. R., Fukuyama, K., (1998) Contacts with agreement: towards face-to-face communication modeling. The Annals of Regional Science, 32:389-406.

Krugman, P., (1991) Geography and trade. The MIT Press, Cambridge, Massachusetts.

Mayard-Smith, J., (1982) Evolution and the Theory of Games. Cambridge University Press, New York.

McMillan, J., Rothschild, M., (1994) Search. In: Aumann, R. J. and Hart, S., (eds.) Handbook of Game Theory, Vol.2:905-927. North Holland, Amsterdam.

Mortensen, D. T., (1982) The matching process as a noncooperative bargaining game. In: McCall, J. J., (ed.) The Economics of Information and Uncertainty, 233-258. University of Chicago Press, Chicago, Ilinois.

Rosenthal, R. W., Landau, H. J., (1979) A game-theoratical analysis of bargaining with reputations. Journal of Mathematical Psychology, 20:233-255.

Sattinger, M., (1995) Search and the efficient assignment of workers to jobs. International Economic Review, 36:283-302.

Vega-Redondo, F., (1996) Evolution, Games, and Economic Behaviour. Oxford University Press, UK.

Weibull, J., (1995) Evolutionary Game Theory. Cambridge University Press, New York.

Young, P., (1993) The evolution of conventions. Econometrica, 61:57-84.

Chapter 5

Communication Process with Bounded Memory

5.1 Introduction

In modern city, much idea and knowledge are aggregated. For exchange of idea among individuals is easy, aggregated effect and externality inefficiency are formed in large city. Face-to-face communication is an important method to exchange idea and knowledge among individuals. The process of such communication activity is characterized by relation with parter's decision. That is to say, for individuals, spontaneous intentions for spontaneous meetings is the premise of face-to-face communication forming. When community is formed by heterogenous individuals, communication forming is greatly affected by meeting partners' private information. If have no meeting partner' private information, individual just can get such information after meeting. On the other hand, if have meeting partners' complete information, it can decide the intension of meeting forming. So consider the possibility of meeting forming, it is possible to have efficient strategy for searching meeting parnter. If individual's preference and search strategy is heterogeneous, information pollution that special individual may receive more meeting applications than necessary may happen. During the process of search meeting partner, inefficiency phenomenon exists. Especially, when individual preference is heterogeneous, these prefered individuals form a group and repeating meeting with these limited members is considered. By heterogeneous preference and search strategy individuals' repeating meeting, social network and organization is sponteneously formed. Considering that meeting process is history dependent, information quantity that individual can retain become important problem. When capacity of memory is bounded, individual rational activity within limited scope can be reached.

By this assumption, individuals social network formed by learning activity within limited range is enlarged. But self-organization process of network by heterogeneous individuals is complex nonlinear question, it is difficult to get an analytic equilibrium solution. In this research, assuming heterogeneous individuals and their bounded memory, i analyzes communication process among individuals and its simulation. This chapter focuses on two person meetings that is the simplest but also most fundamental form of meetings. In what follows, general methodology is investigated in section 5.2. Section 5.3 focuses upon modeling of meeting process and simulation programme algorithm. Simulation experimentation and analysis is investigated in section 5.4.

5.2 Basic Methodology

For face-to-face communication process, search behaviors for meeting partner have important meaning. Regarding with search behaviors, there already exists search theory in operation research. Kobayashi (1993,1994,1998) propse a model to investigate homogeneous individuals repeating meeting process and analyze its negative externality of complexity and thin market phenomenon. The term complexity phenomenon refers to the negative externality that individual in a city have high frequency of meeting, so search cost of its partner become higher. Thin market phenomenon refers to the negative externality of partner choice. For individuals' preference is different, more than neccessary meeting application focus on special agent causes negative externality of information pollution. Assuming rational individual strategy choice and random utility theory, there are several proposals of rational individual decisional traffic behavior model, but have criticism about the property of rational individual decisional experience(Simon,1982). The motivation of individual's rational activity can not be completely achieved in disaggregated environment. There already exists literature that theoretically analyze the model under bounded rationality about the routing problem with bounded memory capacity (Barucci, 2000)(Aghion,1991)(Ferber,1979). But there is not research case applied to communication processes by face-to-face contacts.

In order to realize a two person meeting, two persons should intend to have a meeting. They have to agree with having a meeting. For getting high utility by meeting processes, individuals need to choose high utility partner. Forming such perfect meeting, it is critical to find meeting partner. But it is difficult to get the agreement from partner. Is or isnot possible to utilize meeting partner's information, meeting equilibriums formulated during meeting processes have different characteristics. It is considered that heterogeneous individuals repeating meeting form group among different preferences individuals. So it is possible to relieve information pollution of negative externality that matching application focus on special part of individuals.

It is neccessary that at least two persons agree to have a meeting for its forming and this individual must agree to have this meeting. The process of meeting formation (in brief, meeting process) is composed of 1) the process to find a potential meeting partner and 2) the process to negotiate whether they have a meeting or not. The former is called "the matching process", while the later "the agreement formation process". The meeting can be categorized into two: "spontaneous meetings" and "forced meetings", depending on whether it is formed by someone's order or by their spontaneous intentions. The former includes private meetings such as the one with friends and many business meetings by participants' free choices. The spontaneous meetings can be classified by "how potential meeting partners come to know each other" and "how they start their negotiation over meeting formation"(the matching technology). The later, on the other hand, is the meeting where one of the meeting members or the third party forces persons in concern to participate. In the forced meetings the person or the organization in power decides details of meeting formation. This chapter focuses on "the spontaneous meetings" to be realized by the people's free choices.

If have a meeting should be decided by individual's rationality. A rational individual may have 1)complete memory, 2)no memory, 3)bounded memory about its meeting history. 1) assume absolutely rational individual, but analyze such kind of phenomenon is impossible. 2) assume myopic activity but Kobayashi (1998) already have such kind of assumption. 3) assume rational individual with bounded memory. So assume individuals have bounded memory with meeting history. Comparing with myopic individual, we can analyze meeting equilibrium by influence of bounded memory with meeting history, social capital forming and heterogeneous individual sorting phenomenon.

5.3 Modeling of Meeting Process

5.3.1 Assumption

Assume heterogeneous individuals having repeating meeting process. Consider a city where m agents reside and search for meeting partners on their private information. It is impossible that more than two meetings start within sufficiently small time interval of $\Delta t(= (t+1) - t)$. At time t, the agent who are searching for meeting partners is choosen randomly. Agent $i(i \in [1, m])$ can memorize its meeting history, but the memory is bounded. At time t, the strategy of agents searching for their partners $B_i(t)$ is, 1)strategy 1 that searching from meeting history memory capacity $A_i(t)$ or 2)strategy 0 that searching from the outside of meeting parnters history memory, $\overline{A}_i(t)$. At any time t, if $A_i(t)$ does not reach the limitation of its capacity, agent i' meeting parter agent j should be pushed into directly. If the capacity of $A_i(t)$ already reach its limitation, firstly, randomly choose $j' \in A_i(t)$ and move from $A_i(t)$ to $\overline{A}_i(t)$. After meeting with agent j, agent i get its partner's utility v_j. When repeatly meet with same agent, utility will proportionaly decrease with counts of sucessful meeting $n^s_{1,ij}(t)$ but increase with the counts of not chosen $n^n_{1,ij}(t)$. So $v_{ij}(t) = v_j - \alpha \cdot n^s_{1,ij}(t) + \beta \cdot n^n_{1,ij}(t)$ $(\alpha, \beta isconstant)$.

5.3.2 Modeling of meeting

Assume that at time t, agent i chooses the strategy that can maximize its utility. If choose strategy 0, the expected utility will be $R_{\overline{A_i}}(t)$. If choose strategy 1, the expected utility will be $R_{A_i}(t)$. So at time t, the expected utility that agent i will get can be expressed by

$$R_i(t) = \max(R_{A_i}(t), R_{\overline{A_i}}(t)) \tag{5.1}$$

When choosing strategy 1, agent i will select partner agent j that having maximum expected utility from its history meeting memory group $A_i(t)$.That utility will be $R_{A_i}(t)$. If choosing strategy 0, utility $R_{\overline{A_i}}(t)$ will be the expected utility of all agents. They are expressed by

$$R_{A_i}(t) = \max_{j \in A_i(t)} [(v_{ij}(t)) \cdot E^s[P_{1,ij}(t)]] \tag{5.2-a}$$

$$R_{\overline{A_i}}(t) = (\overline{v}) \cdot E^s[P_{0i}(t)] \tag{5.2-b}$$

$E^s[P_{1,ij}(t)]$ is the subjective probability of agent i meeting with agent j. During time interval $[0, t]$, it can be calculated by the counts of meeting with partners $n^s_{1,ij}(t)$ and searching for partners $n^c_{1,ij}(t)$

$$E^s[P_{1,ij}(t)] = (n^s_{1,ij}(t))/(n^c_{1,ij}(t)) \tag{5.3}$$

Here $\overline{v} = \frac{1}{m}\sum_{i=1}^{m} v_i$. When choosing strategy 0, the subjective probability can be calculated by the counts of successful meeting with partners $n^s_{0,i}(t)$ and the counts of choosing partners $n^c_{0,i}(t)$ from $B_i(t) = 0$

$$E^s[P_{0,i}(t)] = (n^s_{0,i}(t))/(n^c_{0,i}(t)) \tag{5.4}$$

At time t, considering the action that agent i searching for partner agent j, it compare the reservation utility $H_i(t)$ with the utility that can earn from meeting with agent j v_j,then decide if will meet with that agent j. Reserved utility at time t can be decided by the expected utility of $\hat{t} \in [0, t]$.So when taking strategy $B_i(t) = 1, 0$, reserved utility can be expressed by

$$H_i(t) = \begin{cases} R_{A_i}(\hat{t}), B_i(\hat{t}) = 1 \\ R_{\overline{A_i}}(\hat{t}), B_i(\hat{t}) = 0 \end{cases} \tag{5.5}$$

5.4 Simulation Experimentation

5.4.1 Exogenous variables and parametters setting

The number of agents is $m = 100$. For each agent, utility is $v_i = i$. At base case, the maximum members of meeting memory group is $x = 3$. For comparation, unbounded memory case 1 is analyzed. Parameters α,β are set to 1.0. The average of ten times simulation result is showed below.

5.4.2 Experimental results and analyses

Social welfare is defined by the sum of utility that all agents earn during time interval t. Figure 5.1 is the counts of each agent searching for partners during $t = 1,000,000$ for base case. From this simulation result, we can find the phenomenon of information pollution that higher utility agents are more often chosen for potential parters.

Figure 5.2 shows the count of meeting of agent $v = 75$ during [0, 1,000,000] for case 1. The result show that most of the meeting partners' utility just around 75. So when searching for partners, those agents that have similar utility easily form groups. This is called sorting when searching for partners each other.

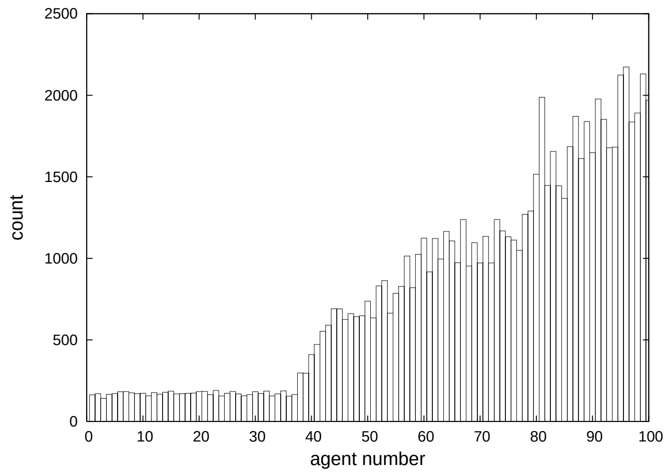

FIGURE 5.1: The counts of searching

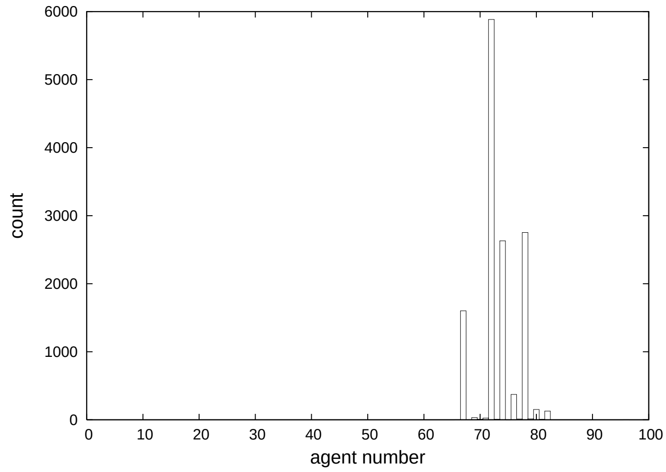

FIGURE 5.2: The counts of meeting(case 1)

5.4.3 Factors analysis

During simulation experimentation, we set exogeneous variables n number of agents, x maximum members of meeting memory group, parameters α and β when calculate bounded utility, length of simulation time constant. The function of utility v_j follows uniform distribution. Among these factors, we analysize the

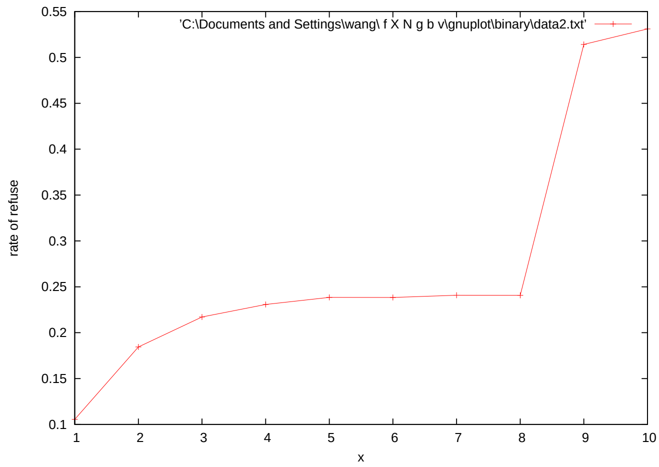

FIGURE 5.3: Average ratio of refuse with maximum of meeting memory group

effect that each of them affect the simulation results and find the key factor that decide the results.

5.4.3.1 Information pollution

To check information pollution, we use the ratio of refuse which is the counts of refuse(not success) to counts of choosing partners. The average ratio of refuse $\overline{r}(t)$ can be formulated by

$$\overline{r}(t) = 1 - n^s(t)/n^c(t) \tag{5.6}$$

Firstly, we analyze the effect of maximun members of meeting memory group x that decided by the capacity of memory. Setting other factors constant, we adjust x to check the ratio of refuse.

Observation 1: *The average ratio of refuse increases with increase in the capacity of memory*

Figure 5.3 shows the average ratio of refuse by $x = 1 \sim 10$ maximum members of meeting group.

With the growing of x, the average ratio of refuse grows. So factor x influence the ratio of counts of not success meeting to counts of choosing partners. This

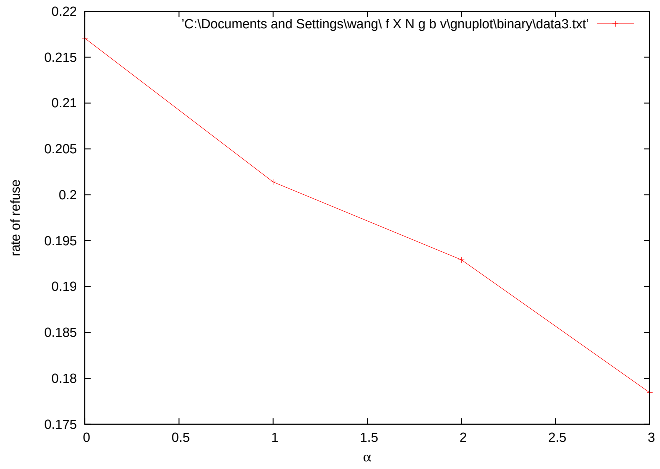

FIGURE 5.4: Rate of refuse with parameter of bounded utility

ratio shows degree of information pollution. Secondly, we analyze the effect of α, the parameter of bounded utility.After setting other factors constant, we adjust α from $0 \sim 3$ to check the average ratio of refuse.

Observation 2: *The average ratio of refuse decreases with increase in parameter* α

Figure 5.4 shows the average ratio of refuse by parameter of bounded utility $\alpha = 0 \sim 3$. With the growing of α, the average rate of refuse decreases.

Thirdly, we analyze the effect of time intervals $t = 100000, 200000, 300000, 400000$. The simulation experimential results show the ratio of refuse almost does not change with t.

For each agent, we describe degree of information pollution by the ratio of counts of successful meeting to counts of being chosen.

Observation 3: *The ratio of counts of successful meeting to counts of being chosen for lower utility decreases with increase in capacity of memory*

Observation 4: *The ratio of counts of successful meeting to counts of being chosen for higher utility increases with increase in capacity of memory*

In Figure 5.5 and Figure 5.6, we note that these two curves have contrary direction. For agent with lower utility, with increase in capacity of memory, the count of being chosen as potential partner decrease and the meeting count also decrease. For agent with higher utility, with increase in capacity of memory, the count of

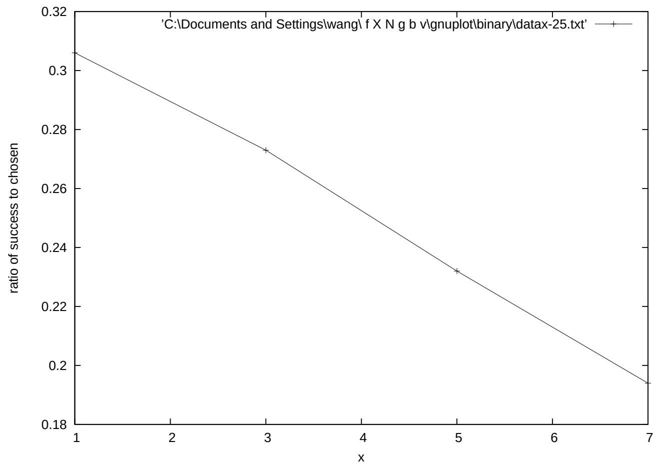

FIGURE 5.5: Ratio of counts of successful meeting to counts of being chosen for agent(25)

being chosen as potential partner increase, but the count of successful meeting approximately keep stable. Information pollution influence higher utility agents more with increase of capacity memory.

5.4.3.2 sorting

In the simulation, we set other factors constant, just let capacity of memory x change to check the sorting phenomenon for different utility agents.

Observation 5: *Sorting phenomenon emerges with increase in capacity of memory x.*

In these figures, we note that, agents with higher utility easily form group than agents with lower utility with increase in capacity of memory x.

5.5 Summary and Recommondations

In this chapter, we have presented face-to-face communication process with bounded memory. The results show, agents with similar utility form a group, sorting phenomenon emerge when repeating meeting within group. Sorting relieve the phenomenon of information pollution by searching for special agents. The capacity of

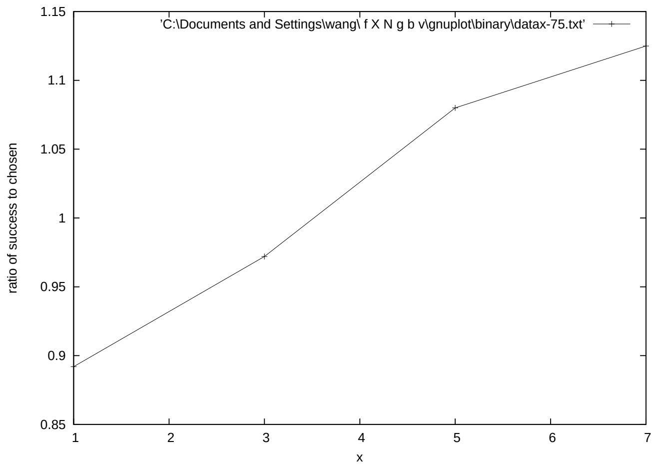

Figure 5.6: Ratio of counts of successful meeting to counts of being chosen for agent(75)

memory is not the key factor to cause information pollution and sorting. Utility function is also one candidate of factor to affect these two phenomenon.

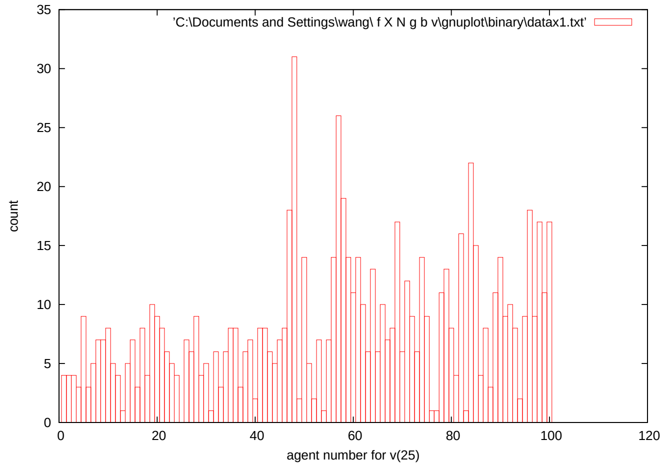

FIGURE 5.7: Counts of successful meeting for agent(25) for x=1

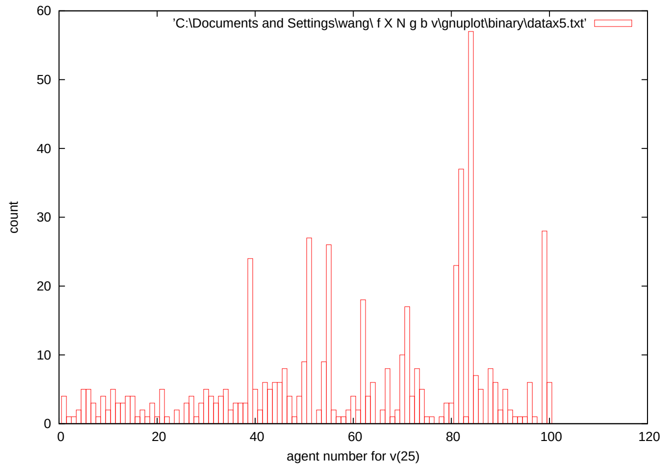

FIGURE 5.8: Counts of successful meeting for agent(25) for x=5

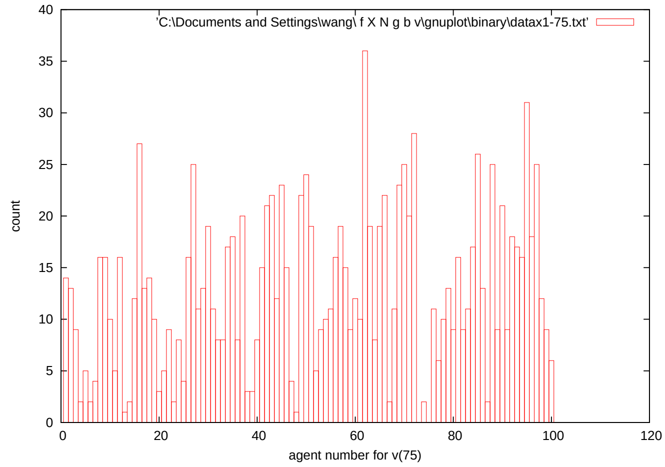

FIGURE 5.9: Counts of successful meeting for agent(75) for x=1

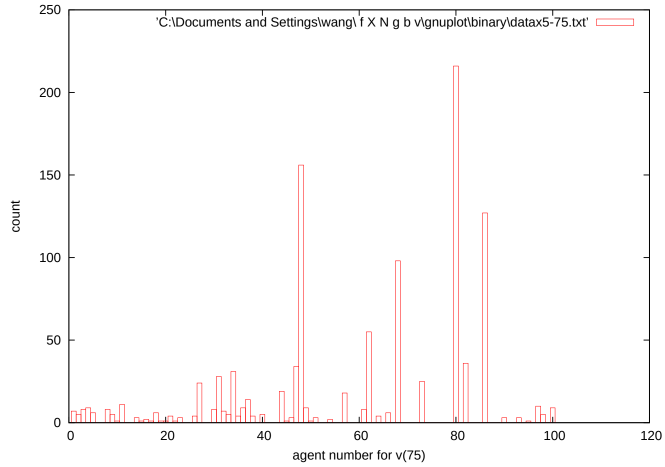

FIGURE 5.10: Counts of successful meeting for agent(75) for x=5

References

Barucci,E., (2000) Exponentially fading memory learning in forward looking economic models. Journal of ecnomic dynamics and control, Vol.24:1027-1046.

Kobayashi, K., (1993) Incomplete information and logistical network equilibria. The Cosmo-Creative Society, Berlin:Springer-Verlag.

Kobayashi, K., Sunao, S. and Yoshikawa, K., (1993) Spatial equilibria with knowledge production with meeting facilities. The Cosmo-Creative Society, Berlin:Springer-Verlag.

Kobayashi, K., (1994) Information, rational expectations and network equilibria. The Annals of Regional Science, 28:369-393.

Kobayashi, K., Roy, J. R., Fukuyama, K., (1998) Contacts with agreement: towards face-to-face communication modeling. The Annals of Regional Science, 32:389-406.

P Aghion, P Bolton, C Harris, B Jllien (1991) Optimal learning by experimentation. The review of economic studies, Vol.58:621-654.

Robert, Ferber and Werner, Z. H., (1979) Social experiments in economics. Journal of econometrics 11:77-115.

Simon, H., (1982) Models of bounded rationality. The MIT press.

Chapter 6

Conclusions

This chapter concluds and summarizes the entire chapters in the dissertation. Each chapter has been thoroughly discussed and deliberated within the scope of works aimed for the study. The conclusions are as follows:

- Chapter 1 clarified the imporatnace of traffice behaviour modelling based on the "communication with others", and attempted to abstract about the methodology to explicitly take into account the development of the information/transportation technologies, in order to advance the traffic policies in the era of the knowledge society.

- In chapter 2, the model described is limited in scope. One cannot draw policy conclusions directly from such a model. There are two purposes for its construction. One is to form a basis for further generalization. In particular, it would be interesting to introduce a search à la Diamond to examine how individuals can coordinate the matching process (Diamond and Maskin 1979; Diamond 1982).The second proposal is to provide an example to contrast with traditional travel behavior models that assume, unrealistically, the absence of mutual agreements and interactions in making decisions about face-to-face communications. Recently, travel demand modeling has been shifting its focus from the traditional trip-based modeling to the activity-based modeling approach (Spear 1996) in which the trip is regarded as one of several options for satisfying the activity, recognizing interpersonal dependencies. In corporation this activity-based approach into the meeting modeling may be beneficial.While the construction of realistic models of human contacts is needed for good communications policy analysis, the existence of this simple model indicates the possibility of constructing consistent behavioral models based on the existence of mutual agreements.

- In chapter 3, we point out that the face-to-face communication is composed of the search behavior for the meeting partners and the agreement formation behavior. The individual meeting behavior is then expressed by using Bellman's principle of optimality. Moreover, the meeting equilibrium to realize in the long-term is described as the rational expectations equilibrium. The properties of the meeting behavior and meeting equilibrium are then clarified. One important result obtained in this study is that the better transportation and communication technologies bring about not only the increased volume of traffic demands but also the qualitative change of increased additive value of meetings.

- In chapter 4, we have presented a model of pair wise face-to-face communications within a large population of heterogeneous agents, and investigated the resulting meeting equilibrium. We have shown that the meeting equilibrium patterns depends highly upon the heterogeneity of agents' preferences and also information availability. We find that while information about types of meeting partners can certainly increases the efficiency of the individual behavior, it does not always improve the natural selection mechanisms. We also show that in order to rescue the agents from meeting coordination failures, policy means by which the society can evolve into more communication-activated equilibrium should be implemented to modify natural selection mechanisms.

- In chapter 5, we had presented face-to-face communication process with bounded meomory. The results show, agents with similar utility form a group, sorting phenomenon emerge when repeated meeting within group. Soring relieve the phenomenon of information pollution by searching for special agents. The capacity of memory is not the key factor to cause information pollution and sorting.